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Comment on Wood *et al.* 2008, 'Impacts of fire on forest age and runoff in mountain ash forests'

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Abstract. Wood *et al*. (2008; FPB 35) concluded their measurements of evapotranspiration (ET) in *Eucalyptus regnans* F.Muell. forest at Wallaby Creek, Victoria showed that ET differs only slightly between regrowth and oldgrowth, contrary to the findings of previous research. We assert that the conclusions of Wood *et al*. are invalid and argue that Wood *et al*. substantially overestimated annual transpiration and rainfall. Monthly whole-forest ET measured by Wood *et al*. using eddy covariance in a 296-year-old stand sum to ~700 mm year^{-1}; consistent with rainfall of 721 mm year^{-1} recorded nearby by the Bureau of Meteorology. However, the Wood *et al*. conclusions were based on 1077 mm annual transpiration at this site, which appears to be estimated from a few months of heat pulse velocity measurements. Transpiration alone cannot be 54% higher than whole-forest ET because the latter includes transpiration, rainfall interception and evaporation from the forest floor. We believe Wood *et al*. made errors in scaling heat pulse velocities to whole-stand annual transpiration. Their rainfall of 1175 mm year^{-1} averages 62% higher than at three Bureau of Meteorology and Melbourne Water sites nearby. The paper also contains inaccuracies in reporting of the literature and numerous other errors.

Additional keywords: eddy covariance, *Eucalyptus regnans*, evapotranspiration, rainfall, sap flow, transpiration.

Introduction

Langford (1976) and Kuczera (1985, 1987) showed that stream flow from some of Melbourne's water supply catchments declined by up to 50% in the first 20 to 30 years after widespread wildfires in 1939. Kuczera's analysis of up to 67 years of stream flow records from eight catchments indicated the magnitude of the decline was related to the proportion of catchment converted by the fire from oldgrowth *Eucalyptus regnans* F.Muell. forest to regrowth of the same species. Kuczera hypothesised stream flows will gradually increase over time as the regrowth forests age. This pattern of a long-term decrease in water yield after fire in oldgrowth *E. regnans*, followed by a gradual recovery, is sometimes referred to as the Kuczera curve. It is important to appreciate Kuczera's analysis identified the underlying water yield–time relationship for a specific set of catchments, by filtering out climate variability in the stream flow record. It could not provide evidence of a causal mechanism for the changes.

In view of the significance of these stream flow changes over large water supply catchments, detailed studies of the forest water balance have since been undertaken to identify the mechanisms. These studies have indicated the change in stream flow from *E. regnans* forests over time is related to changes in evapotranspiration (ET). Dunn and Connor (1993) measured sap velocities and sapwood areas in *E. regnans* overstorey aged ~50, 90, 150 and 230 years. They observed little variation in mean sap velocity between age classes, but large differences in stand sapwood area, leading to large differences in overstorey transpiration.

Haydon *et al*. (1996) analysed a comprehensive dataset on rainfall interception from *E. regnans* forests and reported changes in rainfall interception with forest age, accounting for about one-quarter of the variation in stream flow with age.

Vertessy *et al*. (2001) undertook further measurements of overstorey and understorey transpiration and leaf area index in different aged stands. Based on these data, the rainfall interception versus forest age relationship reported by Haydon *et al*. (1996) and estimates of evaporation from the forest floor (McJannet *et al*. 1996), Vertessy *et al*. (2001) compiled estimates of interception, forest floor evaporation, and understorey and overstorey transpiration across a chronosequence of five age classes of *E. regnans* ranging from 15 to 240 years. They concluded that for an annual rainfall of 1800 mm year^{-1}, total ET declines from ~1371 mm year^{-1} in 15-year-old, to 911 mm year^{-1}

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in 240-year-old forest. Between these ages, total transpiration declines from 835 mm to 547 mm year^{-1} of which the contribution from the understorey increases from 12% to 54%.

This body of evidence showing that ET in regrowth *E. regnans* is significantly greater than oldgrowth *E. regnans*, resulting in balancing differences in catchment water yield, has important implications for forest management in Melbourne's water supply catchments. If the aim is to maximise water yield for water security considerations, then there is a strong case for maintaining oldgrowth forest for as long as possible.

