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# MODELLING FEEDBACK BETWEEN FUEL-REDUCTION BURNING AND FOREST CARBON AND WATER BALANCE IN EUCALYPT FORESTS

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# ABSTRACT

Empirical evidence from Australia shows that fuel-reduction burning significantly reduces the incidence and extent of unplanned fires. However, the integration of environmental values into fire management operations is not yet well-defined and requires further research and development.

While in reality carbon and water processes in forested ecosystems are coupled, effects of fire on these processes are often studied in isolation. Models that simulate the dynamic interaction and feedbacks between these processes are essential for investigations of the effects of fuel management in an environmental setting.

WAVES, a soil-vegetation-atmosphere transfer (SVAT) model, was used to simulate the hydrological and ecological effects of four fuel management scenarios on a forest ecosystem. WAVES was applied using inputs from a set of forest plots across south-east Australia for a period of 1 year after four potential scenarios: (1) no fuel-reduction treatment (unburnt), (2) all litter removed, (3) all litter and 50% of the understorey vegetation removed, 4) all litter and all of understorey vegetation removed.

The impacts of fuel-reduction burning on water processes were mainly due to changes in vegetation interception capacity and soil evaporation. The effect of fuel-reduction burning on evapotranspiration is discussed considering the balance of vegetation biomass in the overstorey and the understorey. Recovery of aboveground carbon as plant biomass was strongly linked to variability in available light and soil moisture. We describe how these modelling efforts can be used for impact assessment in terms of water, vegetation and carbon outcomes for planning of fuel reduction burning.

# INTRODUCTION

Eucalypt forests play a significant role in balances of carbon, water and energy in Australia. These forests are also heavily managed with low-intensity fuel reduction burning (FRB) to reduce the risk of fire spread (Boer et al. 2009; McCaw 2013). Fires contribute significant amounts of carbon to the atmosphere each year as carbon dioxide and other greenhouse gases (van der Werf 2006; Haverd et al. 2013). Accounting for carbon emissions requires a reasonably comprehensive knowledge of the amount of all fuel types that are consumed in a FRB (Strand et al. 2016) and of the carbon stored in the soil (Santín et al. 2015; Jenkins et al. 2016).

In addition to altering carbon balances, forest fires have potential consequences for water availability. Fire can affect the water balance of an ecosystem primarily by changing rates of evapotranspiration – the major component of the water balance (Mitchell et al. 2009; Nolan et al. 2015). Fuel reduction burning on land within water supply catchments is considered to be an effective means of reducing the likelihood and magnitude of large bushfires for protection of water supplies (Ellis et al. 2004). While the effect of bushfires on water yield may be substantial and can potentially last for several decades, the effect of FRB appears to have different characteristics that are not clearly tested yet (William and Jerry 1992; Flerchinger et al. 2016).

In Australia, environmental effects of FRB in forested ecosystems have been investigated regularly for the past few decades using field data, often derived from inventories (e.g. Possell et al. 2015; Volkova and Weston 2015; Jenkins et al. 2016) but also coming from a small number of long-term experimental studies in Victoria (Department of Sustainability and Environment, 2003) and New South Wales (e.g. Harris et al. 2003; Penman et al. 2009). Even so, detailed processes of vegetation growth and water balance, and the feedback between overstorey and understorey vegetation have been difficult to measure in an experimental setting. For example, it is challenging to isolate the effect of FRB on soil evaporation from interception evaporation as part of the combined changes in total evapotranspiration due to fire.

Soil-Vegetation-Atmosphere (SVAT) models have the capacity to quantify each of these feedbacks and identify any offsetting effects in detail. In addition, SVAT models can simulate long term effects from the more immediate effects due to FRB. With recent advances in availability of digital data and remote sensing, the impact of FRB on carbon and water balances in forests can be studied over large areas with significantly lower costs.

In this study we used WAVES, a well-regarded soil-vegetation-atmosphere transfer model, to test four different FRB scenarios and simulate the impact on carbon and water one year after fire. The situations tested include: (1) unburnt (Unburnt), (2) all litter removed (Scenario 1), (3) all litter and 50% of the understorey removed (Scenario 2), and (4) all litter and 100% understorey removed (Scenario 3). We aim to address the following questions for each scenario: What is the impact of FRB on individual plant growth (carbon gain)? What is the impact on hydrological processes? What is the combined effect? How long does it take for processes of carbon and water to return to the pre-burning condition?

