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Retraction notice to 'Impacts of fire on forest age and runoff in mountain ash forests.' [*Functional Plant Biology* 35(2008), 483–492. doi:10.1071/FP08120]

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Refers to: RETRACTED: Impacts of fire on forest age and runoff in mountain ash forests

Functional Plant Biology Volume 35 Issue 6, 2008, Pages 483–492, Stephen A. Wood, Jason Beringer, Lindsay B. Hutley, A. David McGuire, Albert Van Dijk and Musa Kilinc

After due consideration of various issues raised with respect to the Wood *et al*. paper, Stephen Wood and the co-authors unanimously agree to retract the above paper from *Functional Plant Biology*.

Reason: In the paper published in this journal we examined water use across a chronosequence of Australian mountain ash forests using an eddy covariance system measuring forest evapotranspiration (ET) combined with sap flow measurements of tree water use. The paper contained an error in the scaling of sap flow measurements of both overstorey and understorey sap flow data from daily quantities. These errors then transferred to the annual sums that were subsequently also incorrect. We also reported rainfall data from the site that was in error and as a result we can not infer any annual water balances and no longer consider all our conclusions supported. Due to the propagation of error we therefore retract the paper. We thank Dr Benyon and colleagues for pointing out these issues (Benyon *et al*. 2010). We apologise for any inconvenience caused by our paper. We have also circulated an open email to our colleagues.

Reference

Benyon R, Haydon S, Vertessy R, Hatton T, Kuczera G, Feikema P, Lane P (2010) Comment on Wood *et al*. 2008, 'Impacts of fire on forest age and runoff in mountain ash forests'. *Functional Plant Biology* **37**, 1187–1191. doi:10.1071/FP09093

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Impacts of fire on forest age and runoff in mountain ash forests

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This paper originates from a presentation at EcoFIZZ 2007, Richm[illegible], New [illegible]th W[illegible]es, Australia, September 2007.

Abstract. Runoff from mountain ash (*Eucalyptus regnans* F.M[illegible]) forested c[illegible]ments has been shown to decline significantly in the few decades following fire – returning to pre[illegible]levels in the following centuries – owing to changes in ecosystem water use with stand age in a relationship known a[illegible]Kuczera's [illegible]odel. We examined this relationship between catchment runoff and stand age by measuring whole-ecosyst[illegible] exchan[illegible] of water using an eddy covariance system measuring forest evapotranspiration (ET) combined with sap-flow [illegible]asure[illegible]ents of tree water use, with measurements made across a chronosequence of three sites (24, 80 and 29[illegible] since fire). [illegible] the 296-year old site eddy covariance systems were installed above the *E. regnans* overstorey and abov[illegible] rainforest understorey. Contrary to predictions from the Kuczera curve, we found that measurements of who[illegible] for[illegible] [illegible]ecreased by far less across stand age between 24 and 296 years. Although the overstorey tree water use decli[illegible]by 1.8 mm day^{-1} with increasing forest age (an annual decrease of 657 mm) the understorey ET contrib[illegible]ween 1.[illegible]nd 1.5 mm day^{-1}, 45% of the total ET (3 mm day^{-1}) at the old growth forest.

Additional keywords: eddy [illegible]ariance, [illegible]calyptus regnans*, sap flow, transpiration.

Introduction

The future availability [illegible] water for ci[illegible]s fed by forested catchments is a critic[illegible]ssue i[illegible] light of worsening water shortage problems globally ([illegible] *et al*. 2008). Streamflows into water catchments are depende[illegible]n the i[illegible]ts of water from rainfall, but also, critically [illegible]sses thr[illegible] [illegible]aporation from the catchment and transpirati[illegible] fro[illegible] vegetation. Therefore, runoff into these catchm[illegible] can [illegible]ffected by changes in evapotranspiration, which ma[illegible]lt from either forest succession or deforestation. A reduction i[illegible]rest cover due to anthropogenic deforestation or disturbance, suc[illegible]s fire, normally results in a short-term increased runoff into catchments, and the re-establishment of forest cover most often decreases the runoff. These modifications in runoff have been attributed to changes in sapwood area (Vertessy *et al*. 1995, 1997; Roberts *et al*. 2001). Forested catchments return to their initial pre-disturbance state through succession of vegetation (Hibbert 1967; Swank *et al*. 2001), resulting in the runoff returning to the pre-disturbance levels. Hornbeck *et al*. (1993) using 11 water catchments in north-eastern USA (Fernow, Leading Ridge, Marcell and Hubbard brook) showed that after deforestation water yield levels increased by up to 250 mm year^{-1}, returning to the initial levels after 7–25 years.

In Australia, a significant amount of research has taken place on the affect of fire on the water yield changes in eucalypt-dominated water catchments. The most significant of these was by Kuczera (1987), which describes the relationship between mean annual water yield and stand age for a mountain ash (*Eucalyptus regnans* F.Muell.) forested catchment by using rainfall-runoff data from fire affected mountain ash forests. Kuczera's study showed that shortly after a catastrophic fire there was by a distinct period (15–20 years) where water yield decreased (300–400 mm), because of tree growth. After this time, water yield increased to pre-fire levels, taking up to 200 years to fully recover (Vertessy *et al*. 2001). The increase in water yield was due to the replacement of mature forests with younger rapidly growing stand. In eucalypt forests, it is common for a younger regrowth stand to use more water than an old-growth forest because of the rapid growth of the young stands and natural thinning of the mature stands (Andreassian 2004).

In Melbourne, Australia potable water is obtained from 1570 km^2 (157 000 ha) of forested catchments located in the Victorian Central highlands (Melbourne Water 2006) and Melbourne Water Corporation uses water from these

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catchments to supply water for ~2.8 million customers (Melbourne Water 2006). Mountain ash forests cover half of the catchment area yet this area yields ~80% of the stream flow that makes up Melbourne's water supply. This is because mountain ash forests tend to grow on higher rainfall sites where the mean annual rainfall exceeds 1200 mm (Vertessy *et al*. 1995, 2001; Haydon *et al*. 1997; Melbourne Water 2006).

