SOIL CONDITION AFTER BUSHFIRES

Australian Academy of Science

BUSHFIRE EXPERT BRIEF

JULY 2020

OVERVIEW

- Soils are the foundation of biodiversity, human production and ecosystem services
- Bushfires affect the physical, chemical and biological properties of soil condition
- Bushfires affect soil fertility and therefore Australia's agricultural productivity and the recovery of native vegetation
- There is a need for a nationally consistent framework for soil data collection, storage and accessibility
- More work is required to advance soil recovery from bushfires

BACKGROUND

Soils are the foundation of biological ecosystems, human-managed production systems and essential ecosystem services. It is estimated that 95% of our food is produced, directly or indirectly, on our soils[1]. Soils support the growth of plants, serve as home for soil fauna, flora, and microbes, and mitigate the effects of climate change through carbon sequestration[2].

Healthy soils are critical for vegetation growth (which can be used for food, fibre, and fuel), biodiversity and conservation, and ecosystem services such as climate regulation, water quality maintenance and oxygen production[3]. Soils are considered one of Australia's greatest natural resources, and soil condition is directly linked to the productivity of Australia's agriculture industry[4,5].

SOIL PROPERTIES

Biological

- flora
- fauna
- microorganisms

Chemical, physio-chemical and mineralogical

- organic compounds and organic carbon
- nitrogen, phosphorous, potassium, calcium, magnesium, and sulfur
- pH
- hydrophobicity
- clay and moisture content
- particle size distribution, porosity, permeability, and soil structure
- salinity
- hydraulic conductivity

Soil condition includes the biological, chemical, mineralogical and physical properties of soil. The delicate interplay between these properties must be maintained for soils to remain healthy. Soil environments are highly diverse, and this diversity underpins many crucial ecosystems services[6].

BUSHFIRE IMPACTS ON SOIL CONDITION

It is well known that Australian soils have been impacted by fire for thousands of years[7]. However, a combination of extreme heat waves, drought conditions and high accumulative fuel loads at the surface resulted in fires burning at higher than usual temperatures during the Australian 2019–20 bushfires[8]. These bushfires severely damaged millions of hectares of land, impacting both above-ground vegetation and below-ground root mass and soil[9]. Organic matter in the soil matrix may also have been altered; a direct consequence of bushfire is changes in soil condition[10].

Bushfires can be beneficial to soil because the combustion of leaf litter and other organic matter can increase the availability of some nutrients[11,12]. However, sufficiently intense bushfires can cause long-term and sometimes irreversible transformations to soil condition and severely disturb local ecosystems[11,13,14]. These consequences have implications on how we manage our natural resources.

Australia has a land area of 7.7 million square kilometres and is the sixth largest country (after Brazil, Canada, China, Russia and the United States of America)[15]. Due to its size, Australia has diverse climates and soil types[5]. This brief provides an overview of the impacts of bushfire on soil condition and is not intended to provide a comprehensive review of the impact of bushfire in specific regions and soil types. It must be acknowledged that each ecosystem should be assessed and managed on a case-by-case basis, and a 'one size fits all' management plan (pre- and post-bushfire) is not sufficient.

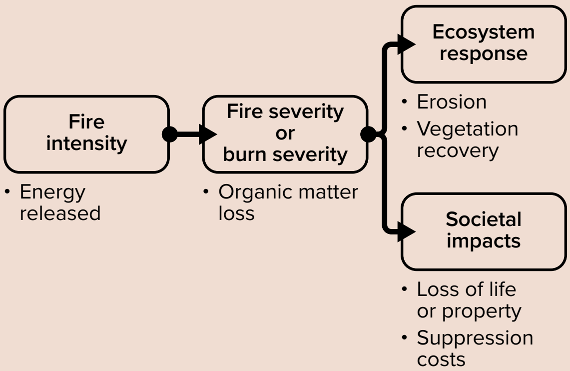
How do bushfires affect soil condition?

During a bushfire

The primary factors affecting soil condition during a bushfire are peak fire intensity and fire duration[10]. These variables are controlled in turn by environmental factors and antecedent conditions at the site such as the type of vegetation, moisture of fuel, fuel load, air temperature, humidity, wind speed and topography[10].

FIRE INTENSITY vs FIRE SEVERITY VS BURN SEVERITY

There is some contention regarding use of the above terms. For the purposes of this document, fire intensity refers to the rate at which fire produces thermal energy. Fire severity or burn severity refers to the loss or decomposition of organic matter, both above and below ground. See figure below for an overview.