# DATA AND METHODS

## EXPERIMENTAL SITE

Our three research sites – Helicopter Spur, Haycock Trig and Spring Gully – are all located within mixed-species forests in NSW, south-eastern Australia. Each site corresponded to one FRB (Table 1).

## WAVES MODEL

There are three main data sets related to the climate, vegetation and soil that are required for simulating the carbon and water balance using WAVES. A detailed description of WAVES is provided by Zhang et al. (1996) and Zhang and Dawes (1998).

Climate data required for WAVES include rainfall, rainfall duration, solar radiation, vapor pressure deficit, and maximum and minimum air temperature. We extracted daily climate data from 0.05° resolution gridded weather data provided by the Australian Bureau of Meteorology (Jones et al. 2009).

Vegetation type-specific parameters for the overstorey and the understorey were taken from the literature or from the model manual (Zhang et al. 1996; Zhang and Dawes 1998).

Measurements of litter and vegetation biomass, and total carbon content in the litter was collected following the methodology described in Gharun et al. (2017) (Table 1).

TABLE 1 MEASUREMENTS OF ABOVEGROUND BIOMASS COLLECTED AS DESCRIBED IN GHARUN ET AL. (2017). TOTAL CARBON CONTENT WAS USED TO CONVERT BIOMASS TO KILOGRAMS OF CARBON PER DAY PER SQUARE METER OF GROUND. FRB: FUEL REDUCTION BURN; HT1: HAYCOCK TRIG; SG1: SPRING GULLY; HES1: HELICOPTER SPUR.

| FRB name | FRB size (ha) | Latitude | Slope (°) | Aspect | Overstorey biomass (t ha$^{-1}$) | Understorey biomass (t ha$^{-1}$) | Litter biomass (t ha$^{-1}$) |
|---|---|---|---|---|---|---|---|
| HES1 | 634 | -33.8 | 5 | NE | 255.5 | 34.8 | 10.7 |
| HT1 | 612 | -33.0 | 4 | NE | 137.8 | 28.8 | 4.8 |
| SG1 | 166 | -34.1 | 5 | NE | 170.9 | 40.9 | 17.3 |

For soil texture, samples were taken from the top 0–10 cm and characterized using the particle size analysis method (PSA). The analytical soil model of Broadbridge and White (1988) (BW soil model) was used to describe the relationships among water potential, volumetric water content and hydraulic conductivity.

## VALIDATION WITH SATELLITE DATA

Timeseries of MODIS LAI were downloaded and LAI values were extracted for each site. MODIS product MOD15A2H which is an 8-day composite dataset with 500 m pixel size were retrieved form the online Data Pool courtesy of NASA Land Processes Distributed Active Archive Centre (LP DAAC). A local polynomial regression (span = 0.3) was used to interpolate 8-day MODIS LAI to daily values.

# RESULTS

After 1 year in unburnt forests carbon stored in the litter layer was predicted to decrease from 0.502 to 0.360 kg C $m^{-2}$ in HES1, from 0.225 to 0.191 kg C $m^{-2}$ in HT1 and from 0.811 to 0.338 kg C $m^{-2}$ in SG1. Removing the understorey reduced the addition of carbon to the litter layer and, after a year, the amount returned to the soil was estimated to be only 0.1 kg C $m^{-2}$ (± 0.03 standard error of the mean) (Figure 1).

