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Net ecosystem carbon exchange of a dry temperate eucalypt forest

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Abstract. Forest ecosystems play a crucial role in the global carbon cycle by sequestering a considerable fraction of anthropogenic CO_2 thereby contributing to climate change mitigation. However, there is a gap in our understanding about the carbon dynamics of eucalypt (broadleaf evergreen) forests in temperate climates, which might differ from temperate coniferous or deciduous forests given their fundamental differences in physiology, phenology and growth dynamics. To address this gap we undertook a three year study (2010 – 2012) using eddy covariance measurements in a dry temperate eucalypt forest in south-eastern Australia. We determined the annual net ecosystem carbon exchange (NEE) and investigated the temporal (seasonal and inter-annual) variability and environmental controls of NEE, gross primary productivity (GPP) and ecosystem respiration (ER). The forest was a large and constant carbon sink throughout the study period, even in winter, with an overall mean NEE of -1062 ± 53 g C m^{-2} yr^{-1}. Gross CO_2 ecosystem fluxes showed no significant inter-annual variability and mean annual estimate of GPP was 2521 ± 35 g C m^{-2} yr^{-1} and ER was 1458 ± 31 g C m^{-2} yr^{-1}. GPP and ER had a pronounced seasonality with GPP being greatest during spring and summer and ER during summer whereas peaks of NEE occurred in early spring and again in summer. High NEE in spring was caused by a delayed increase in ER due to low temperatures. A random forest analysis showed that variability in GPP was mostly explained by incoming solar radiation whilst air temperature was the main environmental driver of ER on seasonal and inter-annual time scales. The forest experienced unusual above average annual rainfall during the first two years of this three year period so that soil moisture content remained relatively high and the forest was not water limited. Our results show the potential of temperate eucalypt forests to sequester large amounts of carbon when not water limited. Our observations can provide data on an underrepresented biome to test and parameterise ecosystem models. However, longer monitoring is needed to assess the inter-annual variability of the carbon sink strength particularly during years with drought conditions.

Keywords. net ecosystem productivity, south-eastern Australia, 2011 La Niña, OzFlux, Wombat State Forest, dry sclerophyll forest, random forest approach

1 Introduction

Terrestrial ecosystems, together with the ocean, take up more than half of the yearly anthropogenic CO_2 emissions and their combined sink strength has increased over the past five decades in step with increased emissions (Ballantyne et al., 2012; Le Quere et al., 2013; Le Quéré et al., 2015). The terrestrial sink has been mostly attributed to the world's forest ecosystems over the last two decades (Le Quere et al., 2013; Pan et al., 2011) and only recently the importance of semi-arid ecosystems in the global carbon sink has been identified (Ahlström et al., 2015; Poulter et al., 2014). Even so, forests play a crucial role in the global carbon cycle and climate change mitigation (IPCC, 2013; Pan et al., 2011).

Nonetheless, uncertainty remains regarding the future trend and strength of this terrestrial carbon sink (Ciais et al., 2013; Mystakidis et al., 2016; Reichstein et al., 2013; Sitch et al., 2015). This is mainly related to the high inter-annual variability in the carbon uptake of ecosystems because of regional and even global variations in climate year-to-year (Ahlström et al., 2015; Reichstein et al., 2013). The balance between gross primary productivity (GPP) and ecosystem respiration (ER) is commonly termed net ecosystem productivity (NEP - that mostly approximates net ecosystem exchange (-NEE)) and can be positive (a carbon sink) or negative (a carbon source), although other carbon exchanges such as dissolved organic transport and/or fire provide a true net ecosystem carbon balance (NECB) (Chapin et al., 2006). Hence, variability in NEP is dependent on variations of the component fluxes GPP and ER and their responses to climate and resource availability (Ahlström et al., 2015; Ciais et al., 2013; Reichstein et al., 2013). While some studies primarily attribute inter-annual variability in NEP to changes in respiration (Cox et al., 2000; Valentini et al., 2000), while others point to a primary dependence on the variability in ecosystem GPP (Ahlström et al., 2015; Jung et al., 2011; Sitch et al., 2015). Across various ecosystems the main environmental factors controlling GPP have been identified being solar radiation, water vapour pressure deficit (VPD) and leaf area index (LAI), while temperature and soil moisture are the main environmental drivers of ER (Baldocchi, 2008; Beringer et al., 2016; Yi et al., 2010). Variability in NEP has also been demonstrated to be strongly influenced by variation in water availability (i.e. changes in rainfall). For instance, while the overall effect of drought conditions has been shown to decrease NEP, it often varies which component, GPP or ER, drought conditions have the greatest impact (Ciais et al., 2005; Reichstein et al., 2007; Schlesinger et al., 2015; Zhao and Running, 2010). It is therefore critical to assess the carbon balance of ecosystems to improve our knowledge of processes controlling NEP (or – NEE) and their response to variability of environmental drivers and climate change. Another factor contributing to the uncertainty of future terrestrial carbon sinks is the still limited empirical data available on forest carbon dynamics to better constrain uncertainties of global and continental process-based carbon models and/or to improve data-driven model frameworks (Haverd et al., 2013a; Jung et al., 2011; Keenan et al., 2012; Roxburgh et al., 2004).

Forests in Australia occupy around 19% of the continent and account for about 3% to forested area worldwide (ABARES, 2013) and, until recently their potential contribution to the global carbon cycle has been ignored. The role of Australian ecosystems generally in the global carbon cycle has had recent attention in the light of the 2011 strong La Niña event and global record terrestrial carbon sink, where Australian ecosystems, particularly semi-arid ecosystems, played a major role in the continental and global carbon uptake anomaly (Haverd et al., 2013b; Haverd et al., 2016; Poulter et al., 2014). Although semi-arid ecosystems have been suggested as dominant drivers in inter-annual variability and trends of the global net carbon sink (Ahlström et al., 2015), little is known about how Australian temperate eucalypt (broadleaved evergreen) forests may contribute to the global sink and inter-annual variability. Two thirds of native forests in Australia are eucalypt forests (92 M ha) and dry temperate eucalypt forests account for the largest proportion (37% or 8.3 M ha) of forest ecosystems in south-eastern and south-western Australia and are of high socio-economic value (ABARES, 2013). Growth and regeneration of temperate forests in the Northern Hemisphere are considered to account for the increasing global terrestrial carbon sink (Pan et al., 2011), although a recent study showed a decline in this trend (Sitch et al., 2015). While studies of the carbon balance in the Northern Hemisphere temperate forests are abundant there are only a handful of studies that have been undertaken in temperate eucalypt forests in Australia and none of these in dry temperate eucalypt forests (Keith et al., 2009a; Keith et al., 2012; Kilinc et al., 2012; Kilinc et al., 2013; Leuning et al., 2005; van Gorsel et al., 2013). The behaviour of temperate deciduous or coniferous forests in the Northern Hemisphere cannot be presumed to be an analogue for temperate eucalypt forests. Apart from being broadleaf evergreen, with mostly sclerophyllous leaves, a key trait of eucalypt forests in Australia is the ability to rapidly and opportunistically respond to changing, either favourable or stressful, environmental conditions (Jacobs, 1955; Keith, 1997). This is an adaptation to disturbances such as fire or drought that are a major component of ecosystems on the Australian continent (ABARES, 2013; Beringer et al., 2015; Whitehead and Beadle, 2004). Moreover, Australian forests are generally water and nutrient limited and soils are highly weathered (Attiwill and Adams, 1993;

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Whitehead and Beadle, 2004). Keith et al. (2009a) showed that a wet temperate eucalypt forest had a high-carbon uptake capacity compared with other forests globally when not limited by water availability. No studies have been published on ecosystem carbon exchange in dry temperate eucalypt forests, where rainfall is considerably lower and soil moisture likely to be a greater limiting factor.

