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Concentrations of sulphur and trace elements in semi-arid soils and plants in relation to geothermal power plants at Olkaria, Kenya

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ABSTRACT

Exploitation of geothermal energy is considered to have minimal ecological impacts. However, this assumption has not been widely studied. We tested the hypothesis that emitted elements from geothermal power plants would be enriched in both plant tissue and soil close to the power plants with consequences for plant health. The concentrations of sulphur, arsenic, boron, antimony and mercury in the soil and leaves of the dominating shrub, *Tarchonanthus camphoratus,* were assayed and associated foliar injury and growth traits assessed at variable distances and directions from two geothermal power plants in Kenya, Olkaria I (operated since 1981) and Olkaria II (since 2003). Sulphur concentration in the leaves was elevated close to the power plants and decreased with increasing distance, implying atmospheric input of sulphur to the ecosystem from the power plants. Similar trends were not detected in soil and with the other elements. Our study design did not support the observed higher degree of leaf injury close to the power plants. Similarly, any association of growth traits with distance or location was not detected. The results were compared with data from a reference site well out of the range of element deposition from the power plants. Overall, the levels of sulphur, arsenic, boron and antimony in leaves of *T. camphoratus* and sulphur, and boron concentration in soil around the Olkaria I and Olkaria II geothermal power plants were higher than at the reference site. Furthermore, the number of healthy leaves per shrub and stem circumference were lower around the power plants than the reference site, while leaf damage and other plant growth traits did not differ. In spite of relatively weak indication of the harmful effects of the geothermal power plants on the dominating shrub species, follow-up experimental studies and studies on more sensitive ecosystem components are recommended to advise existing mitigation measures against chronic exposure from the emitted gases and associated impacts.

1. Introduction

Geothermal energy is listed among those world's renewable energy sources considered to have minimal ecological impacts with a great potential for the future (Bayer et al., 2013; Wong and Tan, 2014). However, a range of non-condensable gases (NCGs) and trace elements typically ranging from less than 0.2% to over 25% weight of steam (Rodríguez, 2014) are emitted from the power plants during the energy conversion process. Some of these components have been reported to deposit in the surrounding ecosystems (Bargagli et al., 1997; Bacci et al., 2000; Paoli and Loppi, 2008), but the consequences are still poorly known. Potentially, they can cause toxicological stress on human beings, plants, and other ecosystem components (Bayer et al., 2013). With increasing utilization of this energy source there is an urgent need for detailed studies on ecological responses to geothermal power plant emissions.

Commonly, the NCG fraction comprises 73–98% w/w carbon dioxide (CO_2), 1–24% w/w hydrogen sulfide (H_2S), 0.02–0.65% w/w methane (CH_4), 0.1–8% w/w hydrogen (H_2), 0.3–16% w/w nitrogen (N_2), 0.1–3% argon (Ar), and traces (<0.001% w/w) of radon, boron, mercury, arsenic, antimony, and ammonia in gaseous and dissolved form (Baldi, 1988; Bargagli et al., 1997; Loppi et al., 1998; Gunerhan, 1999; Loppi, 2001; Bussotti et al., 2003; Rodríguez, 2014). Of these gases, H_2S poses a major concern due to its odour and potential toxicity even at low concentration. The trace elements are also widely

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understood to bio-accumulate in ecosystems causing deleterious consequences (e.g. Kabata-Pendias, 1992).

Our knowledge of the effects of geothermal power plant emission on terrestrial ecosystems is limited, and mainly based on a few studies in the Mediterranean Italy. All these studies indicate increased levels of the emitted elements including sulphur, arsenic, boron, mercury, and antimony in tissues of vascular plants, mosses and epiphytic lichen close to the power plants with an apparent trend of decreased concentrations over increasing distances (Baldi, 1988; Bargagli and Barghigiani, 1991; Panichi and Orlando, 1992; Edner et al., 1993; Ferrara et al., 1994; Loppi and Bargagli, 1996; Bargagli et al., 1997; Loppi et al., 1998; Loppi, 2001; Bussotti et al., 2003). These trends strongly imply atmospheric deposition of sulphur (in H_2S gas form) and trace elements into terrestrial ecosystems from the nearby geothermal power plants.

High concentrations of H_2S gas may have harmful, acute and chronic effects on ecosystems. The H_2S gas molecule is quite unstable in air, and may be oxidized to SO_2 (Kellogg et al., 1972). Mobile sulphur is available to plants primarily in the form of anionic sulphate (SO_4^{2-}) from the soil or as gaseous SO_2 or H_2S which is readily absorbed and assimilated by leaves (Leustek and Saito, 1999). As an essential macro-nutrient for plant metabolism and growth, both deficiency and excess of sulphur will lead to foliar necrosis, leaf lesions and defoliation. Consequently, the long term effects manifest as reduced plant growth, early senescence and chlorosis (Thompson and Kats, 1978; Varshney et al., 1979; WHO, 2000). According to WHO (2000), SO_2 can also alter plant responses to other environmental stresses often intensifying their impacts.

