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The impact of tourism on extremely visited volcanic island: Link between environmental pollution and transportation modes

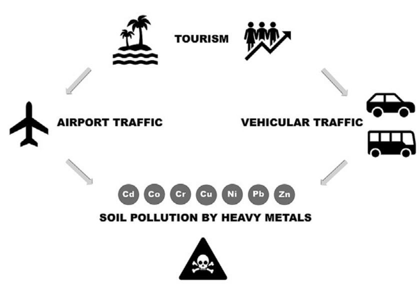
Martin Brtnický [a, b], Václav Pecina [a, b], Michaela Vašinová Galiová [a, b, *], Lubomír Prokeš [c, d], Ondřej Zvěřina [e], David Juřička [a], Martin Klimánek [f], Jindřich Kynický [g]

[a] Department of Geology and Pedology, Faculty of Forestry and Wood Technology, Mendel University in Brno, Zemědělská 1, 613 00 Brno, Czech Republic
[b] Institute of Chemistry and Technology of Environmental Protection, Faculty of Chemistry, Brno University of Technology, Purkyňova 118, 61200 Brno, Czech Republic
[c] Department of Chemistry, Faculty of Science, Masaryk University, Kamenice 5, 625 00 Brno, Czech Republic
[d] Department of Physical Electronics, Faculty of Science, Masaryk University, Kotlářská 2, 611 37 Brno, Czech Republic
[e] Department of Public Health, Faculty of Medicine, Masaryk University, Kamenice 5, 625 00 Brno, Czech Republic
[f] Department of Forest Management and Applied Geoinformatics, Faculty of Forestry and Wood Technology, Mendel University in Brno, Zemědělská 3, 613 00 Brno, Czech Republic
[g] Central European Institute of Technology, Brno University of Technology, Purkyňova 656/123, 612 00 Brno, Czech Republic

HIGHLIGHTS

- The anthropogenic contamination by Cu, Cr and Pb has been found out on Santorini.
- The contamination may represent a moderate ecological risk to local ecosystems.
- Airport traffic is a significant source of soil pollution on the island.
- The dominant factor determining HM content of volcanic island soils is parent rock.
- HM monitoring may serve as background for introducing tourist quotas.

GRAPHICAL ABSTRACT



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ABSTRACT

The enormous tourism boom raises concern about possible negative environmental impacts worldwide. One of the risks posed by tourism may be heavy metal pollution. On the example of the volcanic island of Santorini, a popular tourist destination, pollution of soils categorized according to the tourism load was monitored. Significant anthropogenic contamination by heavy metals, especially Cu, Cr and Pb, was found out. This contamination may constitute a moderate ecological risk to the island ecosystems. Tourism has been shown to be a significant pollution factor as evidenced by the contaminated soils near the airport. Simultaneously, airport traffic has been proved to be an important emitter of Co, Cr and especially Zn. The comparison with other volcanic islands has shown that on Santorini the content of

* Corresponding author. Institute of Chemistry and Technology of Environmental Protection, Faculty of Chemistry, Brno University of Technology, Purkyňova 118, 61200 Brno, Czech Republic.

E-mail addresses: martin.brtnicky@mendelu.cz (M. Brtnický), vaclav.pecina@mendelu.cz (V. Pecina), galiova@fch.vut.cz (M. Vašinová Galiová), prokes@chemi.muni.cz (L. Prokeš), ondrej.zverina@mail.muni.cz (O. Zvěřina), david.juricka@mendelu.cz (D. Juřička), martin.klimanek@mendelu.cz (M. Klimánek), jindrich.kynicky@ceitec.vutbr.cz (J. Kynický).

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heavy metals in soils is significantly lower, despite frequently higher tourism intensity. On this basis, it can be concluded that in case of volcanic islands the dominant factor determining the content of heavy metals in the soil is the parent rock. Given high and ever-increasing intensity of tourism on the island, it can be assumed that soil contamination will continue to rise rapidly. Therefore, without proper steps reducing tourism, increase in soil degradation, growing negative impacts on local ecosystems as well as on the quality of produced wine can be expected on Santorini.

1. Introduction

Tourism is a source of employment and income for local inhabitants, it can be an important component of regional development and can also contribute, for instance, to the preservation of natural and cultural heritage as a source of finance (Pigram and Wahab, 2005; Buckley, 2011; Azam et al., 2018). However, in case of a disproportionately high influx of tourists, there is so-called overtourism (Oklevik et al., 2019) which has already affected, for example, Barcelona, Amsterdam or Rio de Janeiro (Peeters et al., 2018). Then, unduly high tourism entails a number of negatives, such as environmental pollution, ecosystem degradation, soil erosion and may result even in desertification (Zhong et al., 2011; Azam et al., 2018; Drius et al., 2019). In the context of the tourism boom and global change, its environmental impact is becoming an objective of increasing global interest (Li et al., 2014).