The aim of the study was to assess the carbon uptake potential of a dry temperate eucalypt forest and to gain an understanding of its temporal carbon exchange dynamics and controls thereof by using the eddy covariance (EC) technique (Baldocchi, 2008; Baldocchi, 2003; Hutley et al., 2005) as part of the regional OzFlux network (Beringer et al., 2016). Therefore the objectives of our study were to 1) investigate seasonal and inter-annual variability in net ecosystem carbon exchange (NEE), gross primary productivity (GPP) and ecosystem respiration (ER), 2) identify the environmental controls of these CO_2 ecosystem fluxes, and 3) quantify annual estimates of NEE and its component fluxes in a dry temperate eucalypt forest.

2 Materials and methods

2.1 Site description

The Wombat State Forest OzFlux tower site (Fluxnet ID: AUS-Wom) is located in the Wombat State Forest, Victoria, about 120 km west of Melbourne, Australia (37° 25' 20.5" S, 144° 05' 39.1" E). The flux tower is located on a ridge at a mean altitude of 706 m a.s.l. and the terrain within the footprint is relatively level to the east of the tower and with gently sloping gullies (<8◦) towards the southwest and northwest (Griebel et al., 2016). The dry sclerophyll eucalypt forest is dominated by three broadleaved evergreen tree species: *Eucalyptus obliqua* (L’Hérit.), *Eucalyptus rubida* (Deane & Maiden) and *Eucalyptus radiata* (Sieber ex DC). The study site is a ~25 years old secondary regrowth forest with an approximate canopy height of 21-27 m and a basal area of 37 m^2 ha^{-1}. The understorey is sparse and dominated by Austral bracken (*Pteridium esculentum* (G. Forst.) Cockayne), Forest wire-grass (*Tetrarrhena juncea* R. Br.), Tussock Grass (*Poa sieberiana* Sprengel), herbs (e.g. *Gonocarpus tetragynus* Labill., *Viola hederacea* Labill.) and rushes (*Lomandra* spp.) (Tolhurst, 2003). Forest management generally includes rotational low fire intensity prescribed burns of understorey vegetation which has been exempted at the studied area. The climate is cool temperate to Mediterranean with wet, cold winters and dry, warm/hot

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summers. Long-term (2001-2013) mean annual air temperature was 12.1 ± 0.1 °C with mean monthly maximum air temperatures of 26.3 ± 0.5 °C in January and mean minimum air temperatures of 3.2 ± 0.1 °C in July (nearest Bureau of Meteorology (BOM) station Ballarat, 28km SW, Fig. 1a). The silty clay soil overlying clay derived from Ordovician marine sediments and are classified as Acidic-mottled, Dystrophic, Yellow Dermosol (Robinson et al., 2003) that are moderate to highly weathered and exhibit low fertility. The long-term (114 year) mean annual rainfall at the nearest rainfall BOM station (Daylesford, 11km N, Fig. 1b) is 879 ± 18 mm with the highest rainfall occurring during winter and spring. Prior to 2010 and our study period, south-eastern Australia experienced a 13-year drought with a mean annual rainfall of 760 ± 32 mm at the closest BOM station Daylesford. For overview and more detailed site characteristics see Table 1.

2.2 Instrumentation and data aquisition

The guyed Eddy – Covariance (EC) flux tower was established in January 2010 within a fenced compound. The micro-meteorological measurement system was installed at 30 m height and consisted of an open-path infrared gas analyser (IRGA, Li-7500, LI-COR, Lincoln, USA) that measures CO_2 and water vapour concentrations and atmospheric pressure, and a 3D – sonic anemometer (CSAT3, Campbell Scientific Inc., Logan, USA) that measures turbulent wind vectors and virtual air temperature. Instantaneous measurements were carried out at 10 Hz and covariance's were calculated with a block averaging of 30 min and stored on a data logger (CR-3000, Campbell Scientific Inc., Logan, USA). Concurrent measurements of environmental variables included; air temperature (Ta) and absolute and relative humidity (HMP-45C probe, Vaisala, FIN) at 2 m and 30 m height, incoming and reflected shortwave radiation and atmospheric and surface emitted longwave radiation with a CNR1 net radiometer (Kipp and Zonen, Delft, NLD) at 30 m height, rainfall with a tipping bucket rain gauge (CS702, Hydrological Services Pty Ltd., Sydney, AUS) at 1 m height, soil heat flux at 8 cm depth (HFT3 plate, Campbell Scientific Inc., Logan, USA and HFP01 plate, Hukseflux, Delft, NLD), soil temperature (Ts) at 10 cm depth (TCAV Thermocouple probes, Campbell Scientific Inc., Logan, USA) and volumetric soil water content (SWC) at 5 cm depth (CS616 water content reflectometer probe, Campbell Scientific Inc., Logan, USA). All instrumentation was powered by a remote area power system consisting of a diesel generator and a 24V battery bank inverter system (Powermaker Ranger 4.5, Eniquest, QLD, AUS). An automated remote connection using a GSM modem (GPRS/ GSM Quadband Unimax Router and

Ethernet modem, Maxon Australia Pty Ltd, Padstow, NSW, AUS) provided real time information on system status and ensured data acquisition on a daily basis. Additionally data were stored on an external CF (compact flash) cards which were interchanged on a monthly basis. The footprint of the ecosystem flux tower during turbulent conditions extended to about 250 m in south-westerly direction covering a potential source area of 25 ha and measured CO_2 fluxes were constrained to the same forest type and dominant tree species (Griebel et al., 2016).

2.3 Data processing

2.3.1 Quality Control

Quality assurance/ quality control (QA/QC) and eddy covariance flux corrections were performed on the 30 minute covariances following the OzFlux standard protocol and open source code OzFluxQC version 2.9.5 (OzFlux, 2015) using Anaconda Python version 2.7 (Continuum Analytics, Texas, USA). The procedure is described in detail by Eamus et al. (2013) and Cleverly et al. (2013) and in summary included quality filtering via range checks (outlier and spike removal), linear corrections for calibration anomalies and sensor drift, 2D co-ordinate rotation (Lee et al., 2005), WPL correction (Webb et al., 1980), conversion of virtual heat flux to sensible heat flux and correction of ground heat flux for heat storage in the soil layer above. Due to sensor failure, SWC at 10 cm in 2010 was modelled from a linear relationship between SWC at 35 cm and a second sensor for SWC at 10 cm in 2011 and 2012. Periods of data with low turbulence conditions, predominantly during night time, were excluded based on friction velocity (u*). Night time u* was filtered with yearly determined u*- thresholds using the change point detection method after Barr et al. (2013). Annual u* thresholds ranged from 0.56 to 0.69 m s^{-1}. Data gaps occurred due to rainfall and occasional power failure and 61% of data were available over the three year period. Following QA/QC and u* filtering this was reduced to 37%, 47% and 47% in 2010, 2011 and 2012. From this quality filtered data were 66% day-time data and 23% night-time data.

2.3.2 Gap filling

Subsequent gap filling of data was done with the Dynamic Integrated Gap filling and partitioning for OzFlux routine (DINGO). Small data gaps (≤2 hrs) of continuous 30 min flux measurements were filled with linear interpolation. Then, firstly environmental variables (temperature, humidity, radiation, wind speed, atmospheric pressure and rainfall) were gap filled: 1) from linear regressions with AWS (Automated Weather Stations) data from the three nearest Bureau of Meteorology Australia (BoM) weather stations with 30 min records which were ranked after best correlation, 2) with gridded daily satellite data from the Australian Water Availability Project (AWAP, Raupach et al. (2009)) for radiation and in the unlikely event that gaps were still present after applying the above methods then a monthly diurnal means of measured climate variables were used. Soil variables (temperature and soil water content at depths) were gap filled using a simulation of the land surface using AWAP climate data and the CSIRO land surface model BIOS2 (see Haverd et al. (2013a)) adjusted to site observations.. Following gap filling of environmental variables half-hourly NEE data were gap filled using a fast forward artificial neural network (FFNET ANN) with incoming shortwave solar radiation (Fsd), vapour pressure deficit (VPD), SWC, Ts, wind speed (Ws), EVI as input drivers according to Beringer et al. (2007) and Papale and Valentini (2003). EVI was obtained from 8- or 16- day compositing periods of enhanced vegetation index (EVI) as surrogate for leaf area index from MODIS (Moderate Resolution Imaging Spectroradiometer, see Huete et al. (2002)) and interpolated to 30 min as proxy for production related to plant respiration.

