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ORIGINAL ARTICLE

Effects of wildfire on long-term soil CO_2 concentration: implications for karst processes

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Abstract Wildfires reduce soil CO_2 concentration by destroying vegetation and soil-dwelling microbes, thus reducing soil respiration. Post-fire vegetation recovery is primarily determined by vegetation growth forms and modes of regeneration, whereas long-term recovery of soil microbes is largely dependent on vegetation rehabilitation. With previous research focussing on post-fire respiration recovery in the context of CO_2 flux between the soil and atmosphere, there is a lack of studies measuring the long-term response of soil CO_2 concentration in karst environments. Hence, this study aimed to quantify whether soil CO_2 concentration was reduced 5 and 10 years after fires in a karst environment and to consider the implications for karst dissolution processes and speleothem growth rate. Paired sites with burnt and unburnt soil were compared with regards to soil CO_2 concentration, soil temperature and soil moisture. Samples were taken from a grassland community and woodland community burnt 5 years prior and a forest community burnt 10 years prior. The results showed that soil respiration was depressed in the burnt site relative to the unburnt control in the woodland 5 years post-fire. A vegetation survey indicated that there substantially less biomass in the burnt site relative to the unburnt site. In the forest site 10 years post-fire there was no significant difference in soil CO_2 concentration or vegetation between the burnt and control. This demonstrates that soil CO_2 concentration takes >5 years to recover to pre-fire levels in woodlands and <10 years in subalpine forests and is determined by vegetation recovery. This long-term reduction in soil CO_2 concentration caused by fire has the potential to affect karst subsurface processes governed by soil CO_2 which lead to incorrect interpretation of speleothem proxy climate records.

Keywords Speleothem · Fire · Carbon dioxide · Soil CO_2 concentration · Paleoclimate reconstruction · Karst

Introduction

Soils produce CO_2 by plant respiration and microbial processes to achieve partial pressures 1–3 orders of magnitude above atmospheric levels (Appelo and Postma 2005). Soil CO_2 production is from root and microbial respiration, the latter has energy sources from soil organic matter, surface and subsurface dead plant residues and rhizodeposits (organic secretions and root cells) (Kuzyakov 2006). The proportion of root to microbial respiration (measured from efflux) varies between 10 and 90 % depending on vegetation type and growing season (Hanson et al. 2000). Soil carbon dioxide (CO_2) is one of the main drivers of dissolution processes in karst environments (Dreybrodt 1999). Precipitation falling on a karst area with an overlying soil layer absorbs large amounts of CO_2.

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Rainfall infiltrates through the soil and small cracks and fissures of the bedrock dissolving the carbonate minerals on contact. As the carbonate-enriched solution enters a void, such as a cave, where the ambient CO_2 partial pressure (pCO_2) is lower than the pCO_2 of the solution, the excess dissolved CO_2 will outgas causing the solution to become supersaturated with respect to calcite, which then precipitates. It is the build-up of these calcite layers that causes speleothem growth. Speleothem growth rates have provided useful information on paleoclimate where a good understanding of controlling processes has been developed in well-monitored sites (Genty et al. 2000).

There is a global relationship between soil CO_2, climate and karstification. In tropical regions there is a greater degree of karst denudation due to higher pCO_2 of soil water, which results in more variable solutional landforms than temperate, alpine and arctic regions (Brook et al. 1983). This is supported by spatial variations in the pCO_2 of carbonate groundwater. The relationship between vegetation, soil CO_2 and water chemistry also occurs on a regional scale. Calmels et al. (2014) found that a decrease in calcium carbonate dissolution with elevation could be explained by a decrease in soil CO_2 with altitude, with 65 % of the variability in soil CO_2 explained by a shift in vegetation type with altitude. Empirical evidence demonstrates that karst subsurface processes and speleothem-forming drip water respond to changes in soil CO_2 concentration on an annual timescale. Genty et al. (2000) demonstrate that interannual variation in stalagmite growth rate is correlated with mean annual temperature and drip water calcium content, due to soil CO_2 production being dependent on temperature and soil moisture. Tan (2003) used the relationship between soil CO_2 and dissolved and deposited carbonate to build paleotemperature records with an annual temporal resolution in Shihua Cave. Variations in local temperatures can control the deposition of rare earth elements (REEs) in speleothems because the higher temperature increases the soil CO_2 production in the soil, thus lowering the pH and mobilising REEs in the soil and rock (Tan et al. 2014).

Fire reduces soil CO_2 concentrations by removing autotrophic (plant root) and heterotrophic (microbial) sources respiring CO_2 into the soil. There are a wide range of surface temperatures (50 to >850 °C) characterising fire events, depending on fire intensity and weight of fine surface fuel (Bradstock and Auld 1995) with soil temperature decreasing with depth (Neary et al. 1999). Fire intensity is defined as the amount of energy released from the leading fire edge (kW m^{-1}) and is a function of the fuel type, moisture conditions and the rate of spread of the fire (Lindenmayer and Burgman 2005). A crude scale of intensity developed by Gill and Catling (2002) is as follows: (1) low (<350 kW m^{-1}), (2) high (350–3500 kW m^{-1}), (3) very high (3500–35,000 kW m^{-1}) and (4) extreme (>35,000 kW m^{-1}). Prolonged and elevated soil temperatures can cause severe stress and mortality in plants. High temperatures can disrupt cell organisation in soil microbes causing cell death (Schoffl et al. 1999). The extent to which fire impacts total soil respiration is determined by a number of factors including, fire severity (Certini 2005; Bárcenas-Moreno and Bååth 2009; Granged et al. 2011a, b; Pharo et al. 2013), vegetation and microbial age and species (Jenkins and Adams 2010; Gongalsky et al. 2012), fire frequency interval (Hart et al. 2005) and soil moisture (Neary et al. 1999; Zedler 2007; Uribe et al. 2013).

