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Trends in evapotranspiration and streamflow following wildfire in resprouting eucalypt forests

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SUMMARY

The objective of this study was to estimate the recovery trajectory of evapotranspiration (E_t) and streamflow (Q) in resprouting forested catchments following wildfire. Recovery dynamics were assessed in mixed species eucalypt forests in south-eastern Australia which recover from disturbance largely via vegetative resprouting, and to a lesser degree, via seedling recruitment. Changes in E_t were evaluated in two ways. Firstly, we developed semi-empirical models of post-fire E_t following moderate and high severity wildfire. These models were based on datasets of plot-scale E_t, measured within five years post-fire, and published literature on post-fire changes in vegetation structure. Secondly, we analysed long-term Q records (25 years) from a mixed species catchment, including a 1–5 year period following a predominately moderate severity wildfire. We found that the overall length of recovery time for E_t and Q following wildfire was 8–12 years, which is much less than for eucalypt forests recovering via seedlings only. This emphasises the importance of functional responses to fire in forest ecosystems as a key driver of the hydrologic resilience of catchments, with resprouting forest types conferring relatively rapid recovery following disturbance. We also found that the recovery trajectory of post-fire E_t was dependent on fire severity. Increased E_t and consequent declines in Q occurred following moderate severity fire. In contrast, there was no evidence of increased E_t following high severity fire. Based on patterns of long-term Q and rainfall observed in a small mixed species catchment, declines in Q due to increased E_t following moderate severity wildfire were of similar magnitude to Q declines driven by a drought that coincided with the fire. We conclude that the coincidence of wildfire with drought exacerbates reductions in Q under moderate severity fire, resulting in greater Q declines. This is due to the enhanced rates of E_t, primarily driven by regenerating seedlings and higher rates of transpiration from surviving trees.

1. Introduction

Streamflow from forested catchments is highly dependent on climate and the connection between vegetation dynamics and evapotranspiration (E_t). This is most clearly demonstrated following changes in forest cover, with reduced cover resulting in declines in E_t and consequently increased streamflow (Q), with the reverse pattern occurring under increased cover (Bosch and Hewlett, 1982; Hibbert, 1967). Following clearing, reductions in leaf area result in a sharp decline in E_t, driving increased Q, which can last for several years and be as high as 80% (Bosch and Hewlett, 1982; Brown et al., 2005; Hibbert, 1967). Over the longer-term (several years to decades) forest regrowth stimulates an eventual recovery of catchment water balance to pre-disturbance levels. However, in some instances there is an increase in leaf and sapwood area, and consequently E_t, beyond pre-disturbance levels which results in declines in Q (Hornbeck et al., 1993).

For most forest types, the hydrologic responses of catchments to non stand-replacing disturbances such as drought, herbivory or wildfire are not well understood (Adams et al., 2012; Nolan et al., 2014a). Studies on partial disturbance are largely focused on the impacts of partial tree mortality and recovery via seedlings, e.g. from thinning or patch cutting (Bréda et al., 1995; Hawthorne et al., 2013; Stoneman, 1993). This type of disturbance results in different changes to forest structure from that of defoliation, where stand basal area may remain intact but leaf area index, sapwood to leaf area ratio and foliage height distribution are changed (Bellingham and Sparrow, 2000; Moreira et al., 2012; Nolan

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et al., 2014b). This demonstrates a clear need to identify the consequences of partial disturbance on water balance dynamics in forested catchments, in order to better predict long-term fluctuations in water resources.

The response of E_t and consequently Q to disturbance depends, in large part, on the ecological resilience of a given vegetation type. Ecosystem resilience is defined as the ecosystem recovery time following disturbance (Pimm, 1984). Here, we use the time required for E_t, to return to pre-disturbance values following perturbation, as a measure of resilience. The resilience of vegetation to disturbance is dependent upon the functional responses of constituent species. The functional responses of species that survive intense disturbances can be broadly divided into an ability to regenerate predominately via vegetative resprouting, or via seedling germination (Noble and Slatyer, 1980). Resprouting plants typically regenerate faster than seedlings can establish (Clemente et al., 2005; Drake et al., 2009). Thus, forests dominated by resprouting species tend to be more resilient to disturbance than forests dominated by species that regenerate by seed (Clarke et al., 2013).

A major disturbance across many vegetation types is wildfire (Bond et al., 2005). The severity and incidence of wildfire is expected to increase globally in many temperate forests and woodlands as the incidence of extreme fire weather conditions increases under climate change (Bradstock, 2010; Krawchuk et al., 2009; Westerling and Bryant, 2008). This highlights the need to elucidate the resilience of forested catchments to wildfire in order to inform water resource planning. This is illustrated in south-eastern Australia, where over three million hectares of forest were recently burnt over a ten year period in the state of Victoria alone (DSE, 2013). These fires generated concern that E_t may increase, due to the fires, resulting in long-term declines in Q. Much of the burned areas were upland forest which are the source of water for many towns and cities in south-eastern Australia, and are very important catchments for the lower Murray-Darling Basin, Australia's largest. Additionally, during this period streamflows were seriously affected by a 12 year drought; and climate change predictions indicate south-eastern Australia is facing hotter and drier conditions that may heavily impact water resources (CSIRO, 2012). Concerns around the impact of fire on water resources are largely based on the historical response of catchments dominated by ash-type eucalypt forests which regenerate via seedlings after wildfire. In these high water-yielding catchments, long-term increases in E_t have led to declines in Q of up to 50% over many decades (Buckley et al., 2012; Dunn and Connor, 1993; Kuczera, 1987; Langford, 1976; Vertessy et al., 2001). However, the majority of the forested catchments in south-eastern Australia are mixed species eucalypt forests that regenerate via resprouting, which generally enables trees that survive fire to re-establish their canopies relatively quickly.

