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Wildfire effects on soils and soil processes

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Summary

- Fires influence soil physical, chemical and biological processes, but the long-term effects of intense, widespread fires such as those in 2019–20 on these soil processes is little known.
- Fires heat the soil surface, convert the protective layer of litter and vegetation to ash, and may make the surface water repellent. These processes have flow-on effects to soil chemical and biological processes, and run-off and erosion. The nature and magnitude of these effects will vary with soil type and moisture content, but also depend on fire intensity and landscape context.
- The magnitude of erosion varies with slope, soil type, geology, aspect, vegetation cover, fire intensity, fire connectivity and rainfall intensity. Erosion tends to be greater on ridgelines and in steep terrain, and average rates are in the order of 20–80 t sediment ha^{-1} or 47–77 t ha^{-1} for the 2019–20 fires. Recovery of eroded soils from megafires is likely to be very slow, given the extremely low rates of soil formation in Australia (~1 mm every century).
- The effects of large wildfires, such as the 2019–20 fire, on soil nutrient dynamics and subsequent plant growth are complex and uncertain. A single wildfire can substantially reduce soil carbon and nutrient pools, but plant and nutrient pools are likely to recover within a decade. Larger, high temperature wildfires, however, have more substantial effects. They deposit sizeable quantities of ash containing large amounts of phosphorus that have been stored in vegetation. Nitrogen (N) loss and added phosphorus (P) can reduce N:P ratios, with a risk of lasting nitrogen limitation. This retards long-term vegetation recovery, which may be offset by a pulse of recruitment of N-fixing plants such as *Acacia*. Full recovery of nutrient cycles and plant cover and diversity after the 2019–20 fires is likely to be slow in many severely burnt places.
- There is also strong feedback between the recovery of plants and soils and that of soil fauna such as ants and termites that promote water flow through the soil and help to reduce the run-off of water. The extent to which wildfires impact soil-dwelling microbes and arthropods, and then how such impacts on

invertebrate communities will influence soil recovery processes such as litter decomposition and nutrient mineralisation, is poorly resolved.

- There are critical knowledge gaps about the impacts of severe fires, and of fire regimes, on soils, and the broader ecological ramifications of such impacts; and such knowledge gaps severely constrain our ability to manage or mitigate such impacts. Accordingly, our recommendations highlight priority research needs.

Introduction

> *Fire, in result, and an example of such result is erosion, affects each one of us, whether we are of the towns or of the country. The common weal is most grievously threatened by erosion. (Stretton 1939)*

Wildfire is a major ecological process worldwide and an important driver of above-ground processes. Less well understood, however, is how fire affects soils and below-ground processes. Soils support a range of critical ecosystem services. They absorb water, store and release nutrients, filter pollutants, provide a substrate for plants and habitat for biota that drive critical nutrient processes, and are a source of sediment, organic matter and nutrients (DeBano *et al*. 1998).

The 2019–20 wildfires in eastern and southern Australia cast a light on the ecological effects of large-scale wildfires, with significant losses in biodiversity (see Chapters 4–16), plant production, forestry assets and property (see Chapter 2). While the immediate effects of fire on livelihoods and human capital have been devastating, fire is a natural event, and many plant species need fire to initiate germination (Hodges *et al*. 2019; Chapter 9). Yet it is known that megafires, such as the 2019–20 wildfires, are devastating for soils and soil processes, with huge losses of sediment, water, carbon and nutrients, and reductions in soil structural integrity. These changes have substantial flow-on effects to a range of biota, processes and functions at varying spatial scales.

In this chapter we discuss how wildfire affects those soil processes that are associated with the consumption of vegetation, the modification of soil surface structure, and changes in soil carbon and nutrient cycles. These factors alter the way that water moves through the landscape and increase the likelihood of catchment-wide sediment removal. We draw on Australian and international literature, with a general focus on large-scale fires to understand how the 2019–20 wildfires impacted Australian soils. Finally, we recognise critical knowledge gaps and make recommendations to remedy those deficiencies.

