The Long Term Impact of Thinning on Water Yield

by

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Abstract

The city of Melbourne, Australia, relies on forested catchments for most of its water supply. Up to 80% of the total catchment yield originates from mountain ash (Eucalyptus regnans) forests. Forest thinning has been considered as a management option to optimise the water yield of young mountain ash forests, but its long term impact has not been well understood. This study investigated the long term impact of different thinning treatments on vegetation structure and water yield in mountain ash forests so they can be predicted accurately in the future.

The study was conducted at the North Maroondah experimental catchments. A range of thinning treatments (patch-cutting, uniform thinning, understorey removal and strip-thinning) was applied to those catchments in the late 1970s. Most of the thinning treatments resulted in a statistically significant monthly increase in water yield that persisted for more than a decade or until the suspension of streamflow measurement in 1997. The largest cumulative water yield increase in this period was 1833 mm at Crotty Creek. A decrease in water yield was observed in these catchments when the measurement resumed in 2007/2008. The exception to this was Ettercon 2 (understorey removal), where non-significant increase in monthly water yield appeared to persist when the measurement resumed.

Vegetation structure attributes were obtained using Light Detection and Ranging (LiDAR) technology to assess the impact of thinning. The persistence of the water yield increase could be attributed to poor regeneration of mountain ash in the cleared areas after the treatment. The canopy height profiles showed that patch-cutting and strip-thinning have permanently altered the vegetation structure of the catchments, while the impact of uniform thinning on vegetation structure could no longer be identified.

The spatial distribution of leaf area index (LAI) at catchment level was obtained from Quickbird multi-spectral imagery and LiDAR data. The remote sensing parameters were initially calibrated against the in situ LAI measurements obtained by cover and hemispherical photography at Crotty Creek. However, the calibration models were poor because the photography techniques overestimated LAI in the regrowth stands. The LAI distribution was projected based on LiDAR gap fractions.
The remotely sensed overstorey LAI distribution showed that the mean LAI estimate of Ettercon 2 (1.7) was lower than the mean LAI estimate of the control catchment (2.2). This implied that Ettercon 2 had lower ET than the control catchment, which might explain the persistence of the modest water yield increase. However, the overstorey LAI distributions of the other thinned catchments did not fully explain the post-thinning decrease in water yield as their mean catchment LAI estimates were lower than the mean LAI estimate of the control catchment.

The mean overstorey daily transpirations were 0.7 mm day\(^{-1}\) and 1.5 mm day\(^{-1}\) for the regrowth vegetation stands (mainly of *Acacia* spp.) and the retained mountain ash stands at Crotty Creek respectively. In addition to the difference in mean overstorey LAI estimates, the regrowth *Acacia* stands have lower sap flux density and stomatal conductance than the retained mountain ash stands. The transpiration of the regrowth *Acacia* stands is not likely to replace the transpiration of the removed mountain ash stands even if they have similar LAI. Thus, it was hypothesised that the post-thinning decrease in water yield was due to the increased transpiration of the retained mountain ash stands as well as the transpiration of the regrowth vegetation stands.

The recent drought that affected south eastern Australia might have also amplified the magnitude of the water yield decrease. The transpiration measurements indicated that stand transpiration was controlled by evaporative demand rather than water availability. The transpiration was maintained at a high rate during the period of low rainfall at the expense of streamflow.

This study has confirmed that the post-thinning changes in vegetation structure could account for the observed changes in water yield in mountain ash catchments. It has also shown that LAI spatial distribution can be robustly obtained from remote sensing data, particularly from LiDAR data. However, vegetation composition and canopy structure need to be incorporated along with LAI distribution in a process-based hydrological model to model the post-thinning ET of the complex forest structure and predict the long term changes in water yield.
Declaration

I declare that the thesis comprises only my original work towards the PhD. I have made due acknowledgement in the text to all other material used. The thesis is fewer than 100,000 words in length, exclusive of tables, maps, bibliographies and appendices.

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# Table of Contents

Abstract ............................................................................................................................... i
Declarations ........................................................................................................................... iii
Acknowledgements ............................................................................................................... iv
Table of Contents .................................................................................................................. vi
List of Figures ........................................................................................................................ ix
List of Tables ........................................................................................................................ xii

## Chapter 1. Introduction

1.1 Context of the Study ........................................................................................................ 2
1.2 A Review of Mountain Ash Catchment Hydrology ........................................................ 4
1.3 Aim and Research Questions ........................................................................................ 7
1.4 Thesis Structure ............................................................................................................. 8

## Chapter 2. North Maroondah Experimental Catchments

2.1 The Black Spur Catchments ........................................................................................ 15
2.2 The Ettercon Catchments ............................................................................................ 18
2.3 The Crotty Creek Catchment ....................................................................................... 19
2.4 Recent Hydrological and Meteorological Data Collection ........................................... 20

## Chapter 3. The Long Term Changes in Water Yield

3.1 Pre-Treatment: Establishment of Linear Regression Models ....................................... 25
3.2 Post-Treatment: Changes in Water Yield Immediately after Thinning ......................... 30
3.3 Post-Treatment: Recent Measurement Data .................................................................. 37
3.4 Discussion .................................................................................................................... 38
3.5 Conclusion ................................................................................................................... 40

## Chapter 4. Changes in Vegetation Structure based on LiDAR Measurements

4.1 Using LiDAR to Obtain Vegetation Structure Attributes ............................................. 44
   4.1.1 LiDAR specification ............................................................................................. 45
   4.1.2 Data extraction .................................................................................................... 46
4.2 Impact of Thinning Treatments on Vegetation Structure .............................................. 48
4.3 Discussion .................................................................................................................... 56
4.4 Conclusion ................................................................................................................... 58

## Chapter 5. In Situ and Remote Sensing Measurements of Leaf Area Index

5.1 Literature Review .......................................................................................................... 61
   5.1.1 In Situ Measurements of LAI ............................................................................... 61
   5.1.2 Remote Sensing Measurement of LAI ................................................................. 67
5.2 Experimental Design and Procedures ........................................................................... 69
5.2.1 Sampling Strategy at Black Spur ................................................................. 70
5.2.2 Sampling Strategy at Crotty Creek ............................................................. 72
5.2.3 In situ LAI Estimates ................................................................................. 75
5.2.4 Remote Sensing Parameters ...................................................................... 80
5.2.5 Statistical Analysis ..................................................................................... 85
5.3 Results ............................................................................................................. 87
   LAI Estimates from the Pilot Study at Black Spur ........................................... 87
      5.3.1 ........................................................................................................... 87
5.3.2 LAI Estimates at Crotty Creek ................................................................. 89
5.3.3 Modelling LAI Distribution with Remote Sensing Parameters .............. 91
5.3.4 Projection of LAI Spatial Distribution Maps ............................................ 96
5.4 Discussion ....................................................................................................... 105
   LAI distributions ............................................................................................ 105
5.4.1 ............................................................................................................... 105
5.4.2 The Impact of Site Configuration on LAI Measurements at Crotty Creek .. 107
5.4.3 Uncertainties in LAI Measurements .......................................................... 108
5.4.4 Comparison of Techniques ..................................................................... 111
5.5 Conclusion ..................................................................................................... 112

Chapter 6. Estimation of Transpiration with Sap Flow Measurements .......... 115
6.1 Transpiration Measurements in Mountain Ash Forests ............................ 117
6.2 Experimental Design and Procedures .......................................................... 118
6.2.1 Sampling Strategy and Plot Description .................................................... 118
6.2.2 Weather Data Collection ......................................................................... 121
6.2.3 Measurement of Sapwood Width and Sapwood Area ............................ 122
6.2.4 Transpiration of Individual Trees .............................................................. 122
6.2.5 Transpiration at Stand and Catchment Levels ....................................... 124
6.2.6 Stomatal Conductance ............................................................................. 125
6.2.7 Transpiration Model ............................................................................... 126
6.2.8 Catchment Water Balance ....................................................................... 126
6.3 Results .......................................................................................................... 127
   Transpiration Volume .................................................................................... 127
6.3.1 ............................................................................................................... 127
6.3.2 Stomatal Conductance ............................................................................. 132
6.3.3 Transpiration Model .............................................................................. 133
6.3.4 Catchment Water Balance .................................................................... 135
6.4 Discussion ..................................................................................................... 137
   Transpiration Volume .................................................................................... 137
6.4.1 ............................................................................................................... 137
6.4.2 Factors Controlling Transpiration ............................................................ 138
6.4.3 Water Balance ......................................................................................... 140
6.5 Conclusion .................................................................................................... 142
Chapter 7. General Discussion................................................................. 143
  7.1 Summary of Findings........................................................................ 144
  7.2 Post-thinning Interaction of Vegetation Structure and Water Yield...... 147
    7.2.1 Crotty Creek ........................................................................... 147
    7.2.2 Comparison of Different Thinning Treatments ......................... 149
  7.3 General Implication of Findings.......................................................... 152
    7.3.1 Post-Thinning Water Yield........................................................ 152
    7.3.2 Measurements of LAI with Remote Sensing .............................. 153
    7.3.3 Transpiration........................................................................... 153
  7.4 Recommended Future Work .............................................................. 154
Chapter 8. Conclusion.............................................................................. 157
Chapter 9. References............................................................................. 161
List of Figures

Figure 1.1. A general relationship between mean annual streamflow of mountain ash forest and forest age established by Kuczera (1985, 1987). Source: Vertessy et al. (2001). ......................................................... 5

Figure 1.2. The changes in the water balance components of mountain ash stands in the Maroondah catchments over time, with a mean annual rainfall of 1800 mm. The vertical markers indicate the start of the thinning experiments and the start of this study ................................................................. 7

Figure 3.1. Plots of predicted values against residuals from: (a) linear regression model and (b) logarithmic regression model, Ettercon 1 ................................................................. 27

Figure 3.2. Seasonality was detected in the plot of residuals against time, Ettercon 1 ........................................ 27

Figure 3.3. Correlogram of Ettercon 1 residuals: log model, log/sinusoidal model and log/sinusoidal model without AR1 component (disturbance series) ................................................... 29

Figure 3.4. Pre-treatment disturbance values with 95% prediction intervals, Crotty Creek ................................ 29

Figure 3.5. Post-treatment monthly water yield changes and disturbance series of Black Spur 1 (patch-cutting) and Ettercon 2 (removal of understorey vegetation). The treatment effects are significant if more than 5% of the disturbance values fall outside the prediction intervals ................................................................. 31

Figure 3.6. Post-treatment monthly water yield changes and disturbance series of Black Spur 2 and Black Spur 3 (uniform thinning). The treatment effects are significant if more than 5% of the disturbance values fall outside the prediction intervals ................................................................. 32

Figure 3.7. Post-treatment monthly water yield changes and disturbance series of Ettercon 1, Ettercon 4 and Crotty Creek (strip-thinning). The treatment effects are significant if more than 5% of the disturbance values fall outside the prediction intervals ................................................................. 33

Figure 3.8. Mean monthly treatment effects from the treated catchments ............................................................. 34

Figure 3.9. Cumulative annual treatment effects (a) and a time series of annual treatment effect (b) of the treated catchments ................................................................. 35

Figure 4.1. Three dimensional representation of LiDAR’s vegetation hits from a mountain ash stand. .......... 47

Figure 4.2. Maps of maximum vegetation height of (a) Black Spur 1 (patch-cutting), (b) Black Spur 2 and Black Spur 3 (uniform thinning) derived from LiDAR data ......................................................... 49

Figure 4.3. Maps of maximum vegetation height of (a) Ettercon 2 (understorey removal), (b) Ettercon 3 (control catchment) derived from LiDAR data ................................................................. 50

Figure 4.4. Maps of maximum vegetation height of (a) Ettercon 1, (b) Ettercon 4 and (c) Crotty Creek derived from LiDAR data ................................................................................................. 51

Figure 4.5. Aerial view of the Black Spur catchments taken immediately after the treatments in October 1977. Source: Figure 4.2, Third Progress Report – North Maroondah (Aney and O’Shaughnessy 1994) ............................................. 52

Figure 4.6. Average canopy height profiles of the Black Spur 1 (patch-cutting), Black Spur 2 (uniform thinning) and Black Spur 3 (uniform thinning) ......................................................... 53

Figure 4.7. Average canopy height profiles of Ettercon 2 (removal of understorey vegetation) and Ettercon 3 (control catchment) ................................................................................................. 54
Figure 4.8. Average canopy profiles of the strip-thinned catchments: Ettercon 1, Ettercon 4 and Crotty Creek. ......................................................................................................................................................... 55
Figure 5.1. Locations of measurement points in the undisturbed area at Black Spur. ................................. 71
Figure 5.2. Layout of a transect spanning two pairs of retained and regrowth strips. ................................. 72
Figure 5.7. An example of the location of SVI extraction window relative to the in situ LAI photography point. ........................................................................................................................................................... 82
Figure 5.8. Distribution of ARVI values for a range of window sizes. .......................................................... 83
Figure 5.11. The best fit model that predicts hemispherical PAI estimates at 11 m based on GNDVI data. 93
Figure 5.12. The best fit models that predict cover Le estimates at 3 m and 11 m based on LiDAR gap fractions derived using various plot diameters. ........................................................................................... 94
Figure 5.13. Scatter plots of LiDAR's gap fractions against gap fractions from canopy photography. Hem refers to hemispherical photography. ................................................................................................. 95
Figure 5.15. GNDVI distributions of the Ettercon and Black Spur catchments. Areas affected by clouds have been masked and appear black ........................................................................................................ 97
Figure 5.16. GNDVI distributions of Crotty Creek. Areas affected by clouds have been masked and appear black. .......................................................................................................................................................... 98
Figure 5.18. Projected effective LAI distribution map of Black Spur catchments at 3 m and 11 m. 100
Figure 5.19. Projected effective LAI distribution map of Ettercon catchments at 3 m and 11 m. ............... 101
Figure 5.20. Projected effective LAI distribution maps of Crotty Creek at 3 m and 11 m. ......................... 102
Figure 5.21. Mean total and overstorey effective LAI (Le) of the thinned North Maroondah catchments derived from LiDAR data. The error bar indicates standard error of the distribution. 103
Figure 5.22. The comparison of mean effective Le derived from LiDAR, hemispherical photographs and cover photographs at 3 m and 11 m at Crotty Creek. ...................................................................................... 105
Figure 5.23. A diagram of LAI measurements taken in two neighbouring regrowth and retained stands. The difference in vegetation heights resulted in the intrusion of foliage elements in the viewing range of the regrowth stand. ......................................................................................................................................... 108
Figure 5.24. Cover photograph from Crotty Creek that shows two canopy layers, the foliage elements in the layer closest to the camera appear larger than those behind them. .......................................................................... 110
Figure 6.1. Map of overstorey vegetation classification at Crotty Creek, derived from LiDAR data. E. regnans marks the retained strip and Acacia marks the cleared strips. The map also shows the locations of sample plots used in the transpiration measurements (R1, C1, R2, C2) and remote sensing measurements. ............................................................................................................................................... 119
Figure 6.2. (a) A sample layout of the heat probes around the stem, (b) heat probe installation on a mountain ash tree. .............................................................................................................................................. 123
Figure 6.3. The relationships between diameter at breast height (dbh) and sapwood area (SA) in mountain ash (circle) and Acacia (triangle) stands. .............................................................................................. 128
Figure 6.4. Mean daily sap flux density of four sample plots: (a) Retained 1 and Cleared 1, (b) Retained 2 and Cleared 2. .................................................................................................................................................. 129
Figure 6.5. Mean daily transpiration of mountain ash (E. regnans) overstorey, Acacia overstorey and Acacia understorey. ................................................................................................................................. 130
Figure 6.6. Monthly transpiration from December 2009 to January 2011. .................................................. 131
Figure 6.7. Stomatal conductance of mountain ash overstorey, Acacia understorey and Acacia overstorey as functions of mean daytime vapour pressure deficit. ................................................................. 133
Figure 6.9. The components of water balance for the period of 10 December 2009 to 31 December 2010. .................................................................................................................................................. 135
List of Tables

Table 2.1. General characteristics and treatment types of the thinned catchments in the North Maroondah experiment. ................................................................................................................................................. 14
Table 2.2. The pre-thinning characteristics of mountain ash stands in the Black Spur catchments. .......... 15
Table 2.3. Post-thinning changes in top height, stocking rate and basal area increment at the Black Spur catchments.................................................................................................................... 17
Table 3.1. Parameters of the linear regression model of paired catchment ................................................ 28
Table 4.1. LiDAR system configuration and flight detail ............................................................................. 46
Table 5.1. Summary of direct methods to measure LAI. .............................................................................. 62
Table 5.2. Summary of indirect methods to measure LAI. ......................................................................... 63
Table 5.3. Parameter settings used to analyse hemispherical photographs in Hemisfer. ............................... 76
Table 5.4. Parameters required for LAI estimation from cover photograph. ............................................... 78
Table 5.5. Specification of the Quickbird multi-spectral image .................................................................... 81
Table 5.6. Spectral vegetation indices used to model LAI estimates in this study. ........................................ 84
Table 5.7. Mean leaf area index (LAI) from cover and hemispherical photographs obtained at different heights. The standard errors are given in parentheses and 'n' is the number of samples. ......................... 88
Table 5.8. Comparisons of PAI distributions based on heights, strips and photography techniques. The results were statistically significant at p < 0.05, unless when marked as N/S (not significant)................. 91
Table 5.9. Summary of the best regression models between SVIs and in situ PAI........................................ 92
Table 5.10. Summary of the best regression models between LiDAR gap fractions and in situ L_e .................. 92
Table 6.1. Detail of sample plots, overstorey and understorey species, basal area and sapwood area... 120
Table 6.2. Characteristics of sample trees and the number of probes in each tree. ................................. 121
Table 6.3. The best regression models that predicted sapwood area (SA) from diameter at breast height (dbh) for mountain ash (E. regnans) and Acacia................................................................................................................................. 127
Table 6.4. Mean daily sap flux density and mean daily transpiration of the major vegetation groups at Crotty Creek from 10 December 2009 to 31 December 2010, with the proportion of catchment area associated with each vegetation group. Standard errors are presented in bracket. ......................................................... 132
Table 6.5. General linear regression models that describe the relationship between mean daytime VPD and stomatal conductance of the overstorey stands ........................................................................... 132
Table 6.6. Second degree polynomial regressions that model the mean daily transpiration of the overstorey stands based on daily maximum VPD. ..................................................................................... 134
Table 6.7. Catchment water balance of annual water year (April to March). The unspecified volume refers to components of water balance that have not been measured or estimated. ....................................................... 136
Table 7.1. Summary of findings from previous chapters. ............................................................................ 145
Chapter 1. Introduction

Mountain ash stands at Black Spur
# 1.1 Context of the Study

Forested catchments provide water supply to many cities around the world, including Melbourne. Melbourne’s water catchments are located in the central highlands of Victoria. Approximately half of the total catchment area is covered by mountain ash (*Eucalyptus regnans*) forests, which produce 80% of the mean annual streamflow because they grow in high rainfall regions. Thus, understanding the interaction between vegetation and water yield in these catchments is crucial in the management and security of future water supply.

Most studies have shown that the removal of vegetation cover in forested catchments generally results in an increase in water yield (Bosch and Hewlett 1982, Brown *et al.* 2005, Hornbeck *et al.* 1993, Stednick 1996, Swank *et al.* 2001). The magnitude of the increase has been often be related to the reduction in basal area and mean annual rainfall. However, the water yield increase can turn into a water yield decrease as the forest regenerates (Baker 1986, Cornish 1993, Hornbeck *et al.* 1993, Langford 1976, Swank *et al.* 2001). In particular, the regeneration of mountain ash forests after the 1939 wildfires has resulted in 24% reduction of the pre-fire average streamflow in the period of 1944 – 1964 (Langford 1976).

The decrease in water yield in mountain ash forests has been subsequently linked to the relationship between stand age and water yield (Dunn and Connor 1993, Haydon *et al.* 1997, Jayasuriya *et al.* 1993, Kuczera 1985, Langford 1976, Vertessy *et al.* 2001, Watson *et al.* 1999b). Fire enables the germination of mountain ash seedlings, which rapidly grow into dense, uniform-aged mountain ash stands (Ashton 1976). These young stands have higher evapotranspiration and lower catchment water yield than old-growth stands (200+ years) due to their stand density. The density of the stands decreases as they approach maturity so the catchment water yield gradually increases. The relationship between stand age and water yield has also been observed in *Eucalyptus sieberi* (Cornish 1993, Roberts *et al.* 2001) so it might be applicable to other eucalyptus forests.
Chapter 1: Introduction

The 1939 wildfires affected a large proportion of mountain ash catchments that supply water to Melbourne. As the decline in water yield approached its maximum in 1970s, there were some interests in the use of forest thinning to increase water yield (Langford and O'Shaugnessy 1977, O'Shaugnessy et al. 1981). Thinning was expected to increase water yield by reducing basal area and catchment ET. To investigate the impact of thinning treatments on water yield of the 1939 regrowth catchments, a range of thinning experiments were set up in the early 1970s in the North Maroondah area.

Several studies have reported the early results of the North Maroondah thinning experiments (Benyon 1992, Jayasuriya et al. 1993, O'Shaughnessy and Jayasuriya 1994, O'Shaugnessy et al. 1993). As expected, 20-30% increase in water yield was observed for several years after the treatment in most of the thinned catchments. However, those studies have not assessed the changes in water yield beyond the return of the post-thinning water yield towards the pre-treatment level. They also did not compare the impact of the different thinning treatments on vegetation structure and water yield.

The impact of thinning in other forest types has varied (Baker 1986, Hornbeck et al. 1993, Lane and Mackay 2001). Although the proportion of removed basal area might have influenced the water yield increase initially, the composition and amount of regrowth vegetation affected the changes in water yield over a longer term. The regrowth vegetation has also been cited as the cause of water yield decrease. Federer and Gee (1974) proposed that the transpiration of the retained vegetation would increase after strip-thinning or uniform thinning due to increased exposure to radiation, the clothesline effect and greater access to soil moisture.

The assessment of the long term impact of thinning is necessary if it was to be used as a management option to increase water yield. Thinning can transform the vegetation structure (stand density, basal area) of the uniform-age mountain ash forest into a complex, multi-species forest. Over time, the impact of the ageing process of the retained mountain ash stands on water yield might be offset by the water use of regrowth vegetation. Predicting the long term impact of thinning on water yield remains challenging as it must take into account its effect on the spatial distribution and composition of vegetation as well as the changes in vegetation structure due to age.
The response of vegetation stand to thinning is also of fundamental interest in ecophysiology in terms of the changes in plant water use and function.

This study investigated the long term impact of various thinning treatments (uniform, patch-cutting, strip-thinning and removal of understorey) on vegetation structure and water yield at the North Maroondah experimental catchments. The post-thinning interaction between vegetation structure and water yield was examined to establish whether the changes in water yield can be predicted from the changes in vegetation structure. The study utilised spatial distribution of leaf area index (LAI), obtained from remote sensing data, to represent the post-thinning changes in vegetation structure at catchment level. LAI is a biophysical parameter that links vegetation structure and ET. This approach would allow the modelling of post-thinning vegetation changes with a distributed, process-based model to estimate catchment ET and predict the changes in water yield.

1.2 A Review of Mountain Ash Catchment Hydrology

This section presents a review of the current knowledge on the hydrology of mountain ash catchment and its long term response to disturbance. The review was conducted to identify knowledge gaps and to formulate the research questions in this study. The relationships between stand age and the various water balance components of the Maroondah catchments have also been represented to show the expected changes in water yield since the thinning treatment.

Langford (1976) observed that there had been a decrease in water yield in the catchments that were dominated by 1939 regrowth mountain ash. He deduced that the changes in transpiration over time might be the main explanation for the observed changes in water yield. Kuczera (1985, 1987) expanded this idea further by creating a regional two-parameter model to predict long term mean annual water yield trend in mountain ash forests, fitted with data from eight of Melbourne’s water supply catchments. Kuczera’s curve (Figure 1.1) shows a rapid decline in water yield by 20 to 30 years after forest regeneration, then its slow recovery to the pre-disturbance level when the forests reaches maturity at the age of 100 to 150 years.
Chapter 1: Introduction

Figure 1.1. A general relationship between mean annual streamflow of mountain ash forest and forest age established by Kuczera (1985, 1987). Source: Vertessy et al. (2001).

During the 1990s, a series of studies on the factors underlying the decrease of evapotranspiration with age in mountain ash were conducted. The following is a summary of their results:

- Dunn and Connor (1993) established that sap velocity of mountain ash does not vary with age.
- Jayasuriya et al. (1993) measured transpiration with the heat pulse method in plots of different age classes, showing that transpiration decreased with increasing age.
- Haydon et al. (1997) measured the variation in sapwood area and interception loss with stand age. They found that the peak interception loss of 25% occur at age 30, which then declined to 17% at age 200.
- Vertessy et al. (1995) established stem diameter as a reliable predictor of sapwood area, leaf area and transpiration in young mountain ash forests.
- Watson and Vertessy (1996) developed a model that predicts leaf area from stem diameter, which was then used to derive a curve that describes variation in LAI with forest age.
- Watson et al. (1999b) constructed a model of changes in total forest ET with age, fitted with data from paired catchment studies at North Maroondah. Expressed as changes in water yield over time, it was similar to Kuczera’s curve with a few minor
differences: increases in water yield are noted in the first few years of regeneration and the slower rate of recovery to the pre-disturbance level.

- Vertessy et al. (2001) found that decline in sapwood area index and LAI are the primary reasons for decrease in ET in older mountain ash stands. They also estimated the water balance components of mountain ash stands at different stand age. Interception and overstorey transpiration decreased over time, while understorey transpiration and streamflow increased.

All the above studies supported the hypothesis that water yield varies with forest age in mountain ash catchment. Changes in vegetation structural elements, such as sapwood area and leaf area index, over time contribute directly to changes in ET. The experimental results have also verified the roles of sapwood area and leaf area index in controlling ET. Figure 1.2 shows the changes in various water balance components of mountain ash stands in Maroondah catchments over time. The graph is based on the relationships between stand age and those water balance components (Vertessy et al. 2001). The two markers indicate the ages when the thinning experiment started at the North Maroondah catchments and the commencement of this study respectively. The difference in streamflow in this period is 82 mm, which would be the increase in water yield if thinning has not occurred.

Fewer studies have been conducted on the impact of thinning on water yield in mountain ash catchments. Jayasuriya et al. (1993) reported the impact of patch-cutting and uniform thinning in the Black Spur catchments, while Bren et al. (2010) reported the long term impact of uniform thinning in the Blue Jacket catchment. The Black Spur catchments were dominated by 1939 regrowth stands, while the Blue Jacket catchment was dominated by mature stands. Both studies have reported that 20% – 30% increase in annual water yield was observed for a few years after the thinning treatment, followed by a decrease in water yield. The post-thinning regeneration of mountain ash stands has been very limited as the seedlings were suppressed by the retained stands (Bren et al. 2010, O'Shaughnessy and Jayasuriya 1994). Neither of the studies attempted to explain the cause of the post-thinning decrease in water yield. Thus, the long term changes in vegetation structure must be examined to find the cause of the post-thinning decrease in water yield.
Figure 1.2. The changes in the water balance components of mountain ash stands in the Maroondah catchments over time, with a mean annual rainfall of 1800 mm. The vertical markers indicate the start of the thinning experiments and the start of this study.