The development of large tourist centres threatens the environment with a number of pollutants. The greatest threat is posed by the construction of new infrastructure and transport (Lukashina et al., 1996; Davenport and Davenport, 2006). Transport, as an emitter of pollutants, is associated with vehicular traffic (Has-Schön et al., 2006; Chen et al., 2010; Ciarkowska, 2018), shipping (Adamo et al., 2005; Ali et al., 2011) and air transport (Ray et al., 2012; Massas et al., 2016). Due to fuel combustion it can have both a local and global impact, in particular through greenhouse gas emissions (Buckley, 2011; Azam et al., 2018).

Pollutants directly associated with tourism can be represented, for instance, by heavy metals (HMs) (Ali et al., 2011; Li et al., 2014; Ciarkowska, 2018). HMs naturally occur in the environment and many of them are biologically significant, but they can be toxic to plants, animals and humus at excessive concentrations (Nagajyoti et al., 2010; Werkenthin et al., 2014). Due to high anthropogenic emissions, they are one of the most serious environmental pollution problems because of their toxicity, persistence and bioaccumulation (Tam and Wong, 2000; Werkenthin et al., 2014). HMs are mainly addressed in urbanized areas where population may be permanently exposed to their harmful effects through inhalation, ingestion or absorption of contaminated soil or dust particles (Al-Khashman, 2004; Cheng et al., 2014) but they are also addressed, for example, in agriculture (Huang et al., 2018; Mirzaei et al., 2019). The accumulation of HMs in agricultural soil can limit the growth of crops due to phytotoxic effects, endanger the health and function of soil organisms and ultimately have a negative impact on food safety and marketability (Nagajyoti et al., 2010; Kabata-Pendias, 2011; Mirzaei et al., 2019).

As tourism grows, traffic intensity increases, leading to a greater risk to HMs emitted to the environment in tourist destinations (Has-Schön et al., 2006; Li et al., 2014). However, specific research studying soil contamination by HMs due to tourism is very sporadic and insufficient in the scientific literature. This topic was only historically and marginally addressed by Lukashina et al. (1996) and newly Ciarkowska (2018) and Memoli et al. (2019). Given the worldwide significant growth in tourism, such studies are necessary to determine the environmental burden.

Santorini is one of the most popular tourist destinations in the world (Delitheou and Georgakopoulou, 2017) and it is visited by up to 2,000,000 visitors per year (Peeters et al., 2018). For the economy of the island, tourism is the mainstay that generates most of the revenue (Jenkins et al., 2015). Other important sectors linked to tourism are agriculture, fisheries, craft, services and construction. Tourism development has resulted in the growth of tourist infrastructure that spans the whole island (Delitheou and Georgakopoulou, 2017). Santorini is increasingly associated with overtourism, high traffic issues and inquiries about possible negative environmental impacts are emerging (Peeters et al., 2018). For this reason, Santorini was chosen as a suitable model location for monitoring the impact of tourism on soil contamination and further evaluations.

The objectives of this study are to find out whether tourism causes significant contamination of soil by HMs and whether monitoring of this contamination can be used as a basis for management decisions on the protection of nature and human health via several steps: (1) to map the current HM content (Cd, Co, Cr, Cu, Ni, Pb and Zn) in the soil of the island; (2) to calculate indices assessing the level of contamination and the environmental risk; (3) to evaluate the impact of tourism on the contamination of soils exposed to a high risk of pollution; (4) to compare the impact of airport and road transport on soil contamination; (5) to compare the levels of HMs in soils with other islands.

2. Materials and methods

2.1. Study area

Santorini (Thera) is known as a complex of islands in the southern Aegean Sea (36°25′N 25°26′E) and is a part of the Cyclades archipelago in Greece. The largest island is Thera with an area of 75.8 km^2 (Economou et al., 2007).

Santorini is a multicentric volcanic field and its current appearance is the result of volcanic activities (Dominey-Howes and Minos-Minopoulos, 2004). The great eruption, which took place approximately 3500 years ago, led to the formation of a layer of volcanic ash and pumice with a depth of 30–40 m. This material forms the parent rock on which the current island soils, classified as regosols (Vavoulidou et al., 2006) or entisols (Moustakas and Georgoulias, 2005) have been developed. These soils are often affected by erosion which is accelerated by hundreds of years of intensive farming and prevailing strong winds (Economou et al., 2007).

On Santorini Island, only about 15,000 inhabitants live permanently but, in the summer, the number of people on the island can rise to more than 500,000 (Jenkins et al., 2015). The main tourist destination is Thera which is equipped with the necessary infrastructure, including the airport and port. With the appearance and growth of tourism, urban areas of the island have grown rapidly since the 1970s (Economou et al., 2007), fishing and farming villages have turned into seaside resorts (Wadih, 2005). Infrastructure growth saturated with increasing tourism continues, especially in the transport sector (Delitheou and Georgakopoulou, 2017).

Santorini is not only a destination but also a transfer hub from plane to ferry and vice versa for neighbouring islands. The Santorini Airport has served as a civil and military airport since 1972. The ever-increasing tourism is reflected in the increasing number of flights from recent years. While in 1994 there were 6096 flights representing 401,048 passengers carried (Hellenic Civil Aviation Authority (HCAA), 2019), in 2018 there were 20,360 flights with a total of 2,254,926 passengers carried. Eight thousand one hundred fifty-nine international flights which are used almost exclusively by tourists, were carried out and 1,068,022 passengers were transported in 2018 (Santorini Airport, 2019). In addition, Santorini is accompanied by many cruise ships and passenger ones contributing to the growth of tourism on the island (Delitheou and Georgakopoulou, 2017). In 2011, 58% of arrivals were made by air and 42% by sea (Peeters et al., 2018). At the same time, the increasing number of tourists led to increased pressure on the infrastructure on the island and increased traffic (Wadih, 2005).