2.3.3 Partitioning and carbon flux definitions

The partitioning of NEE into its component fluxes GPP and ER was following the assumption of

$$-NEE = NEP = GPP - ER \tag{1}$$

where day time NEE is the difference of GPP and ER, and night time NEE is equal to ER and hence, GPP being negligible/zero. We adopt the conventions in Chapin et al. (2006) where GPP and ER fluxes are designated with a positive sign. Negative NEE fluxes denote a net carbon flux from the atmosphere to the ecosystem, thus a net carbon uptake by the forest ecosystem which equals a positive net ecosystem production (NEP).

One of the most common uncertainties in EC measurements can be an underestimation of night time NEE or ER as turbulent mixing is often lower or absent at night time which can lead to non-detectable vertical and horizontal advection of CO_2 within the canopy (Aubinet et al., 2012; Baldocchi, 2003; Goulden et al., 1996; van Gorsel et al., 2007). Although u* filtering is the most common correction for this underestimation error (Goulden et al., 1996), many studies have reported smaller estimates of ER from u* filtered and gap-filled EC-tower data compared to those from chamber measurements of soil, leaf and stem respiration (Keith et al., 2009a; Lavigne et al., 1997; Law et al., 1999; Phillips et al., 2010; Speckman et al., 2015). Although no independent up-scaled ER estimates from chamber measurements were available from our study site, we used independent daily soil respiration data from a separate study at the same study site (Hinko-Najera, unpublished) to compare its relative contribution to daily tower ER estimates derived from four different data selection and subsequent partitioning methods to reduce a potential underestimation of ER. Of the four methods, three were based on prediction of night time ER and subsequent extrapolation of day time ER and estimation of GPP with Eq. (1). This included (1) whole night or (2) early evening data (van Gorsel et al., 2007) selection from the observed and u* filtered 30 minute NEE data and subsequent training of ANNs to compute ER with Ts, Ta, SWC and EVI as input drivers, and (3) application of a temperature function after Lloyd and Taylor (1994) to u* filtered whole night time NEE (Reichstein et al., 2005). The last partitioning method (4) followed the procedure of Lasslop et al. (2010), where a light response curve was fitted to day time NEE to estimate GPP and subsequently ER across day and night time. The ER respiration estimates that were most consistent with the soil flux data – in terms of the relative contribution of soil respiration exceeding 1 was minimal – was when ER is assumed to be at maximum in the early evening (van Gorsel et al., 2008; van Gorsel et al., 2007).

2.4 Data management and statistical analysis

All data manipulation and statistical analyses on the post QA/QC - DINGO data were performed using R version 3.2.2 (R Core Team, 2015). Differences in seasonal and inter-annual variations of daily means were tested with Kruskal-Wallis rank sum test and Dunn's Test. Relationships between half-hourly data of environmental variables and carbon fluxes (not gap filled quality controlled for 30 min data) were tested with linear regressions and stepwise multiple linear regressions. Night time data were defined as Fsd <1.22 MJ m^{-2} d^{-1} (= 10 W m^{-2}).

The relative importance of environmental drivers on seasonal and inter-annual variability of ecosystem carbon fluxes were assessed using the Random Forest algorithm (Breiman, 2001). This method is based on multiple decision trees that groups observations as a function of independent variables. Each tree in the forest is trained on a random subset of the training dataset. A multiple linear regression is performed in each final node of each tree and the final prediction of the forest is the average of all its trees. The Random Forest has been used to extrapolate maps of biomass (Baccini et al., 2012; Exbrayat and Williams, 2015) and produce global estimates of GPP by extrapolating FLUXNET data (Jung et al., 2009; Jung et al., 2011).

It outputs a measure of the co-variation between vectors of explanatory variable and observations. This importance is computed tree-wise as the fraction of decisions in which an explanatory variable is involved.

The Python implementation of the Random Forest algorithm (Pedregosa et al., 2011) was used to explain four ecosystem carbon and energy fluxes (GPP, ER and NEE) as a function of environmental conditions: Fsd, Ta, SWC and VPD. Two sets of analyses we performed using daily values. First, data were binned per calendar month and the Random Forest was trained independently for each month to assess the seasonal evolution of environmental controls on ecosystem fluxes. Second, this procedure was reproduced while binning data per calendar year to assess the inter-annual variability of these environmental controls. For ER only SWC and Ta were used as environmental drivers.

3 Results

3.1 Seasonal and inter-annual variation in environmental variables

Seasonal and inter-annual pattern in rainfall varied markedly across the three year period (Fig. 1b, 2f). In the first two years unusually high rainfall was observed during the occurrence of two strong La Niña events. Annual rainfall in 2010 and 2011 was 43% and 22% above the long-term mean annual rainfall from the nearest BOM station (Daylesford) which is representative for the study site as an adjustment was less than 1% (Table 1, Table 2). Most of the anomalous rainfall occurred between August 2010 and February 2011 with a 2-fold increase in rainfall during spring 2010 (S-O-N) and a 3-fold increase in rainfall in summer 2010/11 (D-J-F, Fig. 1b). While the annual rainfall in 2012 was close to the long-term mean annual rainfall (Table 1, Table 2), monthly rainfall showed a distinct pattern with the above long-term mean rainfall in February 2012 (2-fold increase) and winter 2012 (J-J-A, +30%) but below long-term mean rainfall from spring 2012 (S-O-N, -37%) onwards (Fig 2.1b, 2.2f).

SWC at 10 cm soil depth generally varied strongly with seasons and was highest during winter with a daily maximum of 0.36 $cm^3\ cm^{-3}$ observed in August 2012 and decreased towards summer reaching a daily minimum of 0.12 $cm^3\ cm^{-3}$ in February 2012 (Fig. 2e). Seasonal variability of SWC was more pronounced in 2012 (CV = 25%) than in 2010 (CV = 18%) as high rainfall led to an absence of a dry period during summer 2010/11 (D-J-F) and SWC remained relatively stable and high throughout 2011 (CV = 13%). SWC in 2011 significantly ($p < 0.001$) differed from 2010 and 2012.

Fsd, Ta, Ts and VPD showed a strong seasonality with maximum values during summer months and minimum values during winter months (Fig. 2b, c, d). Mean daily Fsd was 24 MJ m^{-2} d^{-1} in summer (maximum of 35.5 MJ m^{-2} d^{-1} in January 2011) and 7 MJ m^{-2} d^{-1} in winter (minimum of 0.4 MJ m^{-2} d^{-1} in May 2011, Fig 2.2b). Daily mean temperatures ranged from 2.0 ºC in winter (J-J-A) to 28.2 ºC in summer (D-J-F) for Ta and from 4.8 ºC and 23.6 ºC for Ts (Fig. 2c). Daily maximum VPD of 2.81 kPa was observed in January 2012 (Fig. 2d). Inter-annual variation of Fsd, Ta and Ts were marginal (Fig. 2 b,c) while mean annual VPD was significantly ($p < 0.001$) higher in 2012 (0.47 kPa) compared to 2010 and 2011 (0.36 kPa and 0.32 kPa, Table 2).

3.2 Seasonal and inter-annual variation of CO_2 ecosystem fluxes

A pronounced seasonal pattern was observed in ER and GPP, but less so in NEE (CV = 24%, Fig. 2a, 3).