Since mountain ash trees are a significant vegetative cover in the catchment, they are an important factor in the future of water availability for the city of Melbourne. For example, past studies have shown that the presence of mountain ash trees radically alter the water balance of water catchment areas and that different aged mountain ash stands created by fire or logging have different total tree water use (Langford 1976; Kuczera 1987; Jayasuriya *et al*. 1993; Vertessy *et al*. 1995, 1996, 1997, 2001; Watson *et al*. 1999; Cornish and Vertessy 2001). Hence, bushfires are a crucial, yet infrequent component in the development and life cycle of mountain ash forests and the hydrological cycle. For mountain ash seedlings to survive and grow they need to be exposed in soil with direct sunlight, an environment best created by bushfires (Vertessy *et al*. 2001). Without fire driven regeneration, mountain ash forests would die out in several hundred years through gradual succession to rainforest species (Haydon *et al*. 1997; Vertessy *et al*. 2001). In the 20th century, bushfires have burnt through the Melbourne water catchment areas in 1926 and 1983, which has resulted in the conversion of 80% of the forest in the catchment from old growth (several hundred years of age) to regrowth stands (Vertessy *et al*. 2001). This regeneration process goes through several different successional stages; pole (15–30 years post fire), spar (30–100 years), mature (100–300 years) and old growth (300+ years) (Museum Victoria 2002).

Following fire there is a mass 'seed rain' followed by germination, high growth rates of young *E. regnans* individuals, and intense competition for light and nutrient resources, resulting in thinning over time. Tree thinning continues for the life of the stand but at an almost exponentially decreasing rate (Fig. 1) (Ashton 1976). After 100–200 years large canopy gaps form (Jayasuriya *et al*. 1993; Vertessy *et al*. 2001) that serve to decrease overstorey leaf area (Fig. 2*b*), sapwood area (Fig. 2*a*) and stem density. As a consequence, when *E. regnans* stands age, less water is lost through transpiration by the overstorey, leading to increased runoff into water catchments (England and Attiwill 2006).

Due to this species' importance for commercial timber as well as its dominance of headwater forests in Victoria, a significant amount of study has been has been conducted on mountain ash forests, especially forest hydrological properties. The amount of runoff from *E. regnans* forests into the catchment is known as the water yield and has been closely related to stand age, due to changes in evapotranspiration (ET) over time (Langford 1976; Kuczera 1987; Watson *et al*. 1999; Vertessy *et al*. 2001). An idealised curve developed by Kuczera (1987) describes the relationship between mean annual water yield and stand age for a mountain ash forested catchment by using rainfall-runoff data from fire affected mountain ash forests (Fig. 3). Kuczera's study shows that shortly after the catastrophic fire in 1939 there was a rapid decline in catchment yield of 580 mm over a 27-year period. After this time water yield was predicted to return to pre-fire levels, taking up to 200 years to fully recover (Vertessy *et al*. 2001).

Previous studies have also shown that vegetation succession following fire produces an increasing understorey leaf area as the overstorey leaf area declines (Vertessy *et al*. 2001). These studies have suggested that the understorey ET is negligible because the understorey is decoupled from the bulk atmosphere, being shaded by the tall (85 m) *E. regnans* canopy, more humid, with less turbulent mixing and reduced evaporative demand (Vertessy *et al*. 2001). Therefore, if it is assumed that the understorey ET is negligible then Kuczera's curve is easily explained by the observed decline in overstorey stem density and leaf area index (LAI) with stand age after the initial 30-year peak. The initial decline in catchment yields over the first 30 years is explained by the rapid growth of mountain ash trees following disturbance and increasing stem densities and leaf area.

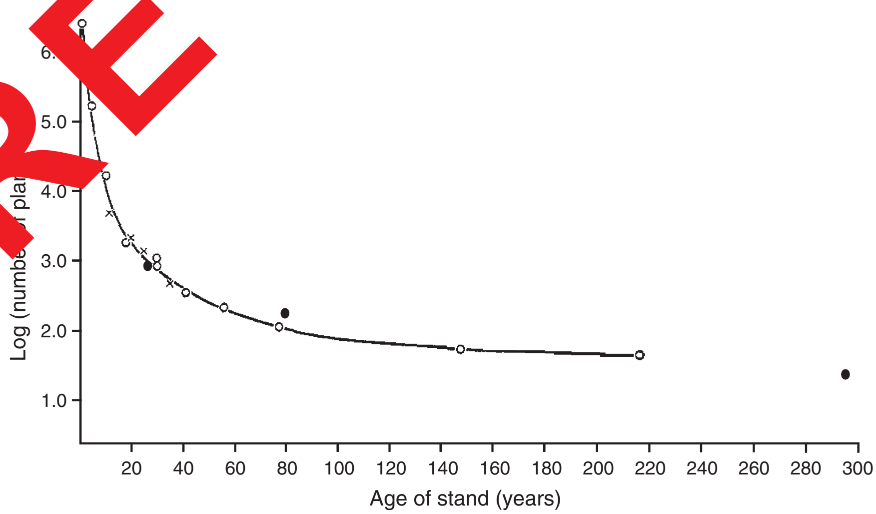

Fig. 1. Relationship between density of trees (plants ha^{-1}) and the age of the stand (years). ○ 1953 assessments; × 1974 reassessments; overlaid with: ● stem density data from this study (Ashton 1976; pp. 399).

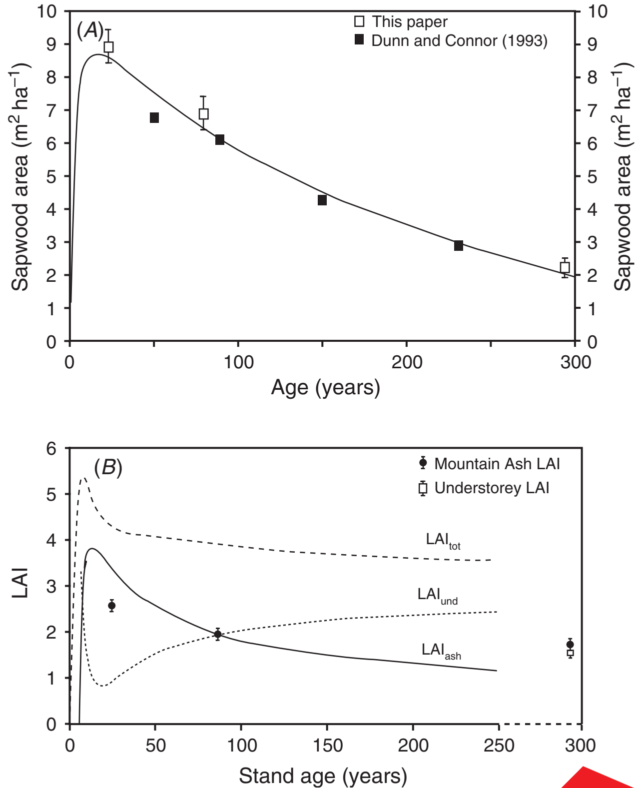

Fig. 2. (*A*) Change in sapwood area with stand age, data from thi[s paper] (open squares) plotted with data from Dunn and Connor (1993) ([closed] squares). Best fit equation $y=(a+c\ln x+e(\ln x)^2)/(1+b\ln x+d(\ln$ [illegible] $a=0.0037$, $b=0.0069$, $c=6.267$, $d=0.0113$, e [illegible], $r^2=0.$[illegible] (*B*) Age-dependant trends in total LAI (LAI_{tot}), m[ount]ain as[h] LAI (LAI_{ash}) and understorey LAI (LAI_{und}) in the Maroon[dah] ca[tchment], [Ce]ntral Highlands, Victoria (Vertessy *et al*. 20[0]1; pp. [illegible]) compared with mountain ash LAI data (closed circles) [and] old grow[th un]derstorey LAI data (open squares) from this study.