2.2. Soil sampling

Four categories of sampling sites were created according to the type of traffic pollution and the intensity of road network utilization. Specifically, these ones are: (1) **Airport (AIR)** which includes sites around the perimeter of the airport area where direct impact of intensive air traffic is expected as a result of enormous tourism; (2) **Airoport - Ferry port road (AFR)** which includes points on the road connecting two main transport links providing services from the island and there, with intensive traffic as a result of tourism; 3) **Urban roads (UR)** include sites situated in continuous built up area which can be called in the local conditions urban area, roads are widely used by tourists; 4) **Rural roads (RR)** include places situated in the agricultural landscape, without continuous development and tourism.

The locations of the individual sampling points are indicated in Fig. S1. A total of 65 samples were collected and taken within 1 m of the roadside. One mixed sample was taken as a background from five different sites of the uninhabited island of Nea Kameni, located in the centre of the Santorini complex. All the samples were collected as a mixed sample of surface soil (0–10 cm) formed by mixing five sub-samples from an area of 1 m^2.

2.3. Sample preparation and analysis

The soil samples were dried at room temperature and subsequently sieved through a nylon sieve (mesh size 2 mm). The pH was measured in 1 M KCl (ISO 10390: 2005). Carbon oxidation state (Cox) was determined by oxidation with a chromium-sulphur mixture (ISO 14235: 1998).

The content of HMs (Cd, Co, Cr, Cu, Ni, Pb and Zn) was measured for each soil sample. Decompositions were performed prior to measurements of the samples. The sample solutions were obtained by decomposing 1 g of soil with the addition of 3 ml of concentrated nitric acid and 9 ml of concentrated hydrochloric acid in an ETHOS EASY microwave digestion oven (Milestone, IT). Microwave decomposition was performed using an optimized temperature programme. Step 1: gradual heating of the vessels to 110 °C for 15 min at 1800 W, Step 2: maintaining of the temperature 110 °C for 15 min at 1800 W and Step 3: cooling for the time period of 10 min. Then, the mineralized solutions were transferred to a well-defined volume of 50 ml.

Concentrations of the selected metals in soil digests were determined by means of atomic absorption spectrometry (AAS) with graphite furnace (GFAAS) and flame atomization (F-AAS) technique.

For determination of the elements presented in relatively low concentrations (Cd, Co, Cu, Cr, Ni and Pb), the GFAAS technique was employed using high-resolution continuum source spectrometer (ContrAA 800G, Analytik Jena, Germany). The content of Zn was determined using flame technique (Solaar 939, Cambridge, UK) employing standard conditions (air-acetylene flame). The digests were diluted 1:2 for measurement using graphite furnace and 1:10 for flame technique.

Measurement conditions (Table S1) were optimized prior to analysis and trueness of the measurement was verified by means of a set of three certified reference materials: Metranal 31 (light sandy soil), Metranal 33 (clay loam soil) by Analytika, Czech Republic, and 2709a (San Joaquim Soil) by NIST, USA. All the determined values were in agreement with the certified values at the 95% confidence interval (*t*-test). The relative standard deviation was, in all cases, below 8%.

2.4. Data treatment

The content of HMs in soil is assessed in compliance with the Dutch Soil Guidelines Target Values and Intervention Values (VROM, 2013). This standard is widely used in research studies throughout the world (Chabukdhara and Nema, 2013; Cheng et al., 2014; Brtnický et al., 2019). Soil contamination and pollution severity was assessed by Enrichment factor (EF), Geoaccumulation index (Igeo) a Nemerow pollution index (IPI_N) and Potential ecological risk index (RI) (see Supplementary data).

2.5. Statistical analysis

Data visualization using box plots and PCA were performed using Origin software. The values of the contents of the elements of interest and the calculated indices were subjected to statistical analysis using the R programme (https://cran.r-project.org/). Basic data diagnostics (identification of outliers, test of normality and heteroscedasticity of data and testing of conformity of individual contents with background value) was performed by means of box plots. Due to the significant non-normal distribution of the data, further analysis of the data was performed using non-parametric statistical tests. The effect of outliers was eliminated by using bootstrap, respectively permutation tests. Both the classical and permutation one-sample Wilcoxon test were used to test the compliance with the background value for individual sets (Conover, 1999; Sheskin, 2004; Hollander et al., 2014).