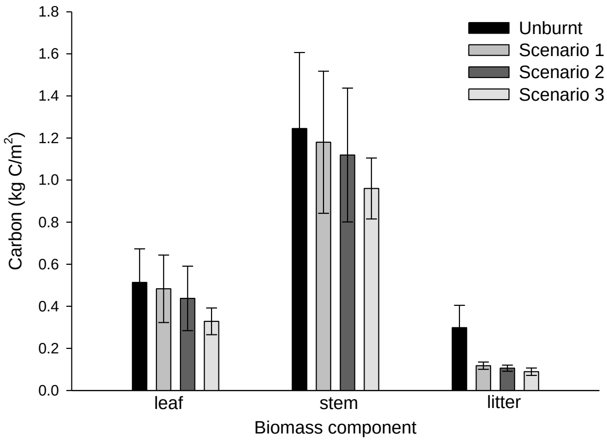


FIGURE 1 PREDICTED ABOVEGROUND CARBON POOLS 1 YEAR AFTER FUEL REDUCTION BURNING. BARS REPRESENT AN AVERAGE VALUE FOR EACH SCENARIO FOR THE THREE SITES (I.E. HAYCOCK TRIG, SPRING GULLY AND HELICOPTER SPUR). ERROR BARS ARE 95% CONFIDENCE INTERVAL.

The highest incremental change in LAI occurred in the absence of the understorey (i.e. all litter and 100% understorey removed). Removing the understorey increased LAI for the overstorey in the site with the most initial understorey biomass (Figure 3, Table 1).

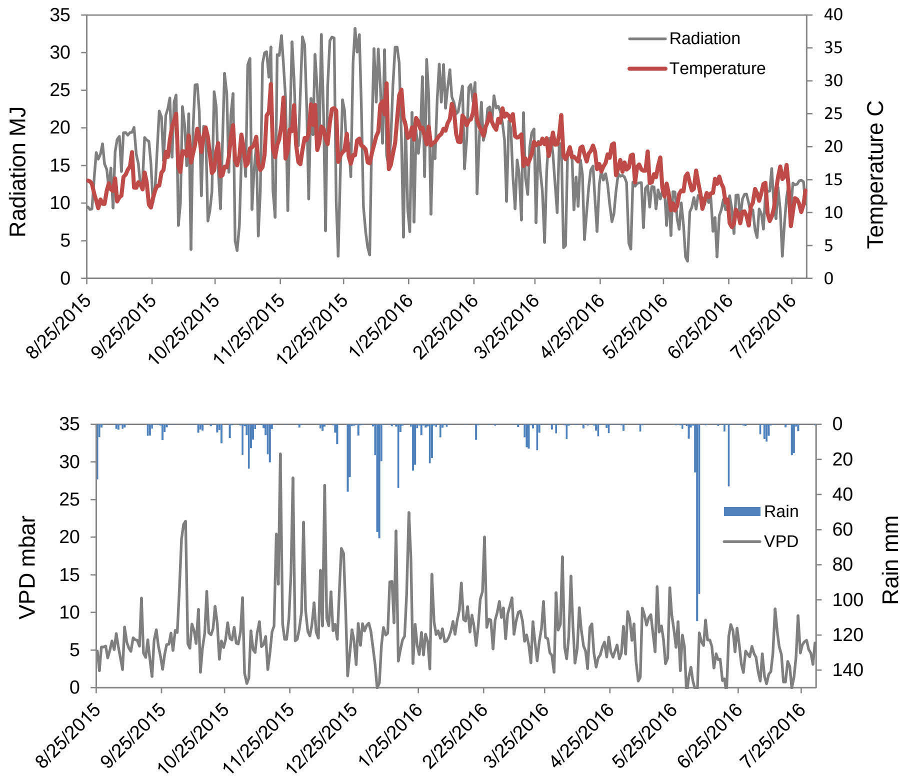


FIGURE 2 AVERAGE CLIMATE CONDITIONS (UPPER GRAPH) RADIATION AND TEMPERATURE; (LOWER GRAPH) VAPOUR PRESSURE DEFICIT (VPD) AND RAINFALL)

FOR THE THREE SITES (I.E. HAYCOCK TRIG, HELICOPTER SPUR AND SPRING GULLY). DATA WAS EXTRACTED FROM DAILY GRIDDED WEATHER MAPS AVAILABLE FROM THE BUREAU OF METEOROLOGY, AUSTRALIA.