Soils exhibit a strong CO_2 concentration gradient with depth. CO_2 production is highest at the surface due to a larger volume of labile carbon substrate for heterotrophic respiration and a higher density of vegetation roots (Risk et al. 2002). However, due to the close proximity of the soil-atmosphere interface there is a high loss rate of CO_2 to the atmosphere via diffusion (Davidson et al. 2006). Carbon dioxide accumulates at depth in the soil as diffusion is retarded due to decreased effective gas diffusivity of soil matrix (Certini et al. 2003). Soil CO_2 also varies depending on vegetation type. Jenkins and Adams (2010) found that in a study of heterotrophic respiration in subalpine Australian ecosystems, heterotrophic respiration was highest in woodlands with a shrub understory and slowest in grassland. Similarly, Vargas and Allen (2008) found that respiration rate was higher in woody vegetation than herbaceous vegetation, with respiration exhibiting a positive correlation with fine root length. Studies have shown that the difference in respiration is due to soil environmental conditions, in particular soil substrate availability, temperature and moisture availability (Raich and Tufekcioglu 2000; Wang et al. 2013).

Microbe populations are initially depressed due to the sterilising effects of heat in the soil but can recover rapidly to pre-fire levels. Hart et al. (2005) describe a short-term reduction in microbial populations caused by heat-induced mortality and relate recovery of microbial communities to long-term plant community fire response. Ginzburg and Steinberger (2012) found that microbial recovery was limited by elevated total soluble nitrogen levels in the first year after fire and that plant growth was fundamental in reducing nitrogen to tolerant levels allowing proliferation of microbes. Indirect changes due to vegetation cover were highlighted as an area for research into the long-term recovery of burnt soil systems (Ginzburg and Steinberger 2012).

The effect of fire on karst subsurface processes is unknown. If this effect is unaccounted for, it could lead to misinterpretation of speleothem proxy climate records. The understanding of the process and response of soil CO_2 concentration is particularly important in Australia where fire is a frequent and widespread occurrence and there is a high density of speleothem-based studies (Goede et al.

1996; Moriarty et al. 2000; Xia et al. 2001; Treble et al. 2003, 2005, 2013; McDonald 2004; McDonald et al. 2007 McDonald and Drysdale 2007; Cuthbert et al. 2014; Rutlidge et al. 2014). This paper aims to quantify the effect of fire on soil CO_2 concentrations in a subalpine karst environment in south-eastern New South Wales after 5 and 10 years and discusses the implications for karst subsurface processes.

Methods

Study site

The forest site burnt in 2003 (°S-35.723°S, 148.490°E) is located at Yarrangobilly Caves and the grassland and woodland sites burnt in 2007 (°S-35.658, 148.479°E) are located at Spicer's Creek in the subalpine region of the Australian Alps in New South Wales (Fig. 1). The control sites are located <1 km from the corresponding burnt sites and were selected due to close proximity and similarity in geology and ecology. The Australian Alps form part of the Great Dividing Range which runs 3700 km from Queensland to Victoria along the eastern seaboard. The sites are situated within a formation of massive Silurian limestone approximately 12 km long and on average 1 km wide (Worboys 1982). The region is characterised by alpine humus soil dominated by the organomineral horizons with less defined boundaries between successive layers (Costin et al. 1952).

Field methods

Vegetation survey data

The contribution of plant root respiration to soil CO_2 efflux is a function of the rate of photosynthetic uptake and the