In general, the forest showed near-continuous net carbon uptake (negative NEE) throughout the three year period, with highest net uptake rates during spring and summer months (seasonal daily means of NEE: -3.55 and -3.52 g C m^{-2} d^{-1}) and lowest rates during autumn and winter months (seasonal daily mean NEE: -2.26 and -2.33 g C m^{-2} d^{-1}, Fig. 2a, 3). Only in January 2011 NEE became distinctly positive (net carbon loss) for a short period (4 consecutive days) as GPP decreased greatly (by ~50%) due to considerably high rainfall and limited solar input. Seasonal variability in NEE was noticeably less pronounced in 2011 (CV = 15%) than in 2010 ($p < 0.001$, CV = 35%) and 2012 ($p < 0.001$, CV = 25%, Fig. 4a). Inter-annual variation of NEE was moderate (CV = 9%) being significant between 2010 and 2012 ($p = 0.002$) with most evident differences during autumn and winter (Table 2, Fig. 4a).

ER was greatest during summer (seasonal daily mean of 5.89 g C m^{-2} d^{-1}), of similar magnitude in autumn and spring (4.03 g C m^{-2} d^{-1} and 4.09 g C m^{-2} d^{-1}, respectively) and lowest during winter (1.98 g C m^{-2} d^{-1}). Similarly, GPP was greatest during summer (seasonal daily mean of 9.41 g C m^{-2} d^{-1}), followed by spring (7.64 g C m^{-2} d^{-1}),autumn (6.29 g C m^{-2} d^{-1}), and least during winter (4.31g C m^{-2} d^{-1}).

Seasonal variability was significant for both ER and GPP ($p < 0.001$) and slightly greater in ER (CV = 39%) than in GPP (CV = 30 %, Fig 2.4 b,c). Inter-annual variation for both was small (CV < 4%). However, ER significantly differed between summers of 2011 and 2012, and winters of 2010 and 2012 (Fig. 4b). GPP in winter 2010 significantly differed from the winters of 2011 and 2012 (Fig. 4c). GPP was strongly correlated with ER at monthly time scales (adj.$R^2 = 0.87$, $p < 0.001$)

but not at daily time scales. The ER/GPP ratio was highest during autumn and summer (0.64 and 0.63) and lowest during spring and winter (0.53 and 0.47).

3.3 Environmental drivers of CO_2 ecosystem fluxes

Half-hourly *day time* NEE across all three years was strongest and significantly correlated with Fsd (r = -0.74, p <0.001, Table 3). Residuals from the linear regression between NEE and Fsd were significantly correlated with both Ta and VPD (adj.R^2 = 0.24 and 0.25, both p <0.001). Fsd and VPD combined could explain 69% (p <0.001) of variation in day time NEE. Similarly, Fsd and Ta combined could explain 69% of variation in NEE (p <0.001). However, a Pearson's correlation matrix of environmental variables (Fsd, SWC, Ta, Ts and VPD) showed a strong co-linearity of between Ta and VPD for day time data (r = 0.86, p <0.001, Table 3) and regressions with Ta instead of VPD had a slightly lower AIC. The influence of SWC on the variability of day time NEE was marginal, with residuals weakly but significantly correlated with SWC (adj.R^2 = 0.03, p <0.001), and multi linear regression models did not improve when SWC was included.

Half-hourly *night time* NEE that had been u* filtered showed stronger correlation with Ta (r = 0.53, p <0.001) than Ts (Table 3) across the three year study period. Ta could explain 28% of variability in night time NEE. SWC was marginally correlated with night time NEE (adj.R^2 = 0.05, p <0.001) and multi linear regression models did not improve when SWC was included.

Seasonal importance of environmental drivers to explain ecosystem carbon fluxes using the Random Forest method are presented in Fig. 5. GPP is controlled by Fsd throughout the year with the relative importance ranging from 0.6 during summer to 0.9 in winter, while ER is strongly dominated by variations in Ta (> 0.9) across all seasons. A clear seasonal variation in the importance of environmental drivers is shown in explaining the seasonal variability in NEE. During winter NEE is predominantly explained by Fsd with a relative importance of 0.6 to 0.8, indicating that GPP limitation by Fsd is imposing a stronger influence on NEE than ER limitation by Ta. However, during summer the relative importance of Fsd decreases to approximately 0.3 as the one of Ta is increasing to 0.6.

The relative importance of environmental drivers on inter-annual time scale presented in Fig. 6 is similar to those on seasonal time scale (Fig. 5) with GPP being almost exclusively dominated by Fsd (> 0.8) while ER is driven by Ta alone. Hence, inter-annual variability in NEE could be almost equally explained by Fsd (0.5) and Ta (0.3 to 0.4). However, there is a notable increase in the importance of VPD and SWC for NEE in 2012 which was a drier year than 2010 and 2011.

3.4 Annual estimates of NEE, GPP and ER

The forest was a considerable and continuous carbon sink during the three year study period with a mean NEE of -1062 ± 53 g C m^{-2} yr^{-1}. Estimates of annual NEE increased from -976 g C m^{-2} yr^{-1} in 2010 to -1158 g C m^{-2} yr^{-1} in 2012 (Table 2). Estimates for both annual GPP and ER increased between 2010 and 2011, whereas in 2012 annual ER decreased and annual GPP was similar to that in 2011 (Table 2). ER was on average 58% of GPP, but this ranged between 60% (2010) and 55% (2012) (Table 2).

4 Discussion

4.1 Seasonal variability of CO_2 ecosystem fluxes

Gross and net CO_2 ecosystem fluxes showed strong seasonality in this dry temperate eucalypt forest, and were mainly controlled by radiation and temperature. On a seasonal time scale, GPP exceeded ER almost continually, even in winter, thus NEE showed a net carbon uptake across all seasons. Daily minimum and maximum rates of ER, and daily minimum rates of GPP were within the reported range for temperate coniferous and temperate deciduous forests compiled by Falge et al. (2002). Although daily maximum GPP rate at our forest site (14.9 g C m^{-2} d^{-1}) were comparable with those from temperate coniferous forests (16.6-26.3 g C m^{-2} d^{-1}), they were much lower than those reported for temperate deciduous forests (22.4-31.0 g C m^{-2} d^{-1}) during growing seasons (Falge et al., 2002). This can be explained by differences in leaf longevity. Reich et al. (1997) showed that potential photosynthesis and leaf respiration increase in similar proportion with decreasing leaf life-span, increasing leaf nitrogen, and increasing specific leaf area. Hence, temperate deciduous forests maximize carbon uptake in their short-lived foliage to compensate for having a shorter growing season compared with evergreen forest (Falge et al., 2002).

Both GPP and ER peaked during summer and were lowest in winter which is similarly typical for temperate *coniferous* forests (Baldocchi, 2008; Baldocchi and Valentini, 2004). However, during spring the increase in ER lagged behind that of GPP, an occurrence similarly typical for temperate *deciduous* forests (Baldocchi, 2008; Baldocchi and Valentini, 2004). Thus, NEE peaked in early spring and again in summer. The delayed increase in ER as compared to GPP in springtime can be attributed to low temperatures limiting microbial decomposition, i.e. soil respiration (Hinko-Najera et al., 2015). This

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pattern was also in correspondence to the observed seasonal hysteresis of their respective major environmental controls temperature and radiation. Similar seasonal variability in GPP and ER was observed in a wet temperate eucalypt forest, however, NEE peaked only during spring in this forest as GPP was limited by water availability during dry summer period (Kilinc et al., 2013). These phenomena highlight that carbon exchange dynamics in this dry temperate eucalypt forest are different in their seasonal behaviour from temperate deciduous or coniferous forests in the Northern Hemisphere (Baldocchi, 2008; Baldocchi and Valentini, 2004; Falge et al., 2002), so the latter should not be used as analogues.

4.2 Environmental drivers of CO_2 ecosystem fluxes

As indicated above the overall main environmental drivers of NEE were radiation and temperature and reflected the individual environmental controls of its gross fluxes GPP and ER. Incoming solar radiation was the single main environmental driver for GPP at half-hourly and seasonal to inter-annual time scales throughout the three year study period whereas temporal variability in ER was predominantly explained by air temperature. Interestingly, the Random Forest analyses revealed a strong seasonal variability of environmental controls on NEE. During winter NEE was mostly explained by incoming solar radiation during winter due to a stronger limitation of GPP imposed by a combination of short-days and cloudiness. The relative importance of radiation and air temperature were comparable in summer, indicating a stronger co-variation of NEE and ER during months when GPP was not radiation-limited.