Comparison of sets was performed by different variants of single-factor ANOVA and mutual comparison: *a) Kruskall-Wallis nonparametric test* (including its bootstrap variant), based on ranking of individual values, together with Nemenyi paired comparison methods (Hollander et al., 2014) and methods Dwass-Steel-Critchlow-Fligner (Hollander et al., 2014); Dunn (Sheskin, 2004); and Conover (1999). Adjustment of probability values (p-values) for pairwise comparisons was performed by the methods of Hochberg-Benjamini (false discovery rate, FDR) and Holm which provides less conservative estimates than FDR (Goeman and Solari, 2014). Then, *b) Van der Waerden test* (Conover, 1999; Sheskin, 2004) and *Lu-Smith test* (Lu and Smith, 1979), based on normalized scores with adjusting of p-values Hochberg-Benjamini (FDR) and Holm were also used, *c) Anderson-Darling k-sample test* (Scholz and Stephens, 1987) and *k-sample Baumgartner-Weiss-Schindler test* according to Murakami (2012), based on the comparison of distribution functions, again with adjustment of Hochberg- Benjamini (FDR) and Holm and the last one applied was *d) Permutation k-sample test*

(Anderson, 2001; Basso et al., 2009) with a combination of Hochberg-Benjamini (FDR) and Holm. In all cases the significance level $\alpha = 0.05$ was used.

3. Results and discussion

3.1. Soils of the island

The average pH of the studied soils on the island is 7.6. The difference between categories is minimal and not statistically significant. The average carbon content is 2.1%. It is mostly found in urban soils, where its average value is 3.0%. On the contrary, the least carbon content is in soils at the airport, specifically 1.7%.

The contents of the HMs in the individual soil categories of Santorini are given in Table 1 and Fig. S2. The average values did not exceed the target values which reflect the possible natural contents of the elements in the soil, for none of the elements. Maximum values exceeded them for Cu, Pb and Zn. It was four times for Cu, once for the UR and RR categories and twice for the AIR category. It was exceeded only once in the case of Pb in the AFR category. It was three times in the case of Zn - once in the UR category and twice in the AIR category. Intervention Values were not exceeded for any element which means that there is no presumption of serious threat to human, animal or plant health.

The Cd content of Santorini soils is not listed in Table 1 and the element is omitted from subsequent statistical analysis. The reason is that its content was below the detection limit (0.01 mg/kg) in 94% of the soil samples, indicating its very low content in the parent rock and merely local enrichment, probably of anthropogenic origin.

Background values were exceeded for all the elements, indicating potential anthropogenic contamination. The background values themselves can be described as very low, as is also mentioned by Vavoulidou et al. (2006) and Moustakas and Georgoulias (2005) who report that the local soils have a very small quantity of products of weathering.

A significant increase in the soils of the island compared to the background values is evident especially in the case of Cr, Cu, Pb and Zn, while in the case of Co and Ni it is not so significant. The division of the elements into these two groups was also confirmed by PCA (Fig. S3). On this basis, it can be assumed that Co and Ni in the soils of the island are predominantly of geogenic origin, while Cr, Cu, Pb and Zn originate predominantly from anthropogenic activities. In the case of this tourist destination, these are mainly represented by traffic that emits these elements in large quantities (Chen et al., 2010; Werkenthin et al., 2014; Massas et al., 2016) and may also be hypothetically associated with tourism as the cause of high traffic on the island. The growth of tourism related to increasing traffic intensity and greater risk posed by Pb is also mentioned in the study by Has-Schön et al. (2006). Similarly, Memoli et al. (2019) points to the possible impact of enormous tourist traffic in finding of soil contamination by Cr, Cu, Ni and Pb but the variability in the values reported in the study raises questions rather than clarifies the issue.

Locally, for instance, docks for recreational and fishing boats associated with Cu, Zn, Pb and Cd pollution (Ali et al., 2011) can be also identified as sources of pollution on the coast. In the case of the RR category, agricultural practices involving the application of fertilizers and pesticides in the vineyards may also be a source of pollution. These agents may lead to the increase in Cd, Cr, Cu, Ni, Pb and Zn (Massas et al., 2016; Mirzaei et al., 2019).

3.2. Assessment of soil contamination and its risk

The average values of soil contamination indices (EF, I_{geo}, IPI_N) by the selected HMs within each category are shown in Table S2 and their range is graphically presented in Fig. 1 and Fig. S4.

The EF confirmed the anthropogenic contributions of HMs to soils in all the categories as it exceeded the limit value of 1.0 for all of them. Cu (Fig. 1a) proved to be the most anthropogenically emitted element, with an increase of more than ten times the natural values in all the categories. On the contrary, Ni proved to be the least anthropogenically emitted element.

According to the I_{geo}, the most serious contamination occurred in connection with Cr, Cu and Pb. In the categories AIR, AFR and UR, the soils are moderately to heavily contaminated with Cr. For Cu, the soils of the categories AFR, UR and RR are moderately to heavily contaminated, while the AIR soils are even heavily contaminated. For Pb, the soils of the categories AIR and RR are moderately contaminated, while the soils of the categories UR and AFR are moderately to heavily contaminated. Pb and Cu reached the most extreme values (Fig. 1b).

According to the IPI_N, the soils of the categories AFR, UR and RR are classified into the class safe. The AIR soils are already in the class precaution, mainly due to several extreme values (Fig. 1c) indicating heavy local pollution.