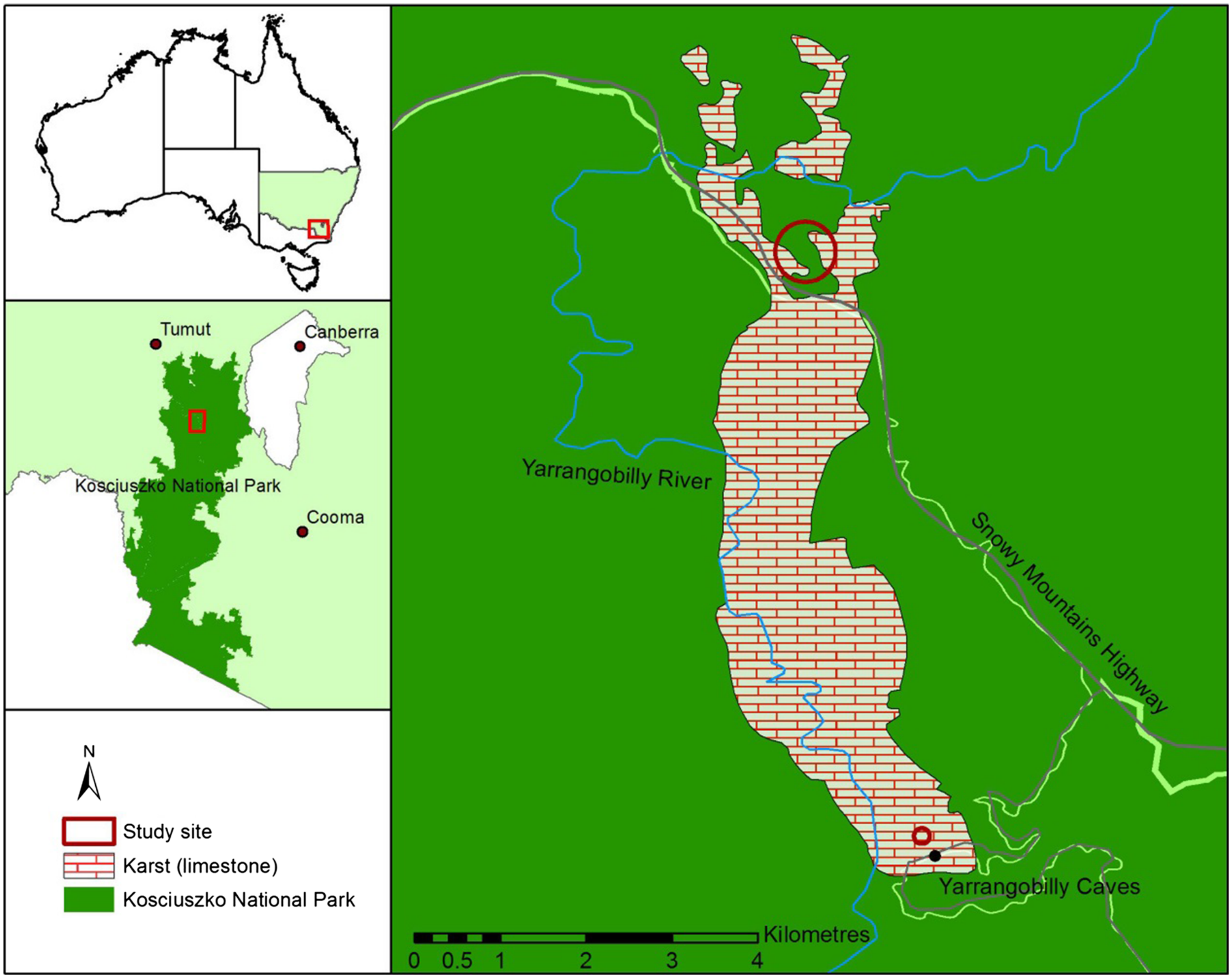


Fig. 1 Location of the woodland and grassland site near Spicer's Creek burnt 5 years ago (*large circle*) and the forest site near Yarrangobilly Caves burnt 10 years ago (*small circle*)

carbon allocation strategies of the species which contribute most of the biomass of the system (Metcalfe et al. 2011). The relative contribution of plant root respiration to soil CO_2 efflux was estimated across the soil sample sites by quantifying structural and compositional differences in vegetation that were evident among the sites.

Horizontal structural classes were differentiated based on height and physiognomy and described in terms of projected foliage cover (PFC), height range and species composition within a 0.1 ha plot spanning the soil sampling area. The relative contributions of individual species to biomass were estimated using their frequency of occurrence as measured by the nested-plot sampling method of Morrison et al. (1995).

The Spicer's Creek grassland site is characterised by a low (<0.2 m) and continuous herbaceous cover dominated by grasses. *Themeda australis* and *Poa sieberiana* contributed most of the biomass with a diverse range of forbs occupying interstitial areas. Woodland adjacent to the grassland at Spicer's Creek is dominated by *Eucalyptus stellulata* with a variable cover of understorey shrubs and a continuous herbaceous ground cover similar in composition to the adjacent grassland. The site at Yarrangobilly was classified as dry sclerophyll open forest (Keith 2004) dominated by *E. pauciflora*.

Long-term continuous soil data

Precipitation and air temperature were measured with a Davis Vantage Pro 2 weather station with a precision of max ± 4 % of total and ±0.5 °C, respectively. A Stevens Hydra Probe II was used to record soil moisture (±0.03 WFV). Soil moisture was converted to VSM % for analysis. Two Vaisala GMP343 CO_2 probes were buried vertically at 20 cm depth in the soil ~5 m apart to measure soil CO_2 concentration. All measurements were logged at 15 min intervals and data stored using a Data taker DT80 data logger.

