RESEARCH ARTICLE

Comparison of two methods for indirect measurement of atmospheric dust deposition: Street-dust composition and vegetation-health status derived from hyperspectral image data

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Abstract This study presents a statistical comparison between the in situ measurements of the elemental composition of street dust and a forest health status classification derived from aerial hyperspectral image data (HyMap). Combining these two methods allowed us to indirectly pinpoint at a high spatial resolution the atmospheric dust emissions and its effects in a study area around the open-pit lignite mine in Sokolov, Czech Republic. The results reveal a statistically significant relationship between increased Al, Na, Li and Sr levels in street dust and decreased forest health status, and the highest number of statistically significant correlations within a 100 m distance from the street-dust sampling points. Differences in lithological composition were unable to sufficiently explain these changes, therefore anthropogenic factors like dust emissions from coal mining and coal combustion, as well as urbanisation and other industries might be the reason for this link. Such studies are a crucial step in developing new high spatial resolution methods for determining atmospheric dust deposition and their effects.

Keywords Coal mining · Dust emissions · Forest health · Hyperspectral imaging · Remote sensing · Street dust

INTRODUCTION

Atmospheric aerosol particles are an important constituent of the atmosphere. Their sources can be natural, like sea spray, forest fires, vegetation or volcanic eruptions or anthropogenic, like industrial, vehicle and aircraft emissions. Their influence is manifold: they scatter and absorb light, act as condensation surface for water or cause stratospheric ozone depletion, thus directly and indirectly

impact weather patterns, cause acid rain effects, reduces visibility or causes health concerns (Kolb and Worsnop 2012). An important component of atmospheric aerosol particles, and thus a potential important environmental pollutant and major health concern in the modern world, especially in urban areas (Li et al. 2016, 2017a, b; Yu et al. 2017), and in areas containing or that used to contain larger industrial or mining complexes (Šajn et al. 2013; Balabanova et al. 2014, 2017; Yu et al. 2017; Bavec et al. 2017), is atmospheric dust, here including combustion-generated soot, windblown fine mineral dust, pollen and other botanic debris. Dust emissions can also lead to negative public view about industrial and mining activities, as demonstrated in a case study of a coal ash storage site (Zierold and Sears 2015). In such cases, it is necessary to measure air quality in order to objectively assess the air quality, determine possible impacts of industrial and mining activities on the environment and public health, and assist decision-makers and public alike.

Air quality monitoring stations are often used to measure and monitor such pollution. However, due to their high cost, the measurements are usually limited to a few locations, linked to densely urbanised areas, or areas surrounding major potential air polluters. The relatively small number of monitoring stations limits possibilities to properly address scientific questions such as the spatial and temporal dispersion of particulates, depositional patterns, influential factors or make it impossible to create detailed maps of atmospheric pollution. This lack of reliable high-resolution data prevents extensive data mining which would assist in establishing whether atmospheric dust concentration and composition are linked with potential negative effects like pulmonary diseases, plant losses including damage to crops and similar. This hinders efficient spatial and land-use planning and implementation of

the best mitigation measures. Thus it would be useful to develop new methodologies that enable high-resolution monitoring of atmospheric dust contamination over larger areas.

One possibility is to collect deposited particles using direct collection methods (i.e. sedimentary pans or similar) or to collect deposited atmospheric dust on snow (Miler and Gosar 2013) or in natural or man-made ‘traps’ like parking lots, streets, garages. Street dust, household dust, attic dust or other urban dusts are among the many materials which can indicate the quantity and chemical composition of atmospheric dust in a certain spatial and time period. However, these materials might contain several particles with a non-atmospheric origin, such as soil particles, construction materials, plant remains or similar. Strictly defined and controlled sampling procedures, proper pre-analytical laboratory preparation (sieving) and appropriate use of data-processing techniques can help reduce the unwanted effects of such particles in final results. Among aforementioned urban dusts, street dust can be most easily collected from many different public areas in urban environments, and contrary to house or attic dust sampling, its collection does not require special permissions. It is a mixture of deposited atmospheric dust and other materials (soil, plant remains, construction materials) found on flat hard urban surfaces like streets, pavements, playgrounds, garages, and is an important environmental indicator especially for urban environments (Almeida et al. 2006; Lu et al. 2009; Žibret 2012).

Another possibility is to measure physical, chemical or biological impacts of atmospheric dust emissions. One common method here is to determine atmospheric pollution by analysing lichens or moss (Balabanova et al. 2014). The biological effects of atmospheric dust pollution can also be measured indirectly, i.e. by determining a plant’s health status.

Modern remote sensing has recently emerged as a tool for monitoring dynamic processes and physical-property induced changes. The use of multispectral imagery (e.g. 4–7 bands) has been demonstrated to map diverse ecosystem types and vegetation systems (Gould 2000; Lamb and Brown 2001; Everitt et al. 2002; Knorn et al. 2009; Vogelmann et al. 2012). State-of-the-art super-spectral satellite data—Sentinel-2 (13 bands)—have been used to discriminate tropical forest types (Laurin et al. 2016), detect drought-stress phenomena in deciduous forests (Dotzler et al. 2015) or distinguish burn severity (Fernández-Manso et al. 2016). Hyperspectral data [also referred to as imaging spectroscopy (IS) data], until today mainly acquired via aerial data acquisitions, provide continuous spectral information (hundreds of narrow bands) and has been successfully