Vertessy *et al*. (2001) noticed reportable differences in their estimate of water balance due to their inclusion of changes in understorey transpiration, calculated using the sap-flow method, but for a 240-year-old forest, the understorey transpiration accounted for only 16.6% of the site water use. Their study also showed the annual canopy interception of rainfall and annual soil and litter evaporation decreased by 7.5 and 1.6%, respectively, from a 15 to a 240-year-old stand, illustrating that the major component affecting the yield in water catchments is the transpiration of the dominant mountain ash trees.

Recent studies such as Watson *et al*. (1999) and Vertessy *et al*. (2001) using a range of methods f[rom] w[ater] balance models to sap-flow techniques to investi[gate] overstor[ey] water use have supported the initial findings by [Kuczera] (19[illegible]). In the case of sap-flow measurements th[is] has been [pre]do[min]antly focussed on the tall overstorey trees (Whitehead and [Bea]dle 2004). However, all these measurem[ents] are [eith]er indirect or measuring only a single component and t[here] have b[een] no direct measurements of total forest ET [u]ndertaken [in] thi[s f]orest type to date.

The obj[ectiv]es of this rese[arch] were to (1) measure sap flux in mountain ash [stan]ds of three different ages to determine the effect of forest age [on] mountain ash water use and compare results w[ith] [illegible]ver based estimates and previous studies; (2) measure the [w]ater use of the understorey of an old growth mountain ash forest [u]sing sap-f[lo]w and tower measurements to more fully investigate [the] contrib[uti]on of the understorey to total forest water use on to[illegible] (3) [sc]ale up sap flux measurements to canopy transpiration to compare results with eddy covariance measurements from [an] old growth stand.

Materials and methods

Site description

All field measurements were conducted in the Wallaby Creek Melbourne Water catchment, located near Kinglake, ~45 km, north-east of Melbourne, in south-eastern Australia (Fig. 4). Three suitable sites were selected that are typical of

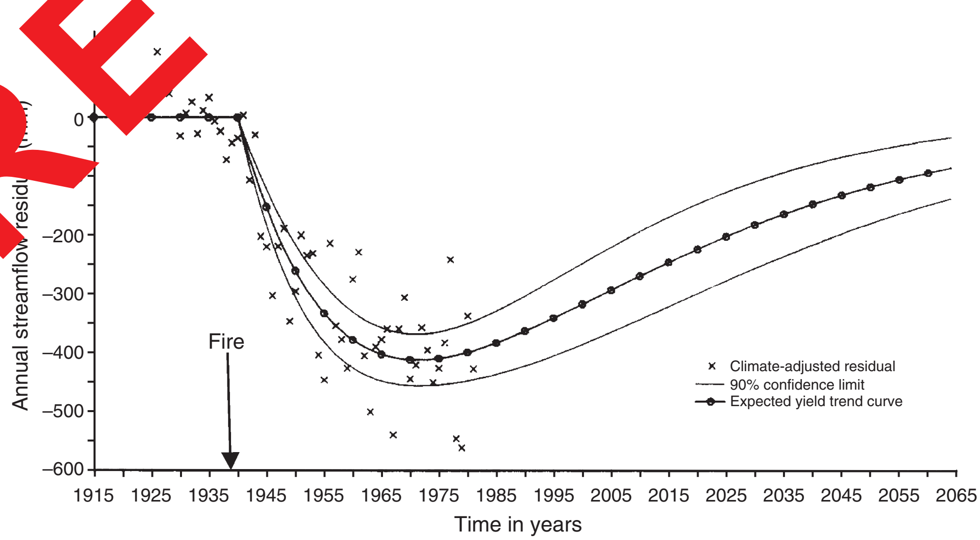

Fig. 3. Climate adjusted residuals of streamflow for Graceburn catchment with Kuczera's predictive model for expected yield following fire in 1939 (Kuczera 1987; pp. 224).

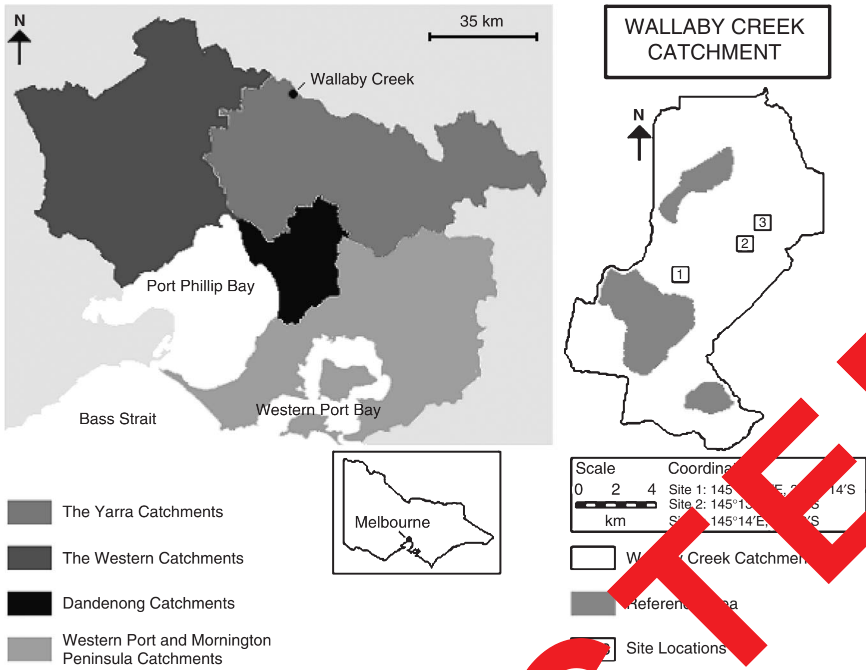

Fig. 4. Location of the Wallaby Creek catchment study site ~[illegible] km north-e[illegible] of Melbourne, Australia. Site (1) 296 years old/EC tower site; (2) 80 years old; site (3) [illegible] years old.

Melbourne's water catchment areas representing different age classes (24, 80 and 296 years) of mountain ash (*Eucalyptus regnans* F.Muell.) forest ranging from 660 to 690 m in altitude. Details of these sites are given by Martin *et al.* (2007).