Table 1 Vegetation characteristics for each site

	Location	Stratum	Growth form	Projected foliage cover (%)	Height min (m)	Height max (m)	Dominant species
Unburnt forest (U1)	Y	Upper (1)	Tree	40	12	20	*Eucalyptus pauciflora*
		Upper (2)	Tree	3	5	7	*E. pauciflora*
		Middle	Shrub	30	0.1	3	*Dodonea viscosa, Acrothamnus hookeri, Cassinia aculeata, Mirbelia oxylobioides*
		Ground cover	Herb	30	0.01	0.3	*Poa sieberiana*
Burnt forest—10 years (B1)	Y	Upper (1)	Tree	30	15	20	*E. dives, E. pauciflora, E. dalrympleana*
		Upper (2)	Tree	10	4	10	*E. dives, E. pauciflora*
		Middle	Shrub	35	0.3	3.5	*Daviesia mimosoides*
		G1	Herb	35	0.01	0.3	*Poa sieberiana*
Burnt woodland—5 years ago (B3)	SC	Upper (1)	Tree (unburnt)	<1	6	7	*E. stellulata*
		Upper (2)	Tree (basal coppice)	4	2	4	*E. stellulata*
		Middle (1)	(Juvenile Eucalyptus)	3	0.1	1	*E. stellulata*
		Middle (2)	Shrub	5	0.7	2	*Linum marginale*
		Ground	Grass	95	0.01	0.8	*Dactylus glomerata, Themeda australis, P. sieberiana*
Unburnt woodland (U3)	SC	Upper (1)	Tree	35	10	19	*E. stellulata*
		Upper (2)	Tree	4	4.5	6	*E. stellulata*
		Middle	Shrub	30	0.5	2.5	*A. hookeri, Linum marginale*
		Ground	Herb	95	0.01	0.4	*Stellaria flacida, Dactylus glomerata*
Burnt grassland—5 years (B2)	SC	Ground	Grass	95	0.01	0.15	*T. australis*
Unburnt grassland (U2)	SC	Ground	Grass	95	0.01	0.2	*T. australis*

SC Spicer's Creek, *Y* Yarrangobilly

Discrete soil data

Soil CO_2 concentration, soil moisture and soil temperature were measured during December 2012 for a woodland burnt in 2003 (10 years ago) and two sites (woodland and grassland) burnt in 2007 (5 years ago) and paired unburnt control sites. Measurements were replicated at different spatial locations within each site in February and March 2013 making a total of 6 samples per site. The two fires are unlikely to have been of similar intensity. The 2003 fire burnt on a slope with broken fuel loads because of lower projected foliage in the under storey. It occurred during the summer after an extended drought period leading to extreme fire conditions. It was likely to have been a high temperature, fast running fire. In contrast, the 2007 site was a prescribed (hazard reduction) burn, which are normally of low to moderate intensity. However, in the wooded areas the fuel loads were well connected resulting in a slow moving, cooler fire that could have burnt in 'hotspots' for a longer duration.

Vaisala GMP343 carbon dioxide probes (55 × 180 mm) were inserted into holes bored 0.2 m deep in the soil surface and covered with soil to measure CO_2 concentrations and temperature every 5 min for 3 h simultaneously at paired sites. Preliminary experiments indicated that the probe took 2 h to equilibrate in the soil following the disturbance caused by auguring, therefore only the last hour of data was used. The measurement range of the probe was 0–5000 ppm with a precision of ±5 ppm + 2 % of the reading. A Vaisala M170 handheld logger was used to record and temporarily store the data. Temperature was measured at one site during the paired soil CO_2 concentration monitoring period. An ICT International MP406 moisture sensor (215 × 44 mm) connected to a MPM160 meter was used to measure volumetric soil water (VSW %) content. The measurement range is 0–100 VSW %. Three measurements of soil moisture were taken from the surface before and after the CO_2 concentration monitoring period. Three soil cores (50 × 60 mm) from each sub-site were collected in February 2013. Bulk density (g cm^3) and total soil porosity (%) were calculated using the method by Carter and Gregorich (2007).

Results

Vegetation survey

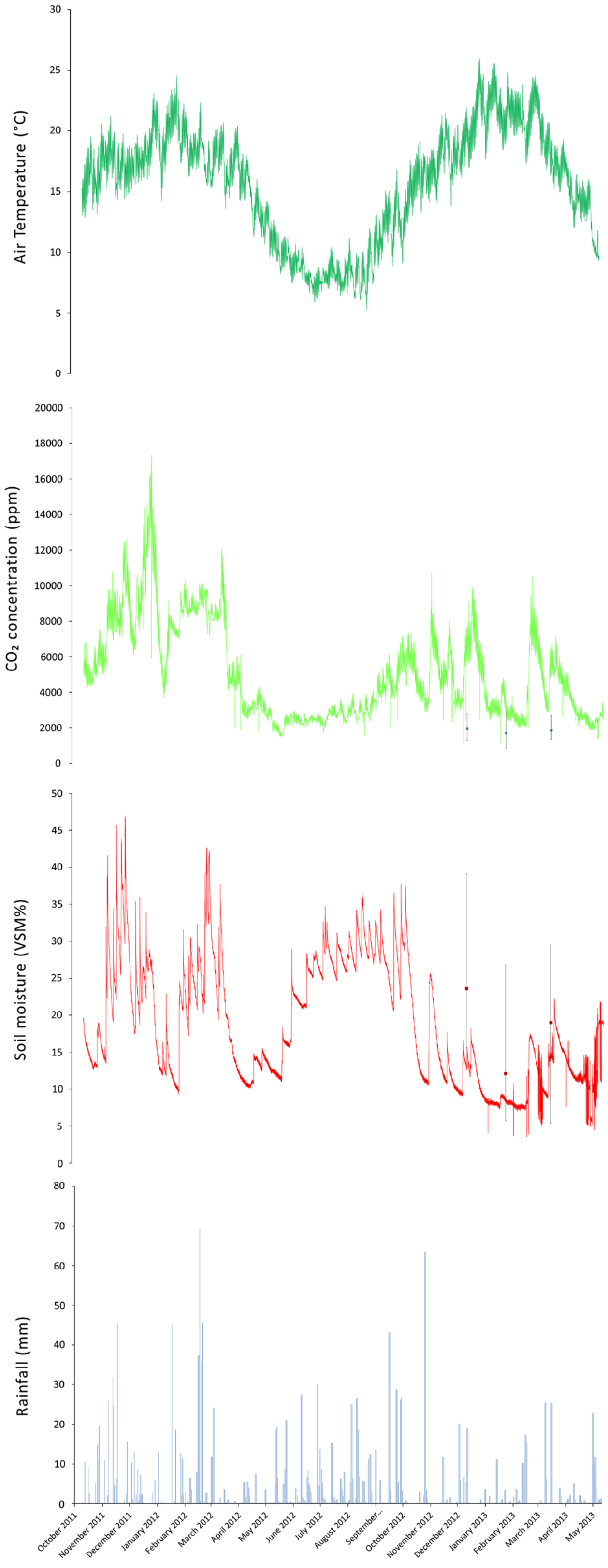
Three structural/compositional classes of vegetation were identified at the sample sites (Table 1). Sites at Spicer's Creek were located in either grassland or grassy woodland while those at Yarrangobilly conformed to a dry sclerophyll forest (Keith 2004).