1.3 Aim and Research Questions

The aim of the study was to investigate the long term impact of thinning on vegetation structure and water yield in order that they can be accurately predicted in the future with a hydrological model. To achieve the aim, the following research questions have been formulated:

- What are the long term hydrological responses to different thinning treatments?
- What are the long term vegetation structural responses to different thinning treatments, i.e. the amount of regeneration of mountain ash or emergence of understorey?
- What is the post-thinning spatial distribution of leaf area index (LAI)?
  - How can it be obtained robustly at catchment scale?
  - Can the change in evapotranspiration be inferred from LAI distribution?
Chapter 1: Introduction

- How do different thinning treatments affect LAI distribution?

All measurements have been conducted in the North Maroondah experimental catchments, which were dominated by the 1939 regrowth mountain ash stands. Initially, the impact of thinning on water yield in the thinned catchments was to be modelled in a distributed, process-based hydrological model based on their remotely sensed LAI distribution. However, the recommissioning of streamflow measurement at Melbourne Water’s catchments did not occur until mid-2008. A large wildfire disturbed those catchments in February 2009. The modelling part of the study was abandoned due to the brief streamflow measurement period.

1.4 Thesis Structure

This study was divided into several components to achieve the aim and answer the research questions. The first component quantified the post-thinning changes in water yield. The second component examined the post-thinning changes in vegetation structure. The third component obtained the spatial distribution of LAI based on \textit{in situ} and remote sensing measurements of LAI. The fourth component measured and compared the transpiration from the retained and regrowth stands. The findings from all the components were integrated to understand the interaction between the post-thinning vegetation structure and water yield.

The structure of this thesis reflects the components of the study. Each component has been presented as a self-contained chapter that covers the context, method, results and some discussion of the measurements. The order of the thesis structure can be outlined as follow:

- Chapter 2 describes the North Maroondah experimental catchments and the thinning treatments conducted in some of those catchments. It also summarises the findings from previous studies that have been conducted in the thinned catchments.
- Chapter 3 quantifies the impact of thinning treatments on water yield based on the results of paired catchment studies at North Maroondah experimental catchments.
Chapter 1: Introduction

- Chapter 4 assesses the impact of the thinning treatments on vegetation structure based on the vegetation height profiles were obtained with Light Detection and Ranging (LiDAR).
- Chapter 5 presents the *in situ* and remote sensing measurements of LAI. The remote sensing measurements were used to produce spatial distribution maps of LAI.
- Chapter 6 presents the results of sap flow measurements at Crotty Creek.
- Chapter 7 integrates the various components of the study to examine whether the post-thinning changes in vegetation structure can fully explain the changes in water yield. It also identifies and recommends future research work that can potentially address some unresolved issues.
- Chapter 8 presents the general conclusion of the study.
Chapter 2. North Maroondah Experimental Catchments

Crotty Creek, one of the North Maroondah experimental catchments
The North Maroondah Experiment was established in 1970 to investigate whether thinning in the regrowth mountain ash (*E. regnans*) forest and control of the initial regrowth density can benefit the long term management of water yield. It consisted of two catchments of old-growth forests and twelve catchments of 1939 regrowth forests. The two old-growth catchments were grouped as the Myrtle catchments, while the regrowth catchments were organised into three groups: Monda, Ettercon and Black Spur (Figure 2.1).

Langford and O'Shaughnessy (1977) described the establishment and characteristics of the North Maroondah experimental catchments in great detail. The catchments are located on the southern slopes of the Great Dividing Range, approximately 60 km northeast of Melbourne. The altitude of the area ranges between 470 to 890 m, with an annual rainfall of 1200 to 1800 mm. The climate is warm, temperate and rainy based on Köppen's classification. The monthly mean maximum temperature is 23°C in January and 9°C in July, while the monthly mean minimum temperature is 11°C in January and 4°C in July. The soils are deep krasnozems, formed from basic igneous rock. They have high permeability and water-holding capacity (soil water storage exceeds 5 m). Lateral flow through the hillslope is the dominant runoff process in the catchments. Davis *et al.* (1999) measured the saturated hydraulic conductivity of the subsoil layer as 1.6 m day⁻¹.

The Crotty Creek catchment was selected as an experimental catchment in 1975 (O'Shaugnessy *et al.* 1981). The aim was to examine the impact of thinning on streamflow and forest growth in a larger catchment than the North Maroondah catchments. Although it is located less than 1 km from the North Maroondah Experimental Area, it lies on the northern slopes of the Great Dividing Range. The catchment is considered to be part of the North Maroondah experimental catchments in this study (Figure 2.1).

This study focuses on the North Maroondah experimental catchments that have undergone thinning treatments: Black Spur, Ettercon and Crotty Creek. Mountain ash stands dominate the overstorey in these catchments. They were approximately 68 years old (1939 regrowth) at the start of the study. The understorey vegetation consists of *Acacia* species and wet sclerophyll species, such as silver wattle (*Acacia dealbata*),
blackwood (Acacia melanoxylon), hazel (Pomaderris aspera), musk daisy-bush (Olearia argophylla), balm mint-bush (Prostanthera melissifolia), mountain correa (Correa lawrenciana) and soft tree fern (Dicksonia antarctica). The general characteristics of the catchments and the thinning treatments are presented in Table 2.1. The next few sections summarise the application of the thinning treatments to the catchments and list available information (forest inventory, changes in streamflow) from previously published reports.

Figure 2.1. North Maroondah experimental catchments.
<table>
<thead>
<tr>
<th>Catchment</th>
<th>Area (ha)</th>
<th>Weir elevation (m)</th>
<th>Aspect (°)</th>
<th>Slope (°)</th>
<th>Planned removed basal area and thinning treatment</th>
<th>Calibration period</th>
<th>Treatment period</th>
</tr>
</thead>
<tbody>
<tr>
<td>Black Spur 1</td>
<td>17.0</td>
<td>521.5</td>
<td>205.6</td>
<td>7</td>
<td>60% Patch Cutting</td>
<td>August 1971 – December 1976</td>
<td>1976-1977</td>
</tr>
<tr>
<td>Black Spur 3</td>
<td>7.7</td>
<td>510.6</td>
<td>119.9</td>
<td>13.8</td>
<td>60% Uniform Thinning</td>
<td>August 1971 – February 1977</td>
<td>1977</td>
</tr>
<tr>
<td>Ettercon 1</td>
<td>11.6</td>
<td>835.0</td>
<td>201.7</td>
<td>7.2</td>
<td>50% Strip Thinning</td>
<td>August 1971 – December 1981</td>
<td>1982</td>
</tr>
<tr>
<td>Ettercon 2</td>
<td>8.8</td>
<td>830.0</td>
<td>138.0</td>
<td>7.1</td>
<td>Understorey removal</td>
<td>August 1971 – December 1981</td>
<td>1982</td>
</tr>
<tr>
<td>Ettercon 4</td>
<td>9.0</td>
<td>822.0</td>
<td>135.34</td>
<td>15.7</td>
<td>50% Strip Thinning</td>
<td>August 1971 – December 1981</td>
<td>1982</td>
</tr>
<tr>
<td>Crotty Creek</td>
<td>122.1</td>
<td>685.0</td>
<td>7.6</td>
<td>358.5</td>
<td>50% Strip Thinning</td>
<td>May 1976 – September 1979</td>
<td>1979-1985</td>
</tr>
<tr>
<td>Ettercon 3</td>
<td>15.0</td>
<td>767.6</td>
<td>196.1</td>
<td>12.5</td>
<td><strong>---------------- Control catchment ----------------</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
2.1 The Black Spur Catchments

The Black Spur group consists of four catchments in the headwaters of Morleys Creek. The pre-thinning characteristics of mountain ash stands in the catchments, surveyed in August 1968, have been summarised in Table 2.2 (Langford and O'Shaugnessy 1977).

Table 2.2. The pre-thinning characteristics of mountain ash stands in the Black Spur catchments.

<table>
<thead>
<tr>
<th>Catchment</th>
<th>Average basal area (m² ha⁻¹)</th>
<th>Density (stem ha⁻¹)</th>
<th>Average height (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Black Spur 1</td>
<td>29.9</td>
<td>367.1</td>
<td>38.6</td>
</tr>
<tr>
<td>Black Spur 2</td>
<td>32.2</td>
<td>429.0</td>
<td>39.0</td>
</tr>
<tr>
<td>Black Spur 3</td>
<td>28.2</td>
<td>334.8</td>
<td>37.9</td>
</tr>
</tbody>
</table>

The thinning treatments were carried out during the summer of 1977/1978 as followed (O'Shaughnessy and Jayasuriya 1994):

- 60% reduction of basal area was planned for Black Spur 1, but only 54% of basal area was actually removed from the densest areas. The thinning was carried out in patches of 80 m diameter. The cleared patches were regenerated with mountain ash at a stocking rate of 1000 stems ha⁻¹.
- 40% uniform thinning was planned for Black Spur 2, which was predicted to generate the smallest detectable changes in water yield and represented normal practice in timber production. The actual reduction of basal area achieved at Black Spur 2 was 33%.
- 60% uniform thinning was planned for Black Spur 3, which represented the upper bound for timber production. The actual reduction of basal area achieved at Black Spur 3 was 50%.
- No thinning was conducted within a 20 m buffer along the streams.
- Black Spur 4 was reserved as the control catchment.

The post-treatment streamflow analysis at Black Spur 4 found that the catchment has very low runoff, so Ettercon 3 was subsequently used as the control catchment.
The mean annual rainfall, measured at the Black Spur Hermitage gauge and at the Black Spur gauge maintained by Melbourne and Metropolitan Board of Works, from 1905 to 1975 was 1660 mm. The Black Spur Meteorological Station was established in the east of the North Maroondah Experimental Area in 1971. It measures rainfall, pan evaporation, temperature and humidity. Three additional rainfall gauges were also established around the catchments to form a network of rainfall stations. The mean annual rainfall from the combined rainfall network from 1971 to 2009 was 1483 mm.

V-notch weirs were installed at all the Black Spur catchments and streamflow measurements commenced in 1971. The measurement was terminated after May 1992 at Black Spur 2, while it was terminated after December 1996 at Black Spur 1 and Black Spur 3. Jayasuriya et al. (1993) reported the impact of the treatments on water yield in Black Spur 1 and Black Spur 3. Up to 30% increases in annual streamflow of the pre-treatment level were observed after the treatment in both catchments. The streamflow at Black Spur 1 returned to the pre-treatment level 11 years after the treatment. The streamflow begun to decline at Black Spur 3, but it had not returned to the pre-treatment level at the cessation of the study.

Growth plots were established to monitor tree growth and regeneration after the treatment. Aney and O'Shaughnessy (1994) reported the effects of the thinning treatments on forest growth based on measurements conducted in 1977, 1979 and 1987 (Table 2.3). Forest inventory from Black Spur 4 has been included as comparison. They found that the stocking rate of regenerated mountain ash in the cut patches at Black Spur 1 declined significantly over a decade. The retained (unthinned) stands had higher mortality than the thinned stands at Black Spur 2, while the stocking rate of the retained and thinned stands were similar at Black Spur 3. The annual increment of basal area was higher in the thinned stands than in the retained stands.
### Table 2.3. Post-thinning changes in top height, stocking rate and basal area increment at the Black Spur catchments.

<table>
<thead>
<tr>
<th>Catchment</th>
<th>Stratum</th>
<th>Treatment</th>
<th>Top height (m)(^1)</th>
<th>Stocking rate (stems ha(^{-1}))</th>
<th>Basal area (m(^2) ha(^{-1}))</th>
<th>Mean annual increment (m(^2) ha(^{-1}) yr(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Black Spur 1</td>
<td>Cut patches</td>
<td>Cleared and regenerated</td>
<td>1000</td>
<td>890</td>
<td>0.0</td>
<td>14.3</td>
</tr>
<tr>
<td>Black Spur 1</td>
<td>Uncut patches</td>
<td></td>
<td>37</td>
<td>47</td>
<td>248</td>
<td>227</td>
</tr>
<tr>
<td>Black Spur 2</td>
<td>Thinned</td>
<td>Light thinning (33%)</td>
<td>46</td>
<td>53</td>
<td>129</td>
<td>122</td>
</tr>
<tr>
<td>Black Spur 2</td>
<td>Unthinned</td>
<td>-</td>
<td>155</td>
<td>140</td>
<td>25.2</td>
<td>33.9</td>
</tr>
<tr>
<td>Black Spur 3</td>
<td>Thinned</td>
<td>Heavy thinning (50%)</td>
<td>40</td>
<td>51</td>
<td>79</td>
<td>78</td>
</tr>
<tr>
<td>Black Spur 3</td>
<td>Unthinned</td>
<td>-</td>
<td>48</td>
<td>48</td>
<td>13.8</td>
<td>20.5</td>
</tr>
<tr>
<td>Black Spur 4</td>
<td>Unthinned</td>
<td>-</td>
<td>48</td>
<td>55</td>
<td>253</td>
<td>201</td>
</tr>
</tbody>
</table>

\(^1\)Top height was measured in the uncut patches at Black Spur 1 and the thinned stands at Black Spur 2 and Black Spur 3.
2.2 The Ettercon Catchments

The Ettercon group consists of four small catchments in the headwaters of Ettersglen Creek (Ettercon 1 and Ettercon 2) and Contentment Creek (Ettercon 3 and Ettercon 4). Ettercon 3 was reserved as the control catchment for the other catchments as well as for Crotty Creek and the Black Spur catchments. The pre-thinning characteristics of mountain ash stands in the catchments, surveyed in August 1968, have been summarised in Table 2.4 (Langford and O'Shaugnessy 1977).

Table 2.4. The pre-thinning characteristic of mountain ash stands in the Ettercon catchments.

<table>
<thead>
<tr>
<th>Catchment</th>
<th>Average basal area (m$^2$ ha$^{-1}$)</th>
<th>Density (stem ha$^{-1}$)</th>
<th>Average height (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ettercon 1</td>
<td>21.0</td>
<td>167.7</td>
<td>38.3</td>
</tr>
<tr>
<td>Ettercon 2</td>
<td>28.7</td>
<td>339.6</td>
<td>35.9</td>
</tr>
<tr>
<td>Ettercon 3</td>
<td>29.8</td>
<td>323.6</td>
<td>35.9</td>
</tr>
<tr>
<td>Ettercon 4</td>
<td>33.3</td>
<td>399.3</td>
<td>35.9</td>
</tr>
</tbody>
</table>

Strip thinning was carried out at Ettercon 1 and Ettercon 4, where vegetation within strips of 35 m wide were alternately removed or retained. Ettercon 2 was subjected to the removal of understorey vegetation.

Streamflow measurements commenced in 1971 at all of the Ettercon catchments. These measurements were terminated after December 1996, except for the continuous measurement at Ettercon 3. Annual forest inventory was conducted in the permanent plots from 1982 to 1989. Benyon (1992) has reported the effect of the strip thinning on forest growth. However, the impact of the thinning treatments on water yield has not been previously published.
2.3 The Crotty Creek Catchment

Crotty Creek is the largest catchment amongst the North Maroondah experimental catchments, with 122 hectare of catchment area. The catchment was selected to investigate the impact of thinning regrowth mountain ash forest on the magnitude and duration of water yield increase. It is located near Narbethong, on the northern slope of the Great Dividing Range. Its elevation ranges from 685 m to 815 m. The mean annual rainfall was 1822 mm for the period of 1977 to 1996. More detailed information about the catchment and the treatment plan can be found in O'Shaughnessy et al. (1981).

Timber assessment was conducted in 1977 to estimate standing tree volumes on the catchment (O'Shaugnessy et al. 1981). The assessment classified the stand characteristics into high, medium and low density regrowth forest. Table 2.5 shows the average stand characteristics for the whole catchment.

Table 2.5. The pre-thinning characteristics of mountain ash stands in the Crotty Creek catchment.

<table>
<thead>
<tr>
<th>Catchment</th>
<th>Average basal area (m² ha⁻¹)</th>
<th>Density (stem ha⁻¹)</th>
<th>Average height (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crotty Creek</td>
<td>46.6</td>
<td>349.6</td>
<td>45.0</td>
</tr>
</tbody>
</table>

Strip thinning was carried out at the Crotty Creek catchment in several stages from the summer of 1979/1980 to the summer of 1985/1986 (O'Shaugnessy et al. 1993). 50% of the total basal area was removed in alternating strips 35 m in width. This resulted in the retained and cleared strips that run parallel to the contours.

Permanent growth plots were established to monitor tree growth and regeneration after the treatment (Incoll 1993). Growth data were collected annually from 1979/1980 to 1989/1990. The mean annual increment of net basal area in the five years following the treatment was 1.04 m² ha⁻¹ year⁻¹ in the unthinned plots, and 0.17 m² ha⁻¹ year⁻¹ in the thinned plots. The stocking rate of regrowth mountain ash seedlings in the thinned strips declined from 21500 stems ha⁻¹ to 2000 stems ha⁻¹ over ten years, based on the measurements from quadrats established in 1979/1980.
Chapter 2: North Maroondah Experimental Catchments

Streamflow and rainfall measurements were recorded from 1976 to 1996. The Second Progress Report of the Crotty Creek Project presented some preliminary results from the post-treatment period (O’Shaugnessy et al. 1993). The post-treatment changes in water yield from 1986/1987 to 1990/1991 were analysed using Soil Dryness Index (SDI) model, Climatic Index (CI) model and REGMOD model (an empirical model with monthly timestep). They reported an increase in annual streamflow of 31%, 21% and 26% respectively. The increase in the monthly base flow was higher than the increase in the monthly storm flow, but the ratio of base flow to storm flow did not change. The average monthly flow between October and March increased, while it had decreased between April and September.

2.4 Recent Hydrological and Meteorological Data Collection

Streamflow at Ettercon 3 and rainfall at the Black Spur meteorological station have been continuously monitored since 1970s by Melbourne Water and its predecessor, Melbourne and Metropolitan Board of Works. Rainfall and streamflow measurements of the thinned catchments were recommissioned for this study (). The recommissioning of the weir at Crotty Creek was part of this project. It involved the installation of pressure sensor and data logger to monitor the flow and desilting of the weir. The desilting process required the construction of a lengthy offtake pipeline to avoid downstream contamination as there is an endangered aquatic species in the stream.
Table 2.6. Recommenement of measurements.

<table>
<thead>
<tr>
<th>Measurements</th>
<th>Commencement</th>
<th>Organisation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Streamflow</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Crotty Creek</td>
<td>March 2007</td>
<td>Melbourne University</td>
</tr>
<tr>
<td>Black Spur 1, Black Spur 2, Black Spur 3, Ettercon 2</td>
<td>June 2008</td>
<td>Melbourne Water</td>
</tr>
<tr>
<td>Ettercon 1, Ettercon 4</td>
<td>September 2008</td>
<td></td>
</tr>
<tr>
<td><strong>Rainfall</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Crotty Creek(^1)</td>
<td>April 2008</td>
<td>Melbourne University</td>
</tr>
</tbody>
</table>

\(^1\)Several gauges were installed: a manual gauge near the weir, a manual gauge and a tipping bucket gauge at a clearing
Chapter 3. The Long Term Changes in Water Yield

The weir at Crotty Creek
Paired catchment studies have been widely used to quantify the impact of forest treatment on water yield. This methodology requires two catchments in the same geographical area that have similar hydrologic response to climatic inputs. A relationship is established between the streamflows of both catchments during a calibration period. After this period, one catchment is subjected to a treatment and the other is retained as a control catchment. The pre-treatment relationship is used to predict the flow of the treated catchment so that the difference between predicted and observed flows can be attributed as the result of the treatment.

The main advantage of paired catchment study is the elimination of climate input variations as both the treated and control catchments are exposed to the same climatic input. The treatment effects can be determined from streamflow measurements, unlike climate-driven catchment models that often require more complex and comprehensive input data. However, the method has some limitations. It is not a predictive tool as treatment effects can only be quantified after the treatment is carried out. The results are not readily applicable to another catchment of different size, characteristics, vegetation and climate. The extrapolation of empirical relationship between sites is difficult (Vertessy 1999). The ability of the method in predicting flows beyond the range of the pre-treatment flows is limited by the statistical constraints of extrapolating a regression relationship. Inferences about treatment effects on extreme events, such as floods, were often made incorrectly without taking into account the potential change in variance and changes in flood frequency (Alila et al. 2009).

This chapter describes how the paired catchment study was utilised to quantify the long term changes in water yield after thinning treatment. It also compares the impact of different thinning treatments. Seven catchments from the North Maroondah experimental area that have undergone different thinning treatments were selected as case studies. Their descriptions and detail on the thinning treatments can be found in Chapter 2. The analysis of streamflow data were divided into three periods that were covered in separate sections: the pre-treatment or calibration period, the immediate post-treatment period until the project suspension in 1996 and the recent observation period that began in 2007. These sections are followed by a discussion of the uncertainties and implications of the results. The last section in this chapter presents the conclusion of this project component.
3.1 Pre-Treatment: Establishment of Linear Regression Models

Pre-treatment flow data are used in paired catchment studies to establish a least-square linear regression model between the control and treated catchment. The regression model needs to meet the following criteria so statistical analysis can be performed on their results (Watson et al. 2001):

- Independence: the residuals from the calibration models should be random and independent of the explanatory variables \(x\). Serial correlation and autocorrelation in the monthly data should be corrected or avoided.
- Linearity: the variance should be homoscedastic or constant over the range of \(x\).
- Normality: the residuals should ideally follow a normal distribution.

Monthly flows, rather than annual flows, were used in this project to establish the linear regression model because of the relatively short pre-treatment period. They were expressed as mean daily runoff in millimetres per day (mm day\(^{-1}\)). Monthly data are more likely to be serially correlated so they violate the requirement of independent variables. This serial correlation should be removed before further analysis is carried out so prediction intervals can be fitted around the predicted values.

A method outlined in Watson et al. (2001) has been followed to meet the criteria of linear regression using monthly data. Linear regression models were established between the control catchment, Ettercon 3, and the thinned catchments. The models were tested and corrected for homoscedasticity, seasonality and serial correlation. All statistical analysis was performed using R version 2.8.1 (The R Foundation for Statistical Computing) software package.

The first step in the regression model development was to perform a least-square linear regression for each pair of catchments:

\[
\hat{y} = b_0 + b_1 x
\]

where \(\hat{y}\) is the predicted monthly flow (expressed in mm day\(^{-1}\)) of the treated catchment, \(x\) is the monthly flow of the control catchment (mm day\(^{-1}\)), \(b_0\) is the intercept and \(b_1\) is the fitted regression coefficient. Flow was the only explanatory variable
included in this model as rainfall was not a significant explanatory variable when it was added to the model.

Linearity of regression models were tested by plotting their residuals against predicted values. Heteroscedascity was detected in the residual plots, which appeared in the form of a C or funnel shape. Base-10 logarithmic transformation was applied to explanatory and predicted variables of the regression model to achieve homoscedascity of the residuals. The following is the general form of the regression models after the logarithmic transformation:

\[ \log \hat{y} = b_0 + b_1 \log x \]  \hspace{1cm} (3.2)

The effect of the log transformation on the residuals is illustrated here using data from Ettercon 1 (Figure 3.1a and b). Data sets from some treated catchments have shown weaker signs of heteroscedascity than others, but the logarithmic transformation was applied to all catchment models to ensure consistency between them.

The next step in the model development was to examine the presence of serial correlation. Seasonality was apparent when the residuals of the log-transformed regression models were plotted as time series (Figure 3.2), which implies the presence of serial correlation (Watson et al. 2001). Sinusoidal trigonometric terms can be introduced as additional independent terms in the regression model to explicitly account for seasonality. The resulting general model after the trigonometric terms were introduced was:

\[ \log \hat{y} = b_0 + b_1 \log x + b_2 \sin\left(2\pi \frac{w}{12}\right) + b_3 \cos\left(2\pi \frac{w}{12}\right) \]  \hspace{1cm} (3.3)

where \( w \) is month (January = 1, February = 2 etc.), \( b_0 \) is the intercept and \( b_1 \) to \( b_3 \) are the fitted regression coefficients. The use of sine and cosine terms is equivalent to adding a sinusoid component with a phase component. Although the individual terms were not statistically significant in some regression models, both terms were significant as a pair.
Chapter 3: The Long Term Changes in Water Yield

Figure 3.1. Plots of predicted values against residuals from: (a) linear regression model and (b) logarithmic regression model, Ettercon 1.

Figure 3.2 Seasonality was detected in the plot of residuals against time, Ettercon 1.

The empirical parameters of the log/sinusoidal regression model for each paired catchment are shown in Table 3.1 along with the coefficient of determination ($R^2$) and the standard errors. These regression models were used to calculate the predicted flow of the treated catchments in the post-treatment period.
Although the introduction of the sinusoidal terms has reduced seasonality in the data, the serial correlation in the residuals of the log/sinusoidal model was still statistically significant (Figure 3.3). The remedy was to fit a stochastic time-series model of the ARMA family to the residuals. A lag-one auto-regressive (AR1) model was chosen as the model to be fitted to the residuals:

$$\log \hat{y}_t - \log y_t = \phi (\log \hat{y}_{t-1} - \log y_{t-1}) + \epsilon_t$$

(3.4)

where $\log \hat{y}_t - \log y_t$ is the residual from the log/sinusoidal regression model at time $t$, $\phi$ is the lag-one autocorrelation coefficient and $\epsilon_t$ is the normally distributed random error term. Removing the AR1 model from the residuals resulted in a series of random error sequence, which Watson et al. (2001) labelled as a disturbance series:

$$a = (\log \hat{y}_t - \log y_t) - \phi (\log \hat{y}_{t-1} - \log y_{t-1})$$

(3.5)

where $a$ is the disturbance value. The lag-one autocorrelation coefficients of the models range between 0.42 and 0.87.

The correlogram of the residuals, shown in Figure 3.3, illustrated the progression in the removal of serial correlation from the residuals. The serial correlation was significant in the logarithmic model, reduced in the log/sinusoidal model and finally no longer statistically significant after the removal of AR1 component. The disturbance values were independent and homoscedastic so that prediction intervals could be fitted around them to gauge the significance of the treatment effect. Most of the disturbance values from the pre-treatment period fall within the 95% prediction intervals, as shown in Figure 3.4. The treatment effect is statistically significant if more than 5% of
disturbance values from the post-treatment period fall outside the 95% prediction intervals.

Figure 3.3. Correlogram of Ettercon 1 residuals: log model, log/sinusoidal model and log/sinusoidal model without AR1 component (disturbance series).

Figure 3.4. Pre-treatment disturbance values with 95% prediction intervals, Crotty Creek.
3.2 Post-Treatment: Changes in Water Yield
Immediately after Thinning

Post-treatment changes in water yield were calculated as the difference between predicted and observed monthly flows of the treated catchments. The post-treatment period discussed in this section is defined from the completion of the treatment until the suspension of the project at the end of 1996. Analysis of the disturbance series was performed on all the treated catchments to determine the significance of the thinning treatment. The treatment effect is significant if more than the expected number of post-treatment disturbance values, which is 5% in this case, fall outside the prediction intervals.

