frontiers in Environmental Science

MINI REVIEW
published: 07 December 2020
doi: 10.3389/fenvs.2020.579343

Biomonitoring Studies in Geothermal Areas: A Review

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Biomonitoring is a widely employed approach to track changes in the environment. Its use to assess the impact of geothermal energy exploitation for power production is comparatively minor, and largely referred to Tuscany, Italy, geothermal fields. Most examples describe impacts on vegetation, particularly lichens. Biomonitoring proved useful as a tool to reveal the distribution of specific contaminants (e.g., mercury and H_2S), and as an overall indicator of the impact on ecosystems. In consideration of the comparatively low cost/benefit ratio, the use of biomonitoring should be encouraged. In particular, it could prove useful to establish the natural background prior to development of geothermal exploitation, and to document any subsequent change.

Keywords: lichen, air quality, geothermal energy, biomonitoring, effluent (discharge) waste water

OPEN ACCESS

Edited by:
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Reviewed by:
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Specialty section:
This article was submitted to Toxicology, Pollution and the Environment, a section of the journal Frontiers in Environmental Science

Received: 02 July 2020
Accepted: 16 November 2020
Published: 07 December 2020

Citation:
Lattanzi P, Benesperi R, Morelli G, Rimondi V and Ruggieri G (2020) Biomonitoring Studies in Geothermal Areas: A Review. Front. Environ. Sci. 8:579343. doi: 10.3389/fenvs.2020.579343

INTRODUCTION

Biomonitoring can be broadly defined as the use of the biota to track changes in the environment (Friberg et al., 2011, and references therein). Biomonitoring is an effective method for assessing anthropogenic impacts on ecosystems. It is widely employed as a complementary technique to integrate and support data recorded by instrumental devices (Conti, 2008), and as a valid alternative to survey large areas, where instrumental analysis would result not feasible, or more expensive. In addition, biomonitoring is crucial to evaluate the biological impact of pollutants (Loppi, 2014).

Following the sharp increase of electrical power (power in the following) production in the 1970's, the potentially adverse environmental impacts of exploitation of geothermal resources began to be explored (e.g., Weissberg and Zobel, 1973; Siegel and Siegel, 1975; Dall'Aglio and Ferrara, 1986). Systematic reviews of these potential impacts were provided, among others, by Bacci (1998), Kristmannsdóttir and Ármannsson (2003), Kagel et al. (2005), Bayer et al. (2013), and Manzella et al. (2018; see also the website geoenvi.eu). The Bacci (1998) book contains a specific section reviewing the results of biomonitoring studies.

This short review is specifically focused on effluent and air emissions from power production plants, which can affect air, water and soil. Geothermal fluids used for recovering heat from the subsurface to the production units have a composition which is different from site to site, and in turn influences the technological solutions adopted to produce power. Fluids used to produce electricity are mainly extracted from deep, high temperature geothermal resources, often in volcanic and magmatic areas, and may contain non-condensable gases (NCG), including CO_2, H_2S, H_2, N_2, CH_4, Ar, Rn, and NH_3; H_3BO_3 and trace elements (mainly Hg, As, Se, Sb, and Cr) may also occur (Kristmannsdóttir and Ármannsson, 2003; Bravi and Basosi, 2014; Bustaffa et al., 2020, and literature therein). Water-soluble gases and particulate matter (PM) may be included in aerosol particles (drift) emitted from cooling towers. NO_x and SO_2 are not directly emitted by geothermal plants, but they can form from the oxidation of H_2S and NH_3 released in the atmosphere. Since

1976, geothermal plants began to use H_2S abatement systems (Matek, 2013). In Italy, starting from 2002, the operating power plants have been equipped with an abatement system (AMIS) for both H_2S and Hg, which nowadays is installed in all the 34 plants in operation (Baldacci, 2004; Sabatelli et al., 2009; Manzella et al., 2018).

Geothermal spent waters (i.e., separated brine and condensate) depending on local geological conditions may be acidic or alkaline and/or highly saline, and they may contain potential contaminants such as dissolved H_2S, H_3BO_3, fluoride, bicarbonate, chlorides, heavy metals (As, Hg, Pb, Cd, Fe, Zn, and Mn), as well as harmful concentrations of Li, Al, and NH_3 (Kristmannsdóttir and Ármannsson, 2003; Shortall et al., 2015). Discharged hot water can also cause thermal pollution. In general, environmental problems related to discharged spent geothermal waters are avoided through re-injection of fluids in the underground, usually in the same geological units from which they have been extracted (Shortall et al., 2015). However, depending on local situations/regulations, in some geothermal fields re-injection is only partial (at least until 2018: Rivera Diaz et al., 2016; Orkuveita Reykjavikur, 2018).

