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ECOSYSTEM MONITORING PLAN FOR GEOTHERMAL POWER PLANTS: BIO-INDICATORS, DATA ACQUISITION AND PROCESSING PROTOCOLS

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ABSTRACT

Geothermal power plants emit a range of non condensable gases (NCGs) and other elements which have the potential to deposit and bio accumulate in ecosystems. These emitted components such as sulphur (from H_2S gas) and trace elements (arsenic, boron, antimony and mercury) pose deleterious long term effects to ecosystem components if not monitored. Some studies in the Mediterranean, sub-tropics and sub-arctic terrestrial ecosystems have revealed deposition and associated impacts of these components in plants and soils, which were used as bio-indicators. The consequences include impacts on plant growth and metabolism. As more of these studies are still limited, wide knowledge on effects of these components and the monitoring protocols to employ for geothermal developers is still lacking. This paper reviews lessons learnt from such studies on effects of geothermal power plant emissions to ecosystems to address the questions, how such studies can be performed, which data needs to be acquired and the processing involved. Knowledge of these studies is important for geothermal power developers to ensure implementation of appropriate mitigation measures for unforeseen environmental impacts to promote sustainable development.

1. INTRODUCTION

1.1 Background

To mitigate and adapt against the effects of climate change, the exploitation of geothermal energy has been favoured globally over fossilised energy in countries with the potential, primarily due to its assumed minimal ecosystem impacts. Countries such as Kenya, Iceland, Italy and others continue to develop the resource owing to its intrinsic stability compared to other renewable energy sources e.g. hydropower (Bertani, 2016). Although assumed to have minimum ecosystem impacts with respect to geothermal well drilling and construction of geothermal power plants (Kristmannsdóttir and Ármannsson, 2003; Ogola, 2004) in which most impacts are usually managed through a nationally approved environmental management plan, knowledge on the impacts of geothermal power plant emissions on ecosystems is still low. Mitigation efforts are based on limited studies that mainly focus on hydrogen sulphide gas emissions and occupational health and safety. Whereas geothermal power plants emit a range of gases that are not condensed at operating temperatures and pressure i.e. the non-condensable gases (NCGs). The amount and composition of NCGs emitted is mainly dependent on the underground reservoir geochemistry characteristic of individual geothermal fields (Axtmann, 1975).

Generally, the NCGs range between 0.2 % and over 25 % weight of steam, in rare cases (Ozcan and Gokcen, 2009) and commonly comprise 78 – 98% w/w carbon dioxide (CO_2), 1 - 24 % w/w hydrogen sulphide (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 % w/w argon (Ar), and traces (<0.001% w/w) of radon (Rn), boron (B), mercury (Hg), arsenic (As), antimony (Sb), and ammonia (NH_4) in gaseous and dissolved form (Axtmann, 1975; Baldi, 1988; Gunerhan, 1999; Ozcan and Gokcen, 2009; Rodríguez, 2014). The fate of these gases is definitely within our ecosystems; therefore, once released into the atmosphere, the gases will deposit and accumulate into ecosystems. Overtime, the accumulated gases have the potential to cause harm to ecosystem components due to their toxic nature even at low concentrations. The main potentially phyto-toxic gases include hydrogen sulphide and the trace elements (Bargagli et al., 1997; Bussotti et al., 1997; Mutia et al., 2016a, 2016b). The effects of these gases have been studied on bio-indicators, mostly plants and soils, especially in the Mediterranean (Bargagli et al., 2003; Bussotti et al., 2003; Loppi et al., 1998; Loppi and Bonini, 2000) with a few studies in the subtropic (Mutia et al., 2016a) and subarctic (Mutia et al., 2016b) terrestrial ecosystems. Results of the studies have provided evidence of deposition and accumulation of these elements in plants and soils with consequences on plant health, particularly plant morphology and physiology (Bussotti et al., 2003; Mutia et al., 2016a, 2016b). However, as mentioned before, knowledge on monitoring of these geothermally emitted elements and compounds and assessment of potential effects is still scarce among geothermal developers and only limited to a few countries among the approximately 51 countries (Bertani, 2016) that are to date generating geothermal power.

To promote sustainable geothermal power development, an understanding of the effects of these emissions into ecosystems in addition to the environmental effects of geothermal well drilling and infrastructure development is important in appropriate implementation of mitigation measures. In this paper, I attempt to answer the question, whether geothermal power plant emissions affect ecosystems by critically reviewing the effects of the emitted elements based on existing literature. In addition, I present a monitoring protocol that can be adopted for use around geothermal projects and a data handling tool for impact predictions.