Figure 3.5, Figure 3.6 and Figure 3.7 show the post-thinning monthly changes in water yield in the treated catchments and their corresponding disturbance series. The graphs cover the period immediately after the thinning until the project suspension at the end of 1996 and the recent data collection that commenced in 2007/2008.

Most of the treated catchments have shown statistically significant increases in water yield that can be attributed to the treatment. The water yield gradually returned to or fell below the pre-treatment level over time. Some catchments have shown large monthly increases in water yield during 1996. The post-thinning increase in water yield at Ettercon 2 has not been statistically significant at 95% confidence level as less than 5% of its post-treatment disturbance values were outside the 95% prediction intervals. The change in water yield from this catchment was excluded from further analysis.
Figure 3.5 Post-treatment monthly water yield changes and disturbance series of Black Spur 1 (patch-cutting) and Ettercon 2 (removal of understorey vegetation). The treatment effects are significant if more than 5% of the disturbance values fall outside the prediction intervals.
Figure 3.6 Post-treatment monthly water yield changes and disturbance series of Black Spur 2 and Black Spur 3 (uniform thinning). The treatment effects are significant if more than 5% of the disturbance values fall outside the prediction intervals.
Figure 3.7 Post-treatment monthly water yield changes and disturbance series of Ettercon 1, Ettercon 4 and Crotty Creek (strip-thinning). The treatment effects are significant if more than 5% of the disturbance values fall outside the prediction intervals.
A seasonal pattern can also be observed in the monthly treatment effects (Figure 3.8). The peak increase in post-treatment water yield occurred in spring at most treated catchments. Similarly, the peak decrease in post-treatment yield occurred also in spring at Black Spur 2. Water yield increase in the treated catchment has been attributed to the reduction of evapotranspiration that is translated into increased streamflow (O'Shaugnessy et al. 1993). However, the timing of the peak monthly increases coincided with the period of pre-treatment peak streamflows rather than peak summer evapotranspiration period.

Figure 3.8. Mean monthly treatment effects from the treated catchments.

Post-treatment annual changes in water yield were obtained from the aggregation of monthly data. The changes in water yield due to thinning are referred here as treatment effects. The treatment effects of the thinned catchments are presented in Figure 3.9 as a cumulative treatment effect to compare the impact of different treatments (a), and as a time series of annual treatment effects and rainfall to show their annual variability (b).
Figure 3.9. Cumulative annual treatment effects (a) and a time series of annual treatment effect (b) of the treated catchments.
Chapter 3: The Long Term Changes in Water Yield

Figure 3.9a shows that strip-thinning resulted in greater increase in water yield than the other treatments. Uniform thinning produced treatment effects of different magnitude at Black Spur 2 and Black Spur 3, which might be due to the difference in thinning proportion. The water yield at Black Spur 2 has decreased below the pre-thinning level prior to the suspension of streamflow measurement in 1992. It was not known whether the trend would have persisted after 1992 as the water yield in Black Spur 3 increased. The treatment effects of patch-cutting at Black Spur 1 were initially similar to those of uniform thinning at Black Spur 3. After the 1982/1983 drought, the treatment effects at Black Spur 1 were lower than those at Black Spur 3.

The impact of different treatment types was examined further using non-parametric tests because they were not normally distributed. Firstly, the Kruskal-Wallis test was used to assess the equality of medians of the treatment effects amongst the six treated catchments. The test showed that the median differed significantly from each other ($p < 0.05$). Secondly, the stepwise multiple comparison procedure was performed to detect differences between the thinning treatments. This test was an extension of the Kruskal-Wallis test with adjustment to ensure the maximum type I error level is less than 0.05 at each stage of comparison (Campbell 1985). The following is a summary of the comparison results:

1. Black Spur 2 has the lowest median annual treatment effects in the group. The treatment effects observed at Black Spur 2 were significantly different from those observed at Black Spur 3 despite being subjected to the same treatment. This might be due to a rapid recovery in stand transpiration that was shown in higher basal area increment in the thinned stands at Black Spur 2 (see Table 2.3).
2. There was no significant difference between treatment effects observed at Black Spur 3, Ettercon 1 and Ettercon 4.
3. Patch-cutting at Black Spur 1 produced significantly lower treatment effects than strip-thinning ($p < 0.05$), with the effects of uniform thinning ranked somewhere between these two treatments ($p < 0.10$). There was greater amount of regrowth mountain ash in the cleared patches than the thinned strips.
Chapter 3: The Long Term Changes in Water Yield

The influence of climatic variation can be seen in the annual treatment effects (Figure 3.9b), although this should have theoretically been removed from paired catchment study. Extremely low rainfall recorded in the summer of 1982/1983 generated very low or negative treatment effects in the Black Spur catchments. Conversely, statistically significant increases in water yield were detected at most of the treated catchments in 1996, which had the highest annual rainfall since the calibration period started. Prior to 1996, the annual treatment effects have been declining towards the baseline in most of the treated catchments.

3.3 Post-Treatment: Recent Measurement Data

The recommencement of streamflow measurements at the North Maroondah catchments was intended to collect new data to investigate the current changes in water yield after the original treatments. The streamflow measurement restarted at the Crotty Creek catchment in March 2007. There are two missing monthly flow data, September 2007 and February 2008 flows due to weir maintenance and failure of a data logger respectively. Data loggers were also reinstalled to measure flows at the Black Spur and Ettercon catchments in July 2008. Changes in water yield or treatment effects were computed as the difference between predicted and observed flows. The predicted flows were obtained from the pre-treatment regression models.

On 7 February 2009, a bushfire destroyed understorey vegetation in some of the North Maroondah experimental catchments. This disturbance also occurred in the control catchment, Ettercon 3, which meant that it could no longer be used as a control catchment in the paired catchment study. Although the flow measurements are still continuing, the data after the bushfire cannot be included in the analysis. This severely limited the number of observation data after the reinstatement of the data loggers.

Increases in water yield or positive treatment effects were observed at Ettercon 1 and Ettercon 2 in the period after the reinstalment of the data loggers. There were only three measurements collected at Ettercon 1 before the February 2009 bushfire so its trend
cannot be verified further. The positive treatment effects at Ettercon 2 covered a longer period and they were statistically significant. The other treated catchments have shown a decline in water yield, with Crotty Creek having the longest post-1996 records. Thus, the analysis of the negative treatment effects will be focused on changes in water yield at Crotty Creek.

The decrease in water yield was observed when the streamflow measurement resumed in March 2007 at Crotty Creek. There was an unexpectedly large decrease in water yield of 44 mm in January 2008. The mean daily runoff recorded at Ettercon 3 in this period was approximately three times the amount recorded at Crotty Creek (1.53 mm day$^{-1}$ and 0.5 mm day$^{-1}$ respectively) so there was a large discrepancy between the predicted and actual runoff at Crotty Creek. Two factors might have contributed to the large treatment effect. During most of December 2007 and January 2008, the daily streamflows at Ettercon 3 have been estimated based on data from Myrtle 1 catchment because of the failure of its data logger. A large and potentially localised storm, with a total of 94 mm of rainfall, was recorded at the Black Spur rain gauge network on 19-21 January 2008. It was possible that the impact of this storm might was much greater at Ettercon 3 (on the southern slope of the Great Dividing Range) than at Crotty Creek (on the northern slope) so the increase in streamflow at Ettercon 3 was much greater than at Crotty Creek.

### 3.4 Discussion

Post-thinning regeneration of mountain ash stands was negligible at most of the thinned catchments because the cleared areas were not subjected to burning. Benyon (1992) reported that there was no substantial overstorey regeneration in the cleared strips at the Ettercon catchments. The poor regeneration of *E. regnans* enabled increases in water yield to be observed longer in the thinned catchments compared to in the clear-felled catchments (Watson *et al.* 2001).

The treatment effects were influenced by treatment type, pre-treatment vegetation condition, climatic conditions and locality of the catchments. There were great differences
in the magnitude and persistence of treatment effects at Black Spur 2 and Black Spur 3, although both catchments were subjected to uniform thinning with 17% difference in basal area reduction. There was no statistically significant difference in the treatment effects of patch-cutting at Black Spur 1 and strip-thinning at the Ettercon catchments, but the treatment effects at Ettercon 1 and Ettercon 4 differed from those at Crotty Creek (p < 0.05) despite being subjected to the same level of strip-thinning treatment. Thus, the variation in treatment effects between catchments subjected to the same treatment could be greater than the variation in treatment effects between catchments subjected to different treatments.

There are several implications of the observed variations in the treatment effects. Treatment effects in one catchment might be difficult to be replicated in another catchment, as they might be affected by catchment characteristics (size, vegetation density) and climatic input (spatial and temporal variation). The use of an empirical model to predict treatment effects should take into account potential differences between the predicted catchment and the catchments used to derive the model. There might also be a non-linear relationship between the magnitude of treatment effects and the amount of removed basal area as observed at Black Spur 2 and Black Spur 3.

The influence of climatic variation on treatment effects in the treated catchments has been highlighted by a few events. The dry period in 1982/1983 caused a short-term decline in water yield at all the Black Spur catchments, while the wet year of 1996 produced substantial increases in water yield at most treated catchments. In both cases, the dry and wet periods generated flows that fell lower outside the pre-treatment range of flows. The influence of climatic variation on treatment effects has been observed in other thinning treatments (Baker 1986, Hornbeck et al. 1993). Extrapolating the regression relationships beyond the range of calibration flows might have exaggerated the impact of the treatments and the prediction limits might no longer be applicable. Alila et al. (2009) suggested that the estimation of treatment effects for extreme events requires a different analysis than simply the extrapolation of the pre-treatment regression relationship.

The resumption of the paired catchment study at Crotty Creek in 2007 has shown a decrease in water yield. However, several factors must be taken into account in
interpreting this trend. This measurement period coincided with a long dry period (drought), where the streamflow at Ettercon 3 was mostly lower than during the calibration period ($p < 0.05$). The regression model was extrapolated to predict the flow at Crotty Creek so the statistical significance of the change in water yield could not be established. The drought might have also amplified the decrease in water yield at Crotty Creek, similar to the decrease in water yield at Black Spur 1 and Black Spur 3 during the 1982/1983 drought. Unfortunately, the turning point from increasing to decreasing water yield could not be observed due to the suspension of streamflow measurement in 1997. The persistence of the decrease in water yield is also unknown as the February 2009 bushfire terminated the paired catchment study.

A comparison of Crotty Creek’s streamflow obtained from the immediate post-thinning period (1985 – 1996) and from the recent measurement period (2007 – 2009) has confirmed the trend of decreasing water yield (Mann-Whitney, $p < 0.01$). The challenge was to examine the changes in post-thinning vegetation and/or the influence of climatic variation (e.g. drought) that resulted in the decrease in water yield. The subsequent measurements carried out in this study were aimed to answer these questions.

### 3.5 Conclusion

Statistically significant increases in water yield were observed immediately after the treatments in all the thinned catchments, except at Ettercon 2. The magnitude and persistence of the post-thinning water yield increase varied between catchments. The largest distinction was between the impact of patch-cutting and strip-thinning ($p < 0.05$), where strip-thinning produced greater magnitude of treatment effects than patch-cutting due to lower regeneration of mountain ash seedlings in the thinned strips. The variation in treatment effects from the same treatment indicates that they might be influenced by catchment characteristics (size, location, vegetation density) and climatic variation.

A decrease in water yield was observed after the streamflow measurement resumed at Crotty Creek in 2007. This trend was also observed at Black Spur 1, Black Spur 3 and
Ettercon 4 with limited data. The statistical significance of this trend has not been able to be established due to the drought, while the February 2009 bushfire has shortened the observation period. The subsequent measurements in this study were undertaken to determine the post-thinning changes in vegetation and the influence of climatic variation that affected the catchment water yield.

This study has also shown the consequences of short calibration period in paired catchment study. The use of monthly streamflows might have increased the number of samples to establish the regression relationship and the statistical impediments (seasonality, serial correlations) could be removed. However, the range of pre-treatment streamflows was still limited. The recent low streamflows at the control catchment fell outside the calibration range due to the drought. The statistical significance of the treatment effects cannot be determined because extrapolation of the regression relationship was required. Further research into this problem is warranted, especially as the occurrence of extreme streamflows might increase in the future due to climate change.
Chapter 4. Changes in Vegetation Structure based on LiDAR Measurements

Left: aerial photograph of Crotty Creek taken in 1985
Right: aerial photograph of Crotty Creek taken in 1995
Chapter 4: The Long Term Changes in Vegetation Structure

Thinning alters vegetation structure and composition by removing some of the forest cover. The configuration of thinning treatment, the amount of removed basal area and the response of the remaining vegetation determined how the cleared area is occupied over time. Based on the post-thinning changes in water yield quantified in the last chapter, it could be hypothesised that the post-thinning vegetation structure has changed over time. Thus, the changes in vegetation structure were examined to establish if they can explain the changes in water yield.

This chapter investigates the long term effects of the thinning treatments on vegetation structure. The first section outlines the use of active remote sensing technology (LiDAR) in obtaining vegetation structure attributes, such as maximum vegetation height, height variance and canopy height profile. The second section presents the changes in vegetation structure due to the treatments. The third section compares those changes as well as discussing their implications on water yield. The last section presents the conclusion drawn from this investigation.

4.1 Using LiDAR to Obtain Vegetation Structure Attributes

Light Detection And Ranging (LiDAR) or laser altimetry emits a laser pulse of near infrared wavelength and measures the time taken for the pulse to be reflected back from the targeted object. This enables the distance between object and sensor to be calculated. The sensor is usually mounted on an aircraft to record vertical distance to the Earth’s surface. The result is an outline of the ground surface and any vegetation that obscure it (Lefsky et al. 2002).

There are two types of LiDAR sensors: discrete-return and waveform-recording (Lefsky et al. 1999). Discrete-return sensor identifies major peaks in the return signal that represent discrete objects in the path of laser illumination, and represent them as return hit. Waveform-recording sensor captures the entire energy waveform returned by each laser pulse.
LiDAR’s ability to penetrate the canopy allows it to directly measure canopy height, canopy cover and vertical distribution of canopy structure. It provides a three-dimensional representation of the vegetation structure. Empirical models have also been used with LiDAR data to predict mean stem diameter, basal area, stand volume, canopy volume, vegetation cover and multi-layered stand structure (Coops et al. 2007, Lefsky et al. 1999, Lovell 2003, Maltamo et al. 2005, Riano et al. 2004, Lefsky et al. 2002). LiDAR can successfully retrieve structural data in dense forests where optical remote sensing would fail due to high biomass.

Lefsky et al. (2002) pointed out LiDAR’s two potential limitations in estimating canopy height. The first one is that accuracy of ground elevation is diminished where dense understorey vegetation obscures the ground surface. The second is that the top of the tree crown might be missed if point density is low. In this study, the broad crowns of mountain ash reduce the risk of underestimating the tree height.

4.1.1 LiDAR specification

LiDAR data from the North Maroondah catchments was acquired on 26th August 2007 with a discrete-return sensor that recorded up to four data points for each laser pulse. Table 4.1 summarises LiDAR system configuration and flight detail. Data points were projected to Geodetic Datum of Australia (GDA94) and classified as ground hits and non-ground (vegetation) hits.
Table 4.1. LiDAR system configuration and flight detail.

<table>
<thead>
<tr>
<th>Sensor type</th>
<th>Optech ALTM3100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flight altitude (m)</td>
<td>800</td>
</tr>
<tr>
<td>Airspeed (km/hr)</td>
<td>220</td>
</tr>
<tr>
<td>Wavelength (Hz)</td>
<td>69</td>
</tr>
<tr>
<td>Pulse repetition rate (kHz)</td>
<td>100</td>
</tr>
<tr>
<td>Laser beam divergence (mrad)</td>
<td>0.3</td>
</tr>
<tr>
<td>Scan angle (degrees)</td>
<td>28</td>
</tr>
<tr>
<td>Mean footprint size (m)</td>
<td>0.16</td>
</tr>
<tr>
<td>Point density (point/m²)</td>
<td>4</td>
</tr>
</tbody>
</table>

4.1.2 Data extraction

The LiDAR Surfacing Toolset 1.1 (Siggins, CSIRO, Australia) was used to process raw LiDAR data into raster format and generate surface maps from the data. Two sets of Digital Terrain Model (DTM) were developed from ground hits using an inverse distance weighted method with 2 m and 10 m grid spacing. The DTM with 10 m resolution was used to generate catchment boundaries, while the DTM with 2 m resolution was used to calculate height of each vegetation hits. Descriptive statistics were calculated from vegetation height data in each 2x2 m cell. They were used to create surface maps of height-related attributes, such as maximum height, mean height and height variance.

The software was also used to extract LiDAR return hits (Figure 4.1) from sample plots to obtain canopy height profiles. The coordinates of the centre of the plot were specified to extract all LiDAR hits within certain radius or width. A circular plot with 15 m diameter was used to obtain a sample canopy height profile. The vegetation heights were calculated from vegetation hits, sorted in ascending order and assigned to a set of height classes. A canopy height profile was derived from the proportions of vegetation hits in all height classes (Lefsky et al. 1999, Maltamo et al. 2005).
Chapter 4: The Long Term Changes in Vegetation Structure

In each of the thinned catchments, the canopy height profiles were obtained from a number of sample plots and averaged to represent the vertical distribution of canopy heights. Table 4.2 provides the number of sample plots used to derive the average canopy height profile. The number of sample plots in Black Spur 1 was based on the number of patches. The number of sample plots in the other catchments was set to the number of strips that can be sampled at Ettercon 1 and Ettercon 4.

Table 4.2. Number of sample plots used to derive the average canopy height profile.

<table>
<thead>
<tr>
<th>Catchments</th>
<th>Number of sample plots</th>
</tr>
</thead>
<tbody>
<tr>
<td>Black Spur 1</td>
<td>7 in the cleared patches, 6 in the retained areas</td>
</tr>
<tr>
<td>Black Spur 2</td>
<td>4</td>
</tr>
<tr>
<td>Black Spur 3</td>
<td>4</td>
</tr>
<tr>
<td>Ettercon 1</td>
<td>4 in the retained strips, 5 in the cleared strips</td>
</tr>
<tr>
<td>Ettercon 2</td>
<td>4</td>
</tr>
<tr>
<td>Ettercon 3</td>
<td>5</td>
</tr>
<tr>
<td>Ettercon 4</td>
<td>4 in the retained strips, 5 in the cleared strips</td>
</tr>
<tr>
<td>Crotty Creek</td>
<td>4 in the retained strips, 5 in the cleared strips</td>
</tr>
</tbody>
</table>
4.2 Impact of Thinning Treatments on Vegetation Structure

Canopy height attributes and distribution from LiDAR data were examined to investigate the long term impact of different thinning treatments on vegetation structure. Historical information on post-thinning forest growth would be used to discuss the changes in vegetation structure. No ground measurement of vegetation height was conducted to validate the LiDAR measurements in this study.

Figure 4.2 to Figure 4.4 show the maps of maximum vegetation height that were derived from LiDAR data. The maximum vegetation height map described the distribution of vegetation heights in the catchment. Different vegetation groups could be identified from the difference in their heights.

Figure 4.7 to Figure 4.8 show the average canopy height profiles of the treated catchments. The canopy layers in the vegetation stands can be identified from the peak of percentage of hits in the profiles.
Figure 4.2. Maps of maximum vegetation height of (a) Black Spur 1 (patch-cutting), (b) Black Spur 2 and Black Spur 3 (uniform thinning) derived from LiDAR data.
Figure 4.3. Maps of maximum vegetation height of (a) Ettercon 2 (understorey removal), (b) Ettercon 3 (control catchment) derived from LiDAR data.
Chapter 4: The Long Term Changes in Vegetation Structure

Figure 4.4. Maps of maximum vegetation height of (a) Ettercon 1, (b) Ettercon 4 and (c) Crotty Creek derived from LiDAR data.
Figure 4.5. Aerial view of the Black Spur catchments taken immediately after the treatments in October 1977. Source: Figure 4.2, Third Progress Report – North Maroondah (Aney and O’Shaughnessy 1994).
Figure 4.6. Average canopy height profiles of the Black Spur 1 (patch-cutting), Black Spur 2 (uniform thinning) and Black Spur 3 (uniform thinning).
Figure 4.7. Average canopy height profiles of Ettercon 2 (removal of understorey vegetation) and Ettercon 3 (control catchment).
Figure 4.8. Average canopy profiles of the strip-thinned catchments: Ettercon 1, Ettercon 4 and Crotty Creek.
4.3 Discussion

The vegetation structure of Ettercon 3 was assumed to be representative of an undisturbed mountain ash catchment. The maximum vegetation height map shows that the heights of 68 year old mountain ash stands were 50 – 70 m (Figure 4.3). The average canopy height profile indicated the presence of three canopy layers from the peaks of vegetation hits (Figure 4.7). The first major peak of vegetation hits at 40 – 65 m above the ground captured the dominant overstorey layer, the second peak at 15 – 20 m captured the mid-storey layer and the third peak at 3 m and below captured the understorey layer.

Patch-cutting has permanently changed the vegetation structure of the Black Spur 1 catchment. The regrowth vegetation stands can clearly be identified in Figure 4.2 as their canopy heights were lower than those of the retained stands in the undisturbed areas. The regrowth and retained stands also had different canopy height profiles (Figure 4.6). Approximately 44% of the vegetation hits from the regrowth stands were recorded below 15 m that suggests that the understorey vegetation was dense. However, the regrowth stands are most likely be dominated by non-eucalyptus species with a small number of regrowth mountain ash trees. Aney and O'Shaughnessy (1994) reported that the stocking rate of regrowth mountain ash has declined from 1000 stems ha$^{-1}$ in 1977 to 890 stems ha$^{-1}$ in 1987 (Table 2.3). A more recent study found that the mean basal area of mountain ash in Black Spur 1 was lower than those found in Black Spur 2, Black Spur 3 or Ettercon 3 (Jaskierniak et al. 2011). It also found that the mean basal area of non-eucalyptus species in Black Spur 1 was higher than in the other catchments.

The impact of uniform thinning on the vegetation structure of Black Spur 2 and Black Spur did not appear to persist after thirty years. The thinned areas (gaps) that are visible in the post-thinning aerial photograph (Figure 4.5) cannot be identified in the map of maximum vegetation height (Figure 4.2). The resolution of the maximum vegetation height map is 2 x 2 m, so any remaining gaps created by the treatment or areas of regrowth vegetation should be detected. The canopy height profiles of both catchments (Figure 4.6) were similar to the canopy profile of Ettercon 3 (Figure 4.7). The greater increase in basal area
in the thinned stands, as shown in the 1987 forest inventory (Table 2.3), suggests that the retained trees took advantage of the extra resources that were available. The retained trees might have continued to expand and eventually eliminated the post-thinning gaps. The recovery in basal area and leaf area would also explain the decline in the post-thinning water yield increase over time and the subsequent decrease of water yield below the pre-thinning level.

The maximum vegetation heights of Ettercon 2 and Ettercon 3 were similar (Figure 4.3) so the removal of understorey vegetation has not affected the overstorey layer. However, the comparison of their canopy height profiles (Figure 4.7) revealed the absence of mid-storey vegetation layer in Ettercon 2. The woody understorey species, (such as *Acacia dealbata* and *Pomaderris aspera*), that were removed during the treatment did not regenerate well because the retained mountain ash stands would have suppressed the growth of their seedlings. The small shrubs and ferns have regenerated more successfully because they required less light. The changes in the vegetation structure have been reflected in the changes in water yield very well. The post-thinning increase in water yield has been modest as the impact of the treatment on catchment ET was not great. The persistence of the increase over time indicated that the total ET of the catchment has remained lower than the pre-thinning period as there has not been a significant post-thinning regeneration of the woody understorey species.

Strip-thinning had a significant impact on the vegetation structure of the treated catchments. Alternating strips of retained and regrowth vegetation stands can still be observed in those catchments after thirty years (Figure 4.4). *Acacia* spp. has dominated the regrowth stands in the cleared strips as the post-thinning regeneration of mountain ash has been insignificant (Benyon 1992, Incoll 1993). This resulted in the difference in maximum vegetation height and height variance between the retained and cleared strips. The width of the cleared strips has been reduced over time as the retained trees along the edges of the retained strips have expanded into the cleared strips (Benyon 1992, Incoll 1993).
4.4 Conclusion

Uniform thinning had the least long term impact on the vegetation structure of the treated catchments. This was due to its similarity to the natural thinning regime of mountain ash forest, where suppressed trees in the stand would die out so the stand density decreases over time. After more than thirty years, the post-thinning vegetation structure resembled the vegetation structure of an undisturbed catchment. The removal of understorey vegetation resulted in the absence of mature woody understorey layer, but its impact on the overstorey layer appeared to be minimal.

Patch-cutting and strip-thinning have permanently changed the vegetation structure of the treated catchments. The thinned areas have been dominated by non-eucalyptus species, mainly *Acacia* spp. These regrowth vegetation stands have a different vegetation structure from the retained mountain ash stands. The difference was detected in the maximum vegetation height map and canopy height profile derived from LiDAR data.

It may be hypothesised that the recent decline in water yield after the initial post-thinning increase might be attributed to the regeneration of new vegetation in the cleared areas and the growth of some of the retained mountain ash trees. However, the vegetation height profiles cannot be used to infer directly ET pattern of the post-thinning vegetation structure. Thus, leaf area index and sap flow measurements were conducted to examine ET distribution of the treated catchments and explain the cause of the decrease in water yield that has been observed in most of the treated catchments.
Chapter 5. *In Situ* and Remote Sensing Measurements of Leaf Area Index

Left: view within a retained stand, right: view within a regrowth stand at Crotty Creek
Chapter 5: *In Situ* and Remote Sensing Measurements of LAI

Leaf area index (LAI) is a measure of leaf surface area per unit ground area. It influences a number of biological and physiological processes, such as photosynthesis, evapotranspiration (ET), net primary production and carbon cycling. The temporal variation of LAI can be used to monitor vegetation changes, growth and health, while spatial variation of LAI can be used to estimate ET, biomass and carbon cycle from local to global scale. In this study, LAI spatial distribution was used to describe and assess the changes in vegetation structure due to various thinning treatments. An LAI distribution map might show the change in ET since the end of the thinning treatment, especially if regeneration of vegetation has occurred in the thinned areas.

LAI spatial distribution at catchment level can be efficiently obtained from remote sensing data. However, ground or *in situ* measurements of LAI are still required to calibrate and validate remote sensing measurements. Quickbird multi-spectral satellite imagery and Light Detection and Ranging (LiDAR) data were utilised in this study to produce LAI spatial distribution maps of the North Maroondah experimental catchments. The parameters of the remote sensing data were calibrated against *in situ* LAI measurements obtained at Crotty Creek. Crotty Creek was selected as the main study site because a range of LAI values were likely to be found in the retained and regrowth vegetation stands.