Biomonitoring has been used to analyse the effects of both industrial effluent/emission and the natural discharge of geothermal fluids. Such effects are superimposed in geothermal areas, although industrial use of fluids for power production tends to concentrate the effusions in restricted areas. Distinction of natural (geogenic) and anthropogenic contributions is obviously all-important to correctly assess the actual impact of geothermal energy production. This review is focused on anthropogenic effects (i.e., those consequent to exploitation of geothermal resource). However, the distinction between geogenic and anthropogenic contributions is not always clear in the literature.

Tuscany, Italy, is notoriously the birthplace for geothermal power production. Industrial production plants have been in operation since 1913 in the Larderello area, since 1950 in the Travale area, and 1955 in the Amiata area (**Figure 1**).

Biomonitoring of environmental modifications in Tuscan geothermal areas has a long history. As early as 1916, Bargagli-Petrucci (1916) described the dramatic changes of vegetation (disappearance of most species typical of the region, especially trees and shrubs) in the proximity of natural emissions in the area of Larderello-Travale. Later on, Vergnano (1953) documented the adverse effects of boron on vegetation in the same area, and Verona (1960) first addressed the specific impact of geothermal plants in terms of boron abundance in leaves. In the twenty years straddling the turn of century, there was a wealth of studies on the ecological aspects of the Tuscan geothermal fields, mostly fueled by researchers at University of Siena. These studies include some extensive surveys conducted on behalf of ENEL (the company running the power stations; ENEL, 1996) and of the regional environmental agency of Tuscany (ARPAT, 2003, 2006). Most studies were devoted to examine the effects on spontaneous vegetation (mainly lichens and mosses), and a good share of them was focused on the use of plants as biomonitors or bioindicators of trace elements emitted by power plants. Only few studies considered the impacts on other segments of the biosphere. In the last 15 years, biomonitoring studies of Tuscan geothermal areas became sparser.

Outside Italy, biomonitoring studies in geothermal areas are comparatively scarce, and include examples from USA, New Zealand, Iceland, Mexico, and Kenia. A number of studies considered the ecological effects, especially on benthic communities, of the inflow of geothermal waters. Most of these studies (e.g., Clements et al., 2011) deal with natural phenomena, but a few (e.g., Resh et al., 1984; Fendick et al., 1989; Barbaro and Feola, 1994; Boothroyd, 2009; Snorrason et al., 2011; Helgason, 2017) investigated the effects of effluents from geothermal power plants, or made inferences on the possible impact of geothermal energy development.

AIR EMISSION—BIOMONITORING OF CONTAMINANTS

As previously noted, several studies were devoted to the use of vegetation (mainly lichens and mosses) as biomonitors of contaminants (typically, Hg and H_2S) released from geothermal plants (Baldi, 1988; Loppi, 1996, 2001; Loppi and Bargagli, 1996; Loppi et al., 1997a, 1998, 1999; Bacci et al., 2000; Loppi and Bonini, 2000; Bargagli et al., 2003; Loppi and Nascimbene, 2010; and references therein). A specific use of lichens as indicators of air quality is based on biodiversity (Giordani, 2019, and references therein; see more under Ecological impacts). More recently, Chiarantini et al. (2016) suggested the use of tree (*Pinus nigra*) barks as biomonitors of airborne Hg in the Monte Amiata area (see also Rimondi et al., 2020a,b). Although the main focus of these latter studies was on the former Hg mines and smelting plants, the results give also some evidence on emissions from geothermal power stations (Lattanzi et al., 2019).

The use of these biological substrates as monitors of airborne contaminants has its inherent limitations and pitfalls, including the following: (i) their exact time of exposure and interaction with the atmosphere may be difficult to estimate (e.g., for barks); (ii) some contaminants (e.g., Hg) are both adsorbed and partly re-emitted by these tissues; (iii) uptake of contaminants may occur both in gaseous and in particulate form, and for higher plants also directly from the soil via the root system, therefore it may be difficult to distinguish the different contributions. In spite of these limitations, the results of these studies suggest that consistent indications on the long term dispersion and spatial distribution in the environment of contaminants such as heavy metals, boron and H_2S can be obtained from these biomonitors. To give just a few examples, Baldi (1988) found that at Travale (Tuscany, Italy) Hg contents in briophytes and soil decrease sharply within 500 m from the geothermal plants. Loppi (2001) showed an increase of Hg concentrations in lichens at Bagnore (Mt. Amiata, Italy), after a new geothermal power plant went into operation. Bargagli et al. (2003) compared the contents of several elements (including, among others, As, B, Cd, Hg, Pb, and S) in oak (*Quercus pubescens*) leaves collected from a wide area of southern Tuscany, including samples close to sulfide deposits, ophiolite outcrops, geothermal plants, industrial sites, and "relatively unaffected sites." The five samples collected near

