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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

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ABSTRACT

Controlled burns also known as managed burns or prescribed fires conducted in fire-prone areas are an efficient and economic option to reduce the frequency and intensity of wildfires. The objective of this study is to investigate the remobilization of potentially toxic metals (PTMs) in the soils of a legacy gold mine site in Central Victoria, Australia after a controlled burn and to describe their temporal variations in concentrations. Soil samples were collected two days before, two days after and five times later (3, 6, 9, 12 months and after major rainfall) in the post-burn environment after a controlled burn, from the Maldon legacy mine site and analysed for PTM concentrations. The results revealed PTM mobilization after the burn and most of the PTMs (As, Cd, Cu, Mn, Ni, and Zn) evidenced an increase immediately after the burn but a reduction in the subsequent post-burn environment. The increase is postulated to be associated with addition of PTM enriched ash to the soil, while the decrease is due to the removal of ash and surface soil by wind activity as well as rainfall runoff and leaching. The PTM mobility is of specific concern due to the negative impacts on human and ecosystems health. Climate change and the resulting projection of increased forest fire frequency highlight the environmental significance, given the expected concomitant increase in PTM mobilization through wildfires and controlled burns. Hence, the practice of controlled burning should be carefully considered as a forest management option in any legacy mining areas and indeed in other areas where PTM contamination is reported.

1. Introduction

Potentially toxic metal (PTM) (As, Cd, Co, Cr, Cu, Mn, Ni, Pb and Zn) contamination associated with mining and mineral processing, places a significant financial and environmental burden on communities around the world (Pearce et al., 2010; Esshaimi et al., 2012; Cobbina et al., 2013; Martin et al., 2013; Schaider et al., 2014; Martin et al., 2016, 2017). This is predominantly because of the negative impacts of PTMs on human and environmental health, particularly their toxicity, bioaccumulation and biomagnification tendency in the food chain and the environmental persistency (Adriano, 2001; Ignatavièius et al., 2006). PTM contamination is a significant problem at legacy or historical mining areas as well, due to the lack of environmental regulations during mining and following closure resulting in the accumulation of millions of tonnes of mine waste materials rich in PTMs. The volume of the land affected by PTMs makes this a significant global issue as more than a million legacy mine sites estimated to exist across the globe (UNEP, 2001; Lottermoser, 2007; Erickson et al., 2008; Zhou et al., 2010; Esshaimi et al., 2012; Zornoza et al., 2012; García-Lorenzo et al., 2014; Armienta et al., 2016).

Soil PTM contamination from both existing and legacy mine sites has been reported from around the world. Harrison et al. (2003) investigated the PTM contamination around the Yerranderie legacy Ag-Pb-Zn mine site in New South Wales, Australia and reported higher PTM (Ag, As, Cd, Cu, Hg, Pb, and Zn) concentrations in soil surrounding the mine site, which are up to 400 times the guideline values. Soil core sample analysis showed that an overall increase occurred in and around 1950, which is coincident with high rainfall and preceded drought periods (Harrison et al., 2003). Similarly, Schaider et al. (2007) studied the levels of Zn, Pb and Cd in a legacy mine site (Tar Creek Superfund site) in Oklahoma, USA and found elevated concentrations of Zn ($9100 \pm 2500\,mg\,kg^{-1}$), Pb ($650 \pm 360\,mg\,kg^{-1}$) and Cd ($42 \pm 10\,mg\,kg^{-1}$) in soil samples, which are relatively labile and are present in bio-accessible mineral phases. In a similar manner, Esshaimi et al. (2012) investigated soil and water contamination in the vicinity of the Kettara abandoned mine, south Morocco and reported high concentrations of Cu, Pb and Zn in the tailings (76, 80, $79\,mg\,kg^{-1}$ respectively) and in soil (68, 52 and $26\,mg\,kg^{-1}$ respectively) samples.