This chapter outlines the process of obtaining LAI distribution maps from *in situ* LAI measurements and remote sensing parameters. The first section provides a literature review on a range of available *in situ* and remote sensing methods to measure LAI. It also provides the reasoning for the selected methods in this study. The experimental design and procedures to obtain *in situ* LAI measurements and remote sensing parameters are outlined in the second section. The third section presents the measurement results, the modelling of LAI spatial distribution and the resulting distribution maps. The fourth section discusses LAI spatial distributions of the different thinned catchments, the uncertainties and limitations in the measurements and LAI modelling, as well as the comparison of techniques. The chapter concludes with a summary of findings and their implications.
5.1 Literature Review

5.1.1 In Situ Measurements of LAI

In situ measurement of LAI can be obtained with direct or indirect methods (Chen et al. 1997, Fournier et al. 2003, Jonckheere et al. 2004). The former requires physical access to canopy elements to measure LAI, while the latter is mostly based on the measurement of light transmission through the canopies. Direct methods are considered to be more accurate than indirect methods because they measure leaf surface area directly. However, they are also more time-consuming and labour-intensive than indirect methods. Indirect methods infer LAI from the transmission of solar radiation through the canopy so they are non-destructive. Table 5.1 and Table 5.2 list direct and indirect methods that are commonly used to measure LAI.

The selection of the most suitable method to measure LAI must take into account the purpose of LAI measurement and the canopy structure of the vegetation. The mountain ash (E. regnans) stands in the North Maroondah experimental catchments are about 70 years old. Their heights reach 60 – 70 m and the understorey vegetation is well established. Most direct methods will be difficult to implement, including allometry that has been used to measure LAI in younger mountain ash forest (Vertessy et al. 1995, Watson and Vertessy 1996). The inclined point quadrant was the least suitable indirect method because of the difficulty in accessing the canopy. Thus, the choices of suitable methods have been limited to indirect methods that estimate LAI from the transmittance of solar radiation.
## Table 5.1. Summary of direct methods to measure LAI.

<table>
<thead>
<tr>
<th>Methods</th>
<th>How LAI is measured</th>
<th>Strength</th>
<th>Limitations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Destructive</td>
<td>Individual trees are felled and the leaves are stripped. Surface area of the leaves is aggregated.</td>
<td>• Most accurate.</td>
<td>• Destructive.</td>
</tr>
<tr>
<td>sampling</td>
<td></td>
<td>• Vertical distribution of leaves can be obtained.</td>
<td>• Time consuming and labour intensive.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Impractical for large trees.</td>
</tr>
<tr>
<td>Allometry</td>
<td>Relies on the relationship between LAI of sample trees, obtained from destructive sampling, and canopy characteristics (e.g. basal area and sapwood area).</td>
<td>• Derived LAI is based on physical measurement.</td>
<td>• Time consuming and labour intensive.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Vertical distribution of leaves can be obtained.</td>
<td>• Established allometric relationship is site-specific.</td>
</tr>
<tr>
<td>Litter trap</td>
<td>Fallen leaves are collected in litter traps for the estimation of LAI.</td>
<td>• Less destructive than other direct methods.</td>
<td>• Assumes that trapped leaves are representative of the stand.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Suitable for deciduous broadleaf forests.</td>
<td>• Measures total LAI over a period of time rather than LAI at a particular moment.</td>
</tr>
</tbody>
</table>
Table 5.2. Summary of indirect methods to measure LAI.

<table>
<thead>
<tr>
<th>Methods</th>
<th>How LAI is measured</th>
<th>Strength</th>
<th>Limitations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inclined point quadrat</td>
<td>Measures the number of contacts between a long needle/probe and green foliage as it is inserted into vegetation canopy.</td>
<td>• Assumption of random distribution of foliage is not required.</td>
<td>• Large numbers of insertion are required to obtain representative data.</td>
</tr>
<tr>
<td>DEMON (CSIRO, Canberra, Australia)</td>
<td>Measures light intensity above and below a canopy. Gap fraction is estimated from the linear average of the transmittance.</td>
<td>• Designed for use in forest environment.</td>
<td>• Difficult to apply in tall canopies.</td>
</tr>
<tr>
<td>Sunfleck / AccuPAR Ceptometer (Decagon Devices Inc., WA, USA)</td>
<td>Measures the average direct transmittance of solar radiation.</td>
<td>• Compute LAI instantaneously.</td>
<td>• Requires clear sky to obtain measurement.</td>
</tr>
<tr>
<td>Plant Canopy</td>
<td>Measures diffuse radiation under</td>
<td>• Compute LAI instantaneously.</td>
<td>• Data needs to be collected at a range of sun angles.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Large variability in measurement results.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Not suitable for coniferous forest because of penumbral effects in the sun fleck fraction.</td>
</tr>
<tr>
<td>Methods</td>
<td>How LAI is measured</td>
<td>Strength</td>
<td>Limitations</td>
</tr>
<tr>
<td>---------</td>
<td>---------------------</td>
<td>----------</td>
<td>-------------</td>
</tr>
<tr>
<td>Analyser LAI-2000 (Licor Inc., Nebraska, USA)</td>
<td>a canopy and in a clearing simultaneously. Utilises fisheye light sensors with five rings.</td>
<td>• A view cap can be used to minimise boundary effects.</td>
<td>• Might be affected by blue light scattering.</td>
</tr>
<tr>
<td>Tracing Radiation and Architecture of Canopies (3rd Wave Engineering, Ontario, Canada)</td>
<td>Measures sunfleck width along straight transects to obtain gap fraction and gap size distributions using quantum sensors.</td>
<td>• Estimates LAI from gap fraction distribution and clumping index from gap size distribution</td>
<td>• Requires clear sky to obtain measurement. • Multiple measurements are needed to get accurate LAI.</td>
</tr>
<tr>
<td>Canopy photography</td>
<td>Captures an image of the canopy from below or above canopy. The image is analysed to compute gap fraction and gap size distributions. Examples of photography techniques: hemispherical, canopy cover (Macfarlane et al. 2007b), multiband vegetation imager (Kucharik et al. 1998).</td>
<td>• Provides permanent records of position, size and distribution of canopy gaps. • Characterise plant canopy structure and light penetration. • Reduces blue light scattering. • Clumping index can be estimated. • Cheaper and more accessible.</td>
<td>• Requires uniform diffuse or overcast sky. • Requires image processing software to analyse image and derive LAI.</td>
</tr>
</tbody>
</table>
Chapter 5: *In Situ* and Remote Sensing Measurements of LAI

**Theoretical background of LAI estimation**

This sub-section outlines the theoretical background of estimating LAI from indirect methods. The estimation of LAI involves a number of assumptions that must be considered in assessing the limitations of a particular measurement method and the accuracy of the measurement result.

The estimation of LAI from solar radiation transmittance through the canopy is based on Beer-Lambert’s extinction law, with the leaves acting as a homogeneous turbid medium:

$$\frac{I_i}{I_0} = \exp(-kL)$$  \hspace{1cm} (5.1)

where $I_i$ is the radiation at level $i$ within the canopy, $I_0$ is the incident radiation above the canopy, $k$ is an extinction coefficient and $L_i$ is LAI above level $i$. The transmitted radiation can be directly measured with line quantum or capacitance sensors.

The ratio of the radiation below the canopy to the radiation above the canopy can also be expressed as gap fraction. The distribution of gap fraction in the canopy can be modelled by Poisson distribution, which assumes that foliage projection is randomly distributed:

$$P(\theta) = \exp\left[\frac{-G(\theta)L}{\cos(\theta)}\right]$$  \hspace{1cm} (5.2)

where $\theta$ is the zenith angle, $P(\theta)$ is the gap fraction, $G(\theta)$ is the projection coefficient of foliage on a plane normal to incoming radiation, $L$ is the leaf area index.

The other parameter that is required to calculate LAI from Equations 5.1 or Equation 5.2 is the extinction coefficient $k$ or the projection coefficient of foliage $G$. They describe leaf angle distribution in the canopy, which is difficult to measure. Thus, it is either modelled from a theoretical distribution (Campbell 1986, Weiss et al. 2004) or set as 0.5 under the assumption of random leaf angle distribution. Miller’s theorem (1967) provides an exact solution that satisfies the assumption of random leaf angle distribution by integrating multiple gap fraction measurements over the hemisphere:
Chapter 5: *In Situ* and Remote Sensing Measurements of LAI

The accuracy of indirect methods depends on how well the assumed foliage distribution matches the distribution in real canopy. Many studies have found that indirect methods tend to underestimate LAI when compared with direct methods because of the non-randomness of foliage distribution in real canopies (Chen *et al.* 1997, Jonckheere *et al.* 2005a, Walter *et al.* 2003). Most indirect methods also cannot differentiate between foliage and non-photosynthetic materials, such as trunks and branches, so they measure plant area index (PAI) rather than LAI. LAI obtained from indirect methods that have not been corrected for the non-random distribution of foliage elements and the contribution of woody materials is commonly referred as effective LAI or $L_e$ (Chen *et al.* 1991).

The introduction of clumping index ($\Omega$) to the Poisson model of gap fraction corrects for the non-randomness of foliage distribution (Nilson 1971). Clumping index is a measure of departure of clumped canopy from idealised canopy that has random foliage distribution. It depends on zenith angle, canopy architectures of individual tree and stand. There are two methods that are widely used to estimate clumping index. The “CC” method derived clumping index from gap size distribution (Chen and Cihlar 1995), while the “LX” method derived it from the on logarithmic average of gap fraction (Lang and Xiang 1986).

The contribution of the non-photosynthetic (woody) materials can be subtracted from the estimated PAI to obtain “actual” LAI (Chen 1996):

$$L = L_i (1 - \alpha)$$  \hspace{1cm} (5.4)

where $L$ is the leaf area index, $L_i$ is PAI, $\alpha$ is the woody-to-total area ratio or the contribution of non-green plant material. The most accurate method to obtain the ratio of woody materials to plant area index is destructive sampling. For deciduous trees, the amount of woody materials can be measured prior to leaf emergence.

**Canopy Photography Technique**
Chapter 5: In Situ and Remote Sensing Measurements of LAI

The most suitable indirect method to estimate LAI for this study is canopy photography. Canopy photography allows LAI and clumping index to be estimated simultaneously. It can be used to measure LAI at various heights above the ground so the understorey vegetation can potentially be excluded from the measurements. Two canopy photography techniques have been employed in this study. Hemispherical photography has been widely and successfully used to estimate LAI in boreal, broadleaf and eucalypt forests (Chen et al. 1997, Jonckheere et al. 2005b, van Gardingen et al. 1999). The other technique is “cover” photography introduced by Macfarlane (2007b) that utilises a regular lens to capture canopy image.

Cover and hemispherical photographs share the same image processing procedure. The photographs must be segmented into a binary (black and white) image to distinguish foliage from sky elements prior to gap fraction analysis. The segmentation process identifies an optimal brightness value (threshold) to separate the foliage from the sky. Misclassification of those elements results in the underestimation or overestimation of LAI. The use of automatic thresholding removes the analyst’s subjectivity in determining the optimal threshold level and is less time-consuming than manual thresholding.

The accuracy of thresholding process can be improved if the image has maximum contrast between the foliage and sky elements. This can be achieved by taking photographs under uniformly diffuse or overcast sky, and overexposing those photographs to enhance the contrast between the foliage and the sky. Zhang et al. (2005) recommended increasing the camera’s exposure by two stops from the reference automatic exposure that is metered under an open sky. The use of high resolution camera also helps to reduce misclassification problem as the frequency of mixed pixels is reduced.

5.1.2 Remote Sensing Measurement of LAI

Remote sensing have been successfully used to estimate LAI in a wide range of environments (Asner. 2004, Chen and Cihlar 1996, Colombo et al. 2003, Kalácska et al. 2004, Morsdorf et al. 2006, Riano et al. 2004, Solberg 2009, Wulder et al. 1998). They also enable LAI to be measured at a large spatial scale efficiently and repeatedly over time.
Chapter 5: *In Situ* and Remote Sensing Measurements of LAI

for monitoring purposes. However, there have been a limited number of studies that utilised remote sensing to measure LAI in Australian forests (Coops *et al.* 1997, Hill *et al.* 2006, Lovell 2003, Watson *et al.* 1999b). This study used both multi-spectral and LiDAR data to obtain the spatial distribution of LAI in mountain ash forest. The following subsections present the literature review on the estimation of LAI from both sources.

**Multi-spectral satellite data**

The use of multi-spectral data to estimate biophysical properties and changes in vegetation is possible because vegetation has distinct spectral reflectance properties. Green vegetation absorbs the visible red wavelength for photosynthesis and reflects high amount of near infrared wavelength (Gates *et al.* 1965). This contrast in spectral reflectance from different regions of the electromagnetic spectrum is used to identify vegetation surface. It is the basis of spectral vegetation index (SVI), such as the Normalised Difference Vegetation Index (NDVI) that incorporates the red and near infrared wavelength.

There are several limitations to the estimation of LAI based on vegetation indices. The relationship between LAI and spectral reflectance is often asymptotic at high LAI or after the canopy cover is fully established (Chen and Cihlar 1996, Fassnacht *et al.* 1997, Turner *et al.* 1999). The contribution from understorey vegetation might also influence reflectance values and introduce noise (Chen 1996, Eriksson *et al.* 2006, Brown *et al.* 2000). The presence of cloud cover limits the use of multi-spectral image in some locations, such as at high altitude and/or in the tropical region.

Considerable effort has been spent on improving and overcoming the limitations of LAI estimation from spectral data. Several vegetation indices have incorporated adjustment factors to account for background reflectance, reduce atmospheric effects, minimise the effects of understorey vegetation and maximise the amount of information available (Huete 1988, Huete *et al.* 1996, Kaufman 1992, Qi 1994, Turner *et al.* 1999). Improvement in LAI estimation has also been achieved through the use of high spatial resolution image (Colombo *et al.* 2003), spectral mixture analysis in conjunction with hyper-spectral data (Asner. 2004) and spatial information (Colombo *et al.* 2003, Wulder *et al.* 1998).
Light Detection And Ranging (LiDAR) data

The use of LiDAR in retrieving vegetation structure attributes has been briefly discussed in Section 4.1. LiDAR-derived variables that describe canopy height or cover have been successfully used to estimate LAI in various forest types (Jensen et al. 2008, Lefsky et al. 1999, Lovell 2003, Morsdorf et al. 2006, Riano et al. 2004, Solberg 2009). In particular, LiDAR vegetation cover can be easily calculated from the proportion of vegetation hits to total hits. Vegetation cover is inversely proportional to gap fraction so it can be related to LAI based on the Beer–Lambert’s extinction law. Both the calculation of gap fraction from LiDAR hits and the estimation of LAI from the gap fraction are shown below:

\[
P_h = 1 - f_{\text{Cover}_h} = 1 - \frac{N_{v,h}}{N_t}
\]

where \( f_{\text{Cover}_h} \) is the vegetation cover at height \( h \) above the ground, \( N_{v,h} \) is the number of vegetation hits above height \( h \), \( N_t \) is the total number of hits (ground and vegetation), \( P_h \) is gap fraction above height \( h \), \( k \) is the extinction coefficient and \( L_{e,h} \) is the effective LAI above height \( h \).

There are several advantages of using LiDAR to estimate LAI compared to optical remote sensing. The ability of LiDAR to penetrate dense canopy means that higher LAI can be measured without the signal saturation problem (Lefsky et al. 1999). Cloud cover does not affect LiDAR’s signal, while it interferes with spectral reflectance. However, the cost of obtaining LiDAR data are currently much higher than the cost of satellite data so the use of LiDAR for repeated measurements or routine monitoring purposes is still limited.

5.2 Experimental Design and Procedures

This section describes the sampling strategy and procedures to obtain in situ LAI estimates and remote sensing parameters. The in situ measurements of LAI were
conducted with cover and hemispherical photography at Crotty Creek. The measurements would be used to calibrate remote sensing parameters, which were used to produce LAI spatial distribution maps for Crotty Creek and the other North Maroondah experimental catchments. However, there has been limited use of photographic techniques to measure LAI in mountain ash forest. A pilot study was conducted at Black Spur to examine the reliability of the two photographic techniques in obtaining LAI measurements. The measurement results from this pilot study were compared against a predicted LAI of mountain ash stands from the LAI – stand age relationship (Watson and Vertessy 1996) as the use of destructive sampling was not possible.

The process of obtaining in situ LAI estimates consisted of the acquisition, processing and analysis of cover and hemispherical photographs, while the process of obtaining remote sensing parameters consisted of calculating SVI from Quickbird multi-spectral image and gap fraction from LiDAR data. The last sub-section outlines the statistical analysis used to generate LAI distribution models from the in situ LAI estimates and remote sensing parameters.

### 5.2.1 Sampling Strategy at Black Spur

The sampling plot for the pilot study was located in an undisturbed area above the Black Spur experimental catchments. This plot is also in the vicinity of a destructive sampling plot used in previous studies on the relationship between leaf area index, stand age and catchment water balance in mountain ash forests (Vertessy et al. 2001, Watson and Vertessy 1996).
Figure 5.1. Locations of measurement points in the undisturbed area at Black Spur.

Two measurement transects were established at the sample plot (Figure 5.1). Each transect has six measurement points, located approximately 10 m apart and marked with flags. Cover and hemispherical photographs were taken in two separate occasions in June 2008. Cover photographs were taken at 3 m and 6 m above the ground at all sampling points, with a limited number of photographs taken at 9 m at some sampling points. Hemispherical photographs were taken at 3 m, 6 m, 9 m and 11 m at each sampling point. The locations of the sampling points were recorded with Trimble ProXR (Trimble, Sunnyvale, CA, USA).
5.2.2 Sampling Strategy at Crotty Creek

The Crotty Creek catchment is made up of alternating retained strips and formerly cleared strips (referred to as “cleared strip” hereafter) after strip-thinning was conducted in 1980-1985. The retained strips are dominated by tall mountain ash (*E. regnans*) stands; while the cleared strips are dominated by *Acacia* species, such as *Acacia dealbata* and *Acacia melanoxylon*. Various mid-storey and understorey shrubs, such as *Correa lawrenzia* and *Polyscias sambucifolius*, occur profusely in some strips.

Stratified random sampling strategy was adopted at Crotty Creek to ensure that potential variations in LAI estimates across the catchment could be captured. The catchment was divided into five zones and the strips were numbered. Initially, each zone was allocated an even number of sampling points based on the proportion of its area to total catchment area. The sampling points were assigned to randomly sample retained and regrowth strips in the zone. Transects were created by grouping consecutive sample strips, their starting points were randomly chosen along the access road. Figure 5.2 shows an example of the layout of sampling points along a transect that cuts through two pairs of strips.

![Figure 5.2. Layout of a transect spanning two pairs of retained and regrowth strips.](image-url)
Chapter 5: *In Situ* and Remote Sensing Measurements of LAI

The first field survey was carried out between May and December 2008. Twenty five pairs of sampling points were planned to be sampled in 2008, but this plan could not be completed due to frequent unfavourable weather conditions (non-uniform cloud cover) and equipment failures. About half of the ten field trips in 2008 failed to yield good quality photographs. Some of the 2008 sampling points were re-sampled in the 2009 field survey. The data from the 2009 field survey were used in the analysis when re-sampling occurred.

The field campaign resumed after the February 2009 bushfire with a modified sampling strategy. Grid sampling was incorporated into the sampling strategy to reduce the influence of local artefacts, such clumps of low-hanging leaves or branches that occupy significant portion of the camera’s field of view at some locations. This sampling strategy was also expected to decrease the probability of plot misregistration when the ground data were compared with remote sensing data. The grid sampling system consisted of a single transect spanning four strips, with three adjacent sampling points in each strip. The measurements from three adjacent sampling points were averaged.

Figure 5.3 shows the locations of the sampling points surveyed in 2008 and the grid sampling points surveyed in 2009. The background image shows a map of maximum vegetation height that was obtained from LiDAR data. Measurements were obtained from twelve sampling points in transect D, but the furthest two strips from the road were affected from fire so they were excluded from the analysis. The 2008/2009 combined data set contained measurements taken from 12 sampling points surveyed in 2008 and 54 sampling points surveyed in 2009. The coordinates of the measurement points were recorded with Trimble ProXR (Trimble, Sunnyvale, CA, USA) and Sokkia GSR1700 CSX (Sokkia Topcon Co. Ltd., Kanagawa, Japan) differential GPS.
Figure 5.3. Locations of sampling points at Crotty Creek, grouped around eight transects. The background image is a map of maximum vegetation height based on LiDAR data, which shows the layout of the retained (dark green) and regrowth (light green) strips.
5.2.3 In situ LAI Estimates

Hemispherical photography

Hemispherical photography was used in this study to estimate in situ LAI. The hemispherical photographs were obtained with Nikon Coolpix 8400 digital camera and FC-8 mm fisheye lens. The zoom setting of the camera was adjusted so that the circular image occupied most of the screen. The camera’s exposure was calibrated at the start of each transect measurement following this procedure (Macfarlane et al. 2007b):

1. The camera setting was set on Aperture-Priority mode (“A”) and the aperture was adjusted to its minimum setting (maximum f-number 7.2).
2. At a clearing, the camera was pointed towards the sky and the automatic shutter speed reading was recorded.
3. At the first measurement point, the camera was set to the manual mode (“M”). The shutter speed was adjusted to two stops lower than the reading at the clearing to overexpose the canopy image, while maintaining the same f-number.

The exposure calibration was conducted at the beginning of each transect measurement only because of the considerable distance between the clearing area and the measurement location.

The hemispherical photograph consists of a circular image with the zenith in the middle and horizons around the edges (Figure 5.4). The image is divided into rings of fixed zenith angle interval and gap fraction is calculated for each ring. A variety of software packages are available to perform the analysis, such as Hemiview (Delta-T Devices Ltd., Cambridge, UK), GLA (Simon Fraser University, British Columbia, Canada), WinSCANOPY (Regent Instruments Inc., Canada) and DHP-TRACWin (Natural Resources Canada, Quebec, Canada). Most of them have a global, manual thresholding algorithm and only one or two methods to estimate LAI from gap fraction. Hemisfer version 1.4.2 (Schleppi, WSL Birmensdorf, Switzerland) was utilised in this study because it offers two automatic thresholding algorithms, the choice to apply global or ring-based thresholding, and various analytical methods to compute LAI, clumping index and leaf angle distributions.
Another advantage of Hemisfer was the ability to incorporate slope correction to the calculation of gap fraction from hemispherical photograph (Schleppi et al. 2007). Slope correction was incorporated into the estimation of \( L_e \) at Crotty Creek catchment because the sampling locations have slopes ranging from \( 3^0 \) to \( 22^0 \). It was not adopted in the analysis of hemispherical photographs from the Black Spur’s plot because the site is relatively flat. The next table shows the selected parameter settings in Hemisfer that were used to perform thresholding as well as to derive \( L_e \) and CC clumping index.

**Table 5.3. Parameter settings used to analyse hemispherical photographs in Hemisfer.**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Settings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of rings</td>
<td>5 – 8 rings, each covers ( 10^0 ) azimuth angle</td>
</tr>
<tr>
<td>Thresholding method</td>
<td>Individual ring, Nobis and Hunziker (2005) algorithm</td>
</tr>
<tr>
<td>Channel</td>
<td>Blue</td>
</tr>
<tr>
<td>Gamma function</td>
<td>2.2</td>
</tr>
<tr>
<td>Effective LAI computation</td>
<td>Miller (1967)</td>
</tr>
<tr>
<td>method</td>
<td>Schleppi et al. (2007) for slope correction</td>
</tr>
<tr>
<td>Clumping correction</td>
<td>Chen and Cihlar (1995)</td>
</tr>
</tbody>
</table>

**Figure 5.4. Hemispherical photograph taken at the Black Spur catchment. The rings were overlaid over the image in the analysis.**
Cover Photography

Macfarlane et al. (2007b) introduced canopy cover photography as an alternative to hemispherical photography to measure LAI. The photograph is obtained with a standard digital camera, producing an image with a narrow range of zenith angles. The cover photographs were mostly captured on the same day as hemispherical photographs at each transect, unless a change in the weather condition prevented it. At the beginning of the photography process, the aperture of the camera was adjusted to its minimum setting (maximum f-number 7.2) and the exposure was set to automatic.

SideLook version 1.1.01 (Nobis, Appleco, Switzerland) was used to compute a threshold level based on an edge detection algorithm (Nobis and Hunziker 2005). The analysis was performed in the blue channel. The recommended threshold level was sometimes manually adjusted when misclassification of segments deemed to occur, judged by comparing the original image and the binary image. The binary image was saved as a bitmap image.

GNU Image Manipulation Program (GIMP) version 2.4.5 (GIMP Development Team) was used to analyse the binary images. Two parameters were derived directly from the image (Macfarlane et al. 2007b): the number of pixels contained in large gaps between canopy crowns (gap size $g_L$), and the total number of sky pixels (total gap $g_T$). The gap size was obtained by selecting large gaps in the image with the wand tool in GIMP and obtaining the number of pixels contained in these gaps from the histogram. The total gap was obtained from the number of sky (white) pixels in the image histogram. Table 5.4 shows how these two basic parameters were used to calculate other canopy parameters required to estimate LAI.
Table 5.4. Parameters required for LAI estimation from cover photograph.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Definition</th>
<th>Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>Foliage cover ($f_f$)</td>
<td>Vertical projection of foliage and branches on the ground</td>
<td>$f_f = 1 - (g_f/\text{total pixels})$</td>
</tr>
<tr>
<td>Crown cover ($f_c$)</td>
<td>Vertical projection of solid crown on the ground</td>
<td>$f_c = 1 - (g_c/\text{total pixels})$</td>
</tr>
<tr>
<td>Crown porosity ($\Phi$)</td>
<td>Vertical projection of foliage and branches within the crowns of individual plants on the ground.</td>
<td>$\Phi = 1 - f_f/f_c$</td>
</tr>
</tbody>
</table>

Two versions of LAI estimation were offered by Macfarlane et al. (2007b), which were based on crown parameters and foliage cover respectively:

$$L_e = -f_c \frac{\ln(\Phi)}{k}$$  

(5.7)

$$L_e = \frac{\ln(1-f_f)}{k}$$  

(5.8)

where $f_c$ is the crown cover, $f_f$ is the foliage cover, $\Phi$ is the crown porosity and $k$ is the extinction coefficient at zenith angle. Equation 5.8 was adopted to estimate LAI in this study because its formulation of gap fraction was similar to gap fraction derived from LiDAR’s vegetation hits. Clumping index at the zenith was derived from the corrected Chen and Cihlar’s method (Macfarlane et al. 2007b):

$$\Omega(0) = \frac{(1-\Phi)\ln(1-f_f)}{\ln(\Phi)f_f}$$  

(5.9)

The extinction coefficient ($k$) of Eucalypt forests has been reported to vary between 0.4 and 0.5 (Breda 2003, Macfarlane et al. 2007a, Macfarlane et al. 2007b). As the extinction coefficient of the *Acacia* stands was unknown, it was more practical to set the extinction coefficient near the zenith for all vegetation groups in this study to 0.5. This means that the absolute difference in LAI values from the retained and regrowth stands could be greater/smaller than the relative difference in LAI estimates.
At the Black Spur study site, the wood-to-total area ratio was estimated by identifying non-photosynthetic materials in the cover photographs and calculating their proportional area. The ratios were 0.170 and 0.175 for photographs taken at 3 – 6 m and 9 – 11 m respectively. LAI was estimated from $L_e$, the Chen and Cihlar’s clumping index (CC) and the wood-to-total area ratio.

