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Controlled burn and immediate mobilization of potentially toxic elements in soil, from a legacy mine site in Central Victoria, Australia

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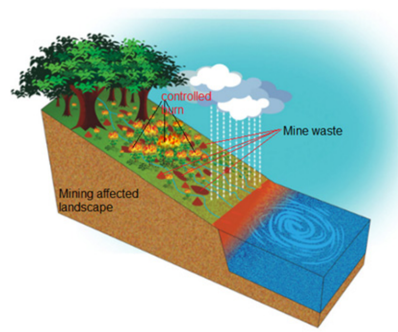
HIGHLIGHTS

- Legacy gold mining sites have elevated potentially toxic element (PTE) concentrations.
- PTEs are sequestered in the soil organic matter and vegetation, limiting its mobility.
- Controlled burns remobilized PTEs such as Zn, Mn, Cd & Hg.
- Liberated PTE mobilized to soil, and may be to air & water environment.
- Controlled burns should be carefully considered as a forest management strategy.

GRAPHICAL ABSTRACT



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ABSTRACT

Conducting controlled burns in fire prone areas is an efficient and economic method for forest management, and provides relief from the incidence of high severity wild fires and the consequent damage to human property and ecosystems. However, similar to wild fires, controlled burns also affect many of the physical and biogeochemical properties of the forest soil and may facilitate remobilization of potentially toxic elements (PTEs) sequestered in vegetation and soil organic matter. The objective of the current study is to investigate the mobilization of PTEs, in Central Victorian forest soils in Australia after a controlled burn. Surface soil samples were collected two days before and after the controlled burn to determine the concentration of PTEs and to examine the physicochemical properties. Results show that As, Cd, Mn, Ni and Zn concentrations increased 1.1, 1.6, 1.7, 1.1 and 1.9 times respectively in the post-burn environment, whereas the concentrations of Hg, Cr and Pb decreased to 0.7, 0.9 and 0.9 times respectively, highlighting considerable PTE mobility during and after a controlled burn. Whilst these results do not identify very strong correlations between physicochemical properties of soil and PTEs in the pre- and post-burn environments, PTEs themselves demonstrated very strong and significant correlations. The mobilization of As, Hg and other toxic elements raise potential health concerns as the number of controlled burns are projected to increase in response to climate change. Due to this increased level of PTE release and remobilization, the use of any kinds of controlled burn must be carefully considered before being used as a forest management strategy in mining-affected landscapes which include areas with high PTE concentrations.

1. Introduction

Potentially toxic elements (PTEs) such as As, Cd, Co, Cr, Cu, Hg, Mn, Ni, Pb and Zn, contribute to contamination in soil and aquatic

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environments, and this is of great concern due to the immediate risks to human and ecosystems health and the perceived persistency of these elements in the environment (Tijani et al., 2005; Zhuang et al., 2014; Soliman et al., 2015). Gold and other metal mining activities may contribute to significant PTE contamination in many rural areas (Sultan, 2006, 2007; Taylor et al., 2010; Pearce et al., 2012; Krishna et al., 2013). Mining, milling and grinding operations, which result in concentrations of fine ore materials, together with the subsequent disposal of tailings and mine and mill waste water, are a source of water, soil and air contamination in the vicinity of the mine site (Schaider et al., 2007; Navarro et al., 2008; Esshaimi et al., 2012; Doronila et al., 2014). This is particularly significant in legacy mine sites, where environmental regulations were neither enforced during active mining, nor at the time of mine closure. For example, Central Victoria, in Australia has a long history of gold mining since 1850 (McDonald and Powell, 2008) and has significantly contributed to the economy with the region producing more than 2500 t of gold (EER, 2015). However, mine closure left tonnes of mine waste materials rich in PTEs in the surface soils with resultant contamination of soils, water, air, and plants (Sultan, 2006, 2007; Pearce et al., 2010, 2012; Martin et al., 2014, 2016). Recent studies have reported As absorption by adults, specifically children living close to these abandoned sites in Central Victorian soils, are of growing concern (Pearce et al., 2010, 2012; Martin et al., 2013, 2014). Furthermore, most of these mine waste materials are located in forest areas, and are un-rehabilitated, leaving them prone to mechanical dispersion, which may increase their mobility and bioavailability.

Forest ecosystems generally absorb PTEs from natural and anthropogenic activities as most have an affinity for soil organic matter (SOM). This is particularly the case for Hg, Cu and Pb (Wei and Yang, 2010; Shcherbov, 2012; UNEP, 2013), and the rate of absorption depends on the amount of SOM, the fixation to clay minerals, local adsorption and desorption processes and their correlation with Al and Fe hydroxides and Mn oxides (Sipos et al., 2005; Kabata-Pendias, 2004, 2010; Reis et al., 2015). After entering forest ecosystems, PTEs may concentrate in the organic layers of the soil, sequester in sediments, form compounds with SOM and may be absorbed by plants and hence become immobile in the system (Grigal, 2003; Hernandez et al., 2003; Biswas et al., 2007; Obrist et al., 2008; Friedli et al., 2009; Shcherbov, 2012). Grigal (2003) reported that 90% of the Hg in the forest ecosystem is found to be associated with SOM in the forest floor, and in addition to Hg, other PTEs such as Cr, Cu and Pb are also found to be strongly bound in the system, whereas, Cd, Co, Mn, Ni and Zn are weakly bound (Tipping, 1998; Lawlor and Tipping, 2003). When forest fire, either as a wild or controlled burn occurs, combustion of the vegetation and SOM causes soil property alterations, which can release the sequestered elements from the system and become labile and will be able to remobilize, mostly through ash and smoke (Odigie and Flegal, 2011, 2014). This is particularly significant in the Central Victoria region of Australia, as the region is prone to wild fires due to weather patterns and types of dense vegetation and controlled burns are regularly applied in the region as a standard fire-risk reduction strategy.