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Moreover, PTM dispersion to downstream and downslope areas was also observed, and this was considered to be due to the surface runoff and strong wind actions (Esshaimi et al., 2012). Other studies such as Clark et al. (2001) from Australia, Zornoza et al. (2012) from Spain, Lee et al. (2001, 2005) from South Korea, Zhou et al. (2010) from China and Cobbina et al. (2013) from Ghana are all significant in this context, as each of these study sites documents the extent of contamination of soil, sediments, water bodies and general vegetation with PTMs from legacy mine sites.

Central Victoria in Australia, is not exempt from PTM contamination as it has seen extensive mining since 1850, and has produced > 2500 t of gold with resulting accumulation of tonnes of mine waste materials rich in PTMs (Sultan, 2006, 2007; Pearce et al., 2010, 2012; Martin et al., 2013, 2014, 2017). Any disturbance of this contaminant pool is of concern, since it will act as a catalyst for enhanced mobility and dispersion of PTMs. One such major agent of disturbance is forest fire, which includes controlled burns (Certini, 2005; Neary et al., 2005; Pereira et al., 2011; Abraham et al., 2017a, 2017b; Alcañiz et al., 2018).

Fires are natural process in many terrestrial ecosystems and some are severely destructive in nature to the vegetation and surface soil (Neary et al., 2005; Beganyi and Batzer, 2011). The human-fire relationship goes back to the pre-historic period, where humans used fire in preparing food, hunting and agricultural land preparation (Pyne, 2016). Recent studies show the adverse and diverse impacts of fire to the environment, economic sustainability and social structures (Smith et al., 2011; Liu et al., 2014). For example, fire may disturb the forest ecosystem structure and functions by affecting the nutrient cycling, vegetation distribution and composition and herbivore distribution (Augustine et al., 2014; Alcañiz et al., 2018), however, some ecosystems are fire dependent (Alcañiz et al., 2018). Fire may alter a range of substantial physical and biogeochemical soil properties and affect the catchment behaviour by affecting key hydrological factors such as infiltration and runoff (Certini, 2005; Shakesby and Doerr, 2006; Knoepp et al., 2008; Verma and Jayakumar, 2012; Abraham et al., 2017b). The contaminant mobilization associated with forest fire is of global significance but region specific (Jovanovic et al., 2011; Costa et al., 2014; Campos et al., 2015, 2016; Abraham et al., 2017a, 2017b). The fire potentiality depends on the increased fuel load, dry weather patterns with increased atmospheric temperature and wind speed, all of which enhance ignition potential (Certini, 2005; Hennessy et al., 2005; Westerling et al., 2006; Alcañiz et al., 2018). Recent climate change studies highlight the increase in frequency and areal extend of fire in many parts of the world in association with rural depopulation, land abandonment and afforestation with fire-prone species (Hennessy et al., 2005; Westerling et al., 2006; Moreira et al., 2009; IPCC, 2013; Campos et al., 2015, 2016). This resulting fuel-rich environment consequently requires added controlled burning events as a fire risk mitigation strategy.

Controlled' or 'prescribed burning' is a type of managed forest fire, where deliberate application of fire, acts primarily to reduce the available fuel load and to reduce the frequency and intensity of wildfires (Hatten et al., 2005; Pereira et al., 2011; Fernandes et al., 2013; Bennett et al., 2014; Alcañiz et al., 2018). This low-to-moderate intensity fire event reduces the fuel load by consuming the understory vegetation and part of the forest floor layers, and has long been considered as an efficient and economic option for fire control (Fernandez and Botelho, 2003; Pereira et al., 2011; Alcañiz et al., 2018). Controlled burning is also used for agricultural land preparation, weed and insect control, biodiversity management among other land management applications (Pereira et al., 2011; Fernandes et al., 2013) and is widely practised in fire-prone areas in the American, European and Australian continents (Wade et al., 1989; Fernandez and Botelho, 2003; Certini, 2005; Castellinou et al., 2010; Pereira et al., 2011). Although it has a number of benefits, controlled burn constitutes a disturbance on the forest environment, alters the ecological processes and affects the properties of the surface soil (Santín and Doerr, 2016; Alcañiz et al., 2018). Moreover, precipitation and subsequent runoff events in the post-burn environment may result in the transport of surface soil and ash, which contains elevated levels of various contaminants, including PTMs to downslope and downstream surface water resources (Ignatavièius et al., 2006; Burke et al., 2010; Stein et al., 2012; Burke et al., 2013; Costa et al., 2014; Abraham et al., 2017b). This has heightened concern that this series of events may act as a contaminant source for potable water resources serving local communities and may negatively impact the health of ecosystems (Ignatavièius et al., 2006; Burke et al., 2010; Smith et al., 2011; Stein et al., 2012; Burton et al., 2016; Abraham et al., 2017a, 2017b).