Grassy woodlands adjacent to the grassland at Spicer's Creek were dominated by *E. stellulata* with a variable cover of understorey shrubs and a continuous herbaceous ground cover similar in composition to the adjacent grassland. The site burnt in 2007 supported substantially less biomass relative to the unburnt site as a consequence of the death of mature trees during the fire (30 %), as well as the almost complete destruction of the mature canopy (Table 1). Individuals which survived the fire were regenerating from basal shoots (coppicing) which had attained heights of up to 20 % of the mature canopy prior to fire. The combined cover of resprouting individuals and post-fire recruits comprised less than 20 % of the cover of *E. Stellulata* measured in unburnt stands (Table 1). There was no difference in composition or cover between the grassland site burnt 5 years ago and the unburnt control at the time of sampling. There was no significant difference in vegetation between the forest site burnt 10 years ago and the unburnt control.

Long-term continuous soil data

The multi-annual data show a seasonal trend in both air temperature and soil CO_2 concentration with depressed values for both during winter (June–August) compared to summer (December–February) (Fig. 2). The drop in soil CO_2 in the summer of 2012–13 corresponds with a drop in soil moisture as a result of lower than average rainfall during this period. The winter minimum and maximum daily air temperatures are 5.7 and 11.6 °C, respectively, with a mean of 8.3 °C, standard deviation of 1 °C. During the summer the average temperature is 20.7 °C with a standard deviation of 2.2 °C, and minimum and maximum of 13.4 and 22.4 °C, respectively. In summer the soil CO_2 concentration ranges from 1884 to 11,766 ppm, with a mean of 4189 ppm and standard deviation of 1901 ppm. In winter soil CO_2 concentration ranges from 1725 to 4225 ppm, with a mean of 2669 ppm and standard deviation of 396 ppm. During summer 2012–13, the soil moisture ranges from with a mean of 10 VSM % and a standard deviation of 3 VSM %. During winter 2012, the soil moisture is lower with a mean of 27 VSM % and standard deviation of 4 VSM % (Fig. 2).

The highest rainfall was received during February 2012 and October 2012. Soil CO_2 concentration was positively correlated with air temperature ($R^2 = 0.512$), soil moisture ($R^2 = 0.463$) and weakly with rainfall ($R^2 = 0.067$) all significant at 95 %. A sensitivity analysis of the regression of long-term soil CO_2 concentration and air temperature revealed that a 50 % increase in air temperature is required to cause a 33 % increase in soil CO_2 concentrations.



◀**Fig. 2** Soil CO_2 concentration, soil moisture, air temperature and monthly rainfall for Yarrangobilly 14/10/2011 to 14/05/2013 measured at 15 min intervals. The markers for soil CO_2 and soil moisture indicating the mean and total range across all burnt and control sites taken from the spot measurement campaign December 2012 to March 2013

Discrete soil data

The rainfall was above the 30-year average for summer 2011–12 whereas more typical for summer 2012–13 (Fig. 2). Throughout the sampling period the soil CO_2 concentrations range from 865 to 3177 ppm. The mean soil CO_2 concentration for all samples is 1901 ppm with a standard deviation of 519 ppm. The measurements sit at the lower end of the multi-annual data (Fig. 2). The measurements sit within the continuous data range for summer 2012–13 which ranges from 1884 to 11,766 ppm with a mean of 4190 ppm.

The soil moisture ranged from 5 to 39 VSM % with a mean of 17 VSM % and standard deviation of 7 VSM %. This was well within the long-term range (3–95 VSM %) and similar to the average long-term average of 20 VSM % taken from 14/10/2011 to 14/05/2013. However, in comparison to the continuous data for summer 2012–13 which ranges from 3.6 to 18.2 VSM % with a mean of 9.8 VSM %, the spot campaign measurements are relatively high. The soil temperature ranges from 12 to 29 °C with an average of 19 °C across all sites. Soil porosity ranged from 46.36 to 68.09 % with a mean of 56.04 % and a standard deviation of 6.43 %. The bulk density ranged from 0.58 to 1.09 g cm^{-3} across all sites with a mean of 0.93 g cm^{-3} and standard deviation of 0.15 g cm^{-3} (Table 2).