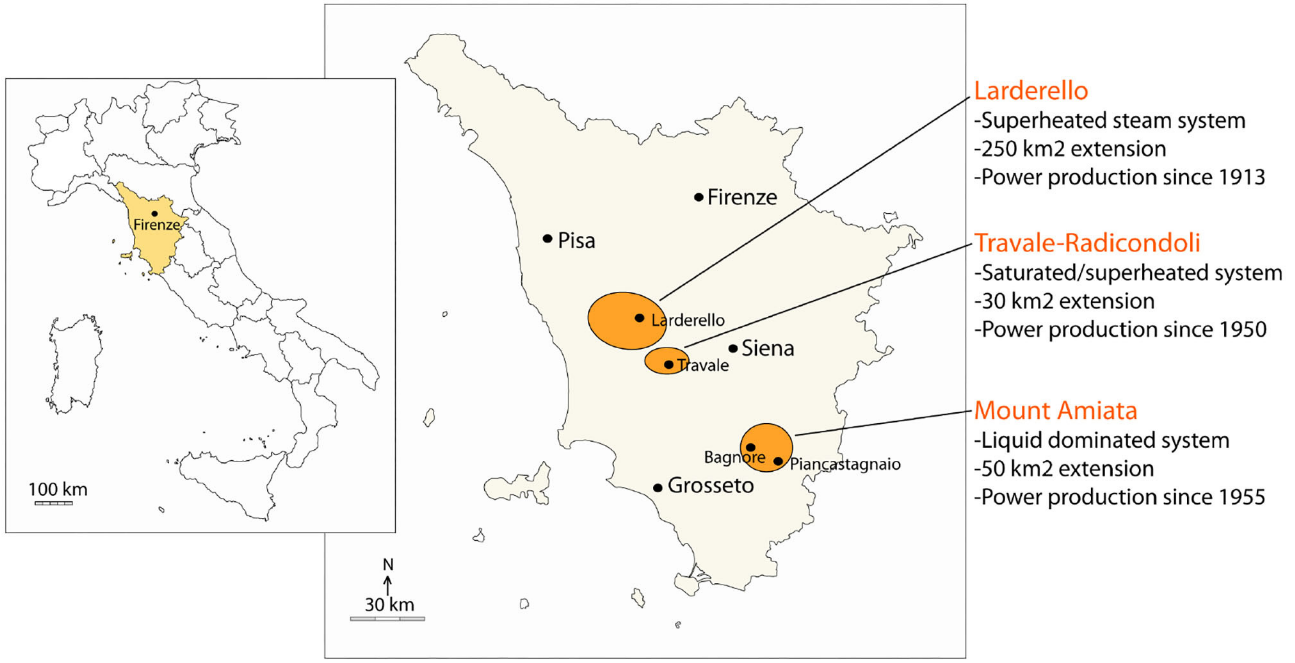

FIGURE 1 | Location of the geothermal areas where electrical power is produced in Tuscany [modified from Manzella et al. (2018)].

geothermal plants showed no statistically significant difference in any of the analyzed elements compared to "unaffected sites." Worthy of mention are two studies that consider the transfer of contaminants to the food web. Barghigiani and Barghigiani and Ristori (1994) conducted a survey of mercury contents of agricultural products of the Mt. Amiata area. Although the study was mainly directed at documenting the impact of former Hg mines and smelting plants, two of their sampling stations were within 500 m distance from geothermal power plants. Mercury contents in the examined products are, in general, lower in these stations than in others more directly affected by past mining and smelting; we notice however a single high value (36 ng/g dry weight) for a fig, possibly because of deposition of airborne mercury. A similar study was conducted by a team of the University of Pisa (Lorenzini, 1996) in the framework of the previously mentioned comprehensive study commissioned by ENEL. The team analyzed B, As, Hg, and Sb in 84 forages and 96 vegetables from 43 sampling points. They concluded that the risk for the population was negligible. No signs of phytotoxic effects were observed, in agreement with low (< 90 mg/kg dry weight) B contents; in all samples but one As and Sb contents were below 1 mg/kg dry weight, whereas 14 samples exceeded 0.5 mg/kg dry weight for Hg, with three samples exceeding 1 mg/kg; however, the single highest value (2.26 mg/kg) was found in an area affected also by past mining.