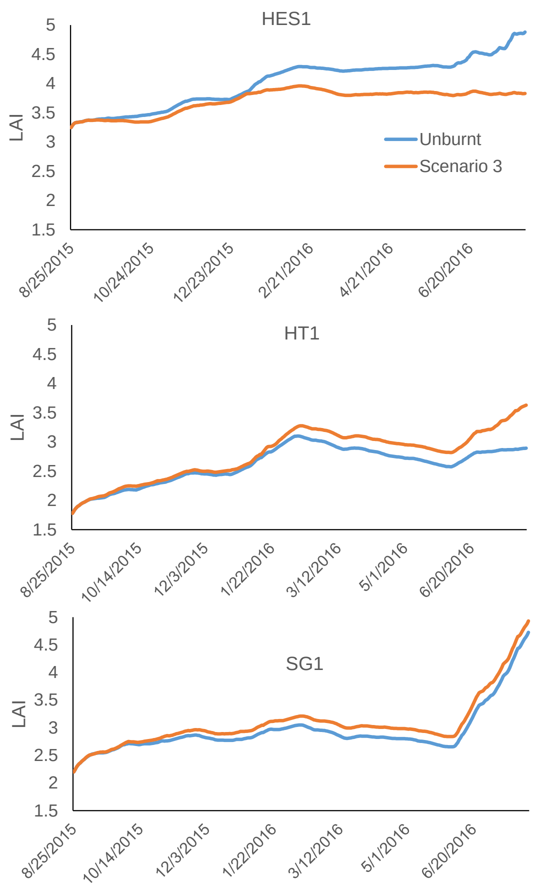


FIGURE 3 OVERSTOREY LEAF AREA INDEX (LAI) RESPONSE TO REMOVING ALL OF THE LITTER AND ALL OF THE UNDERSTOREY (SCENARIO 3) AFTER ONE YEAR FOR SITES (UPPER PANEL) HES1, (MIDDLE PANEL) HT1, AND (LOWER PANEL) SG1.

## HYDROLOGICAL FLUXES

In general, with removal of the understorey, net rainfall (the amount of rainfall reaching the soil) will increase and understorey transpiration will decrease (data not shown). Changes in total ET due to FRB consisted of changes in the amount of understorey ET, an increase in soil evaporation and a decrease in interception and interception evaporation. The combined effect was that average annual evapotranspiration increased with the removal of vegetation by not more than 17% of that in unburnt forest sites (from 859 to 1009 mm $yr^{-1}$ in HES1, from 1032 to 1082 mm $yr^{-1}$ in HT1 and from 1117 to 1234 mm $yr^{-1}$ in SG1). For unburnt forest sites, the average soil evaporation was 53 ± 10 mm $yr^{-1}$, understorey ET was 306 ± 60 mm $yr^{-1}$ and overstorey ET was 623 ± 14 mm $yr^{-1}$. After removal of the litter layer with FRB, soil evaporation increases to 134 ± 9 mm $yr^{-1}$, understorey ET to 308 ± 60 mm $yr^{-1}$ and overstorey ET to 623 ± 13 mm $yr^{-1}$. After removal of the litter layer and 50% of the understorey, soil evaporation increased to 147 ± 10 mm $yr^{-1}$, understorey ET to 245 ± 41 mm $yr^{-1}$ and overstorey to 691 ± 22 mm $yr^{-1}$. After completely removing the understorey, soil ET increased to 166 ± 14 mm $yr^{-1}$, understorey ET to 7 ± 2 mm $yr^{-1}$ and overstorey ET to 935 ± 55 mm $yr^{-1}$.

TABLE 2 TEST OF SIGNIFICANT DIFFERENCE IN PRODUCTIVITY AND WATER FLUX BETWEEN UNBURNT FORESTS AND DIFFERENT BURNING SCENARIOS FOR THE HELICOPTER SPUR (HES1), HAYCOCK TRIG (HT) AND SPRING GULLY (SG1) SITES USING A MANN-WHITNEY-WILCOXON TEST. NS: NOT SIGNIFICANT AT ALPHA = 0.05. ET: EVAPOTRANSPIRATION, E: EVAPORATION