**Measurement at multiple heights**

Both hemispherical and cover photographs were obtained at multiple heights. The hydraulic mast was set up at the sampling point (Figure 5.5). A Nikon Coolpix 8400 digital camera (with or without FC-8 mm fisheye lens) was attached to a custom made steel box, which was mounted on top of a hydraulic mast. The height of the camera from the ground was approximately 3 m. The camera was controlled from a computer in real time with Picture Project (Nikon Corporation, Japan) software. The camera was connected to a laptop computer via USB cable and two repeaters. Picture Project (Nikon Corporation, Japan) was used to control the camera in real time. The mast was extended to the required heights (6 - 11 m) using its hydraulic pump. The photographs were captured when the mast was held level and steady.
Chapter 5: *In Situ* and Remote Sensing Measurements of LAI

5.2.4 Remote Sensing Parameters

**SVI from Quickbird**

A Quickbird multi-spectral image of the North Maroondah Experimental Area was acquired on 23 July 2008 at 10:45 AEST. The Quickbird image has high spatial resolution (Figure 5.6) and four spectral bands. The image specification has been summarised in Table 5.5. The high spatial resolution was expected to improve the accuracy of plot registration and capture local detail, while the four spectral bands enabled a range of SVIs to be calculated and correlated against the *in situ* measurements.
Chapter 5: *In Situ* and Remote Sensing Measurements of LAI

Table 5.5. Specification of the Quickbird multi-spectral image

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensor type</td>
<td>Quickbird</td>
</tr>
<tr>
<td>Image area (square km)</td>
<td>64</td>
</tr>
<tr>
<td>Image centre</td>
<td>Longitude: 145° 36' 0.72&quot;, latitude: -37° 34' 15.24&quot;</td>
</tr>
<tr>
<td>Multi-spectral image resolution (m)</td>
<td>x: 1.91, y: 2.4</td>
</tr>
<tr>
<td>Mean sun elevation (degree)</td>
<td>28.0</td>
</tr>
<tr>
<td>View angle off nadir (degree)</td>
<td>10.3</td>
</tr>
<tr>
<td>Cloud cover (%)</td>
<td>14.9</td>
</tr>
<tr>
<td>Spectral characteristics</td>
<td>Blue (450 – 520 nm), green (520 -600 nm), red (630 – 690 nm) and near-infrared (760 – 900 nm)</td>
</tr>
</tbody>
</table>

Figure 5.6. False colour composite of Quickbird multi-spectral image over the Crotty Creek catchment. The white crosses mark the *in situ* sampling locations used to extract the spectral vegetation indices.
The purchased image was radiometrically calibrated and corrected for sensor and platform-induced distortions. An orthorectification procedure was performed in ENVI version 4.6.1 (ITT Visual Information Solutions, 2008) using digital elevation models (DEM) as reference images. The models were generated from LiDAR data with 5 m resolution for the Black Spur, Ettercon and Crotty Creek catchments.

The mean reflectance value from each spectral band was extracted from a range of window sizes: 5x5, 7x7, 9x9, 11x11 and 13x13 pixels to determine which extent was best correlated with the *in situ* LAI estimates. The largest window size was chosen to fit inside most of the retained and regrowth strips. The GPS coordinates of the sampling locations were used as the centre of the image window (Figure 5.7).

![Figure 5.7. An example of the location of SVI extraction window relative to the in situ LAI photography point.](image)

Seven vegetation indices were selected to model the *in situ* LAI estimates in this study (Table 5.6). These indices utilised all spectral bands in the Quickbird’s multi-spectral image. They were formulated to address different factors that might affect the SVI – LAI relationship, such as soil reflectance, atmospheric effects and spectral saturation. At each sampling strip, the SVIs were calculated for the selected range of window sizes.

Preliminary analysis on the distributions of the SVIs has shown that ARVI distributions had several extreme values, which increased with increasing window size (Figure 5.8). The plots of ARVI – LAI estimates indicated that these values would affect the relationships
disproportionately and result in poor model fits. Thus, ARVI was removed from the list of SVIs used to predict the LAI estimates.

Figure 5.8. Distribution of ARVI values for a range of window sizes.
Table 5.6. Spectral vegetation indices used to model LAI estimates in this study.

<table>
<thead>
<tr>
<th>Spectral Vegetation Index (SVI)</th>
<th>Definitions</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normalised Difference Vegetation Index</td>
<td>[NDVI = \frac{NIR - R}{NIR + R}]</td>
<td>(Rouse et al. 1973)</td>
</tr>
<tr>
<td>Simple Ratio</td>
<td>[SR = \frac{NIR}{R}]</td>
<td>(Jordan 1969)</td>
</tr>
<tr>
<td>Enhanced Vegetation Index</td>
<td>[EVI = \frac{NIR - R}{NIR + C_1 \cdot R - C_2 \cdot B + C_3} \cdot G]</td>
<td>(Huete et al. 1996)</td>
</tr>
<tr>
<td>Modified Soil Adjusted Vegetation Index</td>
<td>[MSAVI = NIR + 0.5 - \sqrt{(NIR + 0.5)^2 - 2(NIR - R)}]</td>
<td>(Qi 1994)</td>
</tr>
<tr>
<td>Atmospherically Reduced Vegetation Index</td>
<td>[ARVI = \frac{NIR - [R - \gamma(B - R)]}{NIR + [R - \gamma(B - R)]}]</td>
<td>(Kaufman 1992)</td>
</tr>
<tr>
<td>Green NDVI</td>
<td>[GNDVI = \frac{NIR - G}{NIR + G}]</td>
<td>(Gitelson et al. 1996)</td>
</tr>
<tr>
<td>Blue NDVI</td>
<td>[BNDVI = \frac{NIR - B}{NIR + B}]</td>
<td></td>
</tr>
</tbody>
</table>

Notes:

- NIR is near-infrared reflectance, R is red reflectance, G is green reflectance, B is blue reflectance.
- C_1 and C_2 are the adjustment factors for aerosol scattering and absorption, C_3 is a canopy background brightness adjustment and G is a gain factor. The coefficients adopted from MODIS-EVI are C_1 = 6, C_2 = 7.5, C_3 = 1 and G = 2.5.
- \(\gamma\) in ARVI is set to 1.
Five regression models were fitted to each SVI data set to predict the LAI estimates (Tagesson et al. 2009):

- Linear model: $L_t = \beta_0 + \beta_1 S$
- Logarithmic model: $L_t = \beta_0 + \beta_1 \ln(S)$
- Power model: $L_t = \beta_0 S^{\beta_1}$
- Growth model: $L_t = \exp(\beta_0 + \beta_1 S)$
- S-curve model: $L_t = \exp(\beta_0 + \beta_1 / S)$

where $L_t$ was PAI, $\beta_0$ was the intercept, $\beta_1$ was the slope parameter and $S$ was the vegetation index. Non-linear models were linearly transformed so a least square regression can be applied.

**Gap fraction from LiDAR data**

LiDAR return hits were extracted from circular plots with a range of diameters: 15 m, 20 m, 25 m and 30 m. They were separated into ground and vegetation hits. The numbers of vegetation hits above 3 m and 11 m were quantified. Gap fraction was calculated for each height based on Equation 5.1. The relationship between gap fraction and *in situ* LAI estimate is assumed to be logarithmic based on the Beer – Lambert’s law of extinction (Equation 5.6).

**5.2.5 Statistical Analysis**

All regression analysis and statistical tests were performed in R version 2.8.1 (The R Foundation for Statistical Computing, 2008). Linear least squares regression was used to model the *in situ* leaf area with the remote sensing parameters. The objective was to find the best model to map LAI spatial distribution at catchment level. The following sub-sections discussed the statistical analysis used to select the best LAI distribution model and data stratification.

**Modelling LAI estimates with SVI**

The selection of the best regression model that predicts *in situ* LAI was carried out in two phases. In the first phase, the best regression model was selected from the various
linear models and window sizes for each SVI. In the second phase, the best SVI model that predicted the LAI data set was selected.

The coefficient of determination, $R^2$, was used to evaluate the fit of the regression models and select the best model:

$$R^2 = 1 - \frac{\sum(y - \hat{y})^2}{\sum(y - \bar{y})^2}$$  \hspace{1cm} (5.10)

where $\hat{y}$ is the model prediction for an observed $y$ and $\bar{y}$ is the mean of $y$ observation. Although $R^2$ values from linearly transformed model and linear models are calculated in different domains, they are still good indicators of the goodness of fit of the models. To choose between two such models when there was a small difference in $R^2$ values, their plots of residual against fitted values were examined to ensure the best model satisfied the requirement of constant variance.

**Modelling LAI estimates with LiDAR gap fraction**

The theoretical relationship between gap fraction and LAI indicates that a no-intercept logarithmic model should be used to predict LAI estimates from LiDAR gap fraction (Solberg 2009). However, fitting a no-intercept model to measurement data solely based on a theoretical assumption creates a few problems. A logarithmic intercept model might fit the actual measurement data better so fitting the no-intercept model results in an inferior predictive model. $R^2$ value calculated from a no-intercept model is inflated as $S_{YY} = \sum(y)^2$ rather than $S_{YY} = \sum(y_i - \bar{y})^2$, where $S_{YY}$ is the total sum of squared residuals with respect to the mean. Therefore, $R^2$ value is not a robust criterion to judge the goodness of fit of the no-intercept models (Draper and Smith 1998).

Both the intercept and no-intercept logarithmic models were fitted to the calibration data. The models’ goodness of fit was assessed by comparing their residual standard errors (RMSE). The intercept model had lower residual standard errors than the no-intercept model so it was regarded as the best model to predict LAI estimates from LiDAR gap fraction in this study.

**Data stratification**
Chapter 5: In Situ and Remote Sensing Measurements of LAI

Results from several studies have indicated that the relationship between SVI and in situ LAI improved when the data were stratified based on forest types, such as hardwood and conifers (Chen and Cihlar 1996, Fassnacht et al. 1997, Tagesson et al. 2009, Turner et al. 1999). The LAI estimates in this study can be stratified based on strip type of the sampling locations (retained and regrowth), which separates the vegetation into mountain ash stands and Acacia stands.

A regression with a dummy variable (strip type) was applied to the calibration data to test the effect of stratification. The null hypothesis was that a single regression line can be used to predict LAI estimates from the retained and regrowth strips. The results showed that the null hypothesis could not be rejected for the SVI – LAI relationships (p > 0.05), but it was rejected for the LiDAR gap fraction – LAI relationships (p < 0.05) at 11 m. Thus, LAI estimates from the retained and regrowth strips were modelled separately using LiDAR gap fraction data.

5.3 Results

5.3.1 LAI Estimates from the Pilot Study at Black Spur

Table 5.7 provides a summary of the mean LAI values at various heights above the ground with the two photography methods. There were only two cover photographs taken at 11 m above the ground so their mean LAI are not presented here. Student’s t-tests were used to examine the effect of measurement heights on LAI estimates and to compare the two photography techniques. LAI values obtained at 3 m were greater than those obtained at higher measurement heights, while the mean LAI estimated from hemispherical photographs at each measurement height was higher than the mean LAI estimated from cover photography.
Table 5.7. Mean leaf area index (LAI) from cover and hemispherical photographs obtained at different heights. The standard errors are given in parentheses and ‘n’ is the number of samples.

<table>
<thead>
<tr>
<th>Measurement heights</th>
<th>Cover</th>
<th>Hemispherical</th>
<th>Difference between techniques</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>n</td>
<td>Mean LAI</td>
<td>n</td>
</tr>
<tr>
<td>3 m</td>
<td>11</td>
<td>2.29 (0.32)</td>
<td>12</td>
</tr>
<tr>
<td>6 m</td>
<td>12</td>
<td>2.14 (0.27)</td>
<td>12</td>
</tr>
<tr>
<td>9 m</td>
<td>9</td>
<td>1.99 (0.18)</td>
<td>12</td>
</tr>
<tr>
<td>11 m</td>
<td></td>
<td></td>
<td>12</td>
</tr>
</tbody>
</table>

The average LAI value of a stand of mountain ash with uniform age was predicted using the relationship outlined in Watson and Vertessy (1996):

\[
LAI = 11.014 t^{-1.624} (t - 5.04)^{1.18} 3.592 (t - 5.04)^{0.319}
\]

where \( t \) is the age of the stand. The predicted mean LAI for 69 year old mountain ash stands was 2.2. This value was within the standard errors of the mean LAI obtained with cover and hemispherical photography (Figure 5.9). Thus, the photography techniques could be used with confidence to measure in situ LAI at Crotty Creek.

Figure 5.9. Mean LAI values from canopy cover and hemispherical photography compared with predicted LAI value for \( E. \) regnans based on LAI-age relationship. Error bars show the standard errors.
5.3.2 LAI Estimates at Crotty Creek

Each photograph was analysed to derive $L_e$ and CC clumping index. PAI was estimated from $L_e$ as the wood-to-total area ratio of the vegetation stands at Crotty Creek could not be estimated. PAI and $L_e$ will be collectively referred as leaf area parameters. They would be used to calibrate the remote sensing parameters to obtain the best LAI distribution model.

Figure 5.10 shows the distribution of PAI and $L_e$ estimates based on vegetation type (retained mountain ash stands or regrowth Acacia stands), height (3 m or 11 m) and photography technique (cover and hemispherical). The leaf area parameters from the hemispherical photographs that are presented in the boxplots were derived with the range of zenith angles limited to $0^\circ - 50^\circ$. The bold line inside the boxplot represents the mean of the distribution, the bottom and top lines of the box represent the 25% and 75% range respectively, and the whiskers were set to twice the interquartile range. The circles represent values greater or less than twice the interquartile range.

Student’s t-tests were used to compare the distributions of leaf area parameters in order to examine the difference in LAI between total and overstorey LAI (measurement heights), retained and regrowth stands and photography techniques. Table 5.8 provides a summary of the comparisons of PAI distributions and their results. N/S refers to not statistically significant difference in the mean of the distributions ($p > 0.05$).
Figure 5.10. Distributions of *in situ* $L_e$ and PAI of the retained mountain ash and regrowth *Acacia* stands at 3 m and 11 m. Hemispherical refers to hemispherical photography derived with $0^\circ$ – $50^\circ$ zenith angles, while cover refers to cover photography.
Table 5.8. Comparisons of PAI distributions based on heights, strips and photography techniques. The results were statistically significant at p < 0.05, unless when marked as N/S (not significant).

<table>
<thead>
<tr>
<th>Comparisons</th>
<th>Samples (n1 and n2)</th>
<th>Main category</th>
<th>Sub-category</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 m and 11 m (total and overstorey)</td>
<td>15, 15</td>
<td>Retained</td>
<td>Cover</td>
<td>PAI_{total} &gt; PAI_{overstorey}</td>
</tr>
<tr>
<td></td>
<td>14, 14</td>
<td></td>
<td>Hemispherical</td>
<td>N/S</td>
</tr>
<tr>
<td></td>
<td>15, 11</td>
<td>Regrowth</td>
<td>Cover</td>
<td>PAI_{total} &gt; PAI_{overstorey}</td>
</tr>
<tr>
<td></td>
<td>15, 11</td>
<td></td>
<td>Hemispherical</td>
<td>N/S</td>
</tr>
<tr>
<td>Retained and regrowth</td>
<td>15, 15</td>
<td>Cover</td>
<td>3 m</td>
<td>PAI_{retained} &gt; PAI_{regrowth}</td>
</tr>
<tr>
<td></td>
<td>15, 11</td>
<td></td>
<td>11 m</td>
<td>N/S</td>
</tr>
<tr>
<td></td>
<td>14, 15</td>
<td></td>
<td>Hemispherical</td>
<td>PAI_{retained} &gt; PAI_{regrowth}</td>
</tr>
<tr>
<td></td>
<td>14, 11</td>
<td></td>
<td>3 m</td>
<td>N/S</td>
</tr>
<tr>
<td></td>
<td>15, 14</td>
<td></td>
<td>3 m</td>
<td>PAI_{cover} &gt; PAI_{hemispherical}</td>
</tr>
<tr>
<td></td>
<td>15, 14</td>
<td></td>
<td>11 m</td>
<td>PAI_{cover} &gt; PAI_{hemispherical}</td>
</tr>
<tr>
<td></td>
<td>15, 15</td>
<td>Regrowth</td>
<td>3 m</td>
<td>N/S</td>
</tr>
<tr>
<td></td>
<td>11, 11</td>
<td></td>
<td>11 m</td>
<td>N/S</td>
</tr>
</tbody>
</table>

5.3.3 Modelling LAI Distribution with Remote Sensing Parameters

The vegetation indices that were derived from the Quickbird multi-spectral image (see Table 5.6) predicted PAI values better than Le values. The best regression models between SVI and PAI for different measurement heights and photography techniques are summarised in Table 5.9. The stratification of data based on vegetation stands was not significant so a single model has been used to predict PAI. Meanwhile, LiDAR gap fraction predicted Le values better than PAI values. The stratification of data based on vegetation stand was significant. The best regression models between LiDAR gap fraction and stratified L_e values are summarised in Table 5.10.
Table 5.9. Summary of the best regression models between SVIs and *in situ* PAI.

<table>
<thead>
<tr>
<th>PAI</th>
<th>Height (m)</th>
<th>Window size (pixels)</th>
<th>Best SVI predictor</th>
<th>Samples</th>
<th>Regression models</th>
<th>$R^2$</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cover</td>
<td>3</td>
<td>5x5</td>
<td>BNDVI</td>
<td>30</td>
<td>$y = 3.51 - 0.26 \ln(x)$</td>
<td>0.17</td>
<td>&lt; 0.05</td>
</tr>
<tr>
<td>Hemispherical</td>
<td>3</td>
<td>9x9</td>
<td>GNDVI</td>
<td>29</td>
<td>$y = 2.1 - 0.30 \ln(x)$</td>
<td>0.22</td>
<td>&lt; 0.05</td>
</tr>
<tr>
<td>Cover</td>
<td>11</td>
<td>5x5</td>
<td>GNDVI</td>
<td>30</td>
<td>$y = \exp(1.06 + 0.001/x)$</td>
<td>0.08</td>
<td>0.15</td>
</tr>
<tr>
<td>Hemispherical</td>
<td>11</td>
<td>5x5</td>
<td>GNDVI</td>
<td>29</td>
<td>$y = \exp(0.92 - 0.44x)$</td>
<td>0.41</td>
<td>&lt; 0.01</td>
</tr>
</tbody>
</table>

Table 5.10. Summary of the best regression models between LiDAR gap fractions and *in situ* $L_e$.

<table>
<thead>
<tr>
<th>$L_e$</th>
<th>Height (m)</th>
<th>Strip type</th>
<th>Best diameter (m)</th>
<th>Samples</th>
<th>Regression models</th>
<th>$R^2$</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cover</td>
<td>3</td>
<td>Retained</td>
<td>30</td>
<td>15</td>
<td>$y = 0.39 - 1.63 \ln(x)$</td>
<td>0.45</td>
<td>&lt; 0.01</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Regrowth</td>
<td>25</td>
<td>15</td>
<td>$y = 1.06 - 1.81 \ln(x)$</td>
<td>0.51</td>
<td>&lt; 0.01</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>Retained</td>
<td>30</td>
<td>14</td>
<td>$y = 1.13 - 0.59 \ln(x)$</td>
<td>0.25</td>
<td>0.07</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Regrowth</td>
<td>15</td>
<td>15</td>
<td>$y = 1.90 - 0.34 \ln(x)$</td>
<td>0.22</td>
<td>0.07</td>
</tr>
<tr>
<td>Cover</td>
<td>11</td>
<td>Retained</td>
<td>20</td>
<td>15</td>
<td>$y = 1.43 - 0.91 \ln(x)$</td>
<td>0.24</td>
<td>0.06</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Regrowth</td>
<td>20</td>
<td>15</td>
<td>$y = 0.39 - 3.20 \ln(x)$</td>
<td>0.54</td>
<td>&lt; 0.05</td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>Retained</td>
<td>20</td>
<td>14</td>
<td>$y = 1.32 - 0.47 \ln(x)$</td>
<td>0.38</td>
<td>&lt; 0.05</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Regrowth</td>
<td>20</td>
<td>15</td>
<td>$y = 1.27 - 1.29 \ln(x)$</td>
<td>0.45</td>
<td>&lt; 0.05</td>
</tr>
</tbody>
</table>
The ability of vegetation indices to predict PAI was relatively poor, as shown by the coefficient of determination ($R^2$) from the best models. The best regression model was between GNDVI from 5x5 pixels and hemispherical PAI at 11 m ($R^2 = 0.41$, $p < 0.01$). Figure 5.11 shows the fitted model with stratified data points to illustrate that a single model can predict PAI of the retained and regrowth stands. Several studies have reported that vegetation indices were positively correlated with in situ LAI estimates (Chen and Cihlar 1996, Fassnacht et al. 1997, Gitelson et al. 1996, Huete 1988, Kaufman 1992, Turner et al. 1999), whereas GNDVI was negatively correlated against PAI here.

The gap fractions derived from LiDAR were more successful than the vegetation indices in predicting leaf area parameters. The best regression model was between LiDAR’s gap fraction and cover $L_e$ at 11 m in the regrowth stands ($R^2 = 0.54$, $p < 0.05$). However, the requirement to stratify the data based on stand types indicated that there might be some discrepancies in the gap fractions obtained by LiDAR and the in situ photography techniques. At 3 m above the ground, a large range of $L_e$ values were correlated against a small range of LiDAR’s gap fractions (Figure 5.12). To examine it further, a comparison of gap fractions obtained by canopy photography and LiDAR was conducted.
Chapter 5: *In Situ* and Remote Sensing Measurements of LAI

Figure 5.12. The best fit models that predict cover $L_e$ estimates at 3 m and 11 m based on LiDAR gap fractions derived using various plot diameters.

Figure 5.13 shows LiDAR’s gap fractions ($g_{fL}$) plotted against the gap fractions obtained with both photography techniques ($g_{fP}$). Gap fractions of the regrowth stands that were estimated by LiDAR were greater than those measured by the canopy photography, especially for the measurements at 3 m. This discrepancy resulted in the poor correlation between LiDAR’s gap fractions and *in situ* $L_e$ values of the regrowth stands. It also explained the poor correlation between GNDVI and *in situ* PAI. The cause of the discrepancies will be discussed in the discussion section.

Figure 5.14 shows the distribution of gap fractions from the *in situ* photography techniques and LiDAR. A greater range of gap fraction was found in the regrowth stands than in the retained stands. Based on LiDAR data, the mean gap fraction of the retained stands was lower than the mean gap fraction of the regrowth stands at both measurement heights. However, the difference was not statistically significant at 3 m ($p > 0.05$). The gap fraction distributions measured by the photography techniques from the two stand types were not significantly different, except for measurements by hemispherical photography at 3 m.
Chapter 5: *In Situ* and Remote Sensing Measurements of LAI

**Figure 5.13.** Scatter plots of LiDAR’s gap fractions against gap fractions from canopy photography. Hemi refers to hemispherical photography.

**Figure 5.14.** Distribution of gap fractions from LiDAR, cover and hemispherical photography (0° – 50° zenith angles) at various heights and vegetation stands.
5.3.4 Projection of LAI Spatial Distribution Maps

The calibration of remote sensing parameters with in situ LAI estimates from Crotty Creek has not been very successful due to some discrepancies in the measurements obtained from the regrowth stands. Yet, it could not be performed based on the in situ measurements from the retained mountain ash stands alone because their range of LAI values was too small. LAI spatial distribution could still be projected from LiDAR’s gap fractions based on Equation 5.6 and the assumption that the extinction coefficient is 0.5 for random foliage distribution. The spatial distribution of GNDVI could be used to indicate the difference in LAI distribution from the retained and regrowth/thinned areas. Thus, GNDVI spatial distribution map and LiDAR’s LAI spatial distribution map were independently produced to assess the impact of thinning at Crotty Creek and the other thinned catchments.

GNDVI distribution map

The regression models have identified that GNDVI as the best predictor of PAI from six vegetation indices that were tested. GNDVI has been previously linked to the amount of chlorophyll concentration rather than LAI (Gitelson et al. 1996), although Fassnacht et al. (1997) have found green-based indices predicted LAI better than red-based indices in mixed-species forest that contains hardwood and conifer species. GNDVI was also shown to correlate better with PAI values obtained at 11 m than at 3 m. This confirmed the results from several studies that found SVI correlates better with overstorey LAI than total LAI (Chen and Cihlar 1996, Eriksson et al. 2006).

Maps of GNDVI distributions were produced from the Quickbird image (Figure 5.15, Figure 5.16). The cloud cover in the Quickbird image has been removed through masking, which appeared as dark areas in the maps. The retained and regrowth stands in the strip-thinned catchments (Ettercon 1, Ettercon 4 and Crotty Creek) can be identified easily in the map from their contrasting GNDVI values. The patch-cut areas in Black Spur 1 can also be identified. The impact of uniform thinning and understorey thinning on GNDVI distribution was more difficult to identify from the maps.
Figure 5.15. GNDVI distributions of the Ettercon and Black Spur catchments. Areas affected by clouds have been masked and appear black.
Chapter 5: *In Situ* and Remote Sensing Measurements of LAI

![Figure 5.16. GNDVI distributions of Crotty Creek. Areas affected by clouds have been masked and appear black.](image)

The impact of different thinning treatments was investigated further by comparing GNDVI profiles of the thinned catchments against the GNDVI profile of Ettercon 3 (the control catchment). The profiles are shown in Figure 5.17 as a frequency distribution of GNDVI values. The following trends have been observed from the graph:

- Black Spur 1 had no strong peak in its GNDVI profile, which indicated a wide range of LAI values were present and distributed evenly in the catchment.
- Black Spur 2 had similar GNDVI profile to Ettercon 3 so they might have similar LAI distribution, while Black Spur 3 had similar GNDVI profile to Ettercon 2 despite of the different treatments.
- The GNDVI profile of Ettercon 4 had two distinct peaks that reflected the contrasting GNDVI values found in the retained and regrowth stands. However, the same trend was not found in the distribution from Ettercon 1 and Crotty Creek.
Chapter 5: *In Situ* and Remote Sensing Measurements of LAI

Figure 5.17. GNDVI profiles of the thinned catchment that show the frequency distribution of GNDVI values as a proportion of total pixels.

**Effective LAI distribution map from LiDAR**

The effective LAI ($L_e$) spatial distribution maps of the thinned North Maroondah catchments were projected from LiDAR’s gap fractions from a cell of 10 x 10 m around the plot centre and an extinction coefficient of 0.5 (Figure 5.18, Figure 5.19 and Figure 5.20).
Figure 5.18. Projected effective LAI distribution map of Black Spur catchments at 3 m and 11 m.
Figure 5.19. Projected effective LAI distribution map of Ettercon catchments at 3 m and 11 m.
Figure 5.20. Projected effective LAI distribution maps of Crotty Creek at 3 m and 11 m.
Figure 5.21. Mean total and overstorey effective LAI ($L_e$) of the thinned North Maroondah catchments derived from LiDAR data. The error bar indicates standard error of the distribution.