Physical processes: heating, ash deposition and repellancy

Fire heats the soil surface

The magnitude of soil surface heating by fire determines the extent to which the major soil components (e.g. nutrients, ions, organic matter) will change during fires. This effect of heating depends on the conductivity of the soil, bulk density (how densely packed the soil particles are) and the moisture content, as well as fuel loads and fire characteristics such as intensity and duration (DeBano *et al*. 1998). Overall, sandy soils are more susceptible to fire than clay soils, not only because they are more conductive (i.e. fire can penetrate deeper into sands), but also because they contain less organic matter, often occur on steep land and are more poorly structured, and therefore erode more easily.

Soil surface temperatures range from ~100°C during mild fire, to 800°C in moderate to high-intensity fires, to 1500°C during extreme fire events, such as many of the 2019–20 wildfires (DeBano *et al*. 1998). While a low to moderate fire will leave some litter and organic matter on the surface, high to intense fires can cause total canopy loss, and the complete combustion of litter and soil organic matter to several centimetres depth. These impacts have the potential to physically alter soil properties that influence infiltration, runoff and erodibility of soil (Fig. 5.1).

In general, organic matter loss commences at temperatures exceeding 100°C. The temperature at which soil constituents (e.g. nutrients and cations) are vaporised depends on their temperature tolerances. Carbon, sulphur and nitrate are volatilised by 200°C, and by ~450–500°C almost all organic matter has been combusted (De Bano *et al*. 1998). Substantial soil physical and chemical changes occur once the surface reaches temperatures of 400–600°C. Most temperature effects occur within a few centimetres of the surface, with values rarely exceeding 150°C at depths of 50 mm (DeBano *et al*. 1998).

Soil temperatures also affect biological processes. Low-intensity fires (e.g. hazard reduction burns) may fail to heat the surface above 40°C at 50 mm depth, thereby failing to break seed dormancy for the germination for some plants (Penman and Towerton 2008). High-intensity fires are therefore critical for the germination of many plant species (Chapter 9).

Ash deposition on the fire ground

Ash comprises charred, loose material < 1 cm in size and is formed from the complete oxidation of vegetation and soil organic matter. Ash loads increase with fire intensity, with values of 1 to 35 t ha^{-1} recorded for low to severe fires (respectively) in Australia

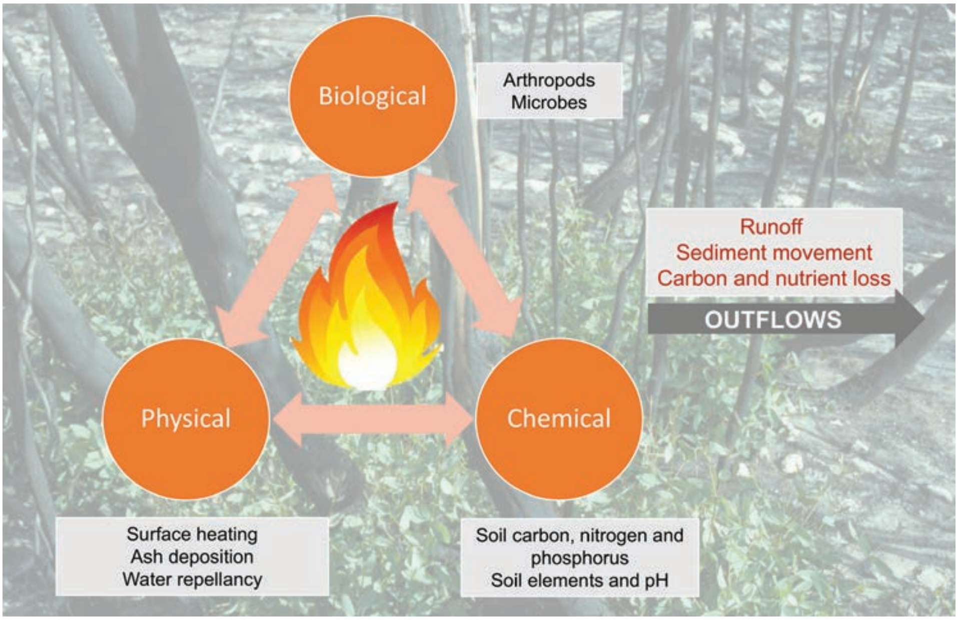

Fig. 5.1. Conceptual model of the direct effects of fire on biological, physical and chemical properties and processes, and resultant outflows.