| Site | HES1 | | | HT1 | | | SG1 | | |
|---|---|---|---|---|---|---|---|---|---|
| | S1 | S2 | S3 | S1 | S2 | S3 | S1 | S2 | S3 |
| $ET_{total}$ | ns | ns | ns | ns | ns | ns | ns | ns | ns |
| $ET_{canopy}$ | ns | ns | ns | ns | ns | $p$ <0.05 | ns | ns | $p$ <0.001 |
| $ET_{understorey}$ | ns | ns | $p$ <0.001 | ns | ns | $p$ <0.001 | ns | ns | $p$ <0.001 |
| $E_{soil}$ | $p$ <0.001 | $p$ <0.001 | $p$ <0.001 | ns | ns | ns | ns | ns | ns |
| $LAI_{canopy}$ | $p$ <0.001 | $p$ <0.001 | $p$ <0.001 | ns | $p$ <0.05 | $p$ <0.001 | $p$ <0.001 | $p$ <0.001 | $p$ <0.001 |
| $LAI_{understorey}$ | $p$ <0.001 | $p$ <0.001 | $p$ <0.001 | ns | $p$ <0.001 | $p$ <0.001 | $p$ <0.001 | $p$ <0.001 | $p$ <0.001 |
| Litter | $p$ <0.001 | $p$ <0.001 | $p$ <0.001 | $p$ <0.001 | $p$ <0.001 | $p$ <0.001 | $p$ <0.001 | $p$ <0.001 | $p$ <0.001 |
| Soil storage | $p$ <0.001 | $p$ <0.001 | $p$ <0.001 | ns | ns | ns | ns | ns | ns |

## VALIDATION WITH REMOTELY-SENSED LAI

The result of a Pearson's correlation test showed a reasonable agreement between MODIS LAI and modelled total LAI (overstorey plus understorey). Outputs of the statistical test (df = 340 and $p$ <0.05) for HES1 was $r$ = 0.69 and $r$ = 0.66 for HT1, but for SG1 this correlation was not significant ($p$ >0.05).

# DISCUSSION

Fuel loads are highly sensitive to climatic conditions, forest productivity and species composition (Gould et al. 2007; de Mar and Adshead 2011). Variation in litter production between sites can be attributed to differences in initial standing biomass of the forest along with differences in local and seasonal climatic conditions that control canopy growth rate (Capellesso et al. 2016). Litter is decomposed over time as a function of temperature and moisture availability at the soil surface and it provides surface resistance to evaporation. It is for this reason that soil evaporation might or might not increase significantly after burning depending on the unburnt litter biomass (Table 2).

Biomass production varies with local site characteristics, including topography (Nippert et al. 2011). In this study, litter production correlated with changes in LAI, particularly during periods of decreasing LAI (when no leaf growth occurred) and less during periods of increasing LAI (data not shown). Removal of the litter layer can sometimes enhance productivity in the understorey layer (Table 2). The impact of burning on site productivity (i.e. canopy and understorey leaf area) however is not always significant (Table 2). Fuel reduction burning affected productivity more (compared to the water balance) in sites with lower initial understorey biomass (see site HT1 in this study).

The mismatch between modelled productivity and satellite data in SG1 could be related to the underlying assumption made about the soil profile (Jackson et al. 2000). Information about the soil beyond the surface was not available and assumptions had to be made about the nature of soil and the arrangement of root biomass in each soil layer. A reverse modelling approach in which soil profile is calibrated against satellite data and then validated with field observations could improve our knowledge of forest productivity and moisture balance at the local scale considerably.

In forests, evapotranspiration continuously provides a feedback to the microclimate below the canopy of each vegetation layer. For example, available radiation is reduced by the amount of energy that is required to evaporate the water intercepted by each vegetation layer (Zhang et al. 1999). In addition, atmospheric VPD, the main driver of transpiration in eucalypt forests (Gharun et al. 2013) is affected by transpiration below each vegetation layer in the previous time step. In some sites, overstorey ET increased significantly after total removal of the understorey (Scenario 3) because there was more soil water available for transpiration. Since ET is directly controlled by the amount of water stored in the soil (Wetzel and Chang 1987; Verstraeten et al. 2008), reduced interception of rainfall by the understorey and lower or limited understorey ET resulted in greater availability of soil moisture for the overstorey trees. The enhanced productivity in the canopy layer is also related to resource partitioning (water availability) after the understorey was removed by burning.