The Wallaby Creek catchment is classified as the margin of a Mediterranean and temperate climate w[illegible] summers and mild winters (Van Pelt *et al.* 20[illegible]). It has received an average of 1190 mm of rainfall per year [illegible] the past 10 years (1996–2006), with an average of 232 mm (20.8%) occurring during the summer months (December, January and February) (Bureau of Meteorology 2007). The site also receives ~380 mm of snowfall per year (Van Pelt *et al.* 2004). The annual average maxim[illegible] a[illegible] minimum temperatures vary between 24.1 and [illegible], respectively (Bureau of Meteorology 2007). Mean mo[illegible]y minimum and maximum temperatures vary between 2 and [illegible]°C in winter, and 16 and 28°C in summ[illegible]

Vegetation

M[illegible]ain ash trees are straight, grey-trunked trees with smooth-ba[illegible] but the first few metres (Ashton 2000*a*). These trees [illegible]ow in cool, deep soiled, mostly mountainous areas up to [illegible]00 m in elevation with very high rainfall of over 1200 mm per year (Vertessy *et al.* 1995, 2001; Haydon *et al.* 1997; Melbourne Water 2006). The understory of the old-growth forest is made up of *Olearia argophylla* (Labill.) F. Muell. ex Benth, *Pomaderris aspera* Sieber ex DC., tree ferns (*Dicksonia antarctica* Labill. and *Cyathea australis* (R. Brown) Domin), as well as *Acacia* trees (*A. dealbata* Link. and *A. melanoxylon* R.Brown) (Van Pelt *et al.* 2004). The understorey at the 1926 regrowth site is sparse, and made up mainly of prickly currant (*Coprosma quadrifida* (Labill.) Rob.). The 1982 re-growth site has a very minimal understory compared with the old-growth site and 1926 regrowth sites. More information on the forest and canopy structure at the old-growth site is given by Van Pelt *et al.* (2004) and further

Table 1. *Eucalyptus regnans* characteristics from each site at the Wallaby Creek sites
DBH, diameter at breast height

Variable	Site age (years)			
	24	80	296	296 understorey
Average stems per ha	898 ± 36	239 ± 10	37 ± 2	278 ± 11
Mean height (m)	21 ± 3	60 ± 5	80 ± 5	8 ± 1
Mean DBH (cm)	26 ± 3	73 ± 3	155 ± 5	14 ± 2
Minimum DBH (cm)	6 ± 3	42 ± 3	95 ± 5	5 ± 2
Maximum DBH (cm)	70 ± 3	121 ± 3	226 ± 5	26 ± 2
LAI	2.62 ± 0.04	2.09 ± 0.04	1.69 ± 0.07	1.67 ± 0.07
Sapwood area ($m^2 ha^{-1}$)	8.9 ± 0.5	6.9 ± 0.5	2.3 ± 0.2	2.1 ± 0.2
Sap velocity ($cm h^{-1}$)	9.1 ± 1.5	12.8 ± 1.1	11.2 ± 1.4	5.0 ± 1.1

information on the history, environment and plant ecology of mountain ash forests is given by Ashton (2000*b*).

The stocking rate, mean height and diameter at breast height (DBH) of *E. regnans* at the three sites are shown in Table 1 and the stocking rate is compared with previous studies in Fig. 1. Tree height was measured using standard forestry techniques (Goodwin 2004), trigonometry and DBH was measured at a height of 5 metres (above the buttress) on the 296-year-old forest and at breast height of 1.3 m on the 24- and 80-year-old forests as well as the 296-year-old understorey. The two dominant species of the understorey of the 296-year-old stand, *P. aspera* and *O. argophylla* had stocking rates of 133 and 145 stems ha^{-1}, respectively (Van Pelt *et al*. 2004).

Soils

The soils of Kinglake and the Hume plateau are rich krasnozemic loams, which are friable, red brown gradational soils with high organic matter contents (15–20%) in the upper 20–30 cm (Ashton 2000*b*). The soil profile at 0–30 cm is a dark brown coarsely friable loam and grades with depth to a red-brown or yellow-brown subsoil clay loam. From a depth of 183–244 cm the soil becomes a sandy loam and from 244–274 cm the soil becomes loamy gravel. Kransnozemic soils provide perfect growing conditions for mountain ash trees as they have a high rate of water infiltration [13–64 mm h^{-1} (Williams 1983)], good aeration and water retention. Mountain ash forest soils are the most productive forest soils in the state of Victoria due to their high organic matter content (Martin *et al*. 2007; Ashton 2000*b*).

Leaf area index

The total single-sided leaf area index (LAI) of each aged stand was measured using an LAI-2000 plant canopy analyser (PCA) (Li-Cor Inc., Lincoln, NE, USA). The LAI-2000 provides a non-destructive means of measuring single-sided leaf area using gap fraction theory (Cherry *et al*. [illegible]). Two PCA's were used; with one left in a clearing, at a range of 1–3 km away from the sites, to record the light conditions automatically every 15 s, whereas the other sensor was used below the canopy. At each site a 200 × 200 m grid with 20-m spacing was established and LAI measurements (121 spot measurements per site across the grid) were taken. Measurements were taken using the four inner rings of the sensor, confining the PCA's view to a radius of [illegible] m at the [illegible] height of ~1.5 m. Due to the dense understorey at the 296-year-old stand, the LAI measured was the total LAI (LAI of overstorey plus understorey), however, several recently fallen trees created a 40 × 40 m gap in the understorey that provided an opportunity to measure the mountain ash LAI only. This overstorey LAI was measured at 20 points in the understorey clearing using the PCA with the quarter view cap and inner ring only to ensure the LAI of only the mountain ash trees above this cleared area was measured.

Transpiration

Transpiration in this study was measured using the heat pulse method (Cohen *et al*. 1985; Dunn and Connor 1993; Hatton *et al*. 1990), between December 2005 and December 2006, which included the summer period of highest water use. Sap flow was measured using sap-flow loggers (Greenspan Technology, Warwick, Qld, Australia) with eight *E. regnans* trees and four understorey trees at the 296-year-old site measured simultaneously over this period. This enabled the water use of overstorey and understorey trees to be compared, once normalised by sapwood area. In addition, four individuals of mountain ash trees at the 24- and 80-year-old sites were also instrumented to examine rates at the younger sites of contrasting structure. For each individual tree, sampling of sap velocity was undertaken at four different points within the sapwood, with measurements made every 30 min across a range of tree diameters at each site (Becker 1998). This provided a relationship between tree size (DBH) and sapwood area with sap flow, which enabled the water use of individual trees to be scaled up to stand water use, following Vertessy *et al*. (1997).