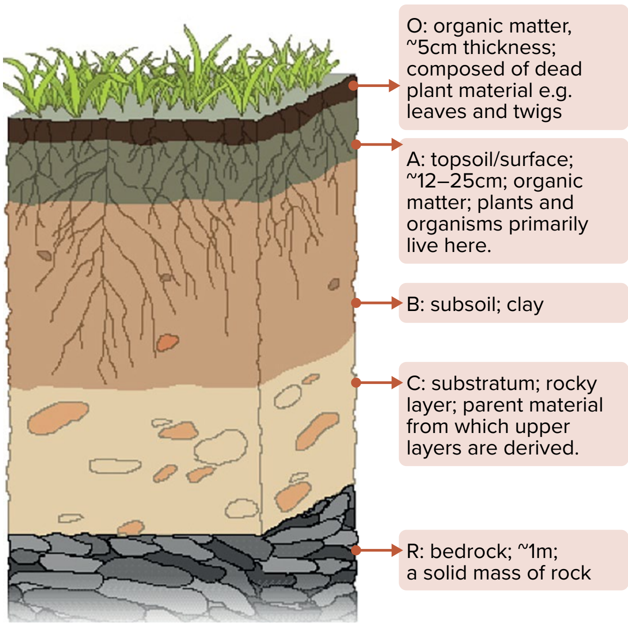


Schematic representation relating fire intensity, fire/burn severity, and their subsequent impacts. Adapted from Keeley (2009)[16].

During a bushfire, soil condition is first impacted by the loss of vegetation and surface organic matter. When surface temperatures exceed 95°C, soil moisture and soluble nutrients held in soil are lost through vaporisation[11]. Depending on the type of fire, soil surface temperatures might rise to 200–300°C,[17] sometimes 500–700°C,[18] and up to 850–1000°C during intense bushfires[19,20].

The changes that a bushfire imparts on soil condition depend on the characteristics of the fire and the affected soil. During a bushfire, the surface organic matter and upper layers of the soil profile (Figure 1), which are often the most nutrient abundant, are generally the most affected. Thermal decomposition of organic matter begins at 200–250°C, and complete degradation occurs around 460°C[21]. Some soil nutrients are more resistant to heat degradation and are not as readily affected as others. An estimation of bushfire impacts on soil condition, as a function of flame temperature, is provided in Figure 2. The maximum flame temperature reached during bushfire has been correlated with the rate of fire spread (including height) and available fuel density[20].

Figure 1. Schematic representation of soil profile, with different layers (horizons) indicated.