2. ECOSYSTEM IMPACTS OF GEOTHERMAL POWER PLANT EMISSIONS

So far, only the concentration and quantity of H_2S gas emission is monitored from geothermal power plants by most geothermal power plant developers globally. This may be because of the high amounts that are exhausted from the projects and the potential effects on human health (Davies, 2008; Finnbjörnsdóttir et al., 2015; Hansell and Oppenheimer, 2004) even at low concentrations. For example, in Iceland, the Hellisheidi geothermal power plant which has a total installed capacity of 303 MWe, an annual average of 10,072 tonnes of H_2S per year is emitted (data for the period 2013 – 2015). In Kenya, at the Olkaria II geothermal power plant that has an installed capacity of 105 MWe, approximately 1,323 tonnes of H_2S are emitted per year (KenGen unpublished data 2013). Data on the amounts of trace element emissions from geothermal power plants is however limited. There is however evidence that these elements may be present in the emissions as their levels have been determined in condensed steam from geothermal wells, e.g. at Olkaria, 13. 1 tonnes per year of arsenic (Simiyu and Tole, 2000), 10.3 tonnes per year of boron (Simiyu and Tole, 2000) and 19,212 grams per year of mercury (Wetang'ula, 2011) have been assessed from the geothermal wells. Similarly, in Iceland arsenic and boron concentrations have been determined in the Nesjavellir geothermal wells (Giroud, 2008). Studies in the Mediterranean also show that trace elements are present in condensed steam from geothermal wells, see Axtmann, (1975). It therefore follows that trace amounts of these elements may be exhausted from geothermal power plants together with H_2S gas and other NCGs. These elements have the potential to bio-accumulate in ecosystems and cause irreversible effects over time, which may initially go un-noticeable but in the long run result into chronic effects. Since in assessments of ecosystem impacts of geothermal power plant emissions, plants have been used as bio-indicators, I will refer to the toxic effects of these elements on plants.

Evidence of sulphur deposition in terrestrial ecosystems from H_2S gas emissions has been revealed in several studies that report increasing sulphur concentrations in plant leaves (including mosses) and soils with decreasing distance away from the power plant (Bargagli et al., 1997, 2003; Bragason and Yngvadóttir, 2009; Bussotti et al., 1997; Bussotti et al., 2003; Mutia et al., 2016, 2016b). According to the field studies and fumigation experiments (MAAS et al., 1987; Thompson and Kats, 1978) that have assessed the effects of hydrogen sulphide gas and or sulphur dioxide gas on different plant species (SO_2 gas is a possible species of converted H_2S gas in air after a chain of sulphur reactions (Kellogg et al., 1972)), excess sulphur enrichment in plant species is reported to affect plant growth and metabolism. The effects are noticeable on leaves and include foliar injuries manifested as necrosis, defoliation and in the long term as reduced growth, early senescence and chlorosis (Bargagli et al., 1997; Bussotti et al., 1997; Bussotti et al., 2003; Maas et al., 1987; Thompson and Kats, 1978; Varshney et al., 1979). Although, H_2S gas is also an important sulphur contributor to plants, which is an essential plant macro nutrient at optimum levels vital for plant growth and metabolism.

Trace elements are also reported to deposit in terrestrial ecosystems as previously mentioned. In field studies (e.g. Bussotti et al., 1997; Bussotti et al., 2003), elevated levels of boron and arsenic in plants are linked to compromised leaf conditions such as leaf area reduction, damaged chloroplasts and reduced chlorophyll contents. Higher boron concentrations in plant leaves have also been correlated to leaf burn and chlorosis and/or necrotic patches mostly at the margins and tips of older leaves that lead to reduced plant growth, loss of leaf area and decreased carbon dioxide gas fixation amongst a wide variety of plant species (Bussotti et al., 1997; Bussotti et al., 2003; Nable et al., 1997). Similar to excess sulphur levels in plants, higher concentrations of trace elements affect growth and metabolism in plants (Kabata-Pendias, 1992; Nagajyoti et al., 2010). For example, high arsenic and mercury concentrations in plants can stimulate physiological effects in plants. Elevated arsenic concentrations can affect metal sensitive enzymes in plants leading to impaired plant growth and ultimately death (Nagajyoti et al., 2010). The ionic form of mercury (mercuric ion: Hg^{2+}) can attach itself to water channel proteins, thus causing leaf stomata to close causing physical obstruction of water flow in plants (Nagajyoti et al., 2010). Further, high levels of Hg^{2+} can also disrupt bio-membrane lipids and cellular metabolism in plants (Nagajyoti et al., 2010). Antimony as well has toxic effects to plants at elevated concentrations related to reduced plant growth and photosynthesis (Vaculík et al., 2015).