Figure 5.21 shows the mean total $L_e$ and the mean overstorey $L_e$ of the thinned catchments. The mean $L_e$ values of the retained mountain ash stands and the mixed species regrowth stands were calculated independently to enable the comparison between vegetation groups where appropriate. The LAI distribution map was segmented based on maximum vegetation height: the height of the regrowth vegetation...
was assumed to be below 30 m in the strip-thinned catchments or below 40 m in the patch-cut catchment (Black Spur 1).

The following observations were made based on the mean and distribution of $L_e$ values for various vegetation stands and catchments:

- The retained mountain ash stands had higher mean $L_e$ than the regrowth stands in the strip-thinned catchments (Ettercon 1, Ettercon 4 and Crotty Creek) and the patch-cut catchment (Black Spur 1). The difference between the two vegetation groups was greater in overstorey $L_e$ than total $L_e$.

- The long term impact of uniform thinning (Black Spur 2 and Black Spur 3) and understorey removal (Ettercon 2) on LAI cannot be detected from the effective LAI distribution maps. This confirmed the findings from GNDVI profiles. The mean overstorey $L_e$ values of Black Spur 2 and Black Spur 3 were slightly lower than the mean overstorey $L_e$ of the control catchment Ettercon 3, which indicated a post-thinning recovery in LAI.

Figure 5.22 shows the comparison of mean $L_e$ values derived from LiDAR data, hemispherical photographs and cover photographs for different vegetation groups and measurement heights. The *in situ* mean $L_e$ was derived from the *in situ* measurements obtained at sampling points, while LiDAR's mean $L_e$ was derived from the retained or regrowth stands in the catchment.
5.4 Discussion

5.4.1 LAI distributions

Crotty Creek

Both the *in situ* and remote sensing measurements showed that the total leaf area estimates ($L_e$ and PAI) at 3 m were greater than the overstorey leaf area estimates at 11 m. The total leaf area estimates were assumed to include leaf area of overstorey vegetation and some understorey vegetation (*Correa lawrenciana*, *Correa lawrenciana*, *Prostanthera melissifolia*, etc). Based on LiDAR data, the difference in the total $L_e$ from the retained and regrowth stands (0.38) was smaller than the difference in the overstorey $L_e$ (0.79). This suggests the abundance of the understorey biomass in the regrowth stands.
Chapter 5: *In Situ* and Remote Sensing Measurements of LAI

LiDAR and the photographic techniques yielded similar estimates of mean $L_e$ of the retained stands, while they disagreed on mean $L_e$ of the regrowth stands (see Figure 5.22). The comparison of gap fractions between LiDAR and the photography techniques has suggested that the photography techniques might have underestimated some of the gap fractions of the regrowth stands, especially at 3 m. The GNDVI distribution was consistent with the distribution of LiDAR's gap fractions, which confirmed the reliability of LiDAR data as the multi-spectral and LiDAR data were acquired independently.

The underestimation of the gap fractions of the regrowth stands by the canopy photography techniques would result in the overestimation of the *in situ* LAI estimates in those stands. It would explain the subsequent poor calibration of the remote sensing parameters and a few other inconsistencies that were observed in the calibration models, such as the negative correlation between GNDVI and *in situ* PAI, or the requirement for two independent models to predict $L_e$ from LiDAR's gap fractions.

The remotely sensed LAI distribution indicated that the mean $L_e$ of the retained stands was higher than the mean $L_e$ of the regrowth stands at both measurement heights. Assuming that the stomatal conductance of mountain ash is higher than the stomatal conductance of *Acacia*, transpiration of the retained stands might be higher than transpiration of the regrowth stands. The total ET of the catchment would have increased since the treatment, but it was unclear if the current total ET would be higher than the ET of an undisturbed mountain ash catchment.

**Other North Maroondah catchments**

The complex responses of the North Maroondah catchments to different thinning treatments can be detected by comparing their LAI distributions (Figure 5.21). Based on their LAI distributions, the amount of biomass in the uniformly thinned catchments (Black Spur 2 and Black Spur 3) appeared to approach the amount of biomass in the control catchment (Ettercon 3). This suggests that the uniformly thinned stands have recovered in terms of LAI. The catchments that were subjected to patch-cutting (Black Spur 1) and strip thinning (Ettercon 1, Ettercon 4 and Crotty Creek) had similar LAI distribution, where $L_e$ of the regrowth stands would be lower than $L_e$ of the retained stands. The cleared patches and strips have been dominated by *Acacia spp.* stands so
they would have similar LAI values. Although the mean \( L_e \) of Ettercon 2 was lower than the mean \( L_e \) of Ettercon 3, the difference might not be due to the impact of the removal of understorey vegetation at Ettercon 2. A small difference in mean LAI between the catchments should be expected due to the natural variation in stand density and locations.

5.4.2 The Impact of Site Configuration on LAI Measurements at Crotty Creek

The complex post-thinning vegetation structure of Crotty Creek has a large impact on the measurements of LAI. The canopy heights of the retained mountain ash stands in the retained strips were greater than those of the Acacia stands in the regrowth strips. The width of the retained strips has increased due to the growth of mountain ash trees along the edges of the retained strips over time (O'Shaugnessy et al. 1993), while the width of the cleared strips has decreased. The difference in canopy heights and the narrowness of the strip resulted in some foliage elements from the retained stands to be captured in the photographs taken in the regrowth stands (Figure 5.23). The foliage intrusion caused the underestimation of gap fractions and the overestimation of leaf area parameters in the regrowth stands. It occurred more extensively in hemispherical photographs than in the cover photographs due to their wider view angle.

The impact of the foliage intrusion can be reduced in hemispherical photographs by restricting the range of view zenith angles used to derive LAI estimates. However, a severe restriction on the view zenith angles would reduce the accuracy of LAI estimate. Several ranges of view zenith angles \((0^0-80^0, 0^0-70^0, 0^0-60^0\) and \(0^0-50^0\)) were utilised to estimate LAI from the hemispherical photographs in this study. The objectives were to improve the accuracy of LAI measurement in each sampling plot and to ensure the matching of measurement footprints between hemispherical photography and remote sensing methods. Meanwhile, the removal of the foliage intrusion in the cover photographs was not possible as it could not be isolated easily or uniformly reduced by resizing the photographs.
Figure 5.23. A diagram of LAI measurements taken in two neighbouring regrowth and retained stands. The difference in vegetation heights resulted in the intrusion of foliage elements in the viewing range of the regrowth stand.

The sampling strategy that was adopted at Crotty Creek has been limited by the width of the strips. The cover and hemispherical photographs were obtained along the middle of the strips rather than across the strips. As previously mentioned, it was difficult to confine the measurement footprint of the photography techniques inside the sample strip. Confining the footprint of the remote sensing measurements was easier because of their discrete measurement units and the definite boundary between vegetation stands. Thus, the comparison of LAI distribution from the retained and regrowth stands based on the remote sensing data would be more accurate than the one based on the in situ data.

5.4.3 Uncertainties in LAI Measurements

In situ measurements

The accuracy of LAI estimate is influenced by the exposure setting of the camera and sky brightness during the acquisition of the image. The hemispherical photographs were obtained using the recommended two stops overexposure relative to the sky reference (Leblanc et al. 2005, Zhang et al. 2005), while automatic exposure was used to obtain the cover photographs (Macfarlane et al. 2007b). The prescribed
overexposure of hemispherical photograph resulted in the underestimation of LAI in low zenith angles (0° – 10°) as it made the region appeared very bright. The height of mountain ash stands has also exacerbated the problem as their crowns were captured in low zenith angles in the hemispherical photographs. The underestimation of LAI due to the overexposure had a greater impact in the retained stands than in the regrowth stands at Crotty Creek.

A uniform cloud cover or a diffuse sky is required to maximise the difference between the sky and foliage in the image. This requirement has slowed down the field survey considerably as the uniform cloud cover condition occurred infrequently or only for a short period of time during the field survey. Hemispherical photography was more sensitive to the background lighting condition than cover photography due to its wide range of view zenith angles. Cover photography was supposed to be less sensitive to the effect of non-uniform cloud cover (Macfarlane et al. 2007b), but the cover photographs that were taken under non-uniform cloud cover have suffered from the reflection of direct sunlight. Thus, both photography techniques require the optimal lighting condition to produce reliable LAI estimates.

The measurement of LAI at multiple heights has highlighted the influence of the distance between the camera and the lowest layer of foliage elements on LAI estimates. $L_e$ value is overestimated when the distance between the camera and the canopy decreases. The foliage elements appear larger and the amount of gap pixels is reduced. This was observed in canopy photographs taken in several cleared strips at Crotty Creek, where some foliage elements dominated the image because of their proximity to the camera (Figure 5.24). The use of clumping should correct this overestimation as clumping increases with increasing distance between the camera and the canopy. Thus, PAI values might provide better estimates of leaf area than $L_e$ when comparing leaf area measured at different heights.
Chapter 5: *In Situ* and Remote Sensing Measurements of LAI

Figure 5.24. Cover photograph from Crotty Creek that shows two canopy layers, the foliage elements in the layer closest to the camera appear larger than those behind them.

Another consequence of the shorter distance between the camera and the canopy is the failure to capture the upper part of the canopy because foliage elements from the lower part of the canopy block it from view. LAI estimates might be underestimated as the camera can only ‘see’ the layer of foliage immediately above it. This problem can increase the discrepancy between an *in situ* LAI estimate and a remotely sensed LAI estimate. Image saturation determines the upper limit of LAI estimate that can be measured from a canopy photograph and this limit might be lower than previously estimated if the distance between the camera and the foliage element is short.

**Remote sensing measurements**

Plot misregistration is a potential source of error that involves the misalignment of a plot’s location in the remote sensing data. It affects the calibration between remote sensing and *in situ* measurements. This potential error was minimised in this study with the use of a differential GPS and a range of window sizes around the plot centre. The differential GPS improved the accuracy of plot registration, while the variable window sizes ensured that the effect of misalignment of the plot centre would be minimised.

Other potential sources of uncertainties and errors in the derivation of SVI from the multi-spectral data were spectral correction, orthorectification process and the presence of cloud cover. Spectral correction is performed to reduce atmospheric
effects on the multi-spectral data. However, it might affect the relationship between spectral bands. Orthorectification is a process of removing terrain distortion from the image. The steepness of some catchments might affect the accuracy of image registration. The presence of cloud cover might distort spectral reflectance in some spectral bands. The effect of cloud cover on SVI values from three sample plots at Cotty Creek was found to be negligible after comparing them to the overall SVI distribution. However, it affected the GNDVI distribution from Ettercon 1 as shown in Figure 5.15 and Figure 5.17.

The use of multiple-return discrete LiDAR has overcome some limitations associated with first-and-last-return LiDAR. The vertical distribution of gap fractions is better represented because return hits from the middle of the canopy can be registered. However, the number of ground returns has been limited by the density of the vegetation of Cotty Creek. This might decrease the accuracy of the generated ground surface, the calculated vegetation heights and the proportion of hits above certain height.

5.4.4 Comparison of Techniques

The prediction of the impact of thinning on water yield requires the modelling of changes in vegetation structure in a hydrological model. LAI temporal and spatial distributions have enabled this to be done. Thus, one of the research questions in this study was related to finding a robust method to obtain LAI distribution at catchment scale. This sub-section will discuss the robustness and reliability of in situ and remote sensing methods that were used to obtain LAI distribution.

The results from the pilot study at Black Spur indicated that cover and hemispherical photography can be used to obtain LAI in mountain ash forests. The two photography techniques produced similar LAI estimates. The similarity in LAI estimates was made possible by the relatively uniform vegetation cover in the plot so the difference in view zenith angles between the techniques did not affect the measurement results. This confirmed that the extinction coefficient of 0.5 used to derive LAI with cover photography was reasonable.
Chapter 5: *In Situ* and Remote Sensing Measurements of LAI

The measurement of *in situ* LAI with hemispherical and cover photography at Crotty Creek has been challenging. Hemispherical photography performed less well than cover photography in this catchment. Its wide viewing angle has made it more sensitive to foliage intrusion and suboptimal lighting condition. However, cover photography cannot be used to estimate LAI if the extinction coefficient is not known. Another independent measurement method (such as hemispherical photography or allometry) is still required to estimate the extinction coefficient if cover photography was to be used to estimate LAI. A recent study by Ryu *et al.* (2010) has found that the combination of cover photography technique and LAI-2000 could provide reliable estimates of clumping index and LAI in oak-savannah environment, which confirmed the need for another method to supplement the measurements from cover photography.

Both the Quickbird multi-spectral image and LiDAR have produced comparable projections of LAI distribution. LiDAR has a few advantages over the multi-spectral image. Gap fraction can be estimated from LiDAR data so it is possible to estimate LAI without calibrating LiDAR data against *in situ* measurements with the assumption of random leaf angle distribution. LiDAR’s gap fractions can be obtained at various heights so LAI can be estimated at different levels of vegetation structure, while SVI is usually associated with overstorey LAI. However, multi-spectral image is less costly to obtain than LiDAR so it can be used for monitoring changes in LAI distribution over time.

### 5.5 Conclusion

The *in situ* LAI measurements were conducted at Crotty Creek to obtain a range of LAI values from the retained and regrowth stands in order to calibrate the remote sensing parameters. The photography techniques were successful in obtaining reliable LAI of the retained stands, but the LAI of the regrowth stands was overestimated due to foliage intrusion from the neighbouring retained stands. This resulted in the poor calibration between the *in situ* measurements and remote sensing parameters.

Despite the calibration problem, the spatial distributions of GNDVI from Quickbird multi-spectral image and gap fraction from LiDAR data can be used to infer LAI spatial
distribution of the thinned North Maroondah catchments. The overstorey LAI of the retained stands was greater than the overstorey LAI of the regrowth stands in the catchments subjected to patch-cutting or strip-thinning (Black Spur 1, Ettercon 1, Ettercon 4 and Crotty Creek). LAI distribution in the other thinned catchments (Black Spur 2, Black Spur 3 and Ettercon 2) was similar to the distribution in the control catchment (Ettercon 3).

An increase in post-thinning ET would explain the decrease in water yield observed in some of the thinned catchments. However, the projected LAI spatial distributions for those catchments have shown that estimated LAI in the regrowth stands was lower than estimated LAI in the retained stands so the average LAI of the catchment might be lower than the average LAI of an undisturbed mountain ash catchment. The impact of the post-thinning LAI distribution on the total catchment transpiration depends on several factors, such as stomatal conductance of the two vegetation groups, microclimate (net radiation, humidity, wind speed) at canopy height and access to groundwater. The sap flow measurements were conducted to independently confirm that there was a difference in LAI distribution between the retained and regrowth stands, and to examine how this difference was translated into transpiration of the stands.
Chapter 6. Estimation of Transpiration with Sap Flow Measurements

Sap flow measurement at Crotty Creek
Chapter 6: Estimation of Transpiration with Sap Flow Measurements

The paired catchment study has shown that there has been a decline in water yield at Crotty Creek since the streamflow measurement recommenced in 2007 (Chapter 3). However, this trend cannot be confirmed beyond a limited period as the bushfire in February 2009 disturbed the vegetation in the control catchment (Ettercon 3). The decline in water yield implied that the evapotranspiration (ET) of the thinned catchment must be greater than ET of an undisturbed catchment.

The complex post-thinning vegetation structure and composition at Crotty Creek has made it difficult to directly infer catchment ET. The remote sensing measurements of leaf area index (LAI) indicated that the mountain ash retained stands had higher overstorey LAI than the regrowth Acacia stands, while there was no significant difference in total LAI between the stands (Chapter 5). As the overstorey layer is dominated by more than one species, the transpiration rates of different vegetation groups are required to estimate catchment transpiration.

Sap flow measurements were conducted at Crotty Creek to obtain the transpiration rates of the dominant vegetation groups and to estimate the total catchment transpiration. The measurements used in this study were obtained from December 2009 to January 2011. A comparison of transpiration from the retained and regrowth stands was made to investigate the impact of changing vegetation structure and composition on catchment transpiration. The length of the measurement period has enabled the examination of whether energy availability or soil water availability has greater influence on the transpiration rate at Crotty Creek. Annual catchment water balance was calculated to assess if an increase in ET was responsible for the decrease in streamflow.

This chapter presents the results of sap flow measurements at Crotty Creek. The first section provides an overview of previous sap flow measurements that were conducted in mountain ash forests. The second section outlines the experiment design and the heat pulse method used in the sap flow measurement. The third section presents the measurement results. The fourth section discusses the implication of these results and the final section presents the conclusion.
6.1 Transpiration Measurements in Mountain Ash Forests

Sap flow measurement has been widely used to estimate the transpiration of mountain ash stands (Dunn and Connor 1993, Jayasuriya et al. 1993, Pfautsch et al. 2010, Vertessy et al. 1995, Vertessy et al. 2001). This method is more suitable than the micrometeorological methods due to the steep terrain of mountain ash forests. Another advantage of the method is its ability to measure water use by different canopy strata or species in the same stand (Pfautsch et al. 2010, Vertessy et al. 1995, Vertessy et al. 2001). Its application at Crotty Creek would allow the comparison of transpiration from the retained and cleared strips.

Previous transpiration studies have discovered a few important relationships that characterise the water use of mountain ash forests:

- Sapwood area and leaf area of mountain ash decline with stand age, but sap flow velocity appears to be independent of age (Dunn and Connor 1993, Vertessy et al. 1995, Vertessy et al. 2001). The decline in overstorey LAI over time is offset by the increase in understorey LAI.
- Haydon et al. (1997) estimated the annual transpiration of mountain ash stands as 720 m\(^3\) per m\(^2\) sapwood area based on measurements reported by Dunn and Connor (1993), while Vertessy et al. (2001) projected the annual transpiration as 691 m\(^3\) per m\(^2\) sapwood area.
- Mountain ash has greater transpiration rate per unit sapwood area than hazel (*Pomaderris aspera*), silver wattle (*A. dealbata*) or blackwood (*A. melanoxylon*) found in the understorey stands (Pfautsch et al. 2010, Vertessy et al. 1995, Vertessy et al. 2001).
- Transpiration from understorey vegetation contributed 12% - 54% of the total stand transpiration depending on stand age and 6% - 16% of the catchment water balance (Vertessy et al. 2001). A recent study on the water use of understorey species by Pfautsch et al. (2010) showed that *Acacia spp.* contributed up to 23-33% of the total water use during the cooler months (May to November) in 66-year-old mountain ash stands.
Chapter 6: Estimation of Transpiration with Sap Flow Measurements

- The total ET of mountain ash forest is approximately 1371 mm year\(^{-1}\) at age 15 years and 911 mm year\(^{-1}\) at age 240 years assuming a mean annual rainfall of 1800 mm (Vertessy et al. 2001)

The transpiration from understorey stands is limited by the presence of the overstorey stands as the understorey layer is exposed to less radiation and wind. At Crotty Creek, silver wattle (Acacia dealbata) and blackwood (Acacia melanoxylon) have been found as overstorey and understorey species following the thinning treatment. This has enabled the comparison of transpiration rates between mountain ash and Acacia stands when they function as overstorey vegetation, as well as the comparison of transpiration rates between Acacia overstorey and understorey stands. The results would further our understanding on the influence of vegetation structure and composition on the transpiration of mountain ash forest.

6.2 Experimental Design and Procedures

6.2.1 Sampling Strategy and Plot Description

Sap flow measurements were conducted in four plots at Crotty Creek. They consisted of two pairs of retained and regrowth stands, which were selected from the sampling plots of LAI measurements. The first pair of plots was selected to represent an area where there was a discrepancy between the in situ and remote sensing measurements of LAI. The second pair of plots was selected to represent an area where silver wattle (A. dealbata) occurs as one of the understorey species in the retained strip and as the dominant overstorey species in the adjacent cleared strip.

The first pair of plots is located in the southern part of the catchment, while the second pair is located in the eastern part of the catchment. All plots covered an area of 15 x 15 m, except for the second retained plot that covered an area of 20 x 15 m to include some silver wattle understorey. The retained mountain ash stands were approximately 71 years old (1939 regrowth), while the regrowth Acacia stands in the regrowth plots were approximately 24 – 29 years old (post-thinning).
Chapter 6: Estimation of Transpiration with Sap Flow Measurements

Figure 6.1 shows a map of vegetation classification at Crotty Creek that has been derived from LiDAR maximum vegetation height. The overstorey vegetation was classified into two classes: mountain ash (*E. regnans*) and *Acacia*. The map also shows the locations of sampling plots used in transpiration measurements.

Figure 6.1. Map of overstorey vegetation classification at Crotty Creek, derived from LiDAR data. *E. regnans* marks the retained strip and *Acacia* marks the cleared strips. The map also shows the locations of sample plots used in the transpiration measurements (R1, C1, R2, C2) and remote sensing measurements.

Table 6.1 provides the topographical information of the sample plots, the dominant species, basal area and sapwood area of the overstorey vegetation in the plots. The basal area and sapwood area of the understorey vegetation were measured in Plot R2, where sap flow measurements were conducted on the silver wattle understorey. Silver
Chapter 6: Estimation of Transpiration with Sap Flow Measurements

wattle contributed 47% to the understorey basal area in R2, while the rest of the woody understorey basal area consisted of hazel (*P. aspera*).

**Table 6.1. Detail of sample plots, overstorey and understorey species, basal area and sapwood area.**

<table>
<thead>
<tr>
<th></th>
<th>R1 (CT2S6 retained)</th>
<th>C1 (CT2S5 cleared)</th>
<th>R2 (BT1S2 retained)</th>
<th>C2 (BT1S2 cleared)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plot area (m²)</td>
<td>225</td>
<td>225</td>
<td>300</td>
<td>225</td>
</tr>
<tr>
<td>Elevation (m AHD)</td>
<td>832.3</td>
<td>836.0</td>
<td>809.5</td>
<td>807.8</td>
</tr>
<tr>
<td>Slope (°)</td>
<td>14</td>
<td>11</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>Aspect (°)</td>
<td>9</td>
<td>3</td>
<td>344</td>
<td>358</td>
</tr>
<tr>
<td>Overstorey species</td>
<td><em>E. regnans</em></td>
<td><em>A. dealbata,</em></td>
<td><em>E. regnans</em></td>
<td><em>A. dealbata,</em></td>
</tr>
<tr>
<td></td>
<td></td>
<td><em>A. melanoxylon</em></td>
<td></td>
<td><em>E. regnans</em>²</td>
</tr>
<tr>
<td>Understorey species</td>
<td><em>Olearia argophylla,</em></td>
<td><em>Hedycarya</em></td>
<td><em>A. dealbata,</em></td>
<td><em>Correa</em></td>
</tr>
<tr>
<td></td>
<td><em>Zieria arborescens</em></td>
<td><em>angustifolia</em></td>
<td><em>Pomaderris aspera,</em></td>
<td><em>lawrenciana</em></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td><em>Correa lawrenciana</em></td>
<td></td>
</tr>
<tr>
<td>Overstorey basal</td>
<td>88.2</td>
<td>23.3</td>
<td>57.4</td>
<td>26.9¹</td>
</tr>
<tr>
<td>area (m² ha⁻¹)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Understorey basal</td>
<td>-</td>
<td>-</td>
<td>2.3</td>
<td>-</td>
</tr>
<tr>
<td>area (m² ha⁻¹)³</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Overstorey sapwood</td>
<td>11.7</td>
<td>7.7</td>
<td>7.3</td>
<td>7.5</td>
</tr>
<tr>
<td>area (m² ha⁻¹)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Understorey sapwood</td>
<td>-</td>
<td>-</td>
<td>0.9</td>
<td>-</td>
</tr>
<tr>
<td>area (m² ha⁻¹)³</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

¹A regrowth *E. regnans* was found in C2 (basal area of 0.04 m²), but it has not been included in the overstorey basal area or sapwood area.

²The understorey layer also included smaller shrubs and ferns (e.g. *Prostanthera melissifolia*, *Dicksonia antarctica*).

³The understorey basal and sapwood areas were not measured except in Plot R2.
Chapter 6: Estimation of Transpiration with Sap Flow Measurements

The sap flow measurements of most sample trees commenced in late November 2009. The measurements included in this study were collected between 10 December 2009 and 31 January 2011. The characteristics of the sample trees and the number of sensor probes installed in each tree have been summarised in Table 6.2.

Table 6.2. Characteristics of sample trees and the number of probes in each tree.

<table>
<thead>
<tr>
<th>Plot</th>
<th>Species</th>
<th>Diameter (cm)</th>
<th>Sapwood area (cm²)</th>
<th>No. of probes</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1</td>
<td><em>E. regnans</em></td>
<td>108.2</td>
<td>961</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td><em>E. regnans</em></td>
<td>70.0</td>
<td>641</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td><em>E. regnans</em></td>
<td>58.3</td>
<td>315</td>
<td>4</td>
</tr>
<tr>
<td>C1</td>
<td><em>A. dealbata</em></td>
<td>31.6</td>
<td>226</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td><em>A. dealbata</em></td>
<td>20.2</td>
<td>109*</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td><em>A. melanoxylon</em></td>
<td>10.2</td>
<td>51</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td><em>A. dealbata</em></td>
<td>17</td>
<td>91</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td><em>A. dealbata</em></td>
<td>22.3</td>
<td>105</td>
<td>4</td>
</tr>
<tr>
<td>R2</td>
<td><em>E. regnans</em></td>
<td>78.9</td>
<td>741</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td><em>E. regnans</em></td>
<td>50.5</td>
<td>326</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td><em>A. dealbata</em></td>
<td>17.6</td>
<td>76</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td><em>A. dealbata</em></td>
<td>13.4</td>
<td>43</td>
<td>4</td>
</tr>
<tr>
<td>C2</td>
<td><em>A. dealbata</em></td>
<td>25.8</td>
<td>150</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td><em>A. dealbata</em></td>
<td>32.1</td>
<td>219</td>
<td>4</td>
</tr>
</tbody>
</table>

*Estimated sapwood area based on the diameter – sapwood area relationship.

6.2.2 Weather Data Collection

A weather station was set up in a logging coupe east of the catchment on 22 December 2009. Solar radiation, rainfall, temperature, wind speed and relative humidity were measured at approximately 3.5 m above the ground. The measurements were obtained at half hour interval and logged using Micropower data logger (Tain Electronics, Victoria, Australia). Vapour pressure deficit (VPD) was calculated from the temperature and relative humidity data. It was used to calibrate the sensitivity of the sap flow logger in measuring low sap flow.
There were several gaps in data from the weather station due to logger failure, such as in February 2010 and May to August 2010. Instantaneous VPD was not available during those periods. The monthly rainfall data for those periods were estimated based on a linear regression relationship between monthly rainfall recorded at Crotty Creek and Black Spur (Station 986045).