According to the RI (Fig. 1d), soils in the categories AIR (157.1) and AFR (184.5) which fall under the category of moderate ecological risk, may pose a certain risk to biota. A closer focus on the risk posed by the individual HMs (Table S3) shows that ecological risk is mainly represented by Cu and Pb. This is mainly due to local soil pollution by these elements and also to the fact that Cu and Pb are ranked among the most toxic metals for both higher plants and certain microorganisms (Kabata-Pendias, 2011). The content of Cu in the AIR soils represents a considerable potential ecological risk, in other categories only moderate potential ecological risk. Pb

Table 1
Contents (mg/kg) of the HMs in the soils of the island.

		Co	Cr	Cu	Ni	Pb	Zn
Airport (n = 19)	Mean	4.9	10.5	22	5.5	7.5	84
	SD	1.2	4.9	23	1.0	4.7	69
Airport − Ferry port (n = 7)	Mean	3.76	8.2	13.6	7.0	24	58
	SD	0.64	2.9	6.2	1.7	36	26
Urban road (n = 13)	Mean	3.50	9.8	15.8	8.0	8.2	67
	SD	0.85	4.5	11.4	4.3	3.3	40
Rural road (n = 25)	Mean	3.6	7.0	13.4	7.1	7.1	45
	SD	1.5	3.0	8.7	4.3	4.4	19
Santorini soils (n = 64)	Mean	4.0	8.7	16	6.8	9.3	63
	SD	1.4	4.2	15	3.5	13.7	47
Background		1.8	1.1	1.3	4.6	1.3	20
Dutch Soil Guideline	Target Value	9	100	36	35	85	140
	Intervention Value	240	380	190	210	530	720

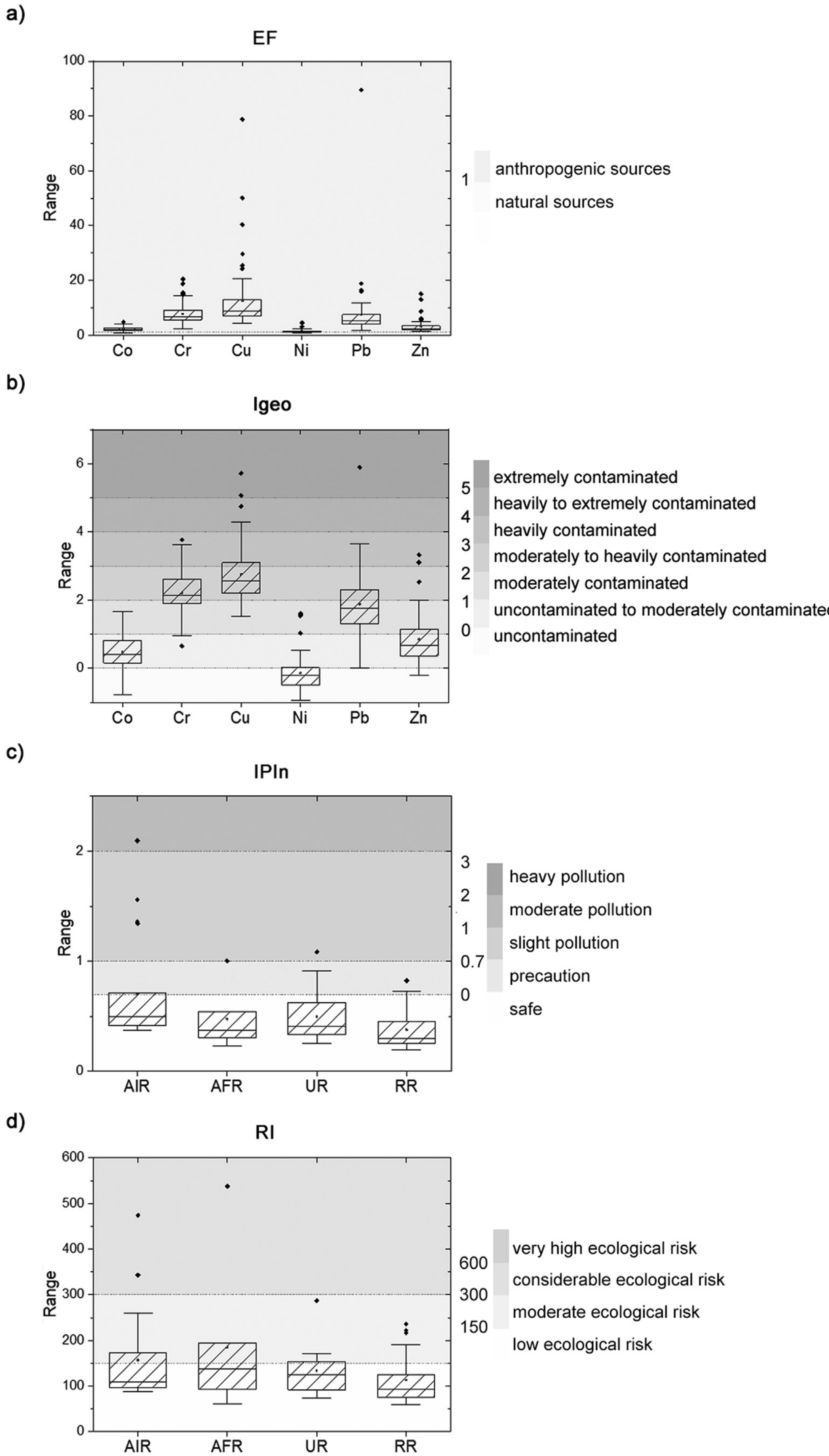

Fig. 1. Pollution and ecological risk indices.

represents a risk only in the AFR category, namely considerable potential ecological risk.