In summary, the accumulation of geothermally emitted elements from geothermal power plant emissions in terrestrial ecosystems has the potential to affect different ecosystem components. Although existing studies do not show extreme impacts of these elements as yet, monitoring mechanisms should be employed to mitigate against any effects that may emerge in the future. In addition, this information will also benefit the public (including scientists and conservationists) and decision makers involved in policy developments who are becoming increasingly aware and questioning the effects of these emissions on the environment. Baseline data and continuous monitoring of these emissions within geothermal power plants will thus assure social acceptability of such projects in promotion of sustainable development.

3. A PROTOCOL TO MONITOR ECOSYSTEM EFFECTS OF GEOTHERMAL POWER PLANT EMISSIONS

NCGs emitted from geothermal power plants are usually dispersed by wind and deposited at different distances from the power plants depending on the prevailing wind, the gas physical-chemical properties, the topography amongst other meteorological and environmental factors (Ólafsdóttir et al., 2013, 2014a, 2014b; Wetang'ula, 2011).

The factor wind direction is quite important in determining where to set-up emission monitoring stations around geothermal power plants in assessment of potential pollution from the power plant emissions. The health of plants and element concentrations (with respect to geothermally emitted elements) has proven a suitable bio-indicator in these assessments, especially the foliar plant parts, as they are the immediate receptors of any atmospheric contaminants. These assessments can also be coupled with soil chemistry measurements as soils are secondary receptors of emitted elements, either directly from the air or through contaminated litter falls. Polluted soils can then cause harm to plants exacerbating the effects of any atmospheric pollutants. Nonetheless, it is important to be aware that soils within geothermally active areas are also prone to sulphur and trace element enrichment from volcanic gases (magma degassing), bedrock, geothermal manifestations such as hot springs and fumaroles and geothermal well test activities. Therefore, establishment of reference stations in areas without geothermal power plants and geothermal/volcanic activities is important for comparison to determine whether there is any effect of pollution from the power plants.

Distance from the power plant has also proven as a robust indicator in providing evidence of geothermal power plant emission and deposition. Monitoring stations may be set from close to the geothermal power plants with others at increasing and different distances away along a transect, e.g. the closest station to the power plant can be somewhere within a 500 m radius from a geothermal power plant. Previous studies indicate evidence of geothermally emitted elements deposited within this distance whose concentrations decrease with increasing distances away (Baldi, 1988; Bargagli et al., 1997; Mutia et al., 2016a). Other stations can be set at 1000 m, 2000 m, 3000 m and 4000 m away along chosen transects. Transects can be chosen and established depending on the prevailing wind profile, i.e. upwind and downwind. See example in (Mutia et al., 2016) and Figure 1. For clear results another transect can be set perpendicular to the main transect (along the prevailing wind direction) for each power plant under study.