The half-hour measurements of mountain ash sap-flow velocities were multiplied by the sapwood cross-sectional area to calculate the transpiration for individual trees. The sapwood depth and sapwood cross-sectional area of each tree used in this study was determined from cores taken with a 5 mm increment borer, taken at breast height (1.3 m) for trees from the 24-, 80- and understorey of the 296-year-old sites. For the old growth site, the cores were collected above the buttresses at a height of ~5 m. The depth of the sapwood was determined from the core by holding it in front of a bright light source, so that the light was able to pass through the vessels. The open vessels in the sapwood are clearly distinct as numerous pinpoints of light. Few or no pinpoints of light can be seen in the heart wood, where most of these vessels are blocked (Dunn and Connor 1993; Jayasuriya *et al*. 1993; Haydon *et al*. 1997). The sapwood depth of the understorey trees at the 296-year-old site was clearly distinguishable as a change in colour when methyl orange dye was added. To measure the sapwood depth with greater accuracy it was measured at four points around each tree (Dunn and Connor 1993; Haydon *et al*. 1997). Sapwood width measurements were used to determine the implantation depth of the heat pulse sensor probes and to calculate sapwood area.

Eddy covariance measurements of forest evapotranspiration

A 110-m tall guyed mast tower was constructed within the old growth stand to record water, carbon and energy exchange data using the eddy covariance technique as part of a larger study that aimed to quantify the carbon, water and energy exchanges within Australia's temperate forests and the factors regulating them over hourly to inter-annual time scales in order to assess the impact of future environmental change. The eddy covariance tower was installed at an elevation of 690 m, with a site slope of ~3°, with adequate fetch in all directions (>1 km) and has been collecting water and CO_2 exchange data continuously since August 2005. For forests, the method involves the deployment of fast response instruments above plant canopies to measure the covariance of vertical wind velocities and scalars such as CO_2, water vapour and temperature (Baldocchi and Meyers 1998). The system is made up of two main instruments, a sonic anemometer (Model CSAT3; Campbell Scientific Inc., Logan, UT, USA) that measures the turbulent wind field, sonic temperature, sensible heat and friction velocity along with an open path gas analyser (LI-7500, Li-Cor) that measures CO_2 and H_2O concentrations and computes the relevant fluxes. The instrument setup follows that by Beringer *et al*. (2007) and Hutley *et al*. (2005). Briefly, there are two eddy covariance systems in operation on the tower; the first is located 95 m above the ground, roughly 25 m above the mountain ash canopy which measured the net exchanges between the whole ecosystem and the atmosphere. The second is located 25 m above the ground and measures fluxes from the understorey (8.3 m above the understorey canopy) and the surface. Obtaining flux data from the two different heights allows differentiation between the overstorey canopy and understorey (vegetation and soil) in terms of CO_2 and H_2O fluxes. These systems sampled flux variables at 20 Hz and recorded half hourly mean fluxes and were strictly quality controlled and gap filled following Beringer *et al*. (2007). Neural network (NN) models were produced for gap filling the flux variables using Statistica software package (Statsoft, Tulsa, OK, USA) following Papale and Valentini (2003) and Beringer *et al*. (2007).

In addition to the eddy covariance systems, net radiation is measured every 30 min by measuring the incoming (Pyranometer CM7B; Kipp and Zonen, Delft, The Netherlands) and outgoing (Pyrgeometer CG2; Kipp and Zonen) radiation fluxes at a height of 110 m. There is also a temperature, CO_2 concentration, relative humidity and pressure profile system that run vertically along the tower (HMP45C; Campbell Scientific Inc.). These profiles were measured at heights of 2, 5, 10, 20 and 45 m.

Results

Leaf area index and sapwood

LAI and tree stand density decreased with forest age (Table 1). At the old growth stand (296-year-old) the LAI of the overstorey and understorey were similar, 1.69 and 1.67, respectively (Fig. 2*b*). Understorey LAI was calculated as total forest [illegible]36), measured at 121 points, minus the overstorey [illegible], measured at just 20 points. Sapwood area for the *E. regn*[illegible] the two dominant understorey species were estimated from species specific regression equations for each site derived from data collected in this study. [illegible]tionship between sapwood area and DBH of individual trees showed a strong relationship ($r^2 = 0.90$) that allowed the stand sapwood area to be calculated by measuring DBH of individuals in the 200 × 200 m plot (Fig. 2[illegible]). The total sapwood area of the mountain ash trees was [illegible]9 ± 0[illegible], 6.87 ± 0.52 and 2.25 ± 0.23 $m^2\ ha^{-1}$ for the 24-, 80- and 296-year-old sites, respectively. The two major understorey species at the old growth site (*C*[illegible]*uria* and *Pomaderris*) had a sapwood area of 0.91 ± 0.21 and [illegible] ± 0.2[illegible] ha^{-1}, respectively.

Mountain ash sap velocity and transpiration

We measured the sap velocity during the summer months to be 9.05 ± 1.5, 12.8 ± 1.1 and 11.2 ± 1.4 cm h^{-1} for the 24-, 80- and 296-year-old stands, respectively. Values of hourly transpiration (Fig. 5) were summed to calculate the daily transpiration rates of the mountain ash trees from the different aged stands. During Melbourne's summer months (December, January and February) the average transpiration from the mountain ash trees at the 24-year-old was 51 L day^{-1} $tree^{-1}$. At the 80-year-old site the average daily transpiration was 251 L day^{-1} $tree^{-1}$ and the 296-year-old site average transpiration was 317 L day^{-1} $tree^{-1}$. During the winter months (July and August) the average