The effect of H_2S on crop and forest plants was experimentally studied in a greenhouse (Thompson and Kats, 1978). Continuous fumigation with 30–100 ppb H_2S gas stimulated plant growth whilst 300–3000 ppb caused patches of dead cells on leaves (leaf lesions), defoliation and reduced or stunted growth. The effect was more noticeable on fast growing species such as grapes, alfalfa, and lettuce than slow growing species such as buckeye and ponderosa pine. Symptoms similar to those observed during the experimental fumigation may be seen in natural ecosystems, such as forests, close to geothermal power plants, indicating stressed environmental conditions (Bussotti et al., 1997).

Increased concentrations of other emitted elements may also be harmful to plants. In Bussotti et al. (1997), high boron and arsenic concentrations in *Quercus cerris* L. leaves were associated with higher crown defoliation around geothermal power plants in Travale, Southern Tuscany. From the same area, Bussotti et al. (2003) reported widespread leaf damage in *Quercus pubescens* Willd., including necrosis and decreased leaf area, which they related to elevated boron and sulphur concentration of geothermal power plant origin. The predominant role of foliar uptake was suggested by, higher boron and sulphur levels in *Q. pubescens* leaves than in soil close to the power plants. Higher boron and sulphur concentrations in superficial soil layers (0–20 cm) than in deeper layers (20–40 cm), indicated atmospheric deposition as the primary origin of these elements (Bussotti et al., 2003).

Very little is known about accumulations of emitted elements from geothermal power plants in semi-arid terrestrial ecosystems in the tropics and their potential impacts. In Kenya, the production of geothermal energy began three decades ago with the development of geothermal resources at the Olkaria geothermal field in the Great Rift Valley and accounts for 37% gross national electricity production today (Omenda et al., 2014). Due to the reliability and assumed minimal ecological and climate impacts of geothermal power compared to other sources, expansion plans are underway in other geothermal fields to meet the current power demand. So far, only a few studies have addressed the environmental impacts of the power plants, all focusing on trace elements in spent geothermal waters and bioaccumulation in aquatic plants (Simiyu and Tole, 2000; Were, 2007). However, solid knowledge of the environmental impacts on the surrounding terrestrial ecosystems is needed to strengthen existing mitigation measures against pollution and to ensure sustainable development of geothermal power plants in Kenya. This study contributes to that knowledge by investigating the ecosystem accumulation of elements emitted from geothermal power plants in Kenya.

We studied the patterns of sulphur and trace element concentrations in plants and soil around two power plants at the Olkaria field, Olkaria I and Olkaria II, and some growth traits of the shrub *Tarchonanthus camphoratus* L. We chose this species as a bio-indicator due to its widespread distribution and dominance in the vegetation at Olkaria. We hypothesized that the concentration of the elements emitted would be enriched in both plant tissue and the soil around the power plants with consequences for plant health. We expected stronger responses around Olkaria II than Olkaria I, because it is a higher output power plant with a higher emission rate of H_2S and Hg (Table 1). To test the hypothesis, we assessed the soil and leaf chemical compositions at different distances along transects along the prevailing wind direction, a key factor in dispersion of atmospheric contaminants around the power plants (Olafsdottir et al., 2014; Wetang'ula, 2011). Further, we assessed the frequency of different leaf damage categories, and measured growth related morphological traits of the shrub. A reference site well out of range of all geothermal activity was also established for comparison.

2. Materials and methods

2.1. Study area and species

The study area is within the Olkaria geothermal field (area, 204 km^2), situated on the floor of the Great Rift Valley of Kenya (Fig. 1), at an average elevation of 2000 m above sea (Omenda, 1998). The topography is dominated by volcanic features mainly steep sided rhyolite and pumice domes, fault scarps, fractures, and the Ol Njorowa Gorge cutting across a purported buried caldera (KenGen, 2004; Omenda, 1998). Annual rainfall is low recording a mean of 634 mm (2000–2013) with a bi-modal pattern. The average minimum and maximum monthly temperatures ranged from 15.9 to 17.8 °C, and 24.6 to 28.3 °C, respectively, for 2001–2012 (Barasa et al., 2012). Annual predominant wind direction is from south and south–south east (Fig. 1) (KenGen 2013, unpublished; Kollikho and Kubo, 2001). The area is classified as semi-arid due to its porous soils coupled with a high evaporation rate of 1000–1700 mm per year (KenGen, 2004). Soils are of volcanic origin containing a mixture of sands, clays and air fall pyroclastics with pumice. The study focused on the surroundings of Olkaria I and II geothermal power plants, which are approximately 3.7 km apart and located within the precincts of the Hells Gate National Park (HGNP). Table 1 shows the main features of the power plants based on available data. Human settlement within the field is minimal due to its location within the HGNP (area, 68.25 km^2). The vegetation is mainly diverse types of grassland and shrub land (Ogola, 2004) with *Tarchonanthus camphoratus* L. covering extensive areas, occasionally interspersed with *Vachellia drepanolobium* (Harms ex Sjöstedt) P.J.H.Hurter (Syn. *Acacia drepanolobium* Harms ex Sjöstedt) and *Vachellia xanthophloea* (Benth.) P.J.H.Hurter (Syn. *Acacia xanthophloea* Benth.) (KenGen, 2004). The shrub *T. camphoratus* is semi deciduous, usually multi-stemmed (Young and Francombe, 1991) reaching 2–6 m height. The stem group of the multi-stem forms is known as a clump and the stem with the largest stem circumference and height is termed main stem.