Multiple regression was used to examine the effect of vegetation type (grassland or woodland), condition (burnt or unburnt), and mean soil moisture, plus their interactions, on mean soil CO_2 concentration at the grassland and woodland sites at Spicer's Creek 5 years post-fire (Fig. 3). The sclerophyll forest sites at Yarrangobilly were analysed separately due to their floristic distinctiveness and greater post-fire age (10 years).

Soil moisture had a significant positive effect on soil CO_2 concentration in the grassy woodland and grassland sites at Spicer's Creek ($p < 0.05$). Vegetation type had a significant effect on soil CO_2 ($p < 0.05$) with higher concentrations on average in the woodland sites than in the grassland sites. There was no significant effect of condition, (i.e. burnt or unburnt) on soil CO_2 concentration across vegetation types. In the woodland community, soil CO_2 at the burnt site was

Table 2 Summary of soil CO_2 concentration, soil temperature, soil moisture, total soil porosity and soil bulk density data at three paired sites from the spot campaign December 2012–March 2013

Site name	Time since fire	Location	Mean soil bulk density, g cm^{-3} (SD)	Mean total soil porosity, % (SD)	Vegetation type	CO_2 concentration (ppm)											
						December		February				March					
						Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
B1	10	Y	1.07 (0.05)	ND	Dry sclerophyll forest	1665	16	3157	14	1639	7	2158	15	2348	29	2023	15
U1	>10		0.97 (0.13)	ND	Dry sclerophyll forest	2669	81	1410	11	1520	8	1979	14	1932	8	2448	30
B2	5	SC	0.94 (0.09)	57.88 (3.46)	Grassland	2247	82	881	7	1501	4	1441	19	2039	11	1506	11
U2	>5		1.00 (0.09)	51.02 (5.85)	Grassland	1831	31	1570	28	1485	7	1213	16	1917	25	1752	32
B3	5	SC	0.72 (0.14)	62.54 (5.5)	Grassy woodland	2252	58	1712	18	1861	13	1376	16	1427	6	1615	34
U3	>5		0.85 (0.07)	57.69 (1.62)	Grassy woodland	3114	29	2897	5	1779	18	2690	13	1672	11	1738	18
						Soil temperature (°C)											
B1	10	Y	1.07 (0.05)	ND	Dry sclerophyll forest					14.5	0.22	14.9	0.21	12.8	0.45	14.6	0.21
U1	>10		0.97 (0.13)	ND	Dry sclerophyll forest	27.3	0.8	14.1	0.05								
B2	5	SC	0.94 (0.09)	57.88 (3.46)	Grassland			16.8	0.57	21.6	0.19	23.6	0.16				
U2	>5		1.00 (0.09)	51.02 (5.85)	Grassland	21.2	0.7							17.6	0.87	17.9	0.2
B3	5	SC	0.72 (0.14)	62.54 (5.5)	Grassy woodland					20.5	0.11	16.8	0.25			21.1	0.91
U3	>5		0.85 (0.07)	57.69 (1.62)	Grassy woodland	16.5	1.07	22.3	0.44					18.3	0.5	22.7	0.75
						Soil moisture (volumetric soil moisture %)											
B1	10	Y	1.07 (0.05)	ND	Dry sclerophyll forest	21.1	6.8	9.6	2.1	9.6	0.7	14.3	3.9	19.3	5.1	15.6	3.7
U1	>10		0.97 (0.13)	ND	Dry sclerophyll forest	22.8	4.3	11.3	3.2	9.4	0.8	15.6	3.7	12.3	4.9	10.5	2.9
B2	5	SC	0.94 (0.09)	57.88 (3.46)	Grassland	22.7	5.0	14.5	2.9	11.1	2.5	10.2	0.8	21.6	0.9	24.5	2.1
U2	>5		1.00 (0.09)	51.02 (5.85)	Grassland	21.7	3.7	12.1	3.7	13.6	4.4	12.1	1.9	18.8	6.0	24.2	1.0
B3	5	SC	0.72 (0.14)	62.54 (5.5)	Grassy woodland	25.0	6.3	14.5	2.9	10.5	2.0	13.1	6.9	22.9	4.0	22.3	3.5
U3	>5		0.85 (0.07)	57.69 (1.62)	Grassy woodland	25.8	8.0	12.4	2.2	9.0	3.1	15.3	4.1	22.5	2.1	21.4	5.2

B burnt site, *ND* no data, *SC* Spicer's Creek, *SD* standard deviation, *U* unburnt site, *Y* Yarrangobilly Caves