Information regarding PTM mobility in the environment is vital for ecosystem management and sustainability due to the potential environmental persistence, toxicity and health impacts on human and ecosystems, together with their potential bioaccumulation characteristics (Adriano, 2001; Ignatavièius et al., 2006; Abraham et al., 2017a, 2017b). Wildfires have been found to mobilize PTMs in the atmospheric, terrestrial and aquatic compartments mostly by the combustion of vegetation and the subsequent release of ash and the burning of soil organic matter (Costa et al., 2014; Kristensen et al., 2014; Campos et al., 2015, 2016; Abraham et al., 2017a, 2017b, 2018). While some studies report the influence of wildfire on PTM mobilization (Odigie and Flegal, 2011, 2014; Kristensen et al., 2014; Burton et al., 2016; Campos et al., 2015, 2016; Odigie et al., 2016; Nunes et al., 2017; Wu and Taylor, 2017), no studies have been reported from a legacy gold mine site, associated either with wildfire or controlled burn. Since, wildfire has the potent to release and remobilize PTMs, we hypothesis that a controlled burn is also able to release and remobilize PTMs, specifically from a legacy mining landscape, even though the burning temperature is comparably low. Hence, the current study is designed (i) to identify the mobility and distribution of PTMs in soil, immediately after controlled burn event and (ii) to identify the temporal variations of PTMs concentrations in the post-burn soil environment. This study provides geochemical information to land and water managers to inform their decision-making to achieve better environmental and health outcomes, including water quality in fire-prone areas (specifically mining affected and PTM affected landscapes) in Australia and in number of countries across the globe.

2. Materials and methods

2.1. Study area

Central Victoria in Australia has hundreds of legacy gold mine sites and most of them are located in forest areas. The study area Maldon is a legacy gold mining township, located 145 km NW of the City of Melbourne and 40 km SW of Greater Bendigo in Victoria, Australia. In the Maldon area, gold mining started in 1853 and the phase of deep mining ceased in 1926, mainly because of difficulties in the mining process, but later (in 1990s) mining restarted in the area with modern technology (Parkweb, 2018). Cradle and gold pan to separate gold from alluvium was the early gold extraction techniques, but later moved to puddling, quartz reef mining, deep lead mining and various forms of sluicing, among them quarts reef mining was the widespread technique (Egold, 2018). Open cut trenches, shafts and adits, which used to access sulphide bearing ores can be seen in the area as mining remnants (Cherry and Wilkinson, 1994; Maldon, 2017). During this early mining period, the area produced 56 t of gold from various mining sites (Cherry and Wilkinson, 1994). Mining and the lack of environmental regulations during historical mining period, resulted in the accumulation of tonnes of mine waste materials in the area, which are rich in PTMs (Sultan, 2006, 2007; Martin et al., 2013, 2014). From an area with a number of legacy mine sites, one, which was located on public land, east of the Union Hill mine was selected for controlled burn related PTM mobility study (Fig. 1). While the study area is a public forest land (State forest) under the jurisdiction, it is located near the Maldon town