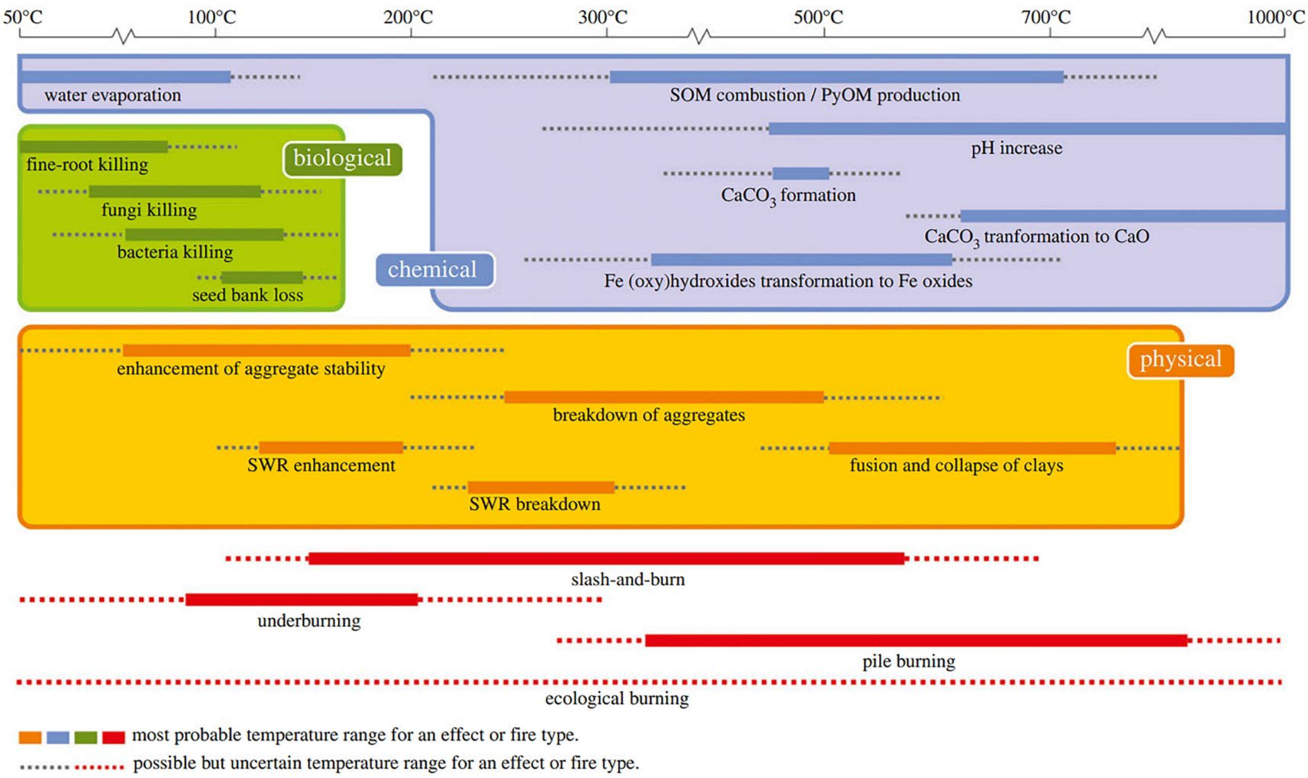


Adapted from the University of Sheffield, *Soil horizons*[56].

Fire may cause severe mineral alterations to soil, which includes the permanent conversion of some minerals into new minerals under a range of temperature conditions[14]. For example, during severe bushfire, clay soils with high organic matter (e.g. peaty clays) form hard, ceramic-like porous fragments within ashy material. Such post-fire soil types have been identified in Australian soils and has led to the introduction of 'burnt soil materials' in the Australia Soil Classification, now classified as 'fusic material'[22]. Extremely high temperature fires (>800°C for more than 1 hour or 600°C for 80 hours) have also been shown to melt very saline acid sulfate soils to form masses of glassed groundmass[14]. These solid masses affect the chemical, physical and biological characteristics of soil condition. Similarly, burnt bone from humans, livestock and wild animals will also permanently transform the availability of phosphorus and therefore further reduce soil condition[23].

Soil can be further damaged if heat from a fire is transferred to underlying soil profiles. For example, severe fires with increased fire duration are linked to the development of non-wettable layers in the soil profile[24]. These non-wettable layers change the way water is absorbed and distributed within the soil, limiting water and nutrient availability and leading to drier soils overall.

Figure 2. Effects of bushfires on the biological, chemical and physical properties of soil and associated temperature ranges. SOM: soil organic matter; PyOM: pyrogenic organic matter; SWR: soil water repellency.



From Santín and Doerr (2016)[27].

HEAT TRANSFER

Heat transfer from the live flames of a bushfire into the underlying soil layers occurs through radiation (the major mechanism of heat transfer), convection, conduction, mass transport and vaporisation/condensation[25,26].

Both the characteristics of a fire and the affected soil impact whether heat is transferred into underlying soil profiles. Variables include fire temperature and duration, which is affected by the availability of oxygen[27,28]. For example, fast burning fires transfer little to no heat down into the soil profile, and heat is restricted to the top 20–30 cm, which comprises the organic matter and topsoil layers (Figure 1)[19]. By contrast, the heat from intensely- and long-burning bushfires can penetrate and persist deep in the soil for several days.

Additionally, intrinsic soil characteristics such as the level of compaction, moisture content, mineral composition and available organic matter influence the amount of heat transfer[26,29]. Finally, dead tree stumps and roots can permit subsoil layers to be burned to depths exceeding two metres[30].

Furthermore, most soil-dwelling organisms, including microorganisms, fungi and soil-dwelling invertebrates, reside within the top layers of soil. An immediate consequence of bushfire to these organisms is a reduction in their biomass. Severe bushfire events with soaring temperatures can result in a complete sterilisation of the upper soil layer[10]. In such cases, reduction in the amount of viable seeds in the soil may also occur[31].

Post-bushfire

Bushfires affect the physical, chemical and biological properties of soil. The overall impact of bushfire on soil condition, and consequently interdependent systems involving soil, are complex and highly variable due to the diverse factors intrinsic to specific bushfires and their local ecosystems[26]. Notably, the recovery time for soil condition also depends on previous and current land use practices, such as animal grazing[26].