Dry temperate eucalypt forests, like most of Australia’s forests, are generally characterised by dry summer periods and thus are greatly influenced by changes in water availability (Haverd et al., 2013a). However, environmental drivers related to water availability such as VPD and SWC had only a minor influence on GPP during summer months and no effect at all on ER as shown by seasonal and inter-annual Random Forest Analyses. Thus, there was no apparent water limitation on carbon dynamics during our study period in this forest. This is in contrast with findings from Keith et al. (2012), van Gorsel et al. (2013) and Kilinc et al. (2013) for wet temperate eucalypt forests. In all these studies ecosystem carbon fluxes were limited by VPD and/or SWC during dry summer months with greatest effects on GPP than ER. However this can be explained by the anomalously high rainfall at our forest site due to strong La Niña events from mid 2010 to early 2011 and early 2012 (BoM, 2012) during most of the study period. The lack of SWC influence on carbon fluxes until spring 2012 was also evident in concurrent studies on soil respiration dynamics at the same study site where SWC did not decline below a certain threshold to be limiting soil respiration (Hinko-Najera et al., 2015) and Random Forest analyses revealed a notable increase of the importance of VPD on NEE in the dry year 2012.

4.3 Carbon balance and inter-annual variability

The dry temperate eucalypt forest was a very strong and continuous carbon sink for all three years. Our mean annual ER/GPP ratio (~0.58) was lower than the mean ER/GPP ratio of 0.76 for Australian ecosystems (Beringer et al., 2016), the 0.80 reported for temperate forests (Janssens et al., 2001; Luyssaert et al., 2007) and the 0.77 derived from a global data base (Baldocchi, 2008). Moreover, our annual estimates for NEE are greater than published estimates for forest ecosystems around the globe collated by Baldocchi et al. (2001) or Luyssaert et al. (2007), and at the upper end of the probability distribution for sites within the global FLUXNET network (Baldocchi, 2014). Although accounted for during data processing and partitioning, the possibility of a remaining underestimation of ER cannot be excluded. Nonetheless, that temperate eucalypt forests in Australia exhibit large carbon uptake ability has been shown in wet temperate eucalypt forests (>1000 mm annual rainfall) only recently, such as a tall old growth forest (930 g C m^{-2} yr^{-1}) (Beringer, 2016), also considered to be the world's most carbon dense forest (Keith et al., 2009b), and previously in a wet temperate eucalypt forest near Tumbarumba (Keith et al., 2009a; Keith et al., 2012; van Gorsel et al., 2013). That forest was a strong sink of ~ 900 g C m^{-2} yr^{-1} during years with average annual rainfall (~ 1400 mm), but this sink was reduced (~ 750 g C m^{-2} yr^{-1}) during the above average rainfall (~ 2000-2200 mm) years of 2010 and 2011 (van Gorsel et al., 2013). Overcast conditions and thus reduced incoming solar radiation explained this reduced sink (van Gorsel et al., 2013). However, NEE estimates we report for our study site are higher than those reported from the Tumbarumba eucalypt forest during the same years of above average rainfall. A possible explanation for the greater net carbon uptake estimates in our dry temperate eucalypt forest might be the higher leaf area index (~ 1.8) than in the wet temperate eucalypt forest (~ 1.4) near Tumbarumba, conferring a higher canopy photosynthetic capacity. Our study supports the conclusion of Keith et al. (2009a) that temperate eucalypt forests have a high carbon uptake potential because they are evergreen, opportunistic and as such photosynthetic carbon uptake can occur throughout the year when conditions are favourable.

Another possible explanation for the higher net carbon uptake estimates at our study site compared to the Tumbarumba forest site is the absence of summer dry periods and a stimulation of growth due to the high rainfall. Prior to the period of high rainfall in 2010-2012 forests throughout temperate Australia experienced a decade long drought that negatively affected NEE and NPP (Haverd et al., 2013b). Keith et al. (2012) and Kilinc et al. (2013) reported as well that drought conditions in the wet temperate eucalypt forest strongly reduced NEE by having a greater negative effect on GPP than ER. Therefore it is likely that the onset of high rainfall in winter/early spring 2010 likely led to favourable conditions for growth and high carbon uptake (Jacobs, 1955; Keith, 1997).

Our data indicate that the main environmental controls (radiation and temperature) for GPP and ER did not vary between years, and as such inter-annual variability of both GPP and ER was small. Regardless, we observed moderate variations in NEE amongst the three years, with an increase in NEE from 2010 through to 2012. The high rainfall in early 2011 led to favourable forest growth conditions throughout 2011 and a stronger increase in GPP rather than ER and thus an increase in NEE from 2010 to 2011, most evident in autumn and winter. This 2011 increase in NEE is in accordance with the observed 2011 global sink anomaly (Haverd et al., 2013a; Haverd et al., 2016; Poulter et al., 2014) which has been mainly attributed to semi-arid ecosystems in Australia (Eamus and Cleverly, 2015; Haverd et al., 2013a). Hence, our results indicate that the global sink anomaly was not only limited to semi-arid ecosystems. The further increase in NEP from 2011 to 2012 was indicated by a reduction in ER as GPP remained steady. Rainfall was lower in 2012 as compared to the previous two years and hence, soil water content decreased towards the end of 2012 (summer) likely influencing ER but not GPP. Given that ER is often dominated by soil respiration, this pattern is in agreement with findings on soil respiration patterns from concurrent studies in the same forest (Hinko-Najera et al., 2015) where low soil water contents led to a decrease in soil respiration.

Nonetheless, longer monitoring will be needed to assess the net carbon sink strength of dry temperate eucalypt forests during years with average climate and under drought conditions, of which the latter is predicted to prolong and intensify (Christensen et al., 2013; CSIRO, 2012).

5 Conclusion

Temperate eucalypt forests are underrepresented in global assessments concerning terrestrial/ forest carbon dynamics and productivity (Baldocchi, 2008; Falge et al., 2002; Luyssaert et al., 2007) and so far no data has been available on ecosystem carbon exchange dynamics from dry temperate eucalypt forests. This study shows that not only wet temperate eucalypt forests but also dry temperate eucalypt forests have a large carbon uptake potential, particular during above average rainfall, and thus adds further evidence that temperate eucalypt forests are strong carbon sinks during favourable conditions (Keith et al., 2009a). Furthermore, carbon dynamics in this dry temperate eucalypt forest, similar to other temperate eucalypt forests, do differ in their seasonal behaviour compared to temperate coniferous and deciduous forest in the Northern Hemisphere owing to the opportunistic response and all year round physiological activity of eucalypts. This study further demonstrates that seasonal and inter-annual variability in carbon uptake were not limited by temperature but predominantly driven by radiation whereas carbon loss from the forest was dominated and overall ecosystem carbon exchange dynamics were not water limited due to the high rainfall. Therefore, temperate eucalypt forests represent a unique forest type and should be considered separately in future classifications of ecosystems regarding their vegetation functional types and potential contribution to the global terrestrial sink strength. Our results provide the various global and continental carbon cycle and land-surface model frameworks with necessary empirical data for parameterisation and model evaluation and hence contribute in reducing uncertainties in ecosystem feedback predictions to climate change.

Author contribution. N. Hinko-Najera, S.K. Arndt, S.J. Livesley and J. Beringer designed the experiment. Field work was primarily carried out by N. Hinko-Najera with help from I. McHugh and J. Beringer. Data preparation and analysis was primarily performed by N. Hinko-Najera with contribution from P. Isaac and I. McHugh (quality control), J. Beringer (DINGO), E. van Gorsel (partitioning) and J-F Exbrayat (random forest approach). N. Hinko-Najera prepared the manuscript with contributions from all co-authors.