(Santin *et al.* 2014). The chemical composition of ash also varies with fire severity. Low-intensity fires generate ash of finely combusted litter and vegetation, whereas extreme fires generate mineral-rich ash (Santin *et al.* 2014). Ash increases the bioavailability of nutrients, particularly nitrates and phosphorus ('ash bed effect', Chambers and Attiwill 1994), releases cations, increases soil pH, and can alter soil composition for several years after fire. Reacidification of burnt soils may take half a century to reach pre-burn soil pH levels (Khanna *et al.* 1996).

Soil surfaces may repel water

The soil beneath Australian vegetation, particularly eucalypts, is generally hydrophobic (non-wetting) due to high concentrations of phenols and oils from decomposing litter, and a proliferation of fungal hyphae (Howell *et al.* 2006). The effects of fire on the wettability of soils are complex; low-intensity fires tend to activate or induce hydrophobicity, which can persist for many months until invertebrates (ants, termites and worms) reactivate their burrows and alter the distribution of hydrophobic hyphae and oils. Hydrophobicity is likely to affect post-fire seedling establishment (Bailey *et al.* 2015), by affecting moisture around seeds. Under moderate or intense fires (above ~400°C) this repellency tends to be reduced (Cawson *et al.* 2016), promoting moisture accumulation and germination (Bailey *et al.* 2015).

Chemical processes: nutrients, carbon and elements

Fire alters soil biogeochemical cycles (Adams *et al.* 2020), and nutrient balances and functions via multiple pathways of losses and inputs (Fig. 5.1; Bowd *et al.* 2019). Fire can reduce soil nutrient pools through volatilization (e.g. conversion of urea to ammonia, which is lost from the soil), leaching (where soluble nutrients are removed from the soil by water), extensive plant uptake as vegetation recovers, and post-fire soil erosion (Bowd *et al.* 2019). Soil carbon and nutrient loss is greatest i) at the surface (Hobley *et al.* 2019), ii) from labile (available or organic) pools, which are susceptible to heating (Butler *et al.* 2018), and iii) at sites that are frequently burnt or under greater fire intensity (Toberman *et al.* 2014).

Elemental responses to fire are varied

Fire reduces elements such as Na, K, Mg, and S through volatilization and consumption of plant tissue (Ludwig *et al.* 1998) but increases others such as Cu, Mn, and Zn through ash deposition (Abraham *et al.* 2018). The greatest losses occur when soil organic carbon is converted to CO_2. For example, 27 t ha^{-1} of carbon were lost from the top 10 cm of the soil during the 2013 wildfire in the Warrumbungles National Park (Tulau *et al.* 2019). These rates are comparable to those values lost during the 2019–20 fires. These soil organic carbon losses may be compensated by short-term increases in ash loads, as shown by studies in eucalypt forests in eastern Australia (1.55 t ha^{-1} C loss cf. 1.67 t ha^{-1} in ash; Krishnaraj *et al.* 2016) and long-term increases through plant regeneration. However, repeated fires are likely to reduce recovery of soil organic carbon (Hobley *et al.* 2019).

Fire typically reduces soil nitrogen pools when ammonia is lost to the atmosphere. Rapid regrowth after fires also increases the demand for nitrogen as microbes take up (immobilise) most of the nitrogen to help them break down organic matter (Chambers and Attiwill 1994). Post-fire systems therefore tend to become nitrogen limited. However, fire releases phosphorus, which is derived from soil parent material, and released when litter and plants combust and are returned as ash (Butler *et al.* 2018). Levels of released phosphorus can be an order of magnitude greater than that in long-unburnt sites (Blake *et al.* 2020). With more frequent and/or intense fires, phosphorus increases, and nitrogen declines, leading to reductions in the N:P ratio and therefore nutrient imbalance. Reductions in the N:P ratio can have substantial effects on vegetation composition and diversity, for example, the easing of phosphorus limitations or increasing nitrogen limitations, as well as on microbial biomass and the abundance of some invertebrates (Butler *et al.* 2017).