As previously noted, bushfires mostly impact the surface organic matter and upper soil layers, which contain significant amounts of soil nutrients, particularly nitrogen and phosphorus. In addition to the loss of soil organic matter, nutrient cycling patterns are also altered depending on the type of vegetation and litter burned. For example, in pine forests the plant matter that is burned can hinder the nitrogen cycle, which can prevent forest regeneration[32,33]. The loss of soil organic matter largely depends on fire intensity, in that high-intensity fires most likely reduce nutrient pools more than low-intensity fires[34,35].

The loss of above-ground vegetation also impacts terrestrial carbon sinks, or the carbon held in soils and vegetation. The combustion of vegetation along with the sizeable amounts of carbon held in soils reduces the total amount of carbon sequestered by terrestrial ecosystems[2,36]. Bushfires can significantly affect soil carbon stock for extended periods of time following a fire event[37].

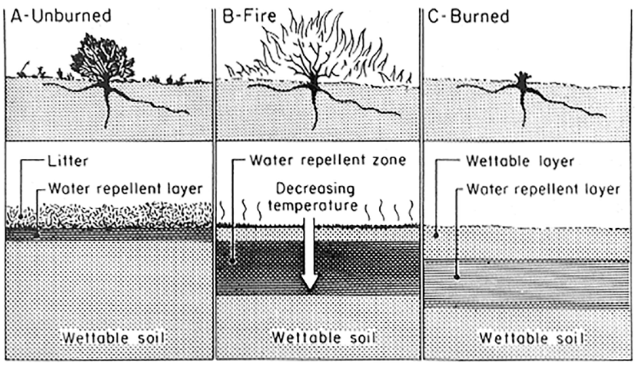
WHAT IS A CARBON SINK?

A carbon sink is a natural reservoir that absorbs more carbon than it releases into the atmosphere.

The rate of decomposition of plant matter may increase immediately following a bushfire, which also impacts the amount of soil carbon lost[36]. Increased decomposition is likely to be a result of increased levels of readily decomposable organic matter, conversion of nutrients into soluble form, and increases in soil temperature and water availability to microorganisms (a result of diminished plant water needs)[38].

Although nutrient availability may increase post-bushfire,[32] it has been demonstrated that this increase does not necessarily offset degraded soil structure[39]. Soil organic matter is important to form soil aggregates from sand, clay and silt particles. These aggregates promote soil porosity. If a bushfire is sufficiently intense, heat radiated into the underlying soil layers can cause a breakdown of soil aggregates, which increases soil erosion potential (Figure 3).

Figure 3. Soil–water repellence as altered by fire



(A) before fire, hydrophobic substances accumulate in the litter layer and mineral soil immediately beneath; (B) fire burns the vegetation and litter layer, causing hydrophobic substances to move downward along temperature gradients; and (C) after fire, a water-repellent layer is present below and parallel to the soil surface on the burnt area.[57]

Soils can become hydrophobic following fire, potentially rendering the soil more repellent to water and less likely to soak up any rain following the bushfire event (Figure 3). Hydrophobicity is mainly caused by the formation of waxy coatings on soils particles and aggregates with the loss of soil organic matter. Water-repellent soils increase water run-off and consequently further promote soil erosion by water. Soils then also become susceptible to wind erosion.

The loss of soil moisture further impacts the recovery of the biological properties of soil such as recolonisation of the soil environment by flora, fauna and microorganisms. Soil biological properties are strongly coupled to organic matter and moisture content. Soil-dwelling organisms rely on the availability of organic material, which are depleted or modified during a bushfire. Biological decomposition, which slowly release essential nutrients over time, also require sufficient moisture. Hydrophobic substances produced by the combustion process can also hinder recovery of the biological properties of soil condition[40].

Bushfires can also alter the physical characteristics of soils. Bushfires where soil temperatures reach 450–500°C result in the denaturation of soil organic acids, leading to large increases in soil pH[10,39]. An increase in soil pH results in alkaline soil conditions and in nutrients that are less soluble and available to plants. At temperatures between 200–800°C and in the presence of organic matter, the heat radiated from bushfires can transform iron oxide found in soils into denser aggregates[41]. Similarly, high temperatures of 500–800°C can result in the formation of titaniferous minerals[42].

The changes in soil condition following a bushfire event have clear implications for soil fertility and, therefore, Australia's agricultural productivity and the recovery of native vegetation. It is difficult to develop a clear management plan for soil condition post-fire without first implementing plans to accurately monitor ecosystems before fires, and documenting fire intensity and severity.