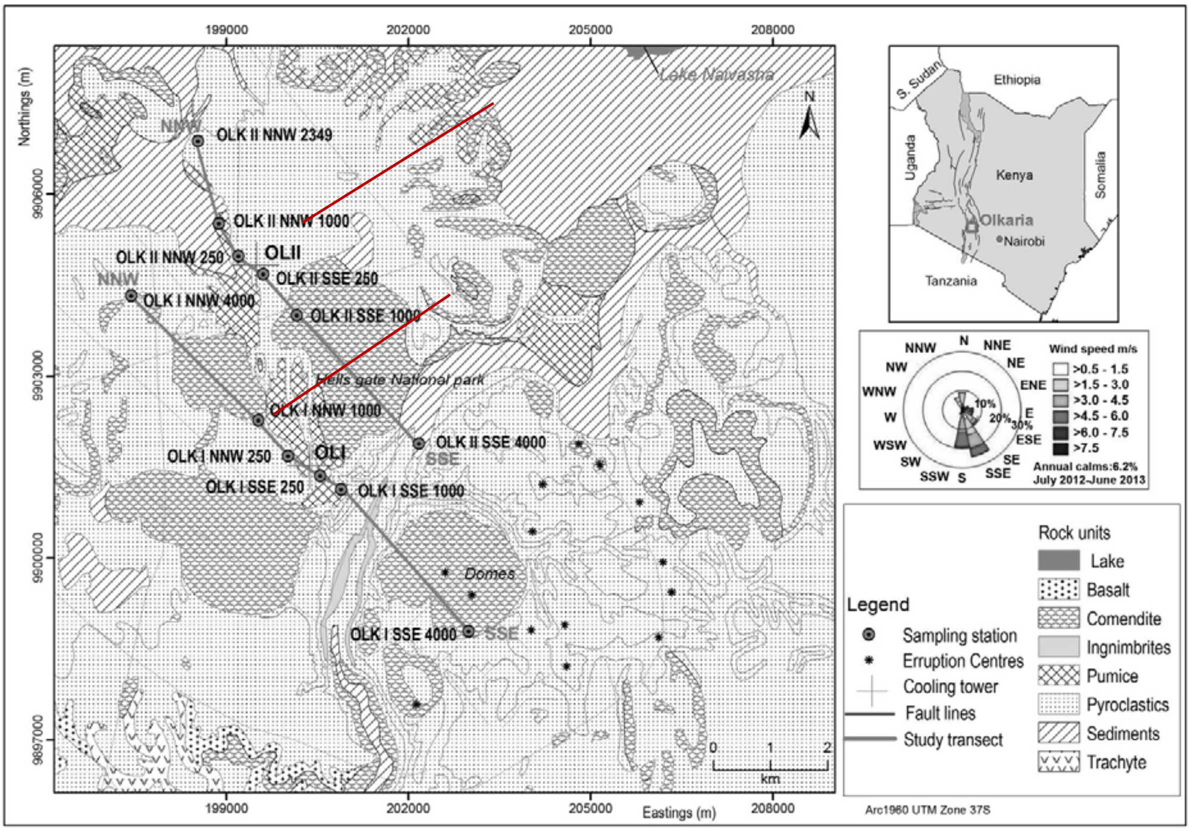

FIGURE 1: Sampling plan for plants and soils around two geothermal power plants at Olkaria Kenya (modified from Mutia et al., (2016a)). The two red lines indicate additional sampling transects that can be incorporated in the main sampling transects (study transect) to increase statistical power for impacts prediction. The main study transects were chosen along the prevailing wind direction which was from SSE to NNW with sampling stations at 250 m, 1000 m and 4000 m away from each power plant.

Perpendicular to each main transect, a sub transect can be established with several monitoring plots (of same vegetation, plot size and topography whenever possible) depending on the vegetation types, wherein measurements and sampling will be carried out, in a hierarchically nested sampling design. Such a replicated protocol and design with large sample sizes is preferred as it reduces chances of errors and biasness. To estimate the best sampling size for maximum effect sizes during data analysis, pre-feasibility studies can be performed on a few samples and statistical power analyses calculated to estimate the sample sizes (Sokal and Rohlf, 2012).

3.1 Plant health assessments

Long term measurements are preferred for plant growth related traits, otherwise for baseline data for geothermal power plants that have already been in operation, it is possible to compare plant growth along the transects with the hypothesis *that the plants would have grown the same over the years in the absence of any geothermal power plant effects*. A dominant plant species can be identified and its characteristics mapped along the transects. Plant growth morphometrics and physiological properties such as abundance, main stem height (stem height), number of plant stems, photosynthesis, leaf area index, number of plant leaves, conditions of leaves (damaged or non-damaged), recruitment of new flowers, main stem circumference, leaf biomass changes among other plant traits can be assessed within plots and compared with similar data from the same plant species at the different sampling stations (Bargagli et al., 1997; Bussotti et al., 1997; Bussotti et al., 2003; Mutia et al., 2016a). Further comparisons are to made with data from reference stations (with same sampling design as study area and plant species). In evaluations of similar effects for non-vascular plants such as mosses, especially in the subarctic, an elaborate monitoring protocol is presented in Mutia et al. (2015).

Plant leaves can then be sampled from the same plants that health assessments had been conducted for sulphur and trace element analysis. Bio-accumulation calculations can also be performed from the element concentration data multiplied by the leaf dry weights and compared for the different distances. Otherwise monitoring stations and plants can be marked for long term assessments to accurately establish bio-accumulation. For non- vascular plants i.e. mosses, the upper 3 cm apical tips of the moss shoots which are the most photosynthetically active are recommended for sampling and plant health assessments. See (Mutia et al., 2015).