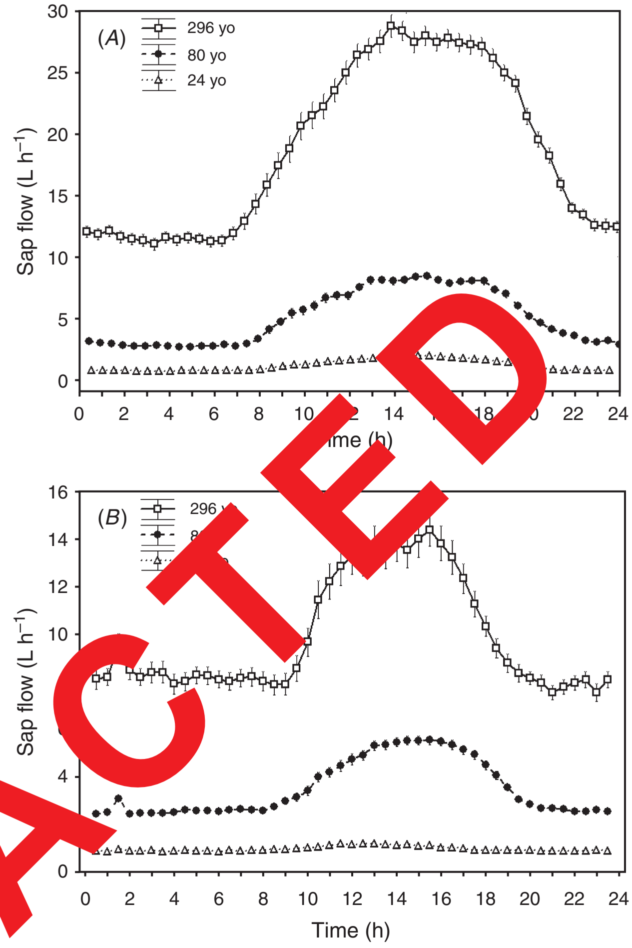

Fig. 5. Ensemble average of the diurnal pattern of sap flow for mountain ash trees at the three different aged sites (24, 80 and 296 years old), (*A*) for summer period 8 December 2005 to 5 February 2006, (*B*) for winter period 1 May 2006 to 30 May 2006 for 296-year-old and from 26 July 2006 to 10 September 2006 for 80- and 24-year-old sites. Standard error bars shown.

transpiration was 43, 109 and 163 L day^{-1} $tree^{-1}$ for the 24-, 80- and 296-year-old stands, respectively.

From the annual data we calculated the average canopy transpiration rates for the 24-, 80- and 296-year-old mountain ash stands to be 3.32, 2.91 and 1.52 mm day^{-1}, respectively, over the study period. From these measurements the mean annual transpiration was estimated to be 1212, 1051 and 555 mm $year^{-1}$ for the 24-, 80- and 296-year-old stands, respectively.

Dunn and Connor (1993) calculated that 69% of total annual potential evapotranspiration occurred during the six warmest months, with 31% occurring during the six coolest months, giving a ratio of 0.45. Using the data collected in this study, it was estimated that 65% of the measured total transpiration occurred during the warmest months with only 35% occurring during the coolest.

The transpiration data in Fig. 5 also showed a positive night-time sap-flow rate for all measured trees, accounting for ~35 and 50% of total sap flow during summer and winter months, respectively. In general, it is often assumed that stomata close at sunset; however, the stomata of some plants stay partially open, allowing night-time transpiration (Dawson *et al*. 2007; Marks and Lechowicz 2007). The primary driver of nocturnal transpiration is vapour pressure deficit (VPD) with strong links to high night-time temperature and available soil moisture. Even if the stomata are closed at night-time, sap flow may continue, due to the refilling of stem and branch capacitance, as this water may have been drawn on during high photosynthesis times (Benyon 1999; Phillips *et al*. 2003; Snyder *et al*. 2003).

In addition, the diurnal graphs of transpiration for the old-growth mountain ash trees show a slight plateau between 1400 to 1600 hours local time (Fig. 5), suggesting a possible hydraulic constraint in water use. This occurs as water stored in the trunks and branches of the trees is used for photosynthesis early in the day and when the evaporative demand is greatest (around solar noon) the tree cannot supply water fast enough because of the suction required to draw up water through the trunk from the soil (Goldstein *et al*. 1998; Dawson *et al*. 2007).

Understorey transpiration

Values of tree transpiration were also summed to calculate the daily transpiration rates of the two main understorey species at the old growth site. The transpiration from *O. argophylla* had a mean value of 20 L day^{-1} during summer and 14.5 L day^{-1} during winter. Scaling this to stand level, the *O. argophylla* had a transpiration rate of 0.59 mm day^{-1}. The main understorey species *P. aspera* transpiration had a mean value of 26 L day^{-1} during summer and 17.1 L day^{-1} during winter, giving an a… transpiration rate of 0.84 mm day^{-1} after scaling to stand …vel. The total transpiration from the two main understorey trees … 1.43 mm day^{-1}, only 0.34 mm day^{-1} less tha… domin… mountain ash stand. However, it should … no… that th… *P. aspera* and *O. argophylla* only accou… …r 90% of the total understorey leaf area, with the other 10% bei… …*Acac*… spp., *D. antarctica* and *C. australis*. H…ce, the … understorey transpiration could be greater th… …easured.

Total transpiration

The annual time seri… of 30-…in sap-flow and eddy covariance data were pooled to p…duc… monthly water use values (Fig. 6*a*). The data show a signifi… seas… variation in total water use that follows … simila… … to potential ET (Fig. 6*b*). The understor… ET w… a larger proportion of the total in summer than winter, … sum… …cause of much higher soil evaporation in summer.

The annua… …T of the 296-year-old site from the whole forest and overstorey w…e derived from the cumulative monthly totals, and the annual transpiration from the understorey was calculated as the cumulative monthly difference between the total ET measured by the eddy covariance tower and the mountain ash transpiration as measured by the sap-flow method (Fig. 6*a*). The whole-ecosystem ET was 1077 mm year^{-1} at the 296-year-old site (Fig. 7). The 20-year-old stand had no understorey, but the 80-year-old site had an estimated understorey LAI that was 10% of the overstorey LAI. After taking this into account, the total forest transpiration for the 80-year-old site was estimated to be 3.2 mm day^{-1} or 1168 mm annually. The transpiration from the 20-year-old site was 3.32 mm day^{-1} or 1212 mm year^{-1}. The result was that the total forest transpiration shows a decreased by only 135 mm annually across the chronosequence (Fig. 7).

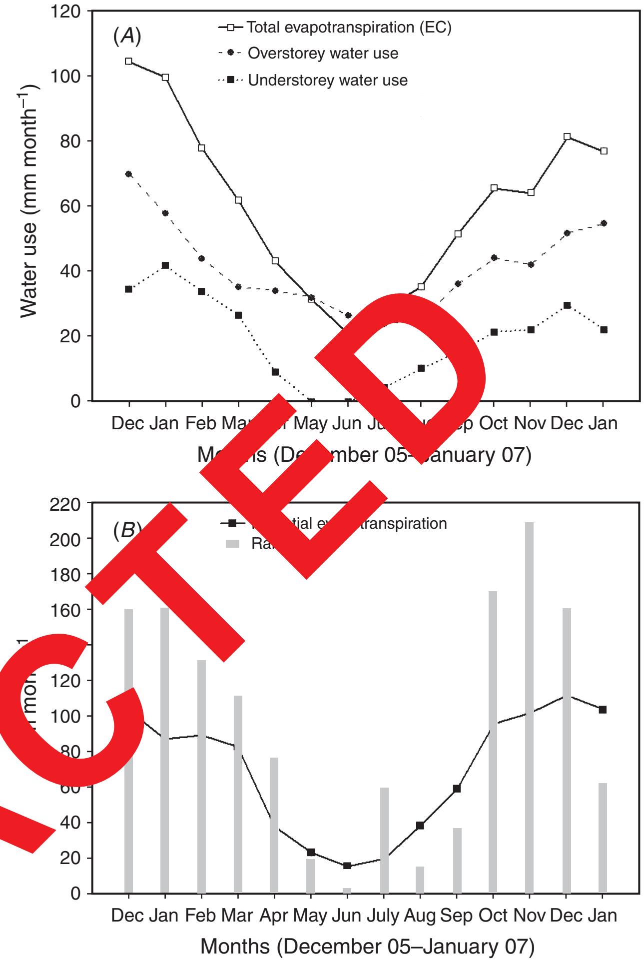

Fig. 6. (*A*) Comparison between the monthly whole-forest evapotranspiration (mm) as measured by the eddy covariance tower, the monthly water use by mountain ash trees (mm) as measured by sap flow and the understorey water use (mm). Understorey water use was calculated as the residual of the total and overstorey measurements. (*B*) Comparison between monthly potential evapotranspiration and rainfall for the 296-year-old site from December 2005 to January 2007.