Daily weather data were also obtained from SILO Data Drill (Natural Resources and Mines, Queensland Government, Australia) for the period of 1 January 2007 to 31 January 2011. The data consisted of maximum and minimum daily temperature, rainfall, evaporation, radiation, vapour pressure, maximum and minimum relative humidity, and potential evaporation.

### 6.2.3 Measurement of Sapwood Width and Sapwood Area

Sapwood is the area of wood that actively conducts water and nutrients. The amount of sap that flows through a tree is a function of sap velocity and the conducting sapwood area. Sapwood width or thickness (cm) was determined by extracting a number of 5-mm diameter increment cores at breast height. The number of core samples depended on the size of the tree. The sapwood width was identified based on a colour change in the core sample that marked the boundary between sapwood and heartwood. The core samples of mountain ash were stained with 1% methyl orange solution to enhance the colour change, while the core samples of the *Acacia spp.* showed the sapwood – heartwood boundary clearly without staining. The average sapwood width obtained from the core samples, tree diameter and bark thickness were used to calculate the sapwood area (cm²).

### 6.2.4 Transpiration of Individual Trees

The heat pulse method was used to measure transpiration of individual trees (Dunn and Connor 1993, Green 1988, Hatton *et al.* 1990). At each measurement point, a set of heat pulse probes were installed in parallel holes that were drilled radially into the stem. Each set of heat pulse probes consisted of a heater probe and two temperature sensor probes. One temperature sensor probe was installed 10 mm above the heater probe, while the other was installed 5 mm below the heater probe. A short heat pulse
was emitted every half hour. The time taken for both temperature sensors to register equal temperature was used to calculate heat pulse velocity (mm hr\(^{-1}\)).

The heat pulse velocity was corrected for probe misalignment and wounding (Swanson and Whitfield 1981). The average wound widths measured from the sample mountain ash trees and silver wattle were 3.4 mm and 4.0 mm respectively. The heat pulse velocity was converted to sap velocity using the volume fractions of water and wood in the sapwood. They were determined with a gravimetrical method from the increment core samples.

Eight sets of probes were implanted in the largest mountain ash trees to measure the sap velocity, while two sets of probes were implanted in the two smallest *Acacia* trees (see Table 6.2). The other samples trees were implanted with four sets of probes. The probes were placed at different depths below the cambium and quadrants around the stems (Figure 6.2), which enabled the radial profile of sap velocity to be obtained. All sensor probes were logged using CR1000 and CR10X data loggers (Campbell Scientific Inc., Logan, UT, USA).

**Figure 6.2.** (a) A sample layout of the heat probes around the stem, (b) heat probe installation on a mountain ash tree.
Chapter 6: Estimation of Transpiration with Sap Flow Measurements

The heat pulse technique has a difficulty in differentiating low sap flow from zero sap flow (Benyon 1999). Hence, a threshold sap velocity was determined for each probe to distinguish low sap flow from zero sap flow. It was derived from the upper 97.5% confidence limit of sap velocity recorded during a period when the sap flow is likely to be zero, such as when the night-time vapour pressure deficit (VPD) was zero (Benyon 1999). The sap velocity below the threshold value was set to zero. The threshold sap velocity was calculated for each month of the measurement period, except for the periods when the half-hour VPD data were unavailable. This adjustment also ensured that night time sap flow could be attributed to actual transpiration driven by the evaporative demand (non-zero VPD) or to the refilling of water in the stem and branches that has been depleted during the daytime, rather than the insensitivity of the probe.

The volume of sap flowing through the xylem tissue was calculated for each tree by multiplying the sap velocity with the conducting sapwood area. The sap velocities at various sapwood widths were integrated based on a weighted average method (Hatton et al. 1990). The hourly sap flow was accumulated over 24 hours to calculate daily sap flow (L day$^{-1}$). Daily sap flux density ($m^3 m^{-2} day^{-1}$) was also calculated for each tree by dividing the daily sap flow of each tree with its sapwood area.

6.2.5 Transpiration at Stand and Catchment Levels

The transpiration from individual sample trees was scaled up to plot/stand level based on the total sapwood area of the plot/stand. The plot sapwood area was estimated from the relationship between diameter at breast height (dbh) and sapwood area. The diameter and sapwood widths were measured from a number of mountain ash, silver wattle and blackwood trees of various sizes inside and outside the plots. A relationship of diameter to sapwood area was established for each vegetation group. The relationship was applied to the diameters of overstorey trees in the plot that have not been sampled to estimate their sapwood area.

An average daily sap flux density was calculated for the dominant vegetation group (mountain ash, Acacia spp.) in each plot. The average daily sap flux density was then multiplied by the total sapwood area of vegetation in the plot to obtain a daily sap flow
Chapter 6: Estimation of Transpiration with Sap Flow Measurements

(L day\(^{-1}\)). The daily sap flow was divided by the plot area to get the transpiration rate in mm day\(^{-1}\).

The catchment transpiration rate was calculated by scaling up the transpiration rates of the vegetation groups (mountain ash overstorey, *Acacia* overstorey, *Acacia* understorey) with their proportions of catchment area. LiDAR’s maximum vegetation height, acquired in 2007, was used to classify the overstorey vegetation into two groups: mountain ash and *Acacia* (Figure 6.1). Vegetation maximum height in the range of 2 – 30 m was classified as *Acacia*, while vegetation maximum height in the range of 30 – 80 m was classified as mountain ash. The classification was verified against the locations of sample plots used in the remote sensing measurements of LAI, which were established in the retained or cleared strips.

The vegetation in the gully has not been distinguished from the mountain ash overstorey stands. Based on the maximum vegetation height, the proportion of catchment area associated with the mountain ash overstorey stands was 73% and the proportion associated with the *Acacia* overstorey stands was 23%.

### 6.2.6 Stomatal Conductance

Stomatal conductance (\(g_c\), mm s\(^{-1}\)) was obtained to investigate the processes that control transpiration at Crotty Creek. It was derived from the inversion of the modified Penman-Monteith equation for canopy (Jarvis and McNaughton 1986):

\[
g_c = \frac{\gamma \Delta E g_a}{\Delta R_n + k \rho C_p D g_a - \lambda (\Delta + \gamma) E}
\]

where \(g_c\) is stomatal conductance (mm s\(^{-1}\)), \(\gamma\) is psychrometric constant (0.066 kPa C\(^{-1}\)), \(\lambda\) is latent heat of evaporation of water (2465 kJ kg\(^{-1}\)), \(E\) is mean daily transpiration (mm d\(^{-1}\)), \(g_a\) is aerodynamic conductance (m s\(^{-1}\)), \(\Delta\) is the slope of saturation vapour pressure – temperature relationship (kPa C\(^{-1}\)), \(R_n\) is net radiation (kJ m\(^{-2}\) d\(^{-1}\)), \(k\) is a constant of 86.4 to convert mm s\(^{-1}\) to m d\(^{-1}\), \(\rho\) is density of air (1.225 kg m\(^{-3}\)), \(C_p\) is specific heat of air at constant pressure (1.01 kJ kg\(^{-1}\) C\(^{-1}\)), and \(D\) is mean daytime VPD (kPa).
The daily transpiration data were obtained from selected days \((n = 58)\) between 29 December 2009 and 31 January 2011, which had mostly non-zero VPD during daytime. The aerodynamic conductance for forest was assumed to be 200 mm s\(^{-1}\) (Kelliher 1993). The net radiation was calculated based on solar radiation measured at the Crotty Creek's weather station, with an albedo of 0.13 for forest.

### 6.2.7 Transpiration Model

The mean daily transpiration has been plotted against meteorological parameters that represent evaporative demand, such as daily maximum temperature and daily maximum vapour pressure deficit (VPD). The relationship between transpiration and temperature/VPD was also used to model daily transpiration, which has enabled the estimation of annual catchment water balance during the period for which the streamflow and rainfall data were available.

### 6.2.8 Catchment Water Balance

The catchment water balance can be formulated as:

\[
P = Q + ET + D + \Delta S
\]

where \(P\) is precipitation, \(Q\) is streamflow measured at the stream gauge, \(ET\) is evapotranspiration, \(D\) is deep drainage and \(\Delta S\) is the change in soil water storage. \(ET\) includes rainfall interception, soil evaporation and vegetation transpiration. Drainage is defined as ground water flow that discharges downstream of the gauging point. Drainage is assumed to be zero, while the change in soil water storage is assumed to be negligible over a long period of time.

Rainfall data were measured at the weather station in the catchment, or estimated based on rainfall data from the Black Spur catchments when data from the weather station were unavailable. The streamflow data were measured at the Crotty Creek weir. The transpiration data were scaled up from plot level to catchment level.

The interception volume was estimated based on the interception – stand age relationship that was applied to the mean annual rainfall of 1800 mm (Haydon \textit{et al.} 1997). The interception rate for 70 year-old mountain ash stands was assumed to be
432 mm or 24% of the mean annual rainfall. The soil and litter evaporation was estimated based on the relationship between transpiration and stand age (Vertessy et al. 2001), which was approximately 108 mm or 6% of the mean annual rainfall at the current stand age.

6.3 Results

6.3.1 Transpiration Volume

Relationship between diameter and sapwood area

The relationship between diameter at breast height (cm) and sapwood area (cm²) was established to efficiently estimate the sapwood area of every tree in the plot. A single model was developed for estimating the sapwood area of Acacia trees based on measurements from silver wattle and blackwood, as only a limited number of blackwood trees were found in the plots. Another model was developed for mountain ash trees.

Sapwood area from 1AT2L12 sample tree (silver wattle) has been excluded from the model as its sapwood depth was much higher than other measurements in the same diameter range. Data collected from the two different parts of the catchments (BT1 and CT2) were combined as location was not a significant variable in the relationship (p < 0.05). The best regression models for the mountain ash and Acacia spp stands are summarised in Table 6.3, while Figure 6.3 plots the diameter against sapwood area and the fitted regression models.

<table>
<thead>
<tr>
<th>Species</th>
<th>n</th>
<th>Regression Models</th>
<th>Standard error</th>
<th>R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>E. regnans</td>
<td>15</td>
<td>SA = 13.98dBH – 404.5</td>
<td>98.08</td>
<td>0.91</td>
</tr>
<tr>
<td>Acacia spp.</td>
<td>25</td>
<td>log SA = 1.518 log(dbh) + 0.130</td>
<td>0.160</td>
<td>0.93</td>
</tr>
</tbody>
</table>
Chapter 6: Estimation of Transpiration with Sap Flow Measurements

Figure 6.3. The relationships between diameter at breast height (dbh) and sapwood area (SA) in mountain ash (circle) and Acacia (triangle) stands.

Sap flux density at plot level

Figure 6.4 shows the mean daily sap flux density \( \text{m}^3 \text{m}^{-2} \text{day}^{-1} \) of the stands in the sampling plots. The comparison of the sap flux density between different vegetation stands has shown:

- The mountain ash overstorey stands in the retained strips had higher sap flux density than the Acacia overstorey stands in the cleared strips. The difference was greatest during the peak transpiration periods.
- The large fluctuation in the sap flux density indicated the sensitivity of the vegetation stands to the changes in climatic conditions.
- The Acacia overstorey stands in Plot C2 and the Acacia understorey stands in Plot R2 had similar sap flux density.
- The mountain ash stand in Plot R2 had higher sap flux density than the stand in Plot R1, which might be due to the difference in aspect. Meanwhile, the Acacia overstorey stand in Plot C2 had lower sap flux density than in Plot C1.
- A seasonal pattern was observed, with higher sap flux density occurring in the warmer months (November to March).
Chapter 6: Estimation of Transpiration with Sap Flow Measurements

Figure 6.4. Mean daily sap flux density of four sample plots: (a) Retained 1 and Cleared 1, (b) Retained 2 and Cleared 2.
Transpiration at stand and catchment levels

The daily sap flux density (m$^3$ m$^{-2}$ day$^{-1}$) and transpiration (mm day$^{-1}$) at stand level were grouped based on species and structural function: mountain ash overstorey stands in the retained strips, Acacia understorey stands in the retained strips and Acacia overstorey stands in the cleared strips. Figure 6.5 shows the mean daily transpiration (mm day$^{-1}$) of the vegetation groups. The transpiration of the Acacia understorey stands during the period of logger failure (June 2010 to August 2010) was estimated based on the sap flux density of the Acacia overstorey stands.

![Graph showing mean daily transpiration of mountain ash (E. regnans) overstorey, Acacia overstorey and Acacia understorey.](image_url)

Figure 6.5. Mean daily transpiration of mountain ash (E. regnans) overstorey, Acacia overstorey and Acacia understorey.

Figure 6.6 shows the monthly transpiration volume accumulated from the daily transpiration rate and the monthly rainfall. The mountain ash overstorey stands had the highest transpiration volume amongst the vegetation groups. Although the Acacia overstorey stands in the cleared strips had similar sap flux density to the Acacia understorey stands in the retained strip, the overstorey stands had greater transpiration...
volume due to their greater sapwood area. The difference in transpiration between the Acacia overstorey and understorey stands was by an order of magnitude.

The monthly transpiration has shown a strong seasonal trend and the influence of rainfall variability. The transpiration during December 2009 – January 2010 was higher than the transpiration during December 2010 – January 2011 as the rainfall in the first period was lower than in the second period.

![Figure 6.6. Monthly transpiration from December 2009 to January 2011.](image)

Table 6.4 provides a summary of mean daily sap flux density and transpiration of the three vegetation groups from 10 December 2009 to 31 December 2010. It also shows the estimated proportions of catchment area based on the overstorey vegetation classification derived from LiDAR maximum height (Figure 6.1). The Acacia understorey stands made up approximately 12% of the basal area of understorey species sampled in the retained strips (Tran 2007). Assuming this composition was uniform across the catchment, the proportion of catchment covered by the Acacia understorey stands was estimated as 9%.
Table 6.4. Mean daily sap flux density and mean daily transpiration of the major vegetation groups at Crotty Creek from 10 December 2009 to 31 December 2010, with the proportion of catchment area associated with each vegetation group. Standard errors are presented in bracket.

<table>
<thead>
<tr>
<th>Vegetation</th>
<th>Sap Flux Density (m³ m⁻² day⁻¹)</th>
<th>Transpiration (mm day⁻¹)</th>
<th>Proportion of catchment area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mountain ash overstorey</td>
<td>1.6 (0.07)</td>
<td>1.5 (0.07)</td>
<td>73%</td>
</tr>
<tr>
<td>Acacia understorey</td>
<td>0.8 (0.05)</td>
<td>0.07 (0.004)</td>
<td>9%</td>
</tr>
<tr>
<td>Acacia overstorey</td>
<td>0.9 (0.04)</td>
<td>0.7 (0.03)</td>
<td>23%</td>
</tr>
</tbody>
</table>

The mean daily transpiration at catchment scale was calculated by applying the proportion of catchment area to the transpiration rates. The mean daily transpiration of the overstorey stands was 1.3 mm day⁻¹ (± 0.06 mm day⁻¹). The mean daily transpiration of the understorey stands at catchment level was not estimated because the Acacia understorey stands contributed only a small proportion to the total understorey basal area.

### 6.3.2 Stomatal Conductance

Figure 6.7 shows the decrease in $g_c$ of the major vegetation groups with increasing mean daytime VPD. Generalised linear model (glm) regression was performed to establish a relationship between mean daytime VPD and $g_c$ of the overstorey stands. The response variable was assumed to have a Gamma distribution, while an inverse link function was adopted to model the relationship (Table 6.5). The inverse link function provided a better fit than the log link function. The maximum $g_c$ for mountain ash from the fitted function was 5.6 mm s⁻¹ and the maximum $g_c$ for Acacia overstorey was 2.4 mm s⁻¹.

Table 6.5. General linear regression models that describe the relationship between mean daytime VPD and stomatal conductance of the overstorey stands.

<table>
<thead>
<tr>
<th>Vegetation</th>
<th>Fitted Function</th>
<th>Deviance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mountain ash overstorey</td>
<td>$y = (0.178 + 0.091 x)⁻¹$</td>
<td>1.11</td>
</tr>
<tr>
<td>Acacia overstorey</td>
<td>$y = (0.423 + 0.170 x)⁻¹$</td>
<td>2.23</td>
</tr>
</tbody>
</table>
6.3.3 Transpiration Model

Two transpiration models were established to predict the mean daily transpiration from the daily maximum air temperature and the daily maximum VPD. SILO daily maximum temperature and VPD data have been used to develop the transpiration models when there were gaps in the weather station data. SILO data correlated really well with the corresponding data from Crotty Creek’s weather station ($r^2 = 0.97$ for maximum temperature and $r^2 = 93$ for VPD).

Figure 6.8 shows a strong relationship between the mean daily transpiration and the daily maximum vapour pressure deficit (VPD). The relationship was best modelled by a second degree polynomial (Table 6.6). The transpiration rate of each vegetation group approached its maximum when the daily maximum VPD was greater than 4 kPa.
Table 6.6. Second degree polynomial regressions that model the mean daily transpiration of the overstorey stands based on daily maximum VPD.

<table>
<thead>
<tr>
<th>Vegetation</th>
<th>Fitted Function</th>
<th>Standard error</th>
<th>Adjusted $R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mountain ash overstorey</td>
<td>$y = 2.01x^2 - 0.19x - 0.28$</td>
<td>0.48</td>
<td>0.88</td>
</tr>
<tr>
<td>Acacia overstorey</td>
<td>$y = 0.84x^2 - 0.06x - 0.12$</td>
<td>0.26</td>
<td>0.82</td>
</tr>
</tbody>
</table>

Figure 6.8. The daily maximum vapour pressure deficit against transpiration of mountain ash overstorey, Acacia understorey and Acacia overstorey.

The mean daily transpiration of the overstorey vegetation groups varied linearly with the daily maximum temperature ($r^2 = 0.71$ for mountain ash and $r^2 = 0.66$ for Acacia). Pfautsch et al. (Pfautsch et al. 2010) have shown that daily maximum temperature predicted mean daily transpiration better than daily maximum VPD in a similar mountain ash forest to the study sites. As the daily maximum VPD predicted transpiration better than the daily maximum temperature in this study, the daily maximum VPD – transpiration relationship would be used to model the overstorey transpiration.
6.3.4 Catchment Water Balance

Figure 6.9 shows the contributions of the different components of water balance at Crotty Creek from 10 December 2009 to 31 December 2010. The total rainfall for the period was 1995 mm. Rainfall interception and soil/litter evaporation were estimated from models that link water use and forest age (see Section 6.2.8). They have been adjusted to reflect the length of the measurement period (13 months). Overstorey transpiration and streamflow were obtained from the measurement data. The unspecified proportion/volume of the water balance referred to components that have not been measured or estimated such as understorey transpiration, the change in soil moisture storage, drainage and measurement errors.

The maximum VPD – transpiration model was applied to SILO’s maximum VPD data to estimate the overstorey transpiration from January 2006 to January 2010. The aim was to calculate annual overstorey transpiration volume and catchment water balance for different years. Although the best-fit model for the maximum VPD – transpiration was a polynomial model, there were no measurement data to verify the projected decrease of transpiration after the maximum transpiration has been reached. The highest daily maximum VPD recorded during the measurement period was 5.5 kPa. For the days when the maximum VPD exceeded this value, the transpiration volume has been limited to the daily transpiration measured at maximum VPD of 5.5 kPa.
Catchment water balance was computed for 2006/2007 to 2010/2011 water year (Table 6.7). Water year from April to March has been used instead of calendar year to preserve the seasonal information. Only streamflow from March has been included in the water balance for 2006/2007 water year as the measurement commenced in February 2007, while the water balance for the 2010/2011 consisted of data from April 2010 to February 2011. They have been included here to show the potential water balance for a very dry year and a relatively wet year respectively.

Table 6.7. Catchment water balance of annual water year (April to March). The unspecified volume refers to components of water balance that have not been measured or estimated.

<table>
<thead>
<tr>
<th>Water year: April to March</th>
<th>Rainfall Volume (mm)</th>
<th>Streamflow Volume (mm)</th>
<th>Interception, Soil &amp; Litter Evaporation Volume (mm)</th>
<th>Overstorey Transpiration Volume (mm)</th>
<th>Unspecified volume %</th>
</tr>
</thead>
<tbody>
<tr>
<td>2006/2007*</td>
<td>894</td>
<td>14</td>
<td>540</td>
<td>529</td>
<td>-21%</td>
</tr>
<tr>
<td>2007/2008**</td>
<td>1368</td>
<td>189</td>
<td>540</td>
<td>519</td>
<td>9%</td>
</tr>
<tr>
<td>2008/2009</td>
<td>1377</td>
<td>230</td>
<td>540</td>
<td>491</td>
<td>8%</td>
</tr>
<tr>
<td>2009/2010</td>
<td>1478</td>
<td>273</td>
<td>540</td>
<td>503</td>
<td>11%</td>
</tr>
<tr>
<td>2010/2011***</td>
<td>2159</td>
<td>396</td>
<td>495</td>
<td>392</td>
<td>41%</td>
</tr>
</tbody>
</table>

*Only streamflow from March 2007 has been included in the annual volume.

** Streamflow for September 2007 has been estimated based on streamflow at Ettercon 3, while no streamflow measurement was available for February 2008.

***All components were measured/estimated up to February 2011 (11 months).

There was at least 188 mm of deficit in the unspecified volume in the 2006/2007 as the ET volume was greater than the total rainfall. The deficit would be greater if the total annual streamflow for 2006/2007 was included in the calculation. Crotty Creek is a perennial stream so its streamflow is not expected to cease during the summer. In contrast to this, a large proportion of the 2010/2011 water year was attributed to the unspecified volume. A wet summer has reduced the overstorey transpiration volume, but there has not been a corresponding increase in streamflow. The implication of this and the previous findings will be discussed further in the discussion section.
6.4 Discussion

6.4.1 Transpiration Volume

The estimation of transpiration volume from sap flow measurement entails some measurement errors and uncertainties. Hatton et al. (1995) have found that the potential errors are greater in estimating transpiration of an individual tree than in scaling up of the measurement to the stand level. Several strategies have been adopted to minimise those potential errors and uncertainties, but there were still some components of the measurement that could cause some underestimation or overestimation of transpiration volume. The failure of one of the sensor probes in some sample trees resulted in no sap velocity being recorded at its sapwood depth, which underestimated the transpiration volume during the failure period. Meanwhile, the transpiration volume from the early part of the measurement period might have been overestimated as the wound width might have been smaller (Swanson and Whittfield 1981).

The scaling up of plot transpiration to catchment transpiration at Crotty Creek was non-trivial due to its complex forest structure. The proportions of catchment area occupied by the mountain ash and Acacia overstorey stands (corresponding to the retained and cleared strips) were required to calculate their contribution to the total catchment transpiration. They were derived based on the assumption that both groups have different range of canopy heights.

The comparison of sap flux density between the overstorey stands indicated that the mountain ash stands in the retained strips transpired at a higher rate per sapwood area than the Acacia overstorey stands in the cleared strips. This confirm previous findings (Vertessy et al. 1995, Vertessy et al. 2001), that showed mountain ash (E. regnans) has higher leaf area efficiency than the species found in the understorey layer, such as hazel (P. aspera) or silver wattle (A. dealbata). The implication of the difference in sap flux
density is that mountain ash and *Acacia* overstorey stands would transpire at different rates with similar LAI.

The *Acacia* overstorey and understorey stands had similar sap flux density, but the transpiration of the *Acacia* overstorey stands was greater by an order of magnitude due to greater sapwood area. The basal area of the *Acacia* overstorey stands was also greater than the basal area of *Acacia* understorey stands of similar forests at Britania Creek and Bunyip River Valley (Pfautsch *et al.* 2010). Thus, the unsuppressed *Acacia* stands in the cleared strips have taken advantage of the additional resources that were available in the absence of mountain ash overstorey stands.

The compositions of non-woody/shrub understorey vegetation in the retained and cleared strips were similar (Tran 2007). Based on her vegetation survey in 2006, the total mean basal area of the non-woody/shrub understorey vegetation was 23.8 m$^2$ ha$^{-1}$ in the retained strips (excluding *Acacia* understorey) and 16.9 m$^2$ ha$^{-1}$ in the cleared strips. This suggests that the transpiration of understorey vegetation in the retained strips might be higher than the transpiration in the cleared strips.

The duration of the sap flow measurement in this study spanned more than 365 days, which was longer than other studies conducted in the mountain ash forests. It has enabled the seasonal variation of transpiration to be observed rather than inferred. The overstorey transpiration during the warmer months (January – March 2010, November – December 2010) contributed approximately 65% to its annual transpiration volume during 2010. The mean daily transpiration during December 2010 to January 2011 (3.2 mm day$^{-1}$) was lower than the mean daily transpiration for the same period in 2009/2010 (2.0 mm day$^{-1}$) due to summer rainfall variability (Figure 6.5).

6.4.2 Factors Controlling Transpiration

The relationship between daily maximum VPD and mean daily transpiration indicated the close coupling of overstorey transpiration rate with the evaporative demand at Crotty Creek. The ability to maintain transpiration at high VPD indicated that the overstorey
stands had access to adequate soil moisture. Night-time transpiration has also been observed in some mountain ash sample trees when there was some vapour pressure deficit and the temperature was above 12\(^{\circ}\)C (e.g. 29 to 31 December 2009, 7 to 12 January 2010). Benyon et al. (1999) have observed that night-time transpiration occurred in a well-watered four-year-old *Eucalyptus grandis* plantation. The difference in transpiration rates between the summers of 2009/2010 and 2010/2011 might be attributed to lower VPD and more rainfall in the summer of 2010/2011 (see Figure 6.6). Thus, the transpiration process at Crotty Creek appeared to be largely controlled by the evaporative demand (energy availability) rather than water availability despite prolonged drought.

The plotting of \(g_c\) against daytime VPD provided some insights into the transpiration of different vegetation groups. The coupling between \(g_c\) and daytime VPD was strong in the mountain ash and *Acacia* overstorey stands. There was a smaller decrease in \(g_c\) of overstorey vegetation at high VPD than at low VPD. This suggests that transpiration regulation in the overstorey stands might be less sensitive at high VPD compared to low VPD. Meanwhile, the coupling between \(g_c\) and daytime VPD was weak in the *Acacia* understorey stands. The canopy of the *Acacia* understorey stands might have been exposed to different radiation, humidity, temperature and wind speed compared to the canopy of the overstorey stands as the understorey canopy is shaded under the overstorey canopy. Thus, the evaporative demand on the understorey canopy might have been different from that on the overstorey canopy.

There was a significant difference in \(g_c\) of mountain ash and *Acacia* overstorey stands. The maximum \(g_c\) of the mountain ash stands was 5.6 mm s\(^{-1}\), while the maximum \(g_c\) of the *Acacia* stands was 2.4 mm s\(^{-1}\). The maximum \(g_c\) of mountain ash stands was within the range of maximum \(g_c\) reported by Connor et al. (1977) for regrowth and mature mountain ash forest. The difference in \(g_c\) between vegetation types might be due to different physiological responses to the environmental variables that drive transpiration, or different aerodynamic conductance resulted from the large difference in canopy height. However, it was not possible to determine whether one or both factors were responsible as \(g_c\) has been derived rather than directly measured. The variation of meteorological variables (radiation, humidity, temperature, wind speed) with canopy height was unknown because they have been measured at a single height.
6.4.3 Water Balance

The greater than average winter/spring rainfall in 2010 had not been translated into higher streamflow at the conclusion of this study, although the overstorey transpiration in the early summer was low. This resulted in a high unspecified volume (539 mm or 27%) in the catchment water balance from 10 December 2009 to 31 December 2010. As the unspecified volume included a number of water balance components, it was necessary to investigate which component has contributed most significantly to the volume and whether it was also responsible for the low streamflow.