Although the Intervention Value (VROM, 2013) has not been exceeded in any case, which is, among other things, a prerequisite for serious endangering of soil functional properties for humans and other animals and plants, RI points to a potential threat. This is because it considers the adaptation of the ecosystem to natural background values, reflecting the sensitivity of the biological community to HMs (Huang et al., 2018). In the case of sensitive organisms, a significant alteration in natural conditions, in this case represented by anthropogenic contamination, can lead to a number of negative impacts on their health (Fasani et al., 2018). For instance, 2–10 fold increase in the content of HMs, such as Cu and Pb over natural values may lead to 20–40% decrease in soil biological activities (Tyler et al., 1989 in Kabata-Pendias, 2011), thus also in this case the contamination could have a negative impact on soil organisms. This assumption may be related to the findings made on Santorini by Vavoulidou et al. (2006) who states that the surface soils of the island have a general lack of soil fauna and clarification of the reason requires further investigation. Similar conclusions of danger of soil degradation due to tourism are also made by Ciarkowska (2018) in Poland, who associates it with a decrease in enzyme activity.

3.3. Influence of tourism on soil contamination of the island

Data visualization using box plots for each HM (not shown) revealed the asymmetry of the distribution, the presence of extreme values, the heteroscedasticity of the data and also the non-normal distribution of all the elements.

Subsequent testing of the compliance of the individual groups (AIR, AFR, UR, and RR) with the background value by Wilcoxon and permutation one-sample test did not indicate statistically significant background compliance for Co, Cr, Cu, Pb and Zn in any of the sets. For Ni, the permutation one-sample test revealed a statistically significant background match with the AFR group, attributed to a small number of measurements ($n = 7$).

The last step was to compare the individual sets separately for the calculated indices. The results of the application of the various tests are summarized in Table S4–S7. Since the results of statistical processing were not influenced by the choice of the method of adjusting the probability values (Hochberg-Benjamini vs. Holm), they are discussed in summary. The only exception was the application of the permutation k-sample test when testing Igeo in Co (Table S4).

All the tests used indicated a statistically significant mismatch between AIR, AFR, UR and RR at both significance levels 0.05 for both EF and I_{geo} calculated for Co, Cr and Zn (Tables S3 and S4). The methods of mutual comparison divided the sets into two groups.

The values of EF for Co (Table S4) were clearly divided into groups „a" (AIR) vs. „b" consisting of the RR and UR files. The AFR group was integrated into the same group as UR and RR by applying 3 tests (Dwass-Steel-Critchlow-Fligner, Anderson-Darling and Baumgartner-Weiss-Schindle) and at the „ab" group interface after using Nemenyi, Dumn, Conover, Van der Waerden, Lu-Smith and the permutation k-sample test. The ambiguity of the inclusion of AFR is attributed to the low number of samples ($n = 7$) and the resulting greater confidence interval width. The situation is very similar to Cr (Table S4), where AIR forms a group „a" vs. RR group „b". For most tests used, the AFR and the UR sets are evaluated at the interface of both „ab" groups except for the application of the permutation k-sample test, where all the analysed sets were evaluated as identical. The permutation test is the only one that works with raw data; it does not perform any transformation or exclude outliers, and therefore works with entire sets. From this point of view, this type of the test can be considered the most reliable. The same results were obtained for Zn (Table S4) – AIR (group „a") vs. RR (group „b"). The remaining AFR and UR groups were not unequivocally incorporated and are therefore at the „ab" interface, except for the result of the permutation test. For the other EF of the studied elements (Cu, Ni, and Pb), the tests used did not indicate a statistically significant agreement of the studied sets thus the methods of mutual comparison were not further applied.

Very similar distribution results were obtained in statistical processing of I_{geo} (Table S5). A difference in the application of two methods of adjusting p-values (B–H vs. Holm) after the application of the permutation k-sample test was identified only in I_{geo} of Co. In general, comparing the results of the statistical analysis EF and I_{geo} for all the elements shows that the permutation test at I_{geo} separates individual sets into groups (Co: AIR vs. RR and UR, AFR at the group interfaces or in the group with UR and RR, Cr and Zn: AIR vs. RR, AFR and UR were not clearly integrated).

Similarly, AIR (group „a") and RR (group „b") stand opposite at IPI_N (Table S6) like I_{geo} or EF for Zn. The AFR as well as UR sets were not included in any groups and thus they are on the border of „ab".

Statistical analysis of RI showed statistically significant agreement of the studied sets in all the tests used except for the Baumgartner-Weiss-Schindler test (Table S7). For this reason, the mutual comparison methods were not further applied in these tests. The Baumgartner-Weiss-Schindler test (B–H and Holm) gave the same grouping as IPI_N.