Comparison with eddy covariance estimates of forest ET

Mean sap-flux transpiration for summer (December, January and February) 2005–06 was compared with the eddy covariance transpiration for the same period (Fig. 8). Tree transpiration was remarkably similar between the eddy covariance (1.64 ± 0.1 mm day^{-1}) and sap-flux methods (1.79 ± 0.1 mm day^{-1}) and any difference was likely due to errors in scaling. The understorey transpiration from the eddy covariance system was 1.47 mm day^{-1} which was only 0.04 mm day^{-1} more than the estimated rate from the sap-flow method. This provides confidence in the sap-flow methodology and the scaling from trees to plot.

The potential evapotranspiration (PET) was calculated for the 296-year-old stand using the Penman–Monteith equation and data from the eddy covariance tower following Beringer *et al.*

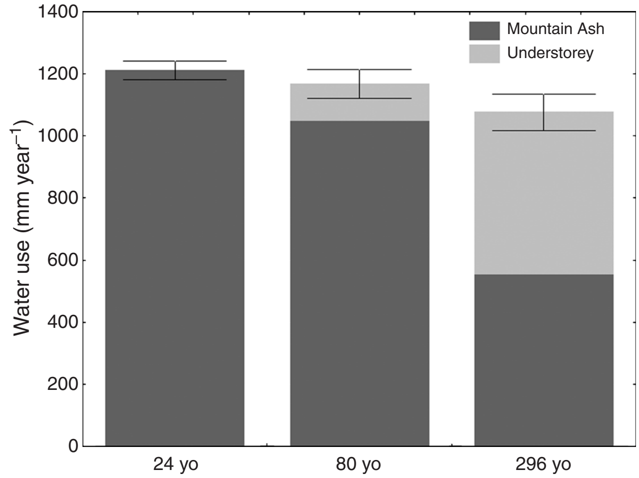

Fig. 7. Change in average annual forest transpiration with stand age, with overstorey and understorey water use given for each site. Standard error bars shown.

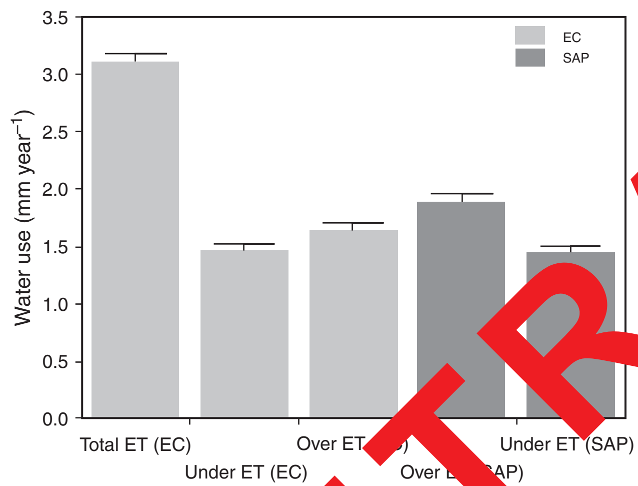

Fig. 8. Comparison of total ET from the ecosystem and understorey ET (vegetation plus soils) measured using the eddy covariance (EC) for summer (December 2005, January and February 2006). The overstorey ET is calculated as the difference between the total and understorey measurements. The [illegible] sap-flow measurements are shown for December, January and February. Standard error bars shown.

(2005). PET was [illegible] ± 6.9 and was less than the annual rainfall (1175 ± 9.8) for that period illustrating the 'wet' nature of these cool wet temperate forests. Hence, the potential runoff of the 296-year-old stand was estimated as 314 mm year^{-1}.

Discussion and conclusions

The results of LAI, stem densities and sapwood area of the mountain ash trees from this study are highly consistent with previous studies, as illustrated when plotted with results by Dunn and Connor (1993), where stand sapwood area was measured at the nearby North Maroondah catchment for four different age classes of mountain ash forests, at 50, 90, 150 and 230 years of age (Fig. 2*a*). The sapwood area is essentially zero after fire and reaches a peak at ~30 years, after which time sapwood area declines steadily with forest age (Fig. 2*a*).

Dunn and Connor (1993) observed that the mean sap velocities in the stems of mountain ash trees in stands aged 50, 90, 150 and 230 years for spring/summer months were 11.5, 11.4, 9.9 and 11.8 cm h^{-1}, respectively (Dunn and Connor 1993). We concur with the conclusions by Dunn and Connor (1993) and Haydon *et al.* (1997), who stated that sap velocity does not vary significantly with forest succession for mountain ash stands. They also estimated a maximum summer time transpiration rate of 1.9 and 0.8 mm day^{-1} for the 50- and 230-year-old stands, respectively. Annually, this result[illegible] in a difference of 383 mm, which was expected to be observed as an increase in water yield. Vertessy *et al.* (2001) showed a similar result with an estimated annual ET difference of 383 mm between a 20- and 220-year-old mountain ash forest, using a water balance method. These two results are much less than the 765 mm difference estimated by Haydon *et al.* (19[illegible]) for a 20- and 220-year-old forest, possibly due to a failure to account for changes in understorey transpiration. Ku[illegible] (1987) showed a similar difference to this with a 580 mm decline in stream flow after forest regeneration from bushfire.

Our results have shown a decrease in sapwood area and transpiration of the overstorey trees, highly consistent with previous studies, but our results contradict past assumptions that the ET from the understorey is negligible. We found that for the oldest site, understorey transpiration makes up 48% of the total in summer, consistent with the ratio of understorey to total forest LAI (Table 1). From our results, we suggest that the water use across different stand ages (after maximum leaf area is reached at ~24 years old) declines only slightly, with a decline of [illegible]4 mm y^{-1} between the 24- and 296-year-old stands.