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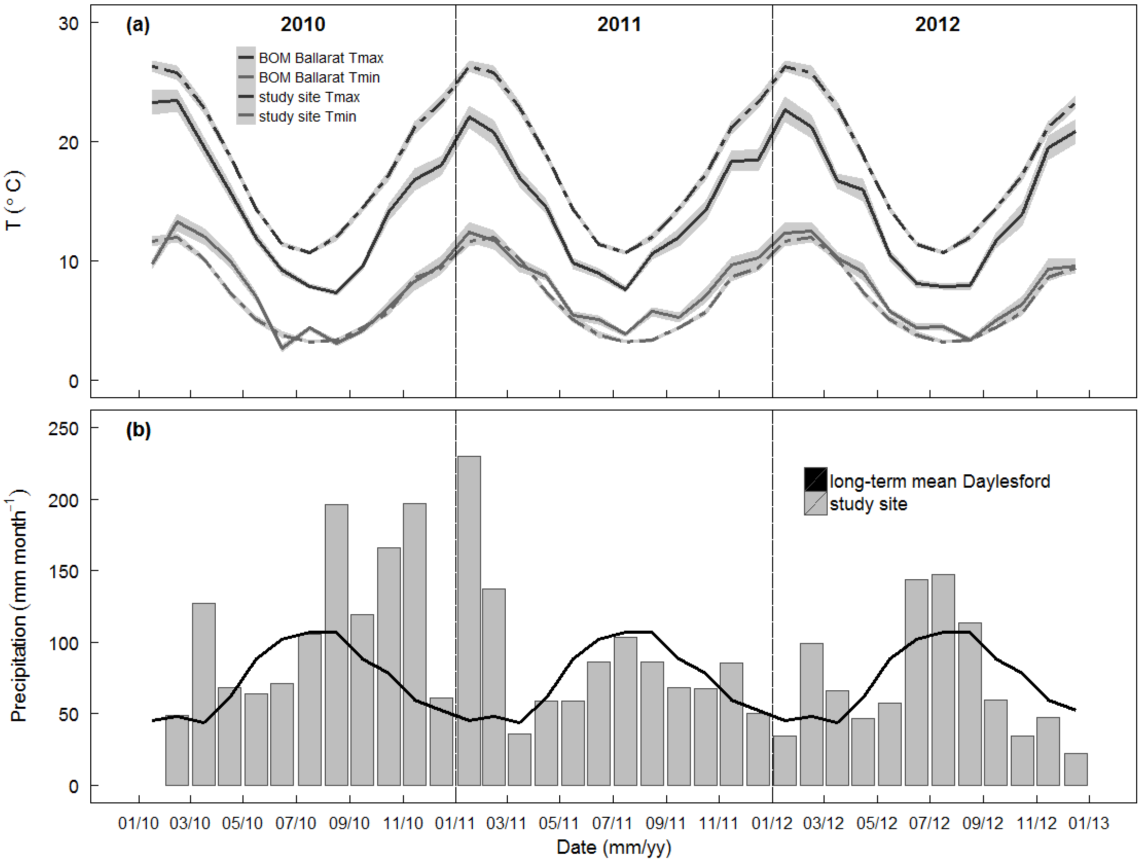
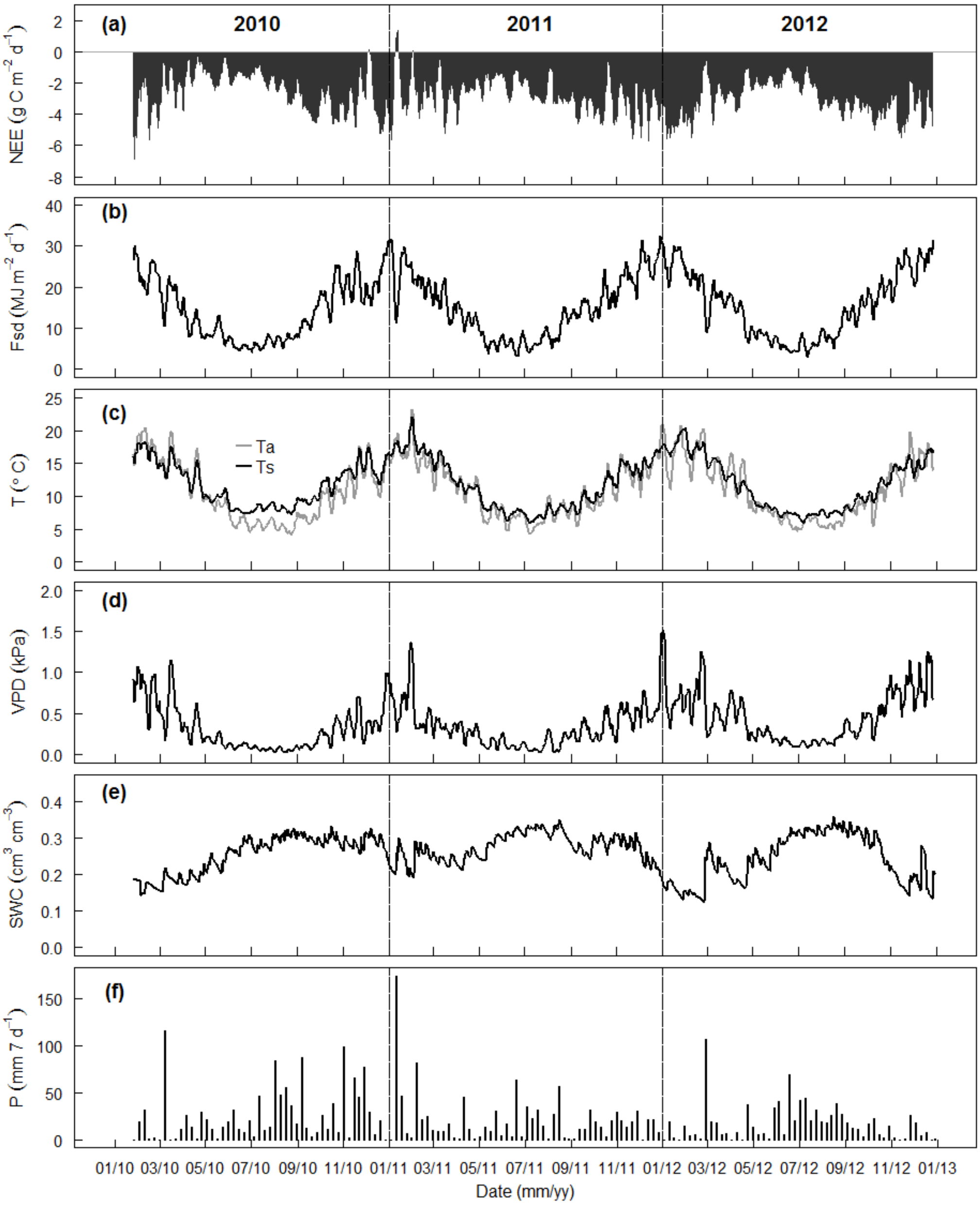


Figure 1: Climate time series of (a) monthly averages of minimum (grey lines) and maximum (black lines) air temperatures from the study site from 2010 to 2012 (solid lines) and from the BoM station Ballarat from 2001 to 2013 (dashed lines), shaded areas indicate ±1SE, and (b) monthly rainfall at Wombat State Forest OzFlux EC tower site from 2010 to 2012 (grey bars) and 114 year long-term monthly mean rainfall at BoM station Daylesford (black line) 675



680 **Figure 2: Time series of daily (a) total net ecosystem exchange (-NEE), daily averages of (b) incoming solar radiation (Fsd), (c) air temperature (Ta) and soil temperature (Ts), (d) vapour pressure deficit (VPD), (e) volumetric soil water content (SWC) and (f) 7-day sums of rainfall (P) from 2010 to 2012; NEE, Fsd, Ta, Ts and VPD are displayed as 7-day running means for better illustration**