The paper by Wood *et al*. (2008) reported estimates of total forest ET across a chronosequence of three *E. regnans* stands at Wallaby Creek, Victoria. It concluded the data showed only a slight difference in annual ET between regrowth and oldgrowth *E. regnans*, contrary to the earlier research summarised above. New research showing little difference in ET between young and old *E. regnans* forests might support a change in catchment management policies. However, given the importance of managing these catchments for water benefits, any change in policy should be based on rigorous and validated data and analysis that can stand up to extensive review.

Inconsistencies in the Wood *et al.* transpiration and evapotranspiration data

The Wood *et al*. main conclusions, that the difference in annual ET between the three stands was only slight and that this was due to previously unreported high water use by the understorey in oldgrowth forest, was based on an estimate of annual transpiration alone of 1077 mm year^{-1} for their 296-year-old stand. The description of the period of sap flow measurement in the text is ambiguous. In the methods, sap flow was reportedly measured for an entire year. However, the estimate of 555 mm year^{-1} transpiration from the 296-year-old overstorey appears to be based on only 2 months sap flow data in summer and 1 month in autumn. From their description of the comparison of flux tower and sap flow data, 522 mm year^{-1} transpiration from the understorey (1.43 mm day^{-1} × 365 days) appears to be based on only 2 months in summer, when understorey transpiration was highest. The sum of 555 and 522 is the 1077 mm 'whole-ecosystem ET' Wood *et al*. reported as the annual total for the 296-year-old stand.

Whole-ecosystem ET is made up of three components: rainfall interception, evaporation from the forest floor and transpiration. Transpiration can be further divided into an overstorey and an understorey component. Wood *et al*. reported measuring whole-ecosystem ET using eddy covariance in their 296-year-old stand. However, the monthly whole-ecosystem ET data in their Fig. 6*A* sum to ~700 mm year^{-1}, not the 1077 mm year^{-1} they reported. The monthly overstorey and understorey 'water use' values in their Fig. 6*A* sum to ~480 mm year^{-1} for the overstorey but only 220 mm year^{-1} for the understorey, contrary to the conclusion by Wood *et al*. that understorey water use in this stand was almost the same as overstorey water use. Apparently, by basing their estimate of annual water use from the understorey on only 2 months of heat pulse velocity measurements in summer, Wood *et al*. overestimated understorey water use by at least 300 mm year^{-1}.

Transpiration includes no allowance for rainfall interception or evaporation from the forest floor, so is not whole-ecosystem ET. Annual transpiration alone cannot be 54% greater than annual total ET and therefore either the sap flow, or eddy covariance method, or both, were in error. Adding previously reported interception and forest floor evaporation (Haydon *et al*. 1996; McJannet *et al*. 1996; Vertessy *et al*. 2001) to the 1077 mm year^{-1} transpiration would have resulted in annual whole-ecosystem ET close to 1400 mm year^{-1} in the 296-year-old stand; twice the sum of the monthly total ET values shown in Wood *et al*. Fig. 6*A*, as determined by eddy covariance.

Guerschman *et al*. (2009), which includes three of the authors from Wood *et al.*, report monthly ET from the same Wallaby Creek flux tower consistent with the monthly eddy covariance ET data shown in Wood *et al*. Fig. 6*A*. Guerschman *et al*. (2009) use these data to validate the wide applicability of a remote sensing-based ET model. Had the higher estimate of 1077 mm year^{-1} annual transpiration alone been used by Guerschman *et al*. (2009), their model would have substantially underestimated ET at Wallaby Creek. We therefore believe Wood *et al*. substantially overestimated annual transpiration.

Possible errors in scaling heat pulse velocities

Although not mentioned by Wood *et al.*, their reported transpiration rates of 1212, 1168 and 1077 mm year^{-1} for the 24-, 80- and 296-year-old stands are extraordinarily high compared with their reported annual potential evapotranspiration of 861 mm and transpiration rates reported elsewhere for this forest type (Dunn and Connor 1993; Haydon *et al*. 1996; Vertessy *et al*. 2001; Pfautsch *et al*. 2010). In higher rainfall, non-water limited catchments in the same forest type, based on the same sap flow measurement technique as used by Wood *et al.*, Dunn and Connor (1993) and Vertessy *et al*. (2001) reported annual transpiration, including from the understorey, of between 679 and 835 mm year^{-1} in regrowth stands and between 396 and 547 mm year^{-1} in oldgrowth stands. Wood *et al*. reported mean sap flux densities and stand sap wood areas 'highly consistent' with Dunn and Connor (1993) and Vertessy *et al*. (2001). Therefore the large difference in annual transpiration between Wood *et al*. and the earlier studies indicates an error in Wood *et al*.'s scaling of heat pulse velocity measurements to the whole stand. When we applied the scaling method used by Dunn and Connor (1993) to the Wood *et al*. mean sap flux density and stand sapwood area data from their Table 1, the annual totals were within or slightly less than the ranges reported by Dunn and Connor (1993) and Vertessy *et al*. (2001), being 709 and 774 mm year^{-1} in the Wood *et al*. 24- and 80-year-old stands and 318 mm year^{-1} in the 296-year-old stand. For the 296-year-old understorey, the sap flux density and sap wood area scale to only 92 mm year^{-1}, or less than one-fifth of the 522 mm year^{-1} Wood *et al*. used as the basis for their conclusions.