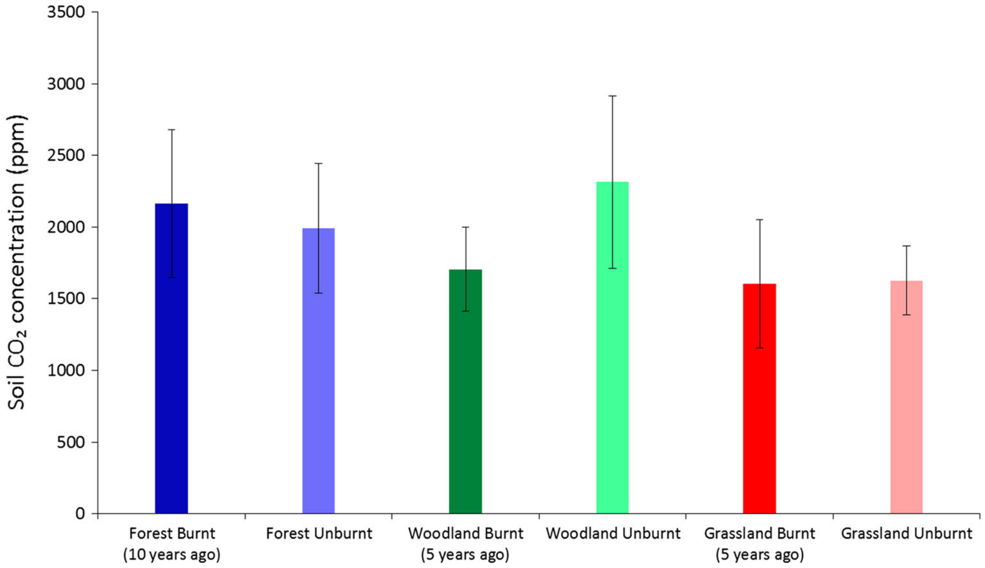


Fig. 3 *Bar chart* comparing the average short-term soil CO_2 concentration measurements between each sampling site ($n = 6$) during the monitoring period December 2012–March 2013

substantially reduced (approximately 700 ppm or 26 % lower) relative to the unburnt control; however, this result was not statistically significant.

There was no significant effect of soil moisture or condition (burnt or unburnt) on soil CO_2 concentration at the sclerophyll forest sites at Yarrangobilly 10 years post-fire.

Soil moisture had a significant positive effect on soil CO_2 concentration. There was no significant relationship between soil CO_2 concentration and soil temperature. Soil moisture was the most effective predictor of CO_2 soil concentrations using a regression best subsets model, as opposed to soil temperature and a combination of soil moisture and temperature.

Discussion

Effect of fire on soil CO_2 concentrations 5 and 10 years after a fire

The depressed soil CO_2 concentration at the burnt relatively to the unburnt woodland sites after 5 years is attributed to a reduction in aboveground biomass. Fire removes aboveground biomass by combustion which reduces the root respiration and thus, autotrophic contribution to soil CO_2 concentration. The results of this study have shown that fire caused a 30 % reduction in mature trees in burnt woodland sites and the complete destruction of the tree canopy. The bulk of the biomass, and hence respiratory output, can be attributed to trees for which there was an 80 % reduction in foliage cover. Furthermore, the sites are equivalent in grass cover but this is assumed to have less influence on CO_2 production. The spatial variation in soil CO_2 concentration within each site could be attributed to the placement of the probes in proximity to tree roots and in areas of high heterotrophic respiration. Separating the heterotrophic and autotrophic respiratory contributions to total soil CO_2 concentration was beyond the scope of this study; however, previous research has confirmed that multi-annual post-fire microbial recovery is strongly dependent on regeneration of vegetation.

There was no significant difference in soil CO_2 concentrations in the woodland site burnt 10 years ago and the unburnt control. This is attributed to the complete recovery of vegetation at the burnt site. A vegetation survey revealed that differences in tree, shrub and ground cover between the burnt and unburnt forest located at Yarrangobilly were minor. The sites were compositionally similar, and differences in composition can be attributed to variability typical for the scale of sampling (Armstrong et al. 2013). The primary difference in biomass contribution between the sites related to the presence of a single dominant at the unburnt site (*E. pauciflora*) compared with the co-dominance of *E. pauciflora, E. dives* and *E. dalrympleana* at the burnt site. However, since the three species are similar in stature and fire response (epicormic resprouters) it is assumed they were functionally equivalent in terms of carbon allocation, and hence CO_2 efflux. This notion is supported by previous research which demonstrated that post-fire recovery of vegetation is dependent on the plant functional type and their associated fire response strategies. For example, obligate resprouters store starch in lignotubers from which new growth emerges following fire. Conversely, other species are killed by fire, but produce seeds that are protected in hard capsules and readily germinate after a fire (Knox et al. 2001).

There was no significant difference in soil CO_2 concentration between burnt and unburnt grassland sites at 5 years post-fire. This supports previous research which indicates grasslands have a rapid post-fire recovery (McCarron and Knapp 2003; Pereira et al. 2013; Voncina et al. 2014). We hypothesise that swift recovery is due to the short duration of grassland fires and a dominance of flaming as opposed to smouldering combustion, which consumes the aboveground biomass causing a brief peak in temperature that is rarely transferred belowground, therefore protecting subterranean shoots and roots from damage (Zedler 2007).

Comparing unburnt controls, the soil CO_2 concentration was substantially lower in grassland site than woodland sites. This is due to lower carbon allocation and hence, CO_2 production. This variation in soil respiration supports the findings of a study conducted on Australian subalpine snow gum woodlands and grasslands where the difference in respiratory output was attributed to greater aboveground biomass in woodlands than grasslands, which increases the volume of carbon substrate for heterotrophic respiration. This relationship between soil carbon content and respiration rate was also evident in the vertical soil profile where both carbon content and respiration decrease with depth (Jenkins and Adams 2010). Alternatively, Jenerette et al. (2009) found that the difference in primary productivity between woodland and grassland sites was due to easier access to groundwater because of the deeper root structure of trees in comparison to grassland, thus increasing primary productivity and consequently soil CO_2 concentrations. Raich and Tufekcioglu (2000) provide a succinct summary of studies comparing respiration rates between vegetation types concluding that the principle controls include the type and amount of plant detritus produced, root biomass and the extent to which vegetation regulates soil temperature and moisture conditions.