Uncertainties and measurement errors that are associated with the components of the water balance might explain some of the unspecified volume. Hatton et al. (1995) estimated the potential errors in estimating the sap flux of individual tree were greater than the errors in scaling up the measurement to the plot/catchment level. The error in the streamflow measurement was approximately 2% of the total volume. The rainfall interception and soil/litter evaporation have been estimated from empirical relationships that are based on stand age (Haydon et al. 1997, Vertessy et al. 2001). Those relationships assumed the mean annual rainfall as 1800 mm. As the rainfall during the measurement period was 1995 mm, the actual rainfall interception might have been underestimated, while the soil/litter evaporation might have been overestimated. Some of these measurement errors and uncertainties would offset each other so their total volume is unlikely to account for all of the unspecified volume.

The estimated transpiration of the *Acacia* understorey stand in the retained strips was 21 mm or 1% of the total water balance. Based on the mean basal area obtained from a vegetation survey in 2006 (Tran 2007), *Acacia spp.* made up only 12% of the understorey vegetation in the retained strips. 76% of the understorey basal area consisted of soft tree fern (*Dicksonia antartica*), musk daily bush (*Olearia argophylla*) and mountain correa (*Correa lawrenciana*). Their transpiration has been assumed to be lower than woody understorey species such as *Acacia spp.* and hazel (*P. aspera*). Vertessy et al. (2001) estimated the proportion of understorey transpiration to the total water balance between
6% and 17% for mountain ash stand age 15 years and 240 years respectively. However, the basal area of *Acacia spp.* understorey in their study was an order of magnitude greater than the basal area measured at Crotty Creek. Thus, the proportion of the understorey transpiration in Crotty Creek’s 2010/2011 water balance would not exceed 10% of the total water balance.

The change in soil moisture storage was the remaining credible explanation for the large amount of unspecified volume in the 2010/2011 water balance. The change in soil moisture storage is often assumed to be negligible over a long period of time, but it is likely to vary at an annual time step. The excess water from above average rainfall and low summer transpiration in 2010/2011 water year might have been used to replenish the soil moisture storage, instead of appearing as streamflow. The refilling of the soil moisture storage suggested that the storage has been depleted in the past. Thus, the comparison of the annual catchment water balance from previous years has been carried out to examine if there has been a deficit in the annual water balance prior to 2010/2011.

The 2006/2007 catchment water balance has shown a deficit of 188 mm. This deficit would be greater if the total volume of streamflow has been measured and included in the calculation. The deficit might be due to the depletion of the soil moisture storage as the vegetation maintained a high ET rate during the warmer months. Allowing that the rainfall interception might have been overestimated because of lower than average rainfall, the unspecified volume for the 2006/2007 water year would still be the lowest of the examined period (2006 – 2011).

It could be hypothesised that the soil moisture storage has been drawn down to maintain vegetation transpiration leading up to and during the 2006/2007 water year. The deficit in soil moisture storage has been carried over in the subsequent three years (2007/2008 to 2009/2010) as each winter/spring rainfall was enough to maintain summer transpiration but not enough to replenish the storage completely. The above average rainfall during the 2010/2011 water year has enabled the soil water storage to be fully replenished, which has prevented a substantial increase in streamflow to be observed during the same period. The streamflow during the winter and spring of 2011/2012 is expected to increase as the soil moisture storage should be full and the transpiration is low.
6.5 Conclusion

The mountain ash overstorey stands have higher sap flux density than the *Acacia* overstorey stands so the transpiration of mountain ash overstorey stands would be greater than the transpiration of Acacia overstorey stands for the same sapwood and leaf area. The difference in $g_c$ between the two overstorey stand types indicated that the post-thinning change in transpiration was due to the change in vegetation composition and structure as well as due to the reduction in basal area of the dominant overstorey stands. However, it was unclear whether the difference in physiological response or aerodynamic conductance was responsible for the observed difference in $g_c$.

The transpiration rate at Crotty Creek appears to be controlled by evaporative demand as demonstrated in the relationship between daily maximum VPD and mean daily transpiration. There was an indication of some regulation/limitation of transpiration at higher VPD, but it was not enough to cease transpiration. The linear relationship between daily maximum temperature and mean daily transpiration implies that an increase in maximum temperature due to climate change will result in an increase in transpiration.

The multi-year catchment water balance has illustrated the interaction between different water balance components over time. It indicated that the soil moisture storage has a considerable depth to maintain transpiration during a low rainfall period. The 2006/2007 catchment water balance suggested a deficit in the soil moisture storage as the estimated ET exceeded rainfall. The soil moisture storage was replenished in 2010/2011, when the above average annual rainfall and the relatively low ET did not increase the streamflow. The winter/spring streamflow of 2011/2012 is expected to be greater than the 2010/2011 streamflow as any excess volume will be translated into streamflow.
Chapter 7.  General Discussion
Chapter 7: General Discussion

The impact of thinning on water yield has been investigated in this study through the measurements of water yield, vegetation structure, LAI and transpiration. The results of those measurements have been outlined and discussed individually in the previous chapters. Those findings are integrated in this chapter to examine whether the post-thinning changes in vegetation structure can fully explain the changes in water yield. This chapter also evaluates the findings against the results from previous studies, as well as identifying unanswered research questions or new questions that emerged from the study.

The first section of this chapter summarises the findings from the major components of the study. The second section integrates the findings to examine the post-thinning interaction between vegetation structure, water yield and climatic variation. The third section discusses the implication of the findings. The last section identifies a few unresolved issues from the study and recommends future research that might address them.

7.1 Summary of Findings

The major components in this study and their results have been summarised in the following table.
Table 7.1. Summary of findings from previous chapters.

<table>
<thead>
<tr>
<th>Objective</th>
<th>Methods</th>
<th>Findings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quantify post-thinning changes in water yield</td>
<td>Paired catchment study</td>
<td>• Statistically significant increases in water yield after the treatment in all thinned catchments, except for Ettercon 2.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Strip-thinning produced the largest and most persisting changes in water yield.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Decreases in water yield were observed in some catchments when streamflow measurements recommenced in 2007/2008.</td>
</tr>
<tr>
<td>Quantify changes in forest structure</td>
<td>Vegetation height profiles acquired from LiDAR maximum height data</td>
<td>• Patch-cutting and strip thinning permanently altered vegetation structure of the catchments.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Regeneration of mountain ash in the cleared areas was poor.</td>
</tr>
<tr>
<td>Obtain current LAI spatial distribution</td>
<td>In situ measurements with hemispherical and cover photography.</td>
<td>Measurements obtained at Crotty Creek:</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• The mean overstorey LAI of the retained mountain ash stands was consistent with the predicted LAI from the age – LAI relationship for mountain ash forest.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• The LAI estimates from the regrowth stands were less reliable than those from the retained stands.</td>
</tr>
<tr>
<td></td>
<td>Remote sensing measurements with Quickbird satellite image and LiDAR gap fraction.</td>
<td>Measurements obtained at Crotty Creek:</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Based on LiDAR data: mean overstorey LAI of retained stands was higher that of regrowth stands, while the total LAI of the retained and regrowth stands was not statistically different.</td>
</tr>
</tbody>
</table>
The spatial distribution of GNDVI was consistent with the spatial distribution of LiDAR’s gap fraction.

The photography techniques underestimated gap fractions of the regrowth stands compared to those obtained with LiDAR.

Measurements obtained from the other catchments:

- The difference in overstorey LAI from the retained and regrowth stands was greater at Ettercon 4 than at Crotty Creek.
- Patch-cutting in Black Spur 1 resulted in a wide range of overstorey LAI values.
- The long term impact of uniform thinning and understorey on LAI distribution appeared to be minimal.

<table>
<thead>
<tr>
<th>Measure transpiration and water balance at Crotty Creek</th>
<th>Sap flow measurement with heat pulse technique</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Mountain ash overstorey stands have higher sap flux density and transpiration rate than <em>Acacia</em> overstorey stands.</td>
<td></td>
</tr>
<tr>
<td>- Mean daily transpiration increased with increasing maximum daily VPD transpiration, while stomatal conductance decreased with increasing mean daytime VPD.</td>
<td></td>
</tr>
<tr>
<td>- The transpiration process was controlled by evaporative demand rather than water availability.</td>
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</tr>
<tr>
<td>- The projected annual water balance from 2006/2007 to 2010/2011 indicated a deficit in the soil moisture storage. The low streamflow in 2010/2011 was due to the refilling of the soil moisture storage.</td>
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</table>
7.2 Post-thinning Interaction of Vegetation Structure and Water Yield

7.2.1 Crotty Creek

Crotty Creek was selected as the focus catchment in this study because of several reasons. Firstly, it was the largest catchment in the North Maroondah experimental area. Secondly, strip-thinning has permanently altered its vegetation structure, which provided an opportunity to investigate the long term impact of thinning and subsequent vegetation regrowth on water yield. Therefore, a range of measurements were carried out to examine the post-thinning interaction between vegetation structure and water yield.

The removal of approximately half the total basal area in the catchment resulted in a statistically significant increase in water yield. The increase persisted until the streamflow measurement was suspended at the end of 1996. The persistence can be attributed to the poor regeneration of mountain ash stands in the cleared strips that limited the post-thinning catchment ET below its pre-thinning volume. As the *Acacia* stands established themselves as the dominant overstorey species in the cleared strips over time, the water yield slowly returned towards the pre-thinning level.

A decrease in water yield was observed when the streamflow measurement resumed in March 2007. Water yield decrease in mountain ash catchment has been associated with the increase in ET in dense, young regrowth stands (Dunn and Connor 1993, Haydon et al. 1997, Langford 1976, Vertessy et al. 1995, Watson and Vertessy 1996). However, the post-thinning regeneration of mountain ash stands in this catchment has been very limited. The total ET of the retained and regrowth stands had to exceed the ET of an undisturbed catchment to account for the decrease in water yield. The recent prolonged drought (1997 – 2009) might have also amplified the decrease in water yield. The LAI and sap flow measurements were conducted to determine if the post-thinning ET might be greater than the ET of undisturbed catchment.
The projected LAI spatial distribution from LiDAR data indicated the mountain ash overstorey stands in the retained strips had greater LAI than the regrowth Acacia overstorey stands in the cleared strips. Total LAI estimates in both stand types were similar. However, the sap flow measurements have shown that mountain ash has higher sap flux density and stomatal conductance than Acacia species. The transpiration of the mountain ash overstorey stands in the retained strips was greater than the transpiration of the Acacia overstorey stands in the cleared strips. This also means that LAI might not be a good predictor of transpiration or ET distribution in the forest that has multiple vegetation groups and structures.

Those results prompted a question on whether the total post-thinning ET can exceed the ET of an undisturbed mountain ash catchment if the ET of the regrowth stands was less than the ET of mountain ash stands that they have replaced. ET of the retained stands must be equal to or greater than ET of the undisturbed stands to explain the decrease in water yield below the pre-treatment level. Although sap flow measurements were not conducted at Ettercon 3 (control catchment) to measure ET due to resource constraints and the February 2009 bushfire, there were several indicators that thinning has increased the growth of the retained mountain ash stands and their ET at Crotty Creek.

The impact of edge effect on vegetation growth has been documented at Crotty Creek (Incoll 1993). The retained trees along the edges grew bigger than the retained trees in the middle of the strips because they have greater access to soil moisture. The classification of vegetation cover based on LiDAR maximum height data suggested that 73% of the catchment area can be associated with mountain ash stands. Allowing that the proportion of vegetation cover might be larger than the proportion of basal area, this still indicated that the retained stands currently occupy more than half of the catchment. Federer and Gee (1974) proposed that the transpiration of the edge trees would be greater than if there were no opening due to increased radiation, less competition for soil moisture and the clothesline effect that transfers warm air from the opening (cleared strip). Thus, transpiration of the retained stand could be greater than transpiration of an undisturbed stand.
The magnitude of the decrease in water yield might have also been amplified by the recent long drought. Extreme climatic events have amplified the magnitude of the changes in water yield during the observation period following the treatment (Chapter 3). The dry period during 1982/1983 suppressed the increase in water yield at the Black Spur catchments to near or below the pre-thinning levels. The recent drought was shown to delay the recovery of water yield at Picaninny Creek after a clear-felling experiment (Bren et al. 2010). The annual water balance at Crotty Creek indicated that the soil moisture storage has been depleted in 2006/2007. Unfortunately, it was impossible to ascertain if the decrease in water yield would persist after the soil moisture storage has been replenished in 2010 as the February 2009 bushfire terminated the paired catchment study. A return to surplus water yield or a negligible change in water yield after 2010 would indicate that the decrease can largely be attributed to the drought rather than the vegetation structure.

7.2.2 Comparison of Different Thinning Treatments

The impact of different thinning treatments on vegetation structure and water yield of the North Maroondah catchments has been variable. Most treatments, except for the uniform thinning, have altered the vegetation structure and composition permanently. Acacia stands occupied the thinned areas where regrowth mountain ash stands have failed to dominate. The post-thinning water yield increase in North Maroondah catchments persisted for slightly more than a decade. Most thinning studies have reported the persistence of water yield increase as less than a decade without further treatment or regrowth control being applied (Baker 1986, Bren et al. 2010, Hornbeck et al. 1993, Lane and Mackay 2001).

The treatments that produce the largest to the smallest cumulative water yield increase in the North Maroondah catchments were 50% strip-thinning, 50% uniform thinning, removal of understorey vegetation and 54% patch-cutting. The cumulative treatment effects at Crotty Creek, Ettercon 4 and Ettercon 1 in the first decade were 1813 mm, 1419 mm and
1382 mm respectively. Decreases in water yield were observed when the streamflow measurements resumed in 2008 and 2008 at Crotty Creek and Ettercon 4 respectively. Based on LAI distribution and sap flow measurements conducted in this study, the decrease in water yield can be attributed to the increase in ET of regrowth Acacia stands in the cleared strips over time and the increase in transpiration of the retained mountain ash stands.

Uniform thinning produced different magnitude of treatment effects at Black Spur 2 and Black Spur 3. The cumulative treatment effects over 14 and 19 years were -191 mm and 1595 mm at Black Spur 2 and Black Spur 3 respectively. The water yield increase in Black Spur 2 persisted for four years, followed by water yield decrease. However, Black Spur 2 and 3 had similar inter-annual variation of the treatment effects. They also had similar vegetation height profiles. The difference in the amount of removed basal area (33% and 50%) might account for some of the difference in the treatment effects. There might also be other factors that have not been captured in the measurements. Both catchments showed decreases in water yield when streamflow measurement resumed in 2008.

Patch-cutting resulted in an annual increase in water yield that persisted for a decade at Black Spur 1, followed by a decrease in water yield from 1987 to 1995. There were two departures from the trend that occurred in 1982 and 1996 that can be attributed to a dry year (1111 mm rainfall) and a wet year (2095 mm rainfall) respectively. The cumulative treatment effect decreased from a maximum of 512 mm in 1987 to 168 mm by 1995. The vegetation height profile and the estimated LAI distribution map of Black Spur 1, based on LiDAR measurements in 2007, have shown the presence and development of regrowth vegetation in the formerly cleared patches. The water yield decrease indicated that the post-thinning ET of the regrowth and retained vegetation might have exceeded the ET of an undisturbed catchment of the same age.

The removal of understorey vegetation at Ettercon 2 has resulted in a small increase in water yield that was not statistically significant at $p = 0.05$. However, this treatment effect persisted until the suspension of streamflow measurement at the end of 1996 as well as when the measurement resumed in 2008. The average vegetation height profile from
sample plots in the catchment has shown the absence of woody mid-storey/understorey vegetation (such as silver wattle, blackwood, hazel, etc) that would have greater ET than the shrubby understorey vegetation (such as tree ferns, daisy-mint bush). Thus, the modest post-thinning increase in water yield might have persisted over time.

Several studies have reported differing accounts on the impact of similar thinning treatments on water yield (Baker 1986, Hornbeck et al. 1993, Lane and Mackay 2001). Hornbeck et al. (1993) reported that 24% of basal area removal in a single block produced larger increase in water yield than 33% strip-thinning or 33% selective thinning in the hardwood forests of north eastern USA. They attributed the smaller treatment effects from strip-cutting and selective thinning to the increased transpiration of the retained stands as the edge trees were exposed to more radiation and ventilation. Lane and Mackay (2001) reported 12% uniform thinning produced larger increase in water yield than 31% patch-cutting in mixed eucalypt forests at Tantawangalo, NSW. They attributed the difference to poor regeneration in the uniformly thinned catchment. In this study, patch-cutting produced smaller increase in water yield than strip-thinning and uniform thinning due to a rapid increase in the transpiration of the regrowth mountain ash seedlings in the patch-cut catchment.

In summary, thinning configuration can influence the abundance and composition of regrowth vegetation as well as affect the transpiration from the retained vegetation. The increased transpiration of the regrowth vegetation and/or the retained vegetation will decrease water yield of the treated catchment. An optimum thinning configuration will maximise water yield increase and minimise the subsequent water yield decrease. The sensitivity of the catchment water balance to changes in the transpiration of regrowth or retained vegetation should be taken into account to select an optimum thinning configuration.
7.3 General Implication of Findings

7.3.1 Post-Thinning Water Yield

Thinning treatments were applied to the North Maroondah catchments to imitate the basal area and density of older forests. This transformation of forest structure was expected to decrease stand transpiration and increase water yield of the catchments. The water yield increase would cease quickly if regrowth mountain ash stands occupy the thinned areas, as initially observed at Black Spur 1. As none of the thinning configurations has been conducive to the long term survival of regrowth mountain ash seedlings, the water yield increases persisted for more than a decade in most catchments.

The transpiration of the regrowth *Acacia* stands and the increased transpiration of the retained mountain ash stands eventually exceeded the transpiration of the removed mountain ash stands. This resulted in a decrease in water yield. However, the post-thinning decrease in water yield is likely to be less than the decrease in water yield observed in young regrowth mountain ash. The estimated changes in streamflow based on the age – water yield relationship for an undisturbed catchment is 82 mm. Although the volume of water yield decrease during the gap in the measurements is unknown, the cumulative changes in water yield for most of the North Maroondah treatment are likely to be greater than the changes caused by the ageing process.

An optimum thinning treatment will increase water yield in the short term and produce positive long term cumulative effect. This might be achieved by considering the timing of the treatment (age of stands when thinning is applied), the type or configuration of the treatment and the management of regrowth.

This study has also highlighted the importance of a continuous long term paired catchment study to investigate the long term changes in water yield and vegetation structure. The difficulty in distinguishing the impact of changes in vegetation structure and drought has been caused by the gap in the streamflow records so the start of the period of water yield decrease was not known. The length of pre-thinning or calibration period should also be
long enough to capture a range of streamflows to ensure the robustness of the relationship between the control and treated catchment.

### 7.3.2 Measurements of LAI with Remote Sensing

Remote sensing has enabled the retrieval of vegetation attributes, such as heights and vegetation cover fraction. The challenge in this study was in calibrating the remote sensing parameters with the *in situ* measurements of leaf area parameters. The configuration and complexity of the post-thinning vegetation structure at Crotty Creek has limited the accuracy of the *in situ* leaf area parameters measurements. However, LAI spatial distribution was successfully projected from LiDAR’s gap fractions.

### 7.3.3 Transpiration

The sap flow measurements have shown that the transpiration of the mountain ash forest is controlled by evaporative demand rather than water availability. The soil moisture storage appears to have a significant capacity to meet the stand water use during a dry period. The mean daily transpiration is strongly influenced by daily maximum VPD and temperature. This confirmed and extended the relationship between mean daily transpiration and daily maximum temperature observed by Pfautsch *et al.* (2010) as the range of daily maximum temperature observed in this study (5° – 39°) was greater. This relationship suggests that any future increase in maximum temperature due to climate change would result in an increase in mean daily transpiration.

The difference in stomatal conductance between the mountain ash and *Acacia* stands suggests that LAI might not be a good predictor of transpiration in forest with complex vegetation structure. It is unclear if the difference was due to physiology or micro-climate at canopy level (e.g. radiation, humidity, wind speed). Further research needs to be conducted to investigate the impact of vegetation composition and structure on the total catchment transpiration.
7.4 Recommended Future Work

The impact of the February 2009 bushfire on vegetation structure and water yield at the North Maroondah experimental catchments has not been fully assessed. An initial observation at Crotty Creek indicated that the fire has affected a small area along the ridge. Some mountain ash stands survived the fire in this area, while *Acacia* stands have been killed. There did not appear to be a significant increase of water yield after the fire, which suggested that its immediate impact on water yield might be small. Meanwhile, the fire has affected a significant proportion of understorey vegetation at Ettercon 3. This has precluded further use of Ettercon 3 as a control catchment in the paired catchment study. A post-fire LiDAR survey will enable the impact of this event on the vegetation structure of the North Maroondah catchments to be documented and assessed.

Assessments of the edge effect were conducted about 8 – 10 years after the strip-thinning treatment at the Ettercon and Crotty Creek catchments (Aney and O'Shaughnessy 1994, Benyon 1992), when the stand age was 48 – 51 years. If the edge effect persists over time, the basal area per hectare of the retained stands might be greater than that of the undisturbed stands of similar age. The retained stands, in particular the edge trees, might also have greater transpiration than an undisturbed stands due to greater exposure to radiation, the clothesline effect in advection and greater access to soil moisture (Federer and Gee 1974). These factors support the hypothesis that ET of the retained stands could be greater than ET of undisturbed stands 30 years after thinning treatment. Thus, a forest inventory and transpiration measurements of the control catchment and a more recent assessment of the edge effect at the treated catchment are required to test the hypothesis.

The ability to predict the long term impact of thinning on water yield will improve the management of water resources from mountain ash catchments. Modelling the long term impact of thinning requires the spatial and temporal changes in vegetation structure and composition to be represented. The temporal changes in vegetation structure have been represented as LAI temporal variation in distributed, process-based hydrological model, such as Macaque (Watson *et al.* 1999a). Theoretically, the spatial changes can be
represented as LAI spatial distribution, which has been obtained from remote sensing data in this study. However, a mapping of vegetation types should be linked to the LAI distribution so transpiration of different vegetation groups can be accurately calculated. Post-thinning vegetation composition and structure need to be represented in process-based model to predict the changes in water yield.
Chapter 8. Conclusion
Chapter 8: Conclusion

This study has investigated the long term impact of a range of thinning treatments on vegetation structure and water yield in North Maroondah experimental catchments. A series of measurements at different scales were conducted to answer the research questions that have been outlined at the beginning of the project. This final chapter of the thesis will present the conclusion that can be drawn from the findings.

The magnitude and persistence of the post-thinning increases in water yield depended on the amount of removed basal area, climatic variability, treatment type (configuration) and the composition of regrowth vegetation. A large increase in annual water yield corresponded to a wet year (1996) at all catchments, while the annual water yield increase ceased temporarily in the dry period in 1982/1983 at the Black Spur catchments. Treatment type influenced the composition of the regrowth vegetation and the transpiration of the retained vegetation. The regeneration of mountain ash has been suppressed in most of the thinned catchments, which allowed the increase in water yield to persist for up to a decade or until the suspension of streamflow measurements in 1997.

A decrease in water yield was observed in most of the thinned catchments when the streamflow measurements recommenced in 2007/2008. This has been more challenging to explain than the increase in water yield for several reasons. The persistence of this trend cannot be verified beyond February 2009 due to a large bush fire that affected some of the experimental catchments. The period of decrease in water yield coincided with a long dry period that affected south eastern Australia (1997 – 2009), which might have amplified the magnitude of the decrease in water yield. Thus the post-thinning changes in vegetation structure and their impact on water yield were examined.

Both cover and hemispherical photography produced reliable LAI estimates of the mountain ash stands at Black Spur and Crotty Creek. However, they might have overestimated LAI of the regrowth *Acacia spp.* stands at Crotty Creek. This was mostly due to the configuration of the site rather than the limitation of the techniques. The overestimation of LAI estimates from the regrowth stands affected the calibration of the remote sensing parameters. Nevertheless, LAI distribution could still be projected from GNDVI and LiDAR’s gap fractions.
Chapter 8: Conclusion

The assessment of post-thinning vegetation height profiles and overstorey LAI distribution indicate that the regrowth vegetation stands are well-established in the strip-thinned and patch-cut catchments. The mean overstorey LAI estimate of the regrowth vegetation (mainly *Acacia*) stands was still lower than the mean overstorey LAI estimate of the retained mountain ash stands. The mean total LAI estimates in both stand types were similar. Meanwhile, the impact of thinning on vegetation structure was not detectable in the uniformly thinned catchment. The LAI distribution of Ettercon 2, where the understorey vegetation was removed, appeared to be lower than the LAI distribution of the control catchment.

Transpiration measurements were obtained from December 2009 to January 2011 at Crotty Creek to examine how the remotely sensed LAI distribution translates into ET pattern. The sap flux density and stomatal conductance of the mountain ash stands were found to be higher than those of the *Acacia* stands. For the same LAI, transpiration of the *Acacia* stands will be lower than transpiration of the mountain ash stands. This implied that the post-thinning decrease in water yield cannot be explained by the transpiration of the regrowth *Acacia* stands alone. The transpiration of the retained mountain ash stands, especially the edge trees, might have increased over time due to greater radiation exposure, the advection clothesline effect and less water stress. The recent drought might have also amplified the magnitude of the water yield decrease in the thinned catchments.

The transpiration measurements have also shown that evaporative demand controlled the transpiration rate rather than water availability at Crotty Creek. Stomatal conductance decreased during the summer months, but they did not reduce the high transpiration rates. This implied access to deep soil moisture storage that prevented water stress. The modelled annual catchment water balance between 2006/2007 to 2010/2011 indicated that a deficit in the soil moisture storage could be carried over for several years until there was enough rainfall to replenish it. This period of deficit in the soil moisture storage was accompanied by low streamflow.
Chapter 8: Conclusion

The ability of to predict the long term impact of thinning on water yield is important to manage water resource in mountain ash catchments. This study has shown that remote sensing data can be used to obtain spatial variation of LAI efficiently. However, the post thinning ET pattern cannot be reliably estimated from the spatial LAI distribution without taking into account the post-thinning vegetation composition and canopy structure. Vegetation composition is important in the transpiration estimation when there is more than one dominant overstorey species, while the interaction between canopy structure and climate variables (radiation, humidity, wind speed) can affect transpiration rates. A range of climatic projections should also be modelled to reflect the possible range of treatment effects as they are sensitive to climatic variation. The prediction of the impact of thinning on water yield with a process-based model will be accurate if the complex interaction of vegetation and water yield can be captured.
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