Fire, however, can also stimulate the germination of seeds of plants such as *Acacia, Casuarina* and leguminous species that fix nitrogen (Adams and Attiwill 1984), leading to a recovery of nitrogen. The rapid recovery of *Acacias* after the intense Warrumbungle fires (Gordon *et al.* 2017) suggests that a similar response from N-fixing plants is likely within a few years of the 2019–20 wildfires.

Outflows: runoff and sediment

Though the impacts of fires on soil is complex, it is likely that the 2019–20 fires had a major impact on landscape stability. Estimates of sediment removal during the 2019–20 wildfires suggest erosion rates ranging from 47 to 77 t ha^{-1} across 5.37 million ha of burn area in New South Wales alone (DPIE 2020), which would represent a phenomenal displacement of 47 million t of soil, after accounting for background sediment movement. The magnitude of erosion depends on terrain (slope, soil type, geology, aspect), remaining vegetation cover, fire intensity and connectivity, and rainfall intensity (Yang *et al.* 2020), but tends to be greatest on steep-sided gullies and ridgelines where fire intensity is greatest (Nyman *et al.* 2014; Tulau *et al.* 2019; Blake *et al.* 2020). Apart from total erosion loads, event-based erosivity estimated using satellite and radar following these mega fires was estimated at ~5 t ha^{-1} month^{-1}, which is ~30 times higher than the pre-fire erosion rates, largely due to intense rainstorms following fire (Yang *et al.* 2020). Furthermore, the magnitude and extent of sediment loss may also increase with the intensity of mechanical disturbance after fire, which in itself creates considerable runoff (Smith *et al.* 2011).

These rates are similar to those from other comparable fire events across temperate areas in eastern Australia. For example, sediment removal following wildfire in the Warrumbungle National Park in 2013 was estimated to be ~25 t ha^{-1} across an area of ~56 000 ha, compared with background pre-fire levels of ~1 t ha^{-1} (Tulau *et al.* 2019; Fig. 5.2). These estimates are consistent with those resulting from subalpine woodland and forest fires in the Snowy Mountains (3–95 t ha^{-1}; Smith and Dragovich 2008), the 1983 Sydney fires (28–64 t ha^{-1}; Atkinson 2012), and 2013 Balmoral fires in Victoria (34 t ha^{-1}; Santin *et al.* 2015). Overall, erosion rates following wildfire can be three orders of magnitude greater than background rates (Langhans *et al.* 2016).

Effects on biodiversity

The impacts of fire on soils have many consequences for biodiversity, with these effects influenced by fire severity and environmental settings. Increased run-off and deposition of soils and ash in aquatic systems after fire leads to major impacts on the health and biodiversity of aquatic systems, that may extend many kilometres downstream of direct fire impacts (Chapter 6), and in some cases to estuarine and coastal marine systems (Chapter 7).

Less well considered are the impacts on the soil biological communities, and the subsequent feedback effects on recovery of ecological structure, function and composition

Fig. 5.2. Surface of the soil after the 2013 Warrumbungles fire showing the complete removal of the surface soil layers by fire and exposure of the B horizon. (Photo: Sally McInnes-Clarke)

(Chapter 11). For instance, soil arthropods and microbes process organic matter and release carbon and nitrogen. Like many faunal groups (Chapters 13–16), arthropods vary greatly in their susceptibility to fire, and the magnitude of impacts of fire on invertebrate communities is influenced by fire severity and fire regimes, and environmental settings. For example, collembola may take many years to return to pre-fire levels (Driessen and Greenslade 2004), affecting the ability of soils to process organic matter. Fire can suppress litter processing taxa such as cockroaches (Arnold *et al*. 2017) and alter predator–prey relationships among litter-dwelling invertebrates (Dawes-Gromadzki 2007).