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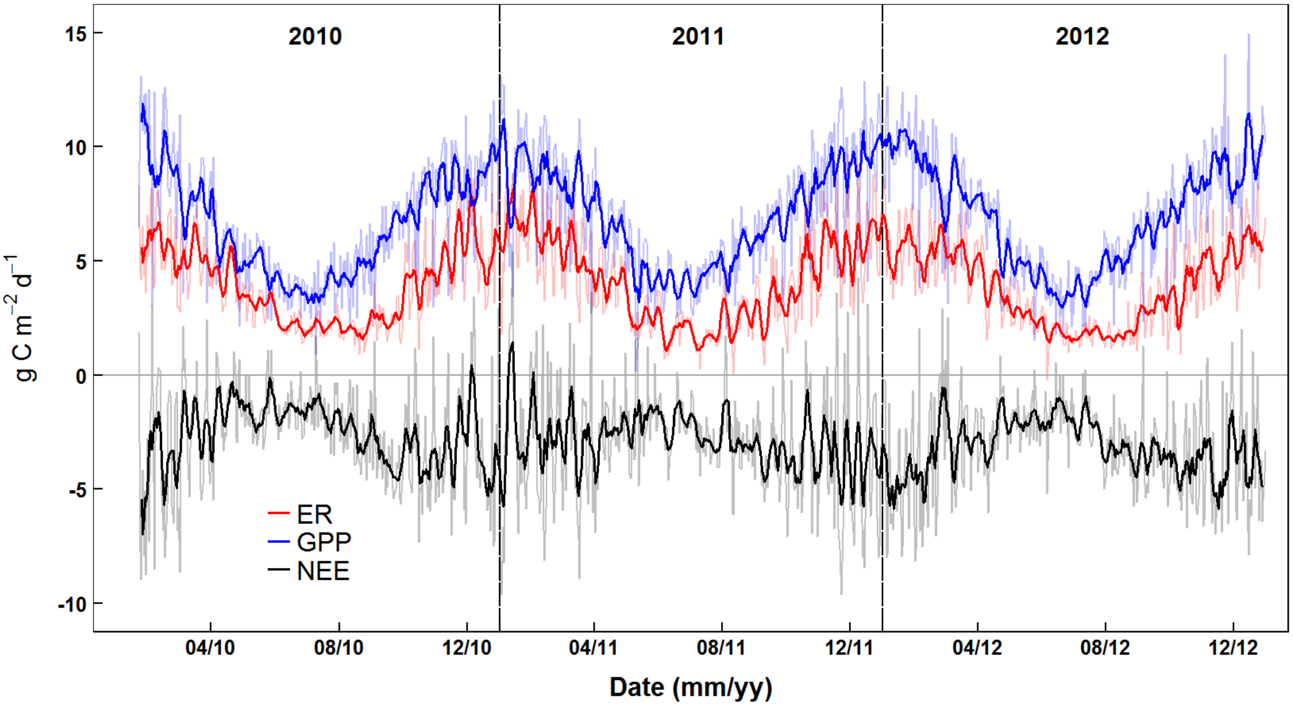

Figure 3: Daily total carbon fluxes of the Wombat State forest OzFlux site from 2010 to 2012: ecosystem respiration (ER, red lines), gross primary productivity (GPP, blue lines) and net ecosystem carbon exchange (-NEE, black lines), 7-day running means (bold lines) are displayed for better illustration.

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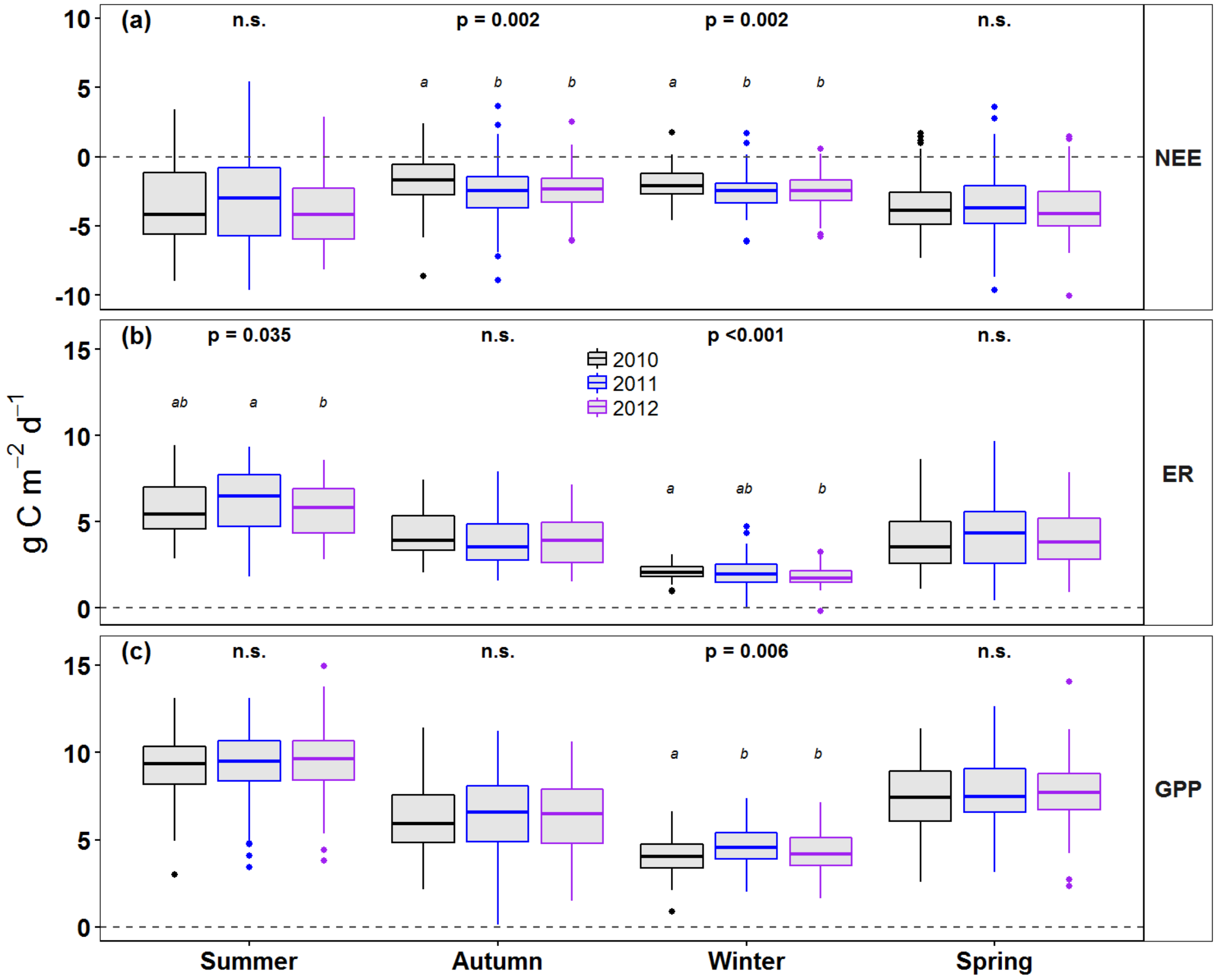

Figure 4: Box- and whisker plots of daily averages of a) -NEE, b) ER and c) GPP for years and seasons; inter-annual differences are displayed for each seasons with p-values (significance level p <0.05), letters indicate year to year differences