Very high night-time sap flux densities reported by Wood *et al.* as shown in their Fig. 5, indicate they might also have omitted to adjust their raw heat pulse velocity measurements to exclude periods of no flow. For example, in winter, night-time sap flow was said to make up half of the total sap flow. Wood *et al*. used the heat pulse technique to estimate sap flux densities, with thermistors placed 5 mm upstream and 10 mm downstream of the heater. This technique always gives apparent sap flow, even when there is none, making it difficult to distinguish between no flow and low flow (Becker 1998). This is because, even without any sap movement, the heat pulse dissipates within a few minutes of firing the heater. Wood *et al*. did not state how they distinguished zero sap flows from low sap flows, or how they accounted for the other well known sources of error in the heat pulse velocity method (Hatton *et al*. 1995).

Anomalies in the Wood *et al.* monthly rainfall data

We believe the Wood *et al*. rainfall data are seriously flawed. Monthly rainfall totals recorded by the Bureau of Meteorology and Melbourne Water at three sites within a few km of the Wood *et al*. flux tower bear no correlation with the Wood *et al*. monthly rainfall totals shown for the measurement period in their Fig. 6*B*.

The Bureau of Meteorology (BOM) lists 126 years of daily and monthly rainfall for Wallaby Creek, recorded ~3 km east of the Wood *et al*. flux tower site. For the period December 2005 to January 2007, there is no statistically significant correlation between the Wood *et al*. monthly rainfall totals in their Fig. 6*B* and BOM monthly rainfall data from Wallaby Creek, from Kinglake West 3 km east of the BOM Wallaby Creek gauge and from a Melbourne Water gauge at Wallaby Creek Quarters, 4.4 km north-east of the BOM Wallaby Creek gauge (Fig. 1). Wood *et al*. reported rainfall for this period was 1175 mm $year^{-1}$; close to their reported mean for the previous 10 years of 1190 mm $year^{-1}$. However, the BOM data show rainfall at Wallaby Creek for the study period was only 721 mm $year^{-1}$ compared with a long-term mean of 1207 mm $year^{-1}$.

Temporal pattern discrepancies between the Wood *et al*. rainfall data and the official BOM Wallaby Creek data are even greater. For the 8 months December 2005 to March 2006 and October 2006 to January 2007, the Wood *et al*. rainfall totalling ~1178 mm was more than three times the BOM rainfall of 379 mm and would equate to the 2nd highest ever recorded at Wallaby Creek for consecutive December–March, October–January periods in the 126 years of records. The BOM dataset for Wallaby Creek indicates that period was in fact one of the driest for that time of year in the full 126 years of record. For the 6-month period from April to September 2006, the Wood *et al*. rainfall of ~240 mm was just over half the 458 mm observed by the BOM. The Wood *et al*. figure suggests the lowest in the 126-year record at Wallaby Creek. Although this 6-month period was relatively dry at Wallaby Creek, it was only the 7th driest on record according to BOM.

Based on 4 years of rainfall measurements between June 1970 and June 1974, the Melbourne and Metropolitan Board of Works concluded mean annual rainfall at locations in regrowth and oldgrowth *E. regnans* forest <1.5 km south-west from the Wood *et al*. flux tower site is only 2% higher than at the Wallaby Creek Quarters located ~6 km to the north-east of the flux tower site (O'Connell and O'Shaughnessy 1975). Based on this and the absence of any statistically significant correlation between Wood *et al*. monthly rainfall and BOM monthly rainfall from Wallaby Creek, we believe the Wood *et al*. rainfall cannot be correct.