Recovery of hydrological function and surface stability generally occurs 18–36 months after fire, depending on vegetation regrowth, reductions in soil repellency and reduced soil erodibility (Smith *et al*. 2011). However, recovery of infiltration capacity may depend on the reinstatement of animal-created pores and burrows of ants and spiders, and even the passages around plant roots (macropores; Holden *et al*. 2014), which drive hydraulic conductivity.

The effect of fire on invertebrates also varies widely among ecosystems, and with fire severity and fire regimes. For example, few differences were found in collembolan communities 12–24 years after fire in a Tasmanian buttongrass community (Driessen and Greenslade 2004) whereas ants were more abundant in burnt sites in arid mallee woodlands (Kwok and Eldridge 2015), suggesting a rapid response to fire in this ecosystem. In contrast, the impact of even a single wildfire may still be evident in some invertebrate communities for at least 50 years (Henry *et al*. 2022). Though the 2019–20 occurred predominantly across forested systems, there is a real opportunity to explore the impacts of fires on the invertebrate communities from different vegetation types, and attempt to understand the subsequent implications for recovery of these ecosystems.

The implications of the fires on the soil microbial community, and the implications for recovery of systems, remain poorly understood. Though soil type, moisture content and temperature determine the response of soil microbes to fire (Chambers and Attiwill 1994), fire reduces soil microbial biomass and therefore soil respiration, even at low temperatures < 120°C, and this effect is greatest close to the soil surface (DeBano *et al*. 1998). Soil heating and reduced soil acidity from ash can alter competition between microbial autotrophs and heterotrophs, thereby promoting soil nitrification (Bauhus *et al*. 1993). Microbial changes may limit vascular plant recovery as fire can destroy specialist microbes that affect seed germination (Senior *et al*. 2018). However, microbial biomass can recover relatively quickly within a few years of fire (Liu *et al*. 2015), but not under frequent or high-intensity fires, which can suppress soil respiration and reduce soil organic carbon pools (Liu *et al*. 2015).

Conclusions

In the report from the Royal Commission into the 1939 fires, Stretton wrote at length on the serious consequences of resultant soil erosion in relation to infrastructure, water quality and livelihoods: ‘The damage to river banks causes encroachments upon and destruction of areas otherwise usable for agricultural and pastoral purposes. Erosion generally is a constant crippling enemy to water supply, whether for the big cities or for the farmer who draws upon an irrigation scheme for the nourishment of his crops and pastures.’ Ecological impacts of such severe fires are also likely to be profound. Soil is the foundation of myriad ecological processes, and hence the influence of wildfires on soils is likely to have many long-lasting ramifications across ecosystems. However, in terms of biodiversity and ecosystem health, knowledge of impacts, and feasible and effective pre- and post-fire management solutions, is limited, and there is a pressing need to address critical knowledge gaps (see ‘Recommendations’ below).

The 2019–20 wildfires will have long-lasting and substantial legacy effects on soils, and hence on the many other environmental components influenced by or associated with soils. Aquatic systems may take many years to recover from the high loads of sediment deposited from burnt areas. Source areas where soil biological activity is low and where soils are shallow will take many thousands of years to recover. This is because natural rates of soil formation in Australia are extremely low (1 mm per century; Stockmann *et al*. 2014). This recovery is likely to become increasingly tenuous with more frequent and intense fires predicted over the next century.

Invertebrates and microbes are critical to ecosystem function, and the feedbacks between fire, soils and ecosystem recovery remain poorly understood (see Chapters 10 and 11). It is critical to try to better understand not only the impacts and outcomes of high severity fires such as those of 2019–20, but also the impacts of multiple fires, and compounding threats such as drought. Only then perhaps can we expect to have a clear picture of the plant and animal communities that we might expect to dominate, or persist in, our landscape into the future.

Recommendations

Our review indicates that there will be many detrimental and diverse impacts of the 2019–20 wildfires on soils, and hence on the health, productivity and composition of environments.