Investigating the impact of fire (planned or unplanned) on the water balance of a forest requires that different components of evapotranspiration (transpiration, soil evaporation, interception evaporation) are investigated separately and interpreted in combination with one another (Sutanto et al. 2012). Removal of the understorey and the litter layer can result in changes in the amount of energy available at the forest floor and underlying soil which affects the sensible and latent heat fluxes that determine ET (Hutley et al. 2000). While FRB might increase transpiration, an increase in soil evaporation following the removal of this layer can counter the overall effect on evapotranspiration depending on the local partitioning of ET before the fire.

# ACKNOWLEDGEMENTS

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# APPENDIX

**Table A1** Vegetation parameters used in the WAVES model. Calibrated parameters are based on parameterization with sap flow data, MODIS evapotranspiration, and soil moisture measurements from Vervoort et al. (2016). LWP: leaf water potential; IRM: integrated rate methodology.

| Vegetation parameter | Overstorey | Understorey | Source |
|---|---|---|---|
| 1 minus albedo of canopy | 0.8 | 0.8 | (Lee 1980) |
| 1 minus albedo of soil | 0.85 | 0.85 | (Dawes et al. 2004) |
| Rainfall interception (m $d^{-1}$ $LAI^{-1}$) | 0.0003 | 0.0003 | (Vertessy et al. 1996; Dunin and O'Loughlin 1988; Hatton et al. 1992) |
| Light extinction coefficient | -0.42 | -0.6 | (Pook 1985) for overstorey, measured by authors for understorey |
| Max assimilation rate (kg $C^{-2}$ $d^{-1}$) | 0.1 | 0.1 | Calibrated |
| Slope of Ball and Berry | 0.9 | 0.9 | (Dawes et al. 2004) |
| Max LWP (m) | -200 | -200 | (Cheng et al. 2014; Dawes et al. 2004) |
| IRM water | 3.4 | 3.4 | Calibrated |
| IRM nutrients | 0.3 | 0.3 | (Hatton et al. 1992; Dawes et al. 2004) |
| Ratio of stomatal to mesophyll conductance | 0.2 | 0.2 | (Dawes et al. 2004) |
| Temperature when growth ½ of optimum (°C) | 15 | 15 | (Dawes et al. 2004) |
| Temperature when growth is optimum (°C) | 20 | 20 | (Küppers et al. 1987; Hatton et al. 1992) |
| Year day of germination (d) | -1 | -1 | (Dawes et al. 2004) |
| Degree-daylight hours for growth (°C hr) | -1 | -1 | (Dawes et al. 2004) |
| Saturation light intensity (µmoles $m^{-2}$ $d^{-1}$) | 1000 | 800 | (Küppers et al. 1987) |
| Maximum rooting depth (m) | 10 | 5 | (Canadell et al. 1996) |
| Specific leaf area (LAI kg $C^{-1}$) | 12.6 | 12.6 | Calibrated |
| Leaf respiration coefficient (kg C kg $C^{-1}$) | 0.00065 | 0.0008 | (Cheng et al. 2014; Vertessy et al. 1996) |
| Stem respiration coefficient (kg C kg $C^{-1}$) | 0.00014 | 0.0012 | (Cheng et al. 2014; Vertessy et al. 1996) |
| Root respiration coefficient (kg C kg $C^{-1}$) | 0.0023 | 0.001 | (Cheng et al. 2014; Vertessy et al. 1996) |
| Leaf mortality rate (fraction of C $d^{-1}$) | 0.0015 | 0.0015 | Calibrated |
| Aboveground partitioning factor | 0.24 | 0.24 | Calibrated |
| Salt sensitivity factor | 1 | 1 | (Dawes et al. 2004) |
| Aerodynamic resistance (s $d^{-1}$) | 15 | 30 | (van de Griend and van Boxel 1989; Leuning et al. 1991; Vertessy et al. 1996) |

**Figure A1** Cumulative effect of fuel reduction burning on (a, c, e) total evapotranspiration (ET) and (b, d, f) soil evaporation one year after fire in forest sites at (a, b) Helicopter Spur (HES1), (c, d) Haycock Trig (HT1) and (e, f) Spring Gully (SG1).