Recovery of E_t following fire in resprouting eucalypt forests, which have low-levels of fire-induced mortality (typically <15%; Abbott and Loneragan, 1983; Benyon and Lane, 2013; Vivian et al., 2008), is often more rapid than ash-type forests (Gharun et al., 2013; Nolan et al., 2014a). The direction of early changes in E_t shows dependence on fire severity, through its effects on vegetation structure and plant canopy architecture (Nolan et al., 2014a). Under moderate severity wildfire, E_t shows some small increases beyond pre-disturbance levels (Nolan et al., 2014a), which has similarly been observed following prescribed fire in Banksia woodland, in conjunction with lower recharge (Silberstein et al., 2013). In contrast, following high severity wildfire, reductions in E_t of up to 41% have been observed in resprouting eucalypt forest (Nolan et al., 2014a).

Catchment water balance research in resprouting eucalypt forests has focused largely on E_t in the early post-fire years (<3 years) and has not included observations of any associated changes in Q (Gharun et al., 2013; Nolan et al., 2014a). Following wildfire in mixed species forests, early observations of Q have found some post-fire increases (Lane et al., 2006; Mackay and Cornish, 1982), which may persist for ten years or more following high intensity fire (Webb and Jarrett, 2013). These early increases in Q are consistent with observations in Californian Chaparral and Mediterranean maquis (Lavabre et al., 1993; Loaiciga et al., 2001). However, it can be difficult to detect increases in Q following fire (Bren, 2012; Feikema et al., 2013), with fire typically associated with drought (Verdon et al., 2004) and declines in Q. The limited research on the effects of fire on mixed species catchments has resulted in uncertain model parameterisation of Q responses (Hill et al., 2008; Lane et al., 2010). These models have been based either on observed trends following timber harvesting, where there can be a marked decline in Q (Cornish and Vertessy, 2001) or a large variation in responses related to species composition and tree basal area (Webb et al., 2012); or an assumption that there is little perturbation in E_t following initial decreases (Watson et al., 1999a).

The objective of this study is to estimate the recovery trajectories of resprouting mixed species catchments following wildfire. We hypothesise that: (i) the magnitude and direction of differences between pre- and post-fire E_t will be dependent on fire severity; (ii) Q will reflect these changes in post-fire E_t, although precipitation is still expected to be the dominant factor driving Q; and (iii) the post-fire E_t recovery of mixed species forests will be faster than ash-type forests, consistent with the greater ecological resilience of vegetation with this regeneration strategy. We use a synthesis of methods, including observations of post-fire E_t and Q, and published literature on post-fire changes in vegetation structure. Analysis of changes in both E_t and Q provides a means of elucidating both the processes driving changed catchment water balance, as well as identification of longer-term trends.

2. Methods

Here, we develop semi-empirical models of post-fire E_t following wildfire of moderate (30–70% canopy scorch) and high (100% canopy scorch) severity in mixed species forests. These models are based on an empirical function developed by Watson et al. (1999b) to predict post-disturbance changes of E_t in *Eucalyptus regnans* F. Muell. forest, which is an ash-type forest (Watson et al., 1999b). This empirical function was designed as a method to interpolate long-term patterns of leaf area index, E_t, or Q, and was originally fitted to modelled E_t data from nine experimental catchments of varying ages. The models we develop here are fitted with data from plot-scale E_t measurements and published literature on post-fire changes in vegetation structure. E_t predictions from these models are then evaluated with long-term Q data from an experimental catchment burnt at predominately moderate severity fire.

2.1. Site descriptions

Empirical observations of post-fire E_t in mixed species forest were undertaken over 1–3 years following the 2009 Black Saturday wildfires at the Maroondah catchment, 37°39′S, 145°34′E (data presented in Nolan et al., 2014a); and over 2.5–5 years following the 2006 Alpine wildfires at the Ella catchment, 36°47′S, 146°34′E (data presented here), both located in south-eastern Australia (Fig. 1). Ella is dominated by three *Eucalyptus* species in the overstorey, and the unburnt forest has a shrubby understorey (Table 1). Mean annual precipitation (P) is 1155 mm at Maroondah and 1412 mm at Ella (Bren and Hopmans, 2007), while mean annual reference E_t (E_0) is 953 mm at Maroondah and 1172 mm at Ella. E_0 was calculated following the FAO 56 method (Allen et al., 1998) using data from a SILO Data Drill, which