However, this review also recognises that many critical knowledge gaps constrain our ability to evaluate the magnitude and duration of such impacts and, even more so, on how such impacts can be managed or mitigated. Such knowledge will become increasingly important for a future in which such megafires are likely to become more prevalent. Accordingly, our recommendations focus mostly on the need to resolve these key knowledge gaps in order to better understand and manage the impacts of megafires such as the 2019–20 wildfires, and fire regimes, on structure, function and composition of future landscapes:

- Remote sensing has provided good understanding of the extent of the 2019–20 fires (e.g. DPIE 2020, Yang *et al*. 2020), but we have poor understanding of the extent and magnitude of impacts of large-scale fires on soil structure, function and composition. Most of our understanding of ecological effects of fire is based on more localised or lower intensity events. There is priority need to build the evidence base from the 2019–20 fires, including to identify those soil and landscape attributes that most influence the levels of erosion and sediment deposition.
- There is a priority need to better understand the responses of soils to fire regimes. Legacy effects of previous fires are likely to drive future fire impacts on soils, but the interactions between previous and future fires is poorly known.
- More research is needed to improve knowledge of the linkages between fire effects on soils, and flow-on effects to other parts of the ecosystem, such as the changes in structure, function and composition of plants and animal communities in terrestrial, freshwater and marine systems.
- Given their importance for the recovery of 'soil health', more research is needed to document and monitor the rate and characteristics of post-fire changes in soil fauna communities.
- Relatively little is known about how we can improve the ecological resilience of soils to cope with the eventual next wave of high-intensity wildfire. Current evidence suggests that recovery of soil function following high-intensity wildfire will be protracted, but techniques to mitigate the effects of fires on soils are not known. Hence, there is a priority need to enhance the evidence base needed to underpin the design and implementation of such mitigation and management techniques.

References

Abraham J, Dowling K, Florentine S (2018) Influence of controlled burning on the mobility and temporal variations of potentially toxic metals (PTMs) in the soils of a legacy gold mine site in Central Victoria, Australia. *Geoderma* **331**, 1–14. doi:10.1016/j.geoderma.2018.06.010

Adams MA, Attiwill PM (1984) Role of *Acacia* spp. in nutrient balance and cycling in regenerating *Eucalyptus regnans* F. Muell. forests. I. Temporal changes in biomass and nutrient content. *Australian Journal of Botany* **32**, 205–215. doi:10.1071/BT9840205

Adams MA, Shadmanroodposhti M, Neumann M (2020) Causes and consequences of eastern Australia's 2019–20 season of mega-fires: a broader perspective. *Global Change Biology* **26**, 3756–3758. doi:10.1111/gcb.15125

Arnold KT, Murphy NP, Gibb H (2017) Post-fire recovery of litter detritivores is limited by distance from burn edge. *Austral Ecology* **42**, 94–102. doi:10.1111/aec.12404

Atkinson GA (2012) Soil erosion following wildfire in Royal National Park, NSW. *Proceedings of the Linnean Society of New South Wales* **134**, 1–13.

Bailey TG, Davidson NJ, Close DC (2015) Patterns of soil water repellency in response to coarse woody debris and fire: implications for eucalypt regeneration in dry forests. *Plant and Soil* **397**, 93–102. doi:10.1007/s11104-015-2605-3

Bauhus J, Khanna PK, Raison RJ (1993) The effect of fire on carbon and nitrogen mineralization and nitrification in an Australian forest soil. *Australian Journal of Soil Research* **31**, 621–639. doi:10.1071/SR9930621

Blake D, Nyman P, Nice H, D'Souza FML, Kavazos CRJ, *et al.* (2020) Assessment of post-wildfire erosion risk and effects on water quality in south-western Australia. *International Journal of Wildland Fire* **29**, 240–257. doi:10.1071/WF18123

Bowd EJ, Banks SC, Strong CL, Lindenmayer DB (2019) Long-term impacts of wildfire and logging on forest soils. *Nature Geoscience* **12**, 113–118. doi:10.1038/s41561-018-0294-2