WHY SHOULD WE MONITOR AND MEASURE BUSHFIRES?

Adequately measuring fire intensity and severity enables researchers to accurately predict ecosystem responses such as water runoff, soil erosion and revegetation.

Ecosystem recovery responses are correlated with fire severity[16]. Responses to address soil condition may include preventative measures against soil erosion, faunal recolonisation and revegetation, or vegetation regeneration (through natural or artificial reintroduction)[10].

Soil monitoring initiatives

Soil assessment and management programs were active in Australia during the Decade of Landcare (1989 to 2000),[43] when state and territory agencies partnered with the Australian Government to undertake the Accelerated Program of Land Resources Assessment[44]. The National Land and Water Resources Audit (1997 to 2008) was another joint jurisdiction initiative that provided data and information on nationwide assessments of Australia's natural resources[45].

In 2002, the now de-funded National Heritage Trust supported CSIRO to develop a soil monitoring guide for land management agencies, industries and community groups[46]. The guide highlights our inadequate understanding of soil and ecosystems and calls for improved monitoring, assessment and experimental science practices, such as understanding responses to disturbances like fire (page 48). The guide also notes the role of fire in vegetation disturbance, which can consequently lead to soil erosion (page 47).

In 2014, the Minister for Agriculture released Australia's National Soil Research, Development and Extension Strategy, 'Securing Australia's soil for profitable industries and healthy landscapes'[47]. The strategy aims to highlight the importance of soils as a natural resource and focus soil science research to better meet the needs of Australian farmers. Despite the destruction of pastoral and horticultural land and potential loss and suffering of livestock caused by bushfire, the strategy does not discuss the management and impact of bushfires on soil condition for these industries.

IT TAKES TIME TO RECOVER

Fire and other disturbances can have extremely long-lasting effects on soil quality. Researchers have found significant effects on nutrient density up to at least 80 years following a fire event[48]. Additional impacts of bushfires include the loss of harvestable fruit and smoke taint, particularly on grapes for wine[49].

The Australian Collaborative Land Evaluation Project (ACLEP) operated for 23 years and was primarily funded by the Australian Government Department of Agriculture and Water Resources, with additional support from CSIRO Land and Water[50]. ACLEP was established to provide a coordinated approach to land resource assessment across Australia[44]. Through the project, digital soil data were collected, collated and disseminated in a consistent format. Unified data management enabled researchers to effectively assess trends in the condition of Australian soils and implement policies and programs to ensure the sustainable use and productivity of soils[51].

The National Committee for Soil and Terrain (NCST) has contributed to developing an agreed framework and national standards for soil assessment: the Australian Soil Classification[22]. The committee previously provided advice to the ACLEP. Representatives of federal, state and territory government agencies comprise the NCST[52].

The Australian Soil Network (ASN) provides national leadership and advocacy for matters relating to soil and terrain. It comprises representatives of rural research and development corporations (RDCs), government agencies, CSIRO, the university sector, and an independent chair.

The Terrestrial Ecosystems Research Network, funded by the National Collaborative Research Infrastructure Strategy (NCRIS), has a Landscapes Program with an ongoing soil digital mapping program that is continually developing the Soil and Landscape Grid of Australia[53,54]. This initiative has expanded from natural ecosystems (many of which are impacted by bushfires) to now include managed ecosystems. However, it does not have a specific focus on monitoring the effects of bushfire on soil condition.

WHAT SHOULD WE DO NOW?

Ongoing surveying and monitoring of soil condition will enable continual management and post-fire assessment and recovery. A nationally consistent framework for soil data collection, storage and accessibility is important to provide the scientific evidence that underpins policy development. The successful recovery of soil condition extends further than the immediate soil ecosystem; interlinked systems such as biodiversity and conservation programs, agriculture and horticultural industries, and broader ecosystem services will also benefit from better monitoring and management of soil condition.

There is an opportunity to improve and implement initiatives to better manage Australian soils. For example, a statement by Soil Science Australia (a not-for-profit, professional association for soil scientists) on 'Supporting bushfire impacted communities and soil ecosystems' describes their ongoing work with state and federal government ministers to ensure soil assessment and management are integrated into the bushfire recovery program[55]. There are ongoing discussions on how to best share knowledge on bushfire management and damage prevention. As policy for soil management and recovery develops, scientific evidence must be a key pillar for evidence-based policy development, and the principles of diversity and inclusion must be upheld to ensure all stakeholders are equally represented and heard.

REVIEWERS

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