Statistical analysis was applied to determine the contribution of airport and road transport to the level of contamination. In this case, the premise of allocating the AIR set compared to AFR, UR, and RR can be considered to be met for almost all the elements and calculated indices. The samples taken around the perimeter of the airport have always been a separate group indicating the increased content of Co, Cr and Zn due to airport traffic. In the similar research to detect airborne contamination, Ray et al. (2012) state air transport as a possible emitter of Cu, Pb, Zn, Cr and Ni elements. At the same time, however, he adds that their source may also be motor vehicles, as it is difficult to distinguish between these two sources. In another similar study, Massas et al. (2016) links air transport with possible emissions of Zn, Pb and Ni. The consensus is therefore that air transport significantly emits mainly Zn. Nevertheless, further research is needed in this topic.

When evaluating the impact of tourism, it is expected that the AIR, AFR and UR sets will be set aside in comparison with the RR one. The results clearly show that the RR set differs statistically due to the low values of contents and indices of Co, Cr and Zn. Conversely, this is not the case of the AIR set that is also being set aside but with contradictory values of the content and indices. The most complicated set represents the samples collected from the sites on the road connecting two main transport links providing transport from the island and there – AFR. For this set, none of the applied statistical methods demonstrated inclusion in the AIR or RR groups and was evaluated at their interface. This is attributed to the small number of data subjected to statistical processing ($n = 7$). Thus, the hypothesis cannot be confirmed or refused in the AFR set. The last group to be evaluated is UR. The study of Ciarkowska (2018) mentions the possible pollution of urban soils by Pb, Zn and Cd due to tourism connected mainly with transport. In this case, the inclusion of UR showed statistical compliance with RR or AFR, and in specific cases also with AIR. In terms of the number of tests and results applied, it is likely that there is an agreement with AFR but it is not possible to unambiguously integrate this set and to confirm the impact of tourism statistically. Again, the tested set was relatively small ($n = 13$). AIR compliance was only detected in EF of Cr and Zn but merely after the application of the permutation k-sample test.

In spite of not entirely clear fulfilment of the initial hypothesis, it can be said that from the point of view of statistical analysis, the influence of tourism has been proved when comparing the results of the sets of two extreme groups, such as airport vs. places situated in the agricultural landscape, without continuous development and significant tourism. However, this is a conclusion that does not consider the level of contamination, only its demonstration. Combined with testing the compliance of the individual sets with the background value, where statistically significant non-compliance was shown, anthropogenic contamination can also be concluded, which was also confirmed by the EF and I_{geo} indices.

The results show that in an area like this, where contamination is still low, the application of statistical methods has been very useful to prove the contamination itself and also the impact of the type of traffic. The same approach should be applied in research studies with a similar topic, even if contamination is at a high level. In such case, the pollutants may already spread to surrounding areas which would normally not be considered problematic. In other words, a high level of contamination can lead to a gradual blurring of the differences between groups and its demonstration should be supported by appropriate statistical approaches. On the other hand, regular inspection of even less polluted tourist areas can prove the increasing effects of individual types of transport. As the mobility of the elements is influenced by a number of factors (Werkenthin et al., 2014), basic data diagnostics, such as monitoring of data distribution, identifying of outliers, testing of normality and heteroscedasticity should be performed on such dynamic systems. Then, all the statistical evaluations must be assessed comprehensively to obtain reliable conclusions, especially regarding the impact on human health, fauna and flora.

The current state of soil contamination of the island may be associated primarily with its development in the context of tourism which began to develop only in the 1970s and transformed fishing villages into tourist resorts (Wadih, 2005). It is therefore the result of fifty years of tourism. But its real dimension can be much larger. Since prevailing strong winds and soil erosion are typical on the island (Vavoulidou et al., 2006; Economou et al., 2007), HMs emitted by traffic can be easily transported off the road and contaminate more distant surroundings. Then, the roadside soils themselves may indicate lower values than would correspond to the level of contamination. A similar phenomenon has been described, for instance, by Chen et al. (2010). On the other hand, their mobility within the soil profile and their current availability for plants may be limited due to the alkaline pH of the island's soils. Further research is necessary in this area.

Given the rapid increase in traffic intensity (Delitheou and Georgakopoulou, 2017; Santorini Airport, 2019) on the island and the overall increase in anthropogenic pressure, soil contamination can be expected to increase rapidly in the future. Subsequent metal accumulation in plants, for example used in agriculture, can reduce their fitness and lead to significant toxic effects (Kabata-Pendias, 2011; Fasani et al., 2018), which may limit the growth of crops and ultimately also negatively affect wholesomeness of the resulting food products and their marketability (Nagajyoti et al., 2010; Mirzaei et al., 2019). This could have negative impacts, for instance, on local wine production. The local wine is of high quality and Santorini is an important wine producing region of the Greece (Vavoulidou et al., 2006).

In addition to contamination, the threat to land resources and agricultural production is represented by erosion associated with construction of tourist infrastructure (Zhong et al., 2011). The anticipated negative impact of increasing soil contamination and degradation may also endanger the ecosystem services of the natural systems of the island which may ultimately lead to tourism damage (Drius et al., 2019).