Assumed negligible understorey transpiration has previously been attributed to low VPD (high relative humidity) within the moist understorey environment that provides a minimal water vapour gradient. However, we were able to measure the relative humidity and vertical gradient using our tower profile. We found that the relative humidity was around 62% and not close to

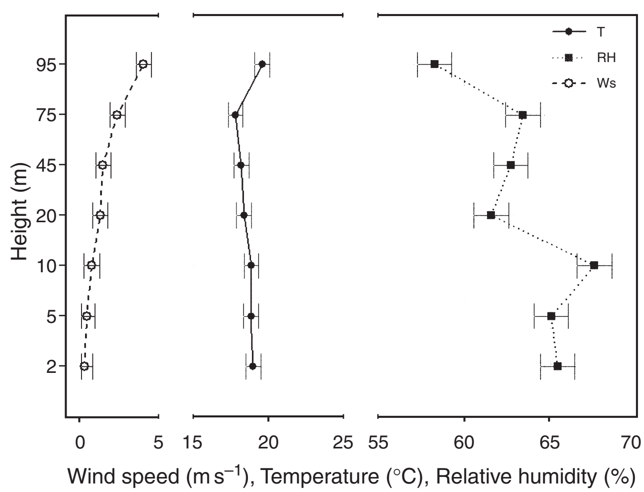

Fig. 9. Comparison of wind speed (m s^{-1}), temperature (°C) and relative humidity (%) at the different measurement heights (2, 5, 10, 20, 45, 75 and 95 m). The overstorey canopy height was 80.44 m and the understorey was 8.3 m.

saturation during daylight hours (0800–1700) in summer (December, January and February) (Fig. 9). In addition, there was a clear water vapour gradient. There was little difference in air temperature within the canopy and wind speeds decreased monotonically. Further, the measured turbulence was modest, as measured by the so called friction velocity (u*) derived from the eddy covariance system that averaged 0.26 m s^{-1} during the day with a peak of over 0.5 m s^{-1}. The overstorey u* measurements had an average value of 0.99 m s^{-1} with a peak around 1.05 m s^{-1}. Many studies have shown that u* values greater than around 0.1 m s^{-1} represent conditions of sufficient turbulent transport to capture fluxes (Aubinet *et al*. 2005; Papale *et al*. 2006). Hence, the values shown for mountain ash forest suggest that canopy mixing was occurring and that turbulent exchange from the understorey is significant from this canopy layer, as demonstrated by the measured water fluxes using both sap-flow and eddy covariance techniques.

The consequence of this higher than expected total forest ET of older stands is that catchment runoff may not increase substantially with stand age once the forest is mature and LAI has peaked. Kuczera's curve is somewhat unique in the literature because it shows no immediate increase in runoff following disturbance, in contrast to most studies of catchment disturbance (fire or clear-felling), which show an initial increase in yield following fire, then followed by a decline in yields associated with vigorous regrowth and then a small decline in ET back to pre-disturbance levels (Jayasuriya *et al*. 1993; Watson *et al*. 1999; Cornish and Vertessy 2001). A[illegible] example is given by Watson *et al*. (1999), who showe[illegible]hat after clear felling, 78% of mountain ash forest in the Pican[illegible] catchment (Central Highlands of Victoria), the a[illegible]l water y[illegible] increased by ~300 mm after 2 years and the[illegible]crea[illegible]d by up [illegible] 200 mm as the forest matured (<25 years o[illegible] Fig. 1[illegible]. Our result of a 135 mm $year^{-1}$ reduction in annual E[illegible]ween [illegible] and 296 years old is more consistent [illegible]n Wats[illegible]t *al*. (1999), who showed that the difference[illegible]m 25-year-o[illegible] pre burn levels was on the order of 15[illegible]m y[illegible]$^{-1}$.

These findings provide additional [illegible]rmation that can be used to further interpret [illegible] refine the rela[illegible]ships suggested by Kuczera. Their catc[illegible]ent y[illegible]d curve was developed using a simple, two paramet[illegible]od[illegible]t to observed catchment data from before and after fire and is therefore an empirical relationship based on a single fire event in 1939. Kuczera's curve has been supported by some water balance studies but has lacked an ecological or plant physiological interpretation. However, our results are the first direct observations of total forest ET across a chronosequence and suggest that the decline in ET may not be as large as predicted by Kuczera's curve but are more consistent with other studies of forest disturbance locally and worldwide. The Kuczera curve has maintained some prominence in State government water resource management (Department of Sustainability and Environment 19[illegible]) and it is, therefore, important that better understand[illegible] o[illegible] forest hydrology these important Melbourne's [illegible]er catch[illegible]nts be obtained and any uncertainties reduced. [illegible] is es[illegible]ially important given climate change [illegible]arios a[illegible]po[illegible]tially permanent declines in mean an[illegible] rai[illegible]fall for [illegible]th-eastern Australia (Whetton *et al*. [illegible]02) [illegible]rocess-based soil vegetation atmosphere transfer [illegible]AT) [illegible]dels could aid in the interpretation [illegible] the ava[illegible]a and will provide the most gain when [illegible]led to hydro[illegible]cal catchment models. Such an effort wi[illegible]equ[illegible]ntegration of the hydrological approach (water balance and catc[illegible]nt models) with an ecosystem ecology a[illegible]h (ecosyste[illegible]uxes and ecological models). This will [illegible] crucial to capture future environmental change including [illegible]imate c[illegible]ge, drought, disturbance (fire) processes and [illegible]nges i[illegible] the water use efficiency of vegetation with in[illegible]atmospheric CO_2 levels.

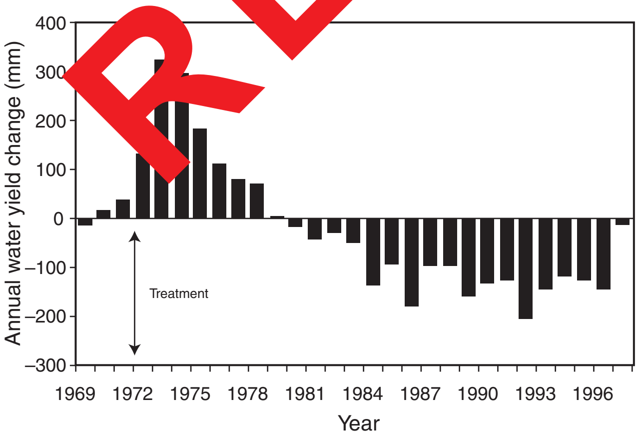

Fig. 10. Mean annual water yield changes after a 78% clear fell logging in the Picaninny catchment, Central Highlands, Vic., 1969–98. Based on analysis reported in Watson *et al*. 1999 (from Vertessy *et al*. 2001; pp. 16).

[illegible]knowledgements

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