Butler OM, Lewis T, Chen CR (2017) Fire alters soil labile stoichiometry and litter nutrients in Australian eucalypt forests. *International Journal of Wildland Fire* **26**, 783–788. doi:10.1071/WF17072

Butler OM, Ekser JJ, Lewis T, Mackey B, Chen C (2018) The phosphorus-rich signature of fire in the soil–plant system: a global meta-analysis. *Ecology Letters* **21**, 335–344. doi:10.1111/ele.12896

Cawson JG, Nyman P, Smith HG, Lane PNJ, Sheridan GJ (2016) How soil temperatures during prescribed burning affect soil water repellency, infiltration and erosion. *Geoderma* **278**, 12–22. doi:10.1016/j.geoderma.2016.05.002

Chambers DP, Attiwill PM (1994) The ash-bed effect in *Eucalyptus regnans* forest: chemical, physical and microbiological changes in soil after heating and partial sterilization. *Australian Journal of Botany* **42**, 739–749. doi:10.1071/BT9940739

Dawes-Gromadzki TZ (2007) Short-term effects of low intensity fire on soil macroinvertebrate assemblages in different vegetation patch types in an Australian tropical savanna. *Austral Ecology* **32**, 663–668. doi:10.1111/j.1442-9993.2007.01752.x

DeBano LF, Neary DG, Ffolliott PF (1998) *Fire's Effects on Ecosystems*. John Wiley & Sons, New York.

DPIE (2020) *NSW Fire and the Environment 2019–20 Summary. Biodiversity and Landscape Data and Analyses to Understand the Effects of the Fire Events*. NSW Department of Planning, Industry and Environment, Sydney.

Driessen MM, Greenslade P (2004) Effect of season, location and fire on Collembola communities in buttongrass moorlands, Tasmania. *Pedobiologia* **48**, 631–642. doi:10.1016/j.pedobi.2004.08.002

Gordon CE, Price OF, Tasker EM, Denham AJ (2017) Acacia shrubs respond positively to high severity wildfire: Implications for conservation and fuel hazard management. *The Science of the Total Environment* **575**, 858–868. doi:10.1016/j.scitotenv.2016.09.129

Henry SC, Kirkpatrick JB, McQuillan PB (2022) The half century impact of fire on invertebrates in fire-sensitive vegetation. *Austral Ecology* **47**, 590–602. doi:10.1111/aec.13141

Hobley EU, Zoor LC, Shrestha HR, Bennett LT, Weston CJ, *et al.* (2019) Prescribed fire affects the concentration and aromaticity of soluble soil organic matter in forest soils. *Geoderma* **341**, 138–147. doi:10.1016/j.geoderma.2019.01.035

Hodges JA, Price JN, Nimmo DG, Guja LK (2019) Evidence for direct effects of fire-cues on germination of some perennial forbs common in grassy ecosystems. *Austral Ecology* **44**, 1271–1284. doi:10.1111/aec.12806

Holden J, Wearing C, Palmer S, Jackson B, Johnston K, *et al.* (2014) Fire decreases near-surface hydraulic conductivity and macropore flow in blanket peat. *Hydrological Processes* **28**, 2868–2876. doi:10.1002/hyp.9875

Howell J, Humphreys GS, Mitchell PB (2006) Changes in soil water repellence and its distribution in relation to surface microtopographic units after a low severity fire in eucalypt woodland, Sydney, Australia. *Australian Journal of Soil Research* **44**, 205–217. doi:10.1071/SR04176

Khanna PK, Ludwig B, Raison RJ (1996) Comparing modelled and observed effects of ash additions on chemistry of a highly acid soil. *Australian Journal of Soil Research* **34**, 999–1013. doi:10.1071/SR9960999

Krishnaraj SJ, Baker TG, Polglase PJ, Volkova L, Weston CJ (2016) Prescribed fire increases pyrogenic carbon in litter and surface soil in lowland *Eucalyptus* forests of south-eastern Australia. *Forest Ecology and Management* **366**, 98–105. doi:10.1016/j.foreco.2016.01.038