Importantly, most studies in Italy were carried out before the introduction of the abatement systems (AMIS) to reduce Hg and H_2S emissions. In more recent studies using *Pinus nigra* barks as the adsorbing substrate (Lattanzi et al., 2019; Rimondi et al., 2020a; and references therein), samples collected near geothermal plants at Piancastagnaio (Mt. Amiata area) showed Hg contents of the same order of magnitude as samples considered as local background, and at least one order of magnitude lower than samples collected near dismissed Hg mines and smelting plants.

Epiphytic lichens are also indicators of geothermal radionuclide pollution. Matthews (2001) monitored local radon emissions from geothermal bores at Wairakei power station (New Zealand), by quantifiyng the radon decay-product (^{210}Pb) deposition rate in the lichens growing in the geothermal area. Loppi et al. (1997b) used lichens as bioaccumulators of radionuclides in the Travale geothermal area. In both studies, results showed that radioactivity in geothermal fields is similar to areas not subject to geothermal exploitation. Therefore, the exploitation of geothermal resources should not cause an increase in radioactivity. However, Loppi et al. (1997b) found a negative association between total β radioactivity in lichens and their distance from geothermal power plants, suggesting that geothermal plants in the area are a source of radionuclide contamination up to a distance of 500 m.

Outside Italy, Mutia et al. (2016) carried out an extensive study of As, B, S, and Sb[1] contents in soil and leaves of the shrub *Tarchonanthus camphoratus* around the Olkaria geothermal field in Kenya. Both soil and leaves collected within 4000 m of geothermal plants showed, in general, higher contents of the four elements with respect of a reference site (>68 km from geothermal plants). However, the spatial patterns were complex;

[1]Hg was also analyzed, but it was always below the reported detection limit of 8.8 µg/g.

a clear decreasing trend with distance was apparent only for S. Moreover, the study did not detect any obvious evidence of deleterious effects in the studied plants.

ECOLOGICAL IMPACTS

Most studies of ecological impacts of geothermal energy refer to spontaneous vegetation. For instance, among the many studies in Italian geothermal areas, to our knowledge only Bargagli et al. (1997) report some data for the impact on edible vegetables and wood mice (*Apodemus sylvaticus*) at Piancastagnaio (Mt. Amiata). As previously mentioned, Bargagli-Petrucci (1916) first described the dramatic changes in vegetation in the proximity of natural emissions in the Travale geothermal field. Later on, Vergnano (1953) documented some adverse effects of boron on trees (*Ulmus montana* and *Populus nigra*) living in the same area. The impact on higher plants (*Quercus pubescens* and others) was further described by Dani and Loppi (1994), Bussotti et al. (1997, 2003), and Chiarucci et al. (2008). The described effects typically include leaf decoloration and apical necrosis, and usually fade away at <500 m from the geothermal plants (see, however, Bussotti et al., 2003). The effects of boron excess in geothermal areas on a set of ecophysiological parameters in the lichen *Xanthoria parietina* were assessed by Pisani et al. (2009). They showed that lichen viability and damage to plasma membrane can profitably be used as indicators of early biological effects of boron pollution. An experimental study by Paoli and Loppi (2008) showed that lichens can be used as early warning indicators to detect a worsening of air pollution around geothermal power plants. After testing a set of ecophysiological parameters, results showed that cell membrane damage, expressed by changes in electrical conductivity, can be used to detect early effects of geothermal air pollution.

As noted above, a widely used ecological indicator of air quality is lichen biodiversity, expressed directly as indicator of air purity (IAP, e.g., Loppi, 1996; Loppi and Nascimbene, 1998), or, perhaps more correctly, as index of lichen diversity (ILD; e.g., Loppi and Nascimbene, 2010). For example, comparison of changes in the biodiversity of lichens in a 8-years timespan in the geothermal area of Travale was correlated to an improvement of air quality, as suggested by colonization of some lichen species in areas where lichens were previously absent (Loppi, S. et al., 2002). Similarly, in the nearby geothermal area of Loppi and Frati L, (2002) found increasing biodiversity with distance from geothermal power plants, suggesting that air pollution from geothermal installations, mainly hydrogen sulfide, is the main cause of the observed impoverishment in lichen communities close to old power plants (when the AMIS technology was not yet implemented).