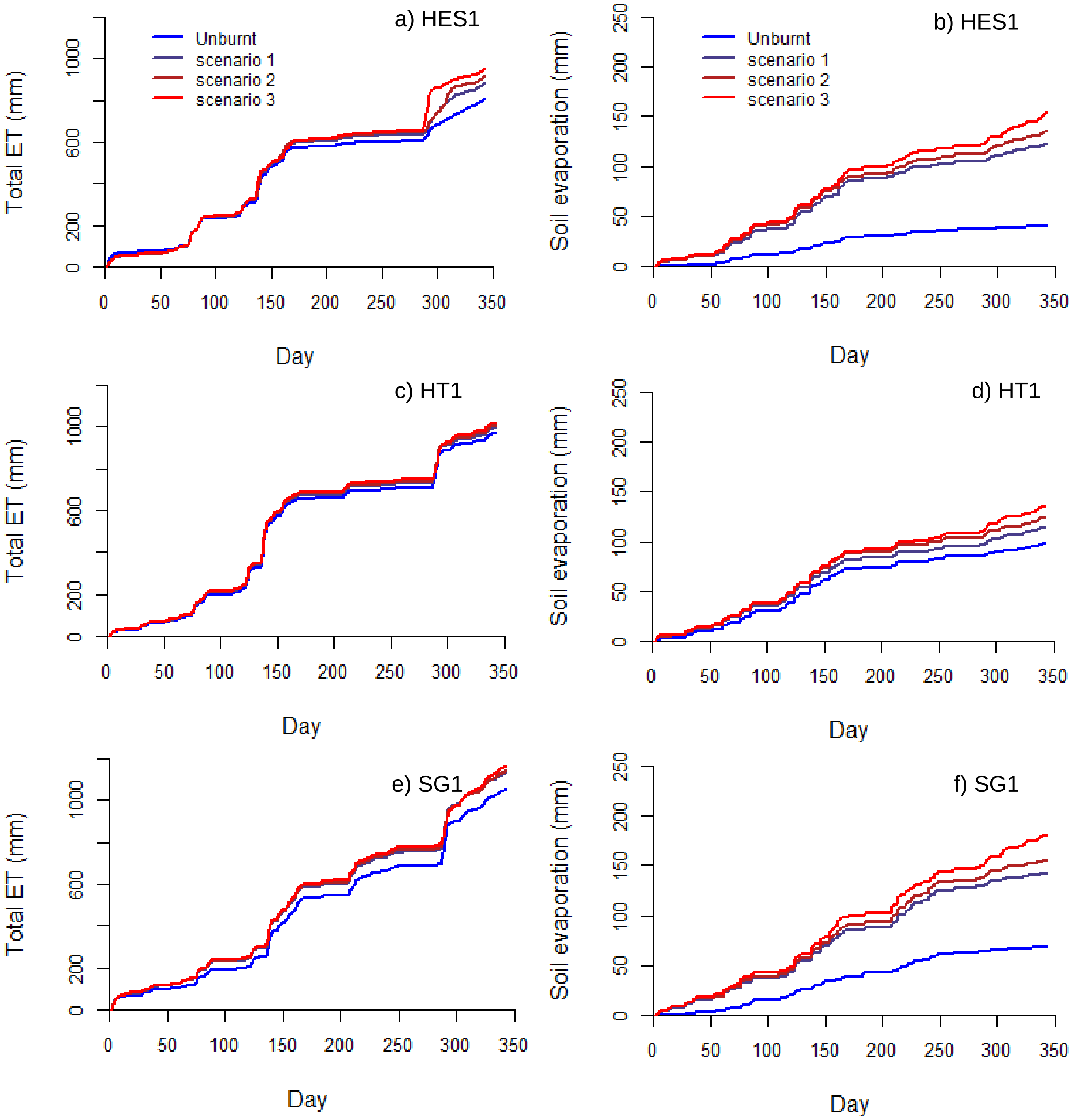
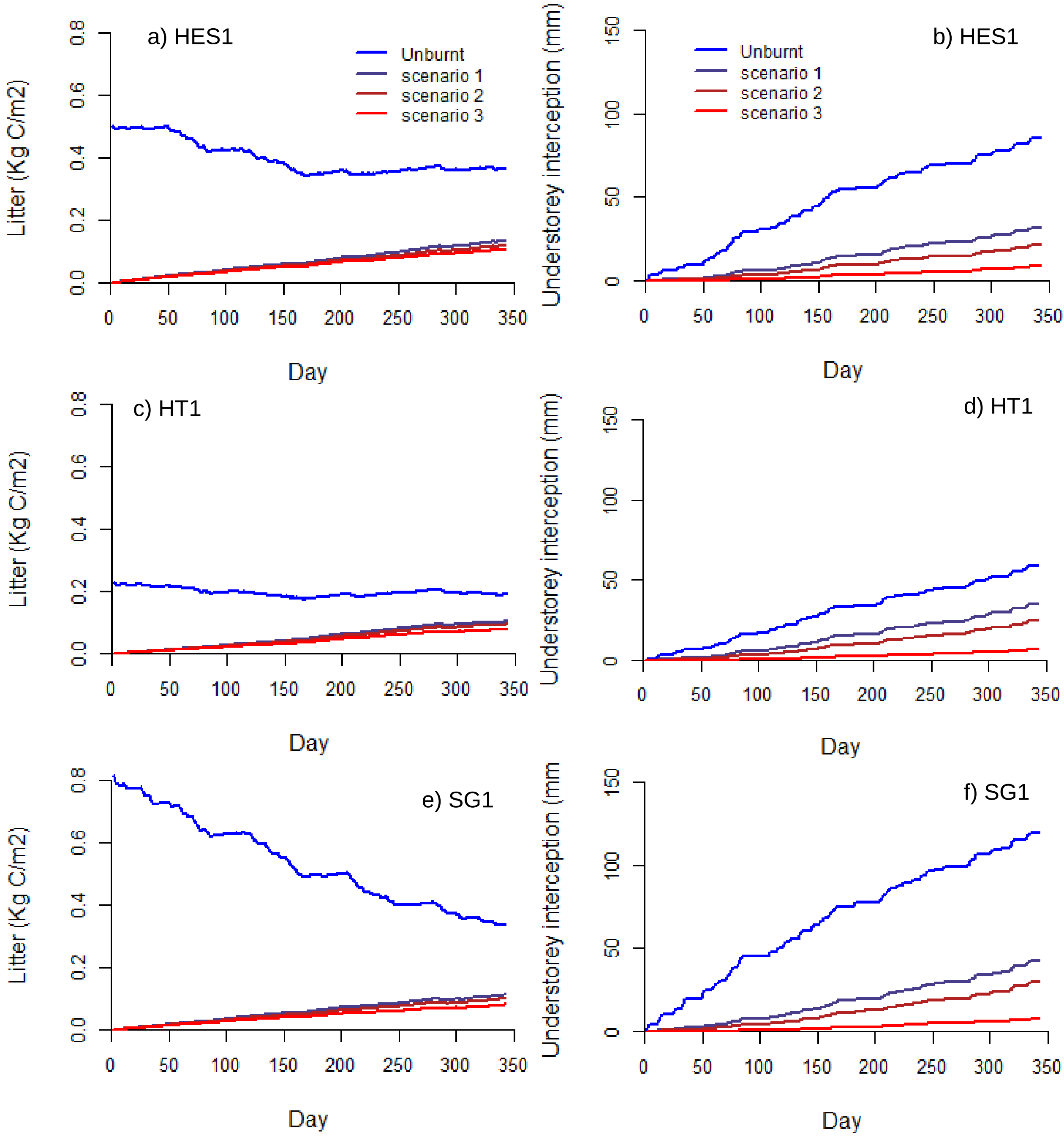


**Figure A2** Cumulative effect of fuel reduction burning on (a, c, e) litter production and (b, d, f) understorey interception for one year after fire in forest sites at (a, b) Helicopter Spur (HES1), (c, d) Haycock Trig (HT1) and (e, f) Spring Gully (SG1).



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