Kwok ABC, Eldridge DJ (2015) Does fire affect the ground-dwelling arthropod community through changes to fine-scale resource patches? *International Journal of Wildland Fire* **24**, 550–559. doi:10.1071/WF14088

Langhans C, Smith HG, Chong DMO, Nyman P, Lane PNJ, *et al.* (2016) A model for assessing water quality risk in catchments prone to wildfire. *Journal of Hydrology* **534**, 407–426. doi:10.1016/j.jhydrol.2015.12.048

Liu X, Chen CR, Wang WJ, Hughes JM, Lewis T, *et al.* (2015) Vertical distribution of soil denitrifying communities in a wet sclerophyll forest under long-term repeated burning. *Microbial Ecology* **70**, 993–1003. doi:10.1007/s00248-015-0639-y

Ludwig B, Khanna PK, Raison RJ, Jacobsen KL (1998) Modelling cation composition of soil extracts under ashbeds following an intense slashfire in a eucalypt forest. *Forest Ecology and Management* **103**, 9–20. doi:10.1016/S0378-1127(97)00173-4

Nyman P, Sheridan GJ, Smith HG, Lane PNJ (2014) Modeling the effects of surface storage, macropore flow and water repellancy on infiltration after wildfire. *Journal of Hydrology* **513**, 301–313. doi:10.1016/j.jhydrol.2014.02.044

Penman TD, Towerton AL (2008) Soil temperatures during autumn prescribed burning: implications for the germination of fire responsive species? *International Journal of Wildland Fire* **17**, 572–578. doi:10.1071/WF07092

Santin C, Doerr SH, Chafer CJ (2014) Ash deposition during wildfire and its threat to water quality. In *Advances in Forest Fire Research*. (Ed. DX Viegas) pp. 1658–1660. Imprensa da Universidade de Coimbra, Coimbra, Portugal.

Santin C, Doerr SH, Otero XL, Chafer CJ (2015) Quantity, composition and water contamination potential of ash produced under different wildfire severities. *Environmental Research* **142**, 297–308. doi:10.1016/j.envres.2015.06.041

Senior JK, O'Reilly-Wapstra JM, Schweitzer JA, Bailey JK, Potts BM (2018) Forest fire may disrupt plant-microbial feedbacks. *Plant Ecology* **219**, 497–504. doi:10.1007/s11258-018-0811-9

Smith HG, Dragovich D (2008) Post-fire hillslope erosion response in a sub-alpine environment, south-eastern Australia. *Catena* **73**, 274–285. doi:10.1016/j.catena.2007.11.003

Smith HG, Sheridan GJ, Lane PNJ, Bren LJ (2011) Wildfire and salvage harvesting effects on runoff generation and sediment exports from radiata pine and eucalypt forest catchments, south-eastern Australia. *Forest Ecology and Management* **261**, 570–581. doi:10.1016/j.foreco.2010.11.009

Stockmann U, Minasny B, McBratney AB (2014) How fast does soil grow? *Geoderma* **216**, 48–61. doi:10.1016/j.geoderma.2013.10.007

Stretton LEB (1939) 'Report of the Royal Commission into the Causes of and Measures Taken to Prevent the Bush Fires of January, 1939'. Government Printer, Melbourne.

Toberman H, Chen CR, Lewis T, Elser JJ (2014) High-frequency fire alters C:N:P stoichiometry in forest litter. *Global Change Biology* **20**, 2321–2331. doi:10.1111/gcb.12432

Tulau MJ, McInnes-Clarke SK, Yang XH, McAlpine RA, Karunaratne SB, *et al.* (2019) The Warrumbungle Post-Fire Recovery Project – raising the profile of soils. *Soil Use and Management* **35**, 63–74. doi:10.1111/sum.12467

Yang XH, Zhang MX, Oliveira L, Ollivier QR, Faulkner S, *et al.* (2020) Rapid assessment of hillslope erosion risk after the 2019–2020 wildfires and storm events in Sydney drinking water catchment. *Remote Sensing* **12**, 3805. doi:10.3390/rs12223805