Controlled or prescribed burning is the deliberate application of fire to forest fuels or agricultural lands, mainly in autumn or spring (but may also be applied in late winter) under stipulated settings to ensure such that well-defined targets are achieved (Wade et al., 1989). Preparation for agriculture and tree restoration, control of weeds and insects populations, wildlife habitat management, maintenance of biodiversity, fuel level reduction and other land management practices are usually the intention of careful application of controlled burns (Fernandez and Botelho, 2003). In general, controlled burns are of low to moderate intensity, and consume most of the forest floor layers and understory vegetation, with no or little damage to the canopy trees (Úbeda et al., 2005). The burn reduces the occurrence of a subsequent wildfire, or can reduce its intensity, by reducing the fuel loads both vertically and horizontally, which directly improve the fire control measures (Hatten et al., 2005). Therefore, controlled burning is considered to be a valuable tool in forest protection and wildfire mitigation (Fernandez and Botelho, 2003; Certini, 2005; Castellinou et al., 2010) and is practised in the fire prone forest landscapes in many countries in Europe, North and South America and Australia.

Fire intensity equates to the release of thermal energy as a result of the physical combustion process, and is defined as the measure of time averaged energy flux (Keeley, 2009). Severity is the response of an ecosystem to fire, which is gauged by the product of fire intensity and residence time (Certini, 2005; Neary et al., 2005; Keeley, 2009). Physically fire intensity is quantified using temperature, flame height, duration of fire, and the emission of pyrogenic gases (Lentile et al., 2006). It is mostly controlled by fuel (vegetation) types and density, moisture content in the fuel, weather pattern, topography and other local factors (DeBano et al., 1998). Intensity can be measured by measuring the fire temperature using thermocouples or can be inferred from the observation of flame length and fire spread rate (Smith and Wooster, 2005; Dennison, 2006). Fire severity provides information about how fire intensity affects ecosystems and is sometimes used wrongly as a synonym for fire intensity (Certini, 2005; Keeley, 2009). Fire severity measures are based on number of methodologies, and among them, observation of ash colour is significant (Úbeda et al., 2009; Pereira et al., 2011). Another relevant term is 'burn severity', which sometimes is mistakenly used for fire severity. Burn severity identifies the impact of fire on soil and plants when the fire is extinguished, and is related to the post-fire phase. Further fire-related information is available in a number of studies (Certini, 2005; Neary et al., 2005; Lentile et al., 2006; De Santis and Chuvieco, 2007; Murphy et al., 2008; Safford et al., 2008; Keeley, 2009; Parsons et al., 2010; Mataix-Solera et al., 2011).

The intrinsic character of any kind of forest fire is the complex process of heat release during biomass combustion (Bento-Gonçalves et al., 2012). The burning biomass and ash can transfer heat to the soil surface, and it may reach up to 30 cm depth in the case of high severity wild fires (DeBano, 2000). As a result, fire can change the physicochemical, mineralogical and biological properties of the forest soil and surface materials (Certini, 2005; Verma and Jayakumar, 2012). However, most of these alterations are ephemeral, such as pH and electrical conductivity (EC) (Arocena and Opio, 2003), with only a few being perpetual (Certini, 2005), and all alternations depend on fire severity (Dzwonko et al., 2015). Similar to wildfires, controlled burns also affect soil properties, but, often to a limited extent (Arocena and Opio, 2003; Castro et al., 2011; Pereira et al., 2011; Melendez-Perez et al., 2014). Fire typically increases pH values and EC of the soil, makes significant alterations in SOM levels, decreases soil permeability and porosity, resulting in the reduction of hydraulic conductivity and causing considerable loss in nutrient levels (Certini, 2005; Verma and Jayakumar, 2012). With these soil property alterations, many authors reported that wild fire is able to release PTEs (metals) from plants and soil organic matter from their sequestered phase (Odigie and Flegal, 2011, 2014; Burton et al., 2016; Kristensen et al., 2014; Odigie et al., 2016). For example, Ignatavicius et al. (2006) reported an increase in concentrations of Pb, Cu, and Zn (21 to 74%) in Lithuanian river waters (August–September 2002) one month after a series of 497 forest and peat bog fires in the region. Similarly, remobilization of Fe, Mn and Hg after the 2009 Station Fire in Los Angeles, USA was observed (Burton et al., 2016). In conjunction with this, Kristensen et al. (2014) reported the remobilization of natural and industrial Pb (4 to 23 mg kg^{-1}) after three wild-fires in Australia (the Tostaree Fire in Victoria, at Red Hill and the Kelmscott Fire in Western Australia). In addition to this, Odigie et al. (2016) linked the occurrence of PTEs in the sediments of the Lake Thomson in Chile with forest fires which occurred in mid 1900s. Though these studies were directed to establish the consequence of wild fire on PTE mobility, there is a general lack of research in the global literature on the effects of controlled burns in PTE mobility, specifically on legacy mining landscapes.

Forest fire and subsequent PTE mobilization is particularly pertinent to legacy mining areas because of the presence of an extensive volume of tailings and other mine waste materials with elevated PTE