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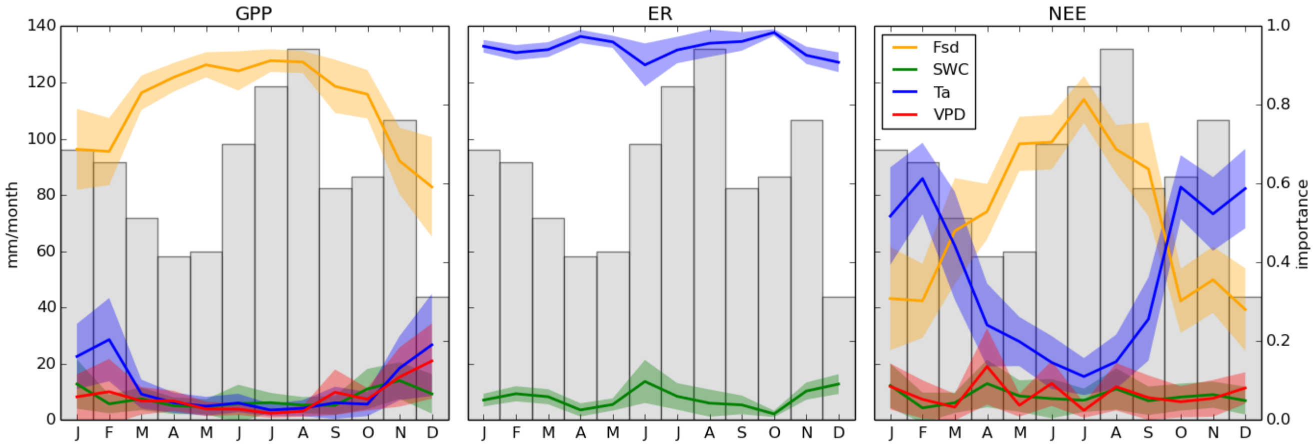

700 **Figure 5: Seasonal importance of the environmental variables incoming solar radiation (Fsd, yellow line), air temperature (Ta, blue line), vapour pressure deficit (VPD, red line) and volumetric soil water content (SWC, green line) to explain variability in gross primary productivity (GPP), ecosystem respiration (ER) and net ecosystem carbon exchange (NEE); thick lines and shading represent the average ± 1 standard deviation of the importance across 1000 decision trees; grey bars indicate average monthly rainfall over the period 2010-2012.**

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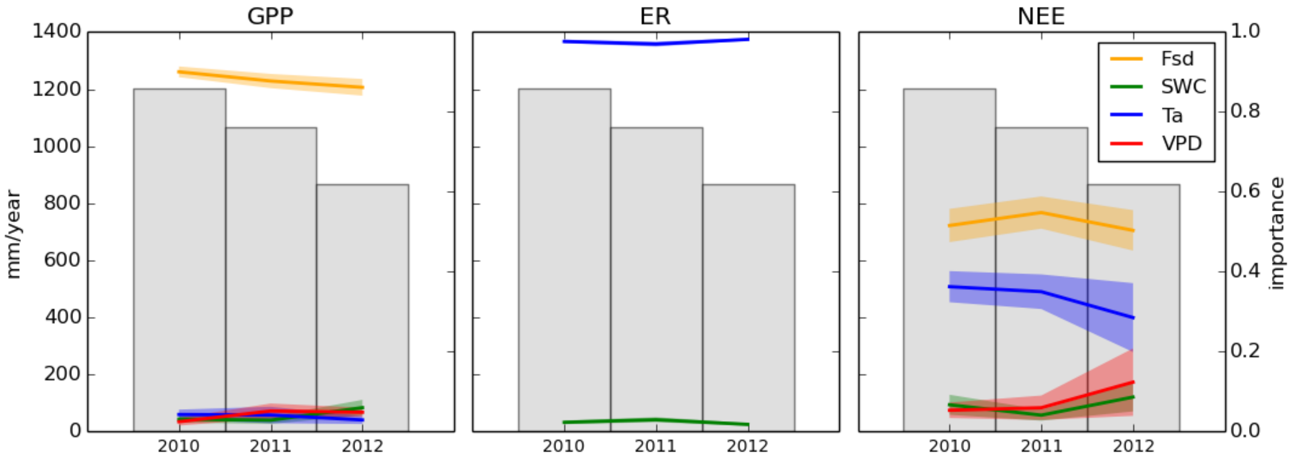

710 **Figure 6: Annual importance of the environmental variables incoming solar radiation (Fsd, yellow line), air temperature (Ta, blue line), vapour pressure deficit (VPD, red line) and volumetric soil water content (SWC, green line)to explain variability in gross primary productivity (GPP), ecosystem respiration (ER) and net ecosystem carbon exchange (NEE); thick lines and shading represent the average ± 1 standard deviation of the importance across 1000 decision trees; grey bars indicate annual precipitation over the period 2010-2012.**

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Table 1: Site and tower characteristics for the Wombat State Forest OzFlux-site

Location	37° 25' S, 144° 05' E
Elevation a.s.l. (m)	706
Forest size (ha)	70 000
Tower height (m)	30
Canopy height (m)	25-27
Canopy species	*Eucalyptus obliqua*, *E. rubida*, *E. radiata*
Understorey species	*Pteridium esculentum*, *Tetrarrhena juncea*, *Poa sieberiana*, *Lomandra* spp.
Mean annual air temperature (°C)	11.0 ± 0.1
Mean annual rainfall (114 yrs, mm)#	879 ± 18
LAI (leaf area index m^2 m^{-2})	1.81*
Tree density (ha^{-1})	1316*
Tree dbh (cm)	18.6*
Litterfall (g m^{-2} yr^{-1})	1120 ± 52
Soil type	acidic-mottled, dystrophic, yellow Dermosol
Soil depth (cm)	50cm
pH	4.83 ± 0.02
Bulk density (0-10 cm, kg m^{-3})	0.94 ± 0.02
C/N	30.9 ± 0.5
Sand (%)	45.4 ± 1.8
Silt (%)	27.9 ± 1.9
Clay (%)	26.7 ± 0.4

where applicable: mean of n = 3 ± 1SE; # BoM station Daylesford, 11 km N of study site),* Moore (2011)

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Table 2: Annual averages of incoming solar radiation (Fsd), air temperature (Ta), soil moisture content (SWC), vapour pressure deficit (VPD), annual sums of rainfall (P), net ecosystem productivity (NEE), ecosystem respiration (ER) and gross primary productivity (GPP) at the Wombat State Forest from 2010 to 2012; CV – coefficient of variation for inter-annual variation, inter-annual differences are indicated with * ($p<0.001$), ** ($p<0.01$) or *ns* (not significant), letters indicate year to year differences**

Year	**Fsd** (MJ m^{-2} d^{-1})	**Ta** (ºC)	**Ts** (ºC)	**SWC** (v/v)	**VPD** (kPa)	**P** (mm)	**NEE** (g C m^{-2})	**ER** (g C m^{-2})	**GPP** (g C m^{-2})
2010^{a}	15.0	11.0	12.1	0.25*a*	0.36*a*	1254	-976*a*	1475	2451
2011	15.3	11.1	11.8	0.27*b*	0.32*a*	1070	-1053*ab*	1502	2555
2012	15.8	11.1	11.8	0.24*a*	0.47*b*	872	-1158*b*	1399	2557
CV (%)	2.5 *ns*	0.5 *ns*	1.2 *ns*	6.6 ***	20.0 ***	17.9	8.6 **	3.6 *ns*	2.4 *ns*

[a] includes extrapolated values until 21st of January, estimates without extrapolation, i.e. 344 days:
P (mm): 1229, NEE (g C m^{-2}): 896, ER (g C m^{-2}): 1346, GPP (g C m^{-2}): 2243

Table 3: Pearson's correlation matrix of 30min quality controlled non gap filled NEE and environmental variables (Fsd: incoming solar radiation, SWC: soil water content, Ts: soil temperature, Ta: air temperature, and VPD: vapour pressure deficit), DT: day time, NT_u*: night time u* filtered, significance level: < 0.001: *, < 0.01: **, < 0.5: *, > 0.5: *n.s.***

	variable	SWC	Ta	Ts	VPD	NEE	n
DT	Fsd	-0.18***	0.40***	0.48***	0.38***	-0.74***	16750
	SWC		-0.55***	-0.52***	-0.44***	0.01n.s.	
	Ta			0.88***	0.86***	0.03***	
	Ts				0.72***	-0.09***	
	VPD					0.05***	
NT_u*	SWC		-0.51***	-0.63***	-	-0.22***	6368
	Ta			0.83***	-	0.53***	
	Ts				-	0.45***	