3.2 Soil measurements and other environmental factors

Soil sampling for sulphur and trace element analysis should be performed at the sampling points as the plants. Other physical characteristics of soils can be measured as co-variables, since variations in soil properties as a result of other environmental factors besides pollution can affect plant growth and health. Soil measurements such as % moisture, % soil carbon, % soil nitrogen, soil temperature amongst other soil properties may be assessed. Monitoring of other environmental factors within the sampling areas such as precipitation, air temperatures etc. is also important in these assessments.

3.3 Data processing

The statistical computing language R (R Development Team, 2010) for biological data analysis is a powerful for handling such large datasets, Figure 2.

To be able to predict the statistical effect of the predictors on the response variables i.e. the effects of ´Distance from the power plant ´and ´wind direction´ on the concentration of geothermally emitted elements in plants and soils or the effects on plant health, one approach would be to use linear mixed effect models in analysing the data with the predictors distance from the power plant and wind direction as fixed factors. Random factors need also to be decided for feeding into the models. In this case the sampling stations can be included as random factors. The response variables would then be concentrations of sulphur and trace elements in plants and soils and the measured plant traits (see details on model structures in Mutia et al., 2016a, 2016b). The effects of interaction of distance and direction on the response variables needs also to be considered and included as fixed factors whenever significant, so as the co-variates especially if they improve the models. For cases where concentration data is below detection, prior to running the models, data can be $Log_e(X+V)$ transformed with v indicating the lowest concentration value measured. One should be careful with interpretations during such transformations. Multi-collinearity should also be assessed e.g. according to Zuur et al. (2010).

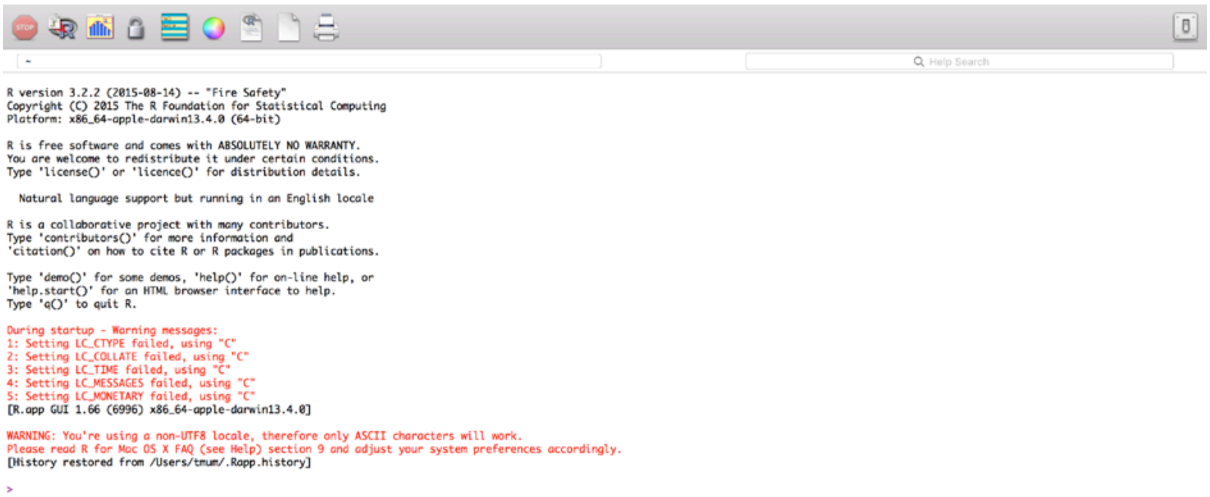

FIGURE 2: The R version 3.2.2 statistical analysis interface. The software is free of charge to download from https://www.r-project.org/

4. CONCLUSION

To complement the bio-indicators data, emission data on the amount of trace elements and sulphur (as H_2S gas) needs to be included in the sampling monitoring plan to establish whether trace elements are emitted from geothermal power plants, if any. The monitoring time frame should run for a period of five years to establish any observed trends or changes. Samples can however be collected on quarterly basis for chemical analysis and data trends studied overtime. Otherwise the other measurements can be scheduled annually. Further, it is necessary for all geothermal developers to develop a similar or an improved ecosystem monitoring system against the geothermal power plant emissions to strengthen mitigation measures.

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