Although not mentioned by Wood *et al.*, the ~700 mm flux tower annual ET evident from summing the monthly totals shown in their Fig. 6*A*, is similar to the BOM rainfall of 721 mm $year^{-1}$ for that period. If both are correct, the similar magnitude of annual ET and annual rainfall suggests rainfall was sufficiently low that water availability limited ET, possibly masking expected age-related differences in ET.

BOM data for Wallaby Creek indicate mean annual rainfall between 1997 and 2005 of ~1058 mm, compared with the long-term mean of 1207 mm. After this long drought, and given the very low rainfall in 2006, the high annual transpiration reported by Wood *et al.*, for example the 1212 mm $year^{-1}$ for the 24-year-old site, is unlikely, particularly as this included no interception or forest floor evaporation, supporting our contention the Wood *et al*. transpiration data are a substantial overestimate.

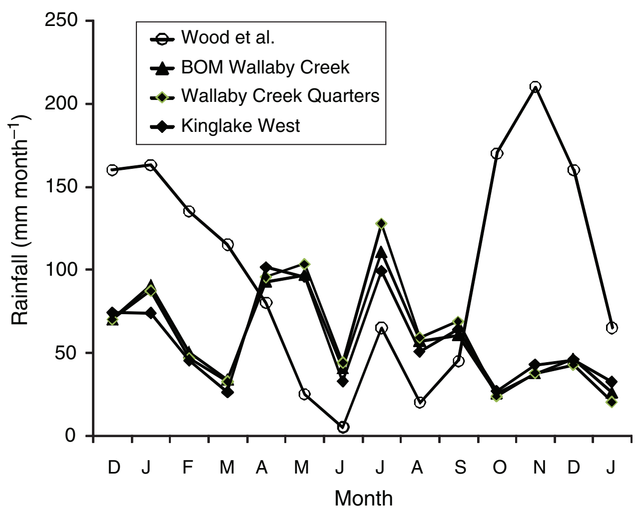

Fig. 1. Comparison of the Wood *et al*. monthly rainfall for the period December 2005 to January 2007 (Wood *et al*. Fig. 6*B*) with monthly rainfall totals for the same period from BOM and Melbourne Water rain gauges (BOM Sites 88060, 588026 and 86374) located within a few km of the Wood *et al*. flux tower site.

Errors in reporting of the forest hydrology literature

Wood *et al*. suggested their results were 'the first direct observations of total forest ET across a chronosequence'. However, this is not correct as they only measured ET in one stand and did not use this annual ET measurement in their conclusions. In reporting that previous authors had assumed understorey ET to be negligible, Wood *et al*. did not accurately report estimates of transpiration and ET from earlier studies by Dunn and Connor (1993) and Vertessy *et al*. (2001). Understorey transpiration estimated by Dunn and Connor (1993) in oldgrowth *E. regnans* was 29% of total transpiration. Vertessy *et al*. (2001) report understorey transpiration comprises an increasing proportion of total ET as these forests age and that evaporation from the forest floor is also significant. For a 240-year-old *E. regnans* stand, Vertessy *et al*. (2001) estimate understorey transpiration of 298 mm $year^{-1}$, compared with overstorey transpiration of 249 mm $year^{-1}$, rainfall interception of 262 mm $year^{-1}$ and soil and litter evaporation of 102 mm $year^{-1}$, giving total ET of 911 mm $year^{-1}$, or ~200 mm $year^{-1}$ more than the sum of the monthly ET data shown in Fig. 6*A* of Wood *et al*. Thus, according to Vertessy *et al.* (2001), in their 240-year-old *E. regnans* stand, understorey transpiration contributed 54% of total transpiration, which is a higher percentage than reported by Wood *et al*. This is contrary to the Wood *et al*. statement that Vertessy *et al*. (2001) had reported 'the understorey transpiration accounted for only 16.6% of the site water use'. The contributions reported by Vertessy *et al.* (2001) were percentages of 'site water balance' (rainfall), not percentages of 'site water use' (ET).

Additional comments on Wood *et al.*

We believe the problems described above are sufficiently serious to preclude acceptance of the paper's conclusions. Several other issues also cast doubt on the conclusions of Wood *et al*.

Wood *et al*. reported that their study sites were 'typical of Melbourne's water catchment areas' (p. 485). In fact, the Wallaby Creek sites are atypical in three influential determinants of stream flow and evapotranspiration: rainfall, slope and aspect. The mean annual rainfall at Wallaby Creek of 1207 mm is substantially less than almost every other catchment containing significant proportions of *E. regnans* forest. Vertessy *et al*. (2001) report that mean annual rainfall in *E. regnans* catchments near Melbourne is between 1200 and 2800 mm. Wallaby Creek is at the driest end of this large rainfall range, precluding sensible extrapolation of the results from Wood *et al*. to most of Melbourne's other *E. regnans* catchment areas.