The long-term multi-annual soil CO_2 concentration was positively correlated with both air temperature and soil moisture. A best subsets regression model demonstrated that air temperature was the best single predictor of soil CO_2 concentration ($R^2 = 0.26$). This supports previous research which indicates the dependence of soil respiration on seasonal and interannual temperature variation (Keller et al. 2006). The spot campaign CO_2 data were positively correlated with soil temperature and soil moisture; however, a best subsets regression model indicates that soil moisture, rather than temperature, was the best indicator of soil CO_2 concentration. This appears to be also supported in the multi-annual data if you compare the two summers: soil moisture appears to have quite an impact on soil CO_2, despite what the regression model says.

The mean soil CO_2 concentration is 26 % higher at the unburnt control than at the woodland site burnt 5 years prior. A sensitivity analysis of the regression of the multi-annual soil CO_2 concentration and air temperature data reveals that a 36 % increase in air temperature is required to cause an increase in soil CO_2 concentration comparable to the effect of fire after 5 years. This suggests that the magnitude of the impact of fire on lowering soil CO_2 concentrations 5 years after a fire in grassy woodland is comparable to a 36 % increase in air temperature.

Implications for karst processes

Speleothem growth is controlled by a number of factors including effective precipitation, temperature, infiltration amount, soil CO_2 production, cave-air CO_2 concentration, drip rate, drip water calcium concentration, prior calcite dissolution and bedrock/soil thickness (Cowan et al. 2013). Some factors have a confounding effect on calcite growth, for example while a higher temperature makes conditions more favourable for soil-dwelling organisms and plants, therefore increasing the soil CO_2, it also reduces infiltration volume and, consequently, drip rate. Soil thickness is also a major variable determining the amount of CO_2 dissolved in the infiltrating solution, and likewise whether the contact time with carbonate minerals in the bedrock is sufficiently long to allow equilibria with carbonate minerals. Both factors will affect the Ca concentration of the speleothem-forming drip waters. Despite being a complex process, the two basic requirements for cave speleothem growth to occur are sufficiently high soil CO_2 concentrations to allow for carbonate dissolution and precipitation and availability of water for recharge (Baker et al. 1993).

Soil CO_2 concentration determines the amount of calcite that can be dissolved at equilibrium. An infiltrating solution with a lower concentration of dissolved CO_2 has a lower capacity for dissolving calcium carbonate and delivers a solution with a lower Ca concentration to the cave. Calcium concentration of drip water has been positively correlated with calcite growth (Genty et al. 2000).

Speleothem growth rate has been widely used as the key proxy in paleoclimate reconstructions (Brook et al. 1999; Qin et al. 1999; Holmgren et al. 2001; Hou et al. 2002; Tan 2003; Trouet et al. 2009). Wildfire has occurred throughout the Holocene in a wide range of environments including boreal forests in China and Russia, savannah grasslands in Africa, tropical forests in Thailand and temperate forest in the USA and Europe (Carcaillet et al. 2002). For example, charcoal records from lake sediments in the Scottish Highlands revealed that landscape-level burning of vegetation and large-scale fire occurred throughout the course of the Holocene and were linked to the development of heath and blanket mire communities (Froyd 2006). In China, soil charcoal records reveal that biomass burning was high during the late Holocene and disturbance caused by human induced fires has steadily increased during the last 3100 years (Chang Huang et al. 2006). In fire prone areas, the accuracy of paleoclimate speleothem proxy records could be affected if annual growth laminae were driven by seasonal fluctuations in soil CO_2. In fire prone areas, reduced speleothem growth following fire could be erroneously interpreted as a climatic change. This means that the seasonal fluctuations in speleothem growth, exhibited as seasonal couplets with differing crystal fabric, would be less pronounced (Munoz et al. 2009). Annually resolved stalagmite growth rate records from regions from Scotland (Proctor et al. 2000) to China (Tan et al. 2014) could be affected not only by climate but also by the effects of wildfire on soil CO_2.

Conclusions

- Soil CO_2 concentration in the woodland site was substantially lower in burnt sites after 5 years. The difference was attributed to a change in vegetation community structure caused by a reduction in biomass and removal of more established tree individuals. However, there was no difference in soil CO_2 concentration between the burnt and unburnt grassland sites after 5 years, indicating that post-fire recovery of soil CO_2 concentrations varies between vegetation types.
- There was no significant difference in soil CO_2 concentrations between the forest site burnt 10 years prior and the paired unburnt site suggesting that the respiration post-fire recovery time in subalpine woodland is 5–10 years.
- Fire could affect karst processes driven by a decrease in the CO_2 enriched infiltration water which leads to lower calcium concentration in the drip water.
- This study has highlighted the importance of fire as a process that could cause a multi-annual non-linear response in karst subsurface processes, e.g. speleothem growth rate in the context of paleoclimate proxy records in fire prone regions such as Australia.

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