Santorini is increasingly associated with overtourism and questions about possible negative environmental impacts are emerging (Peeters et al., 2018). The results show that the current situation is unsustainable. It is essential to reduce tourism and introduce tourist quotas which will reduce the rate of increase in contamination and soil degradation. At the same time, it is advisable to continue in soil monitoring, which may lead to the state of better understanding of the HMs mobility in such environment and also better identification of pollution emitters on the example of this locality, which may serve as a model.

3.4. Comparison with other volcanic islands

In comparison with other volcanic islands (Table 2), two things are evident: high variability of HM contents in soils and significant influence of natural conditions. Most islands show markedly higher values for all the HMs, even though their contents are often given merely by geogenic origin and are not directly influenced by anthropogenic activities. Based on these findings, it may be concluded that although tourism can make a significant contribution to soil contamination in volcanic islands, the amount of HMs

Table 2
Average contents of HMs (mg/kg) on tourist attractive volcanic islands.

	Cd	Co	Cr	Cu	Ni	Pb	Zn	Reference**
Réunion (France)	0.2		300	58.0	206		162	1
Santiago (Cape Verde)*	0.2	45.9	135	51.8	137	5.9	83.6	2
Santa Maria (Portugal)*	n.d.	71.2	801	75.4	277	44.0	132	3
São Miguel (Portugal)*	n.d.	3.8	23.0	30.6	12.8	31.4	174	3
La Gomera (Spain)*			2.2	0.3	4.8		2.2	4
El Hierro (Spain)*	1.3	44.2	87.0	43.7	103		85.2	5
Jeju (Korea)*	0.4	77.0	662	49.0	170	44.0	125	6
Hawaii (USA)		66.0		122	294	56.0	282	7
Lesbos (Greece)		43.6	1673	28.9	1379	26.1	80.0	8
Santorini (Greece)	n.d.	4.0	8.7	16.4	6.8	9.3	62.5	This study

* Undisturbed natural soils.
**[1] Doelsch et al. (2006).
[2] Pinto et al. (2015).
[3] Amaral et al. (2006).
[4] Mora et al. (2012).
[5] Mendoza-Grimón et al. (2014).
[6] Ahn and Chon (2010).
[7] Sutherland and Tack (2000).
[8] Kazakou et al.(2010).

emitted by tourism is only a minor enrichment factor on a tourist-attractive volcanic islands globally. The geological bedrock of the island and other natural factors that lead to the majority of soil enrichment are important.

In view of the potential negative impacts on natural ecosystems due to high tourism as an emitter of HMs, primarily islands with a naturally low HM content, whose anthropogenically increased amount may lead to more severe impacts on native biota, which may be more sensitive to higher than natural contents of metals, should be monitored. Conversely, islands with a naturally high HM content and good adaptation of local ecosystems should be primarily monitored for possible health risks to humans. The threat to tourists is negligible in short-term visits but the local population's chronic intake of higher amounts of HMs from the environment can lead to a number of negative health impacts (Chabukdhara and Nema, 2013; Huang et al., 2018; Mirzaei et al., 2019).

4. Conclusions

On the island of Santorini, significant anthropogenic contamination with HMs, especially Cr, Cu and Pb, has been found. This contamination may already represent a moderate ecological risk to local ecosystems.

A significant influence of tourism on contamination of the island has been proved by the example of soil pollution near the airport. Airport traffic has been proved to be an important emitter of Co, Cr and especially Zn.

Compared to other volcanic islands, the detected HM content was mostly significantly lower. On this basis, it can be concluded that in the case of volcanic islands, whether used for tourism or with the potential for tourist use, the dominant factor determining the content of HMs in the soil is the parent rock respectively natural conditions.

Given the increasing intensity of tourism and related activities, it is expected that soil contamination of the island will grow rapidly which may have a negative impact on local ecosystems and, in the future, on the quality of the wine produced. It is therefore essential to reduce tourism by introducing tourist quotas which will reduce the rate of increase in contamination and soil degradation.

Tourism causes significant contamination of soil by HMs. Monitoring of this contamination can be used as a basis for decision making in tourism management and can contribute to the protection of nature and human health as part of fulfilment of environmental challenges within tourism sustainability.

CRediT authorship contribution statement

Martin Brtnický: Conceptualization, Data curation, Investigation, Methodology, Project administration, Resources, Visualization, Funding acquisition, Resources, Supervision, Writing - original draft. **Václav Pecina:** Conceptualization, Data curation, Investigation, Methodology, Project administration, Resources, Visualization, Writing - original draft. **Michaela Vašinová Galiová:** Formal analysis, Project administration, Supervision, Validation, Visualization, Writing - original draft. **Lubomír Prokeš:** Formal analysis, Data curation, Visualization. **Ondřej Zvěřina:** Investigation, Data curation. **David Juřička:** Data curation, Software, Validation, Writing - review & editing. **Martin Klimánek:** Data curation, Software, Validation. **Jindřich Kynický:** Methodology, Project administration, Writing - review & editing.

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Appendix A. Supplementary data

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