Loppi et al. (2006, and references therein) also concluded that the alteration of the natural state around Mt. Amiata geothermal plants is moderate, and does not extend beyond few hundred meters from the source. Brunialti et al. (2012), in their study in the Larderello-Travale area, concluded that "the lichen communities …. were mainly influenced by factors such as land use and tree species….rather than by factors related to geothermal power exploitation." In conclusion, the available evidence suggests that the ecological impact of geothermal plants in Tuscany is low to moderate, and confined within a distance of 500–1,000 m from the plants.

Del Rio Mora (2014) documented the impact on *Pinus* spp. of emissions from the Los Humeros geothermal field, Mexico. Obvious signs of plant damage (e.g., needle necrosis and premature bud abortion) were observed only in the "immediate" vicinity of the emission source (exact distance not stated); however, a correlation is reported between boron abundance in needles and the occurrence of a pest (*Essigella californica*).

Gonzalez-Acevedo et al. (2018) analyzed several elements in water, soil and plants in the surroundings of the Cerro Prieto, Mexico, geothermal field. Although emissions from the field may have contributed some elements to the environment, contributions from many other sources (both natural and anthropogenic) were suggested; only the high sulfur contents in subaerial (leaves and stem) parts of the shrub *Allenrolfea occidentalis* was directly ascribed to H_2S emissions from the field.

Using isotope ratios (C, N, S, and Pb) in moss (*Rhacomitrium Lanuginosum*) around the geothermal power plant in Hellisheið*i, Iceland, Gautason and Widory (2015) concluded that "The results do not support the contention that geothermal H_2S is responsible for the decline in vegetation around geothermal power plants."

Detailed studies of the effects of the input of effluents from geothermal power stations on the ecosystems in the affected water bodies were provided by Snorrason et al. (2011) and Helgason (2017). The first study addressed the impact of warm effluents from the Nesjavellir geothermal power plant on benthic invertebrate communities in lake Þ*ingvallavatn, Iceland. Thermal pollution caused a rise of 7–12°C of water temperature with respect to reference sites, inducing detrimental effects on the gastropod *Radix peregra* and several chironomid species, transforming a relatively diverse community to a species-poor community. Such effects were, however, confined to the southwest shore of the lake, where the warm effluent input occurs. Helgason (2017) investigated the effects of effluents from the Krafla, Iceland, geothermal field on the aquatic ecosystem in the stream Hlíð*ardalslækur. The author reported a significant shift in periphyton and invertebrate community composition, and a decrease in diversity value downstream of the power plant. The changes in the physical attributes (especially temperature), due to the effluent input and seasonality, favored cyanobacterial assemblages dominated by few genera, while penalized the other algal genera. However, these effects resulted evident only in the closest (ca. 500 m) site downstream of the effluent input.

CONCLUDING REMARKS

Geothermal resources are an important addition to our quest for sustainable energy production, and in general represent a suitable local alternative to conventional sources. However, as any other anthropic activity, their exploitation has potential environmental impacts. A sustainable development requires a reliable monitoring of these impacts, as part of mitigation planning and for assessing its environmental imprint. Biomonitoring techniques are a powerful instrument to document the environmental effects of human activities. Specific applications to geothermal energy are comparatively scarce worldwide, except for Italy, but should be encouraged. Useful results can be obtained for (a) identification of the spatial distribution of airborne contaminants, such as H_2S and mercury; (b) assessment of the overall impact on ecosystems, making reference to appropriate indicators (e.g., biodiversity). We emphasize that in geothermal areas the anthropogenic activity is generally superimposed to natural manifestations, or fossil evidence of past hydrothermal systems, like ore deposits. Biomonitoring may be especially effective to establish the natural background conditions *before* actual exploitation (i.e., to discriminate natural from man-induced impacts, or to point out the consequences of changes in the production or mitigation strategies). For instance, once a mitigation strategy (e.g., the AMIS plants in geothermal facilities in Italy) is made effective, new surveys in areas studied before could document the long term effectiveness of the installation.

AUTHOR CONTRIBUTIONS

PL: general concept and preliminary draft. RB: ecology. GR: geothermics. GM and VR: geochemistry. All authors: final text.

FUNDING

The activity leading to this paper has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 818242.

ACKNOWLEDGMENTS

This communication arises from data collected for the GEOENVI project (geoenvi.eu), and is funded by the same project. We thank Adele Manzella, leader of the CNR team in the project, for her encouragement and support. We acknowledge the useful comments by two reviewers.

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.