The study highlights a potential shortcoming of using eddy covariance in forests in heterogeneous terrain. The topography, soils, vegetation and microclimate in the high rainfall, forested catchments so critical to eastern Australia's water supplies vary over short distances. Because the eddy covariance method is limited to use in relatively flat terrain, and it provides an integrated estimate of fluxes derived from an unknown area, it is of little use in mountainous terrain for any studies requiring quantification of spatial variation in water vapour and CO_2 fluxes.

On the basis of their Fig. 7, Wood *et al*. stated (p. 489 and 491), the difference in annual ET between the 24- and 296-year-old stands was only 135 mm. However, contrary to this, they also reported the decline in water use between age 24 and 296 was 364 mm year^{-1} (p. 490). No explanation for the 364 mm is given anywhere in the paper.

For the 1207 mm mean annual rainfall of this catchment, even a 135 mm year^{-1} change in ET is not slight if placed in the context of stream flow. For example, if the Wood *et al*. estimates of annual rainfall and annual transpiration from the 24-year-old stand were correct, total conversion of a catchment from 100% oldgrowth *E. regnans* to 100% regrowth *E. regnans*, would dry up the stream; a potentially serious consequence in any catchment supplying water to a large city.

Wood *et al*. cited the Picaninny experimental catchment at the Coranderrk long-term research site as supporting their conclusions. The Picaninny catchment has similarly relatively low long-term mean rainfall (1228 mm year^{-1}, Bren *et al*. 2010). However, partial conversion of a mixed eucalypt forest from mature, 150–200 years old, to regrowth resulted in a long-term maximum decline of more than 50% in annual stream flow, compared with an undisturbed control (Bren *et al*. 2010). By inference, this finding demonstrates a strong control of forest age on ET, and this is at odds with the conclusions of Wood *et al*.

Similarly, the conclusions of Wood *et al*. are not consistent with the substantial declines in stream flow observed by Langford (1976) and Kuczera (1985, 1987) in the four decades after wildfires in 1939. These stream flow records integrate the effects of spatial and temporal variations in rainfall and ET that occurred across eight catchments ranging in area from 4 to 907 km^2, over periods of 29 to 67 years. The results of a 14-month study in one research plot in each of three stands separated by up to 5 km, in an atypically dry catchment, during a severe drought, cannot validly be said to have contradicted Kuczera's analysis. Wood *et al*. offered no alternative explanation for why stream flows declined by as much as 50% in areas where oldgrowth *E. regnans* forest was converted to regrowth. Such declines have been reported in several paired catchment studies in this forest type (Bren *et al*. 2010) and in other wet eucalypt forests (Cornish and Vertessy 2001; Lane and Mackay 2001).

Conclusions

We believe that such a large number of inconsistencies and errors as evident in Wood *et al*. (2008) must preclude acceptance of the conclusions. The most serious shortcomings are:

1. Wood *et al*. evidently disregarded their 14 months of eddy covariance ET measurements, basing their conclusions on substantially higher estimates of transpiration alone, which appear to have been derived from a few months of heat pulse velocity measurements.
2. We believe Wood *et al*. substantially overestimated transpiration by incorrect scaling of their heat pulse velocity measurements to the whole stand and by not properly distinguishing low sap flow from zero sap flows.
3. We believe the monthly rainfall totals reported by Wood *et al*. were not from the Wallaby Creek catchment for the period of their study. In our view, contrary to the impression given in the paper, rainfall during the study period was actually substantially below the long-term mean and sufficiently low that expected differences in forest water use with age might not be evident.

Wood *et al*. noted 'The Kuczera curve has maintained some prominence in State government water resource management' and reported that 'our results suggest the decline in ET may not be as large as predicted by Kuczera's curve'. We caution against any use of Wood *et al.* in planning forest management actions or in predicting the potential effect of such management actions on water yields from these important catchment areas. We believe the problems in the Wood *et al*. paper illustrate the importance of ensuring that the science underlying natural resources management policies and decisions is based on rigorous and validated data and analysis that can stand up to extensive review. We believe this paper cannot safely be cited and are pleased the authors have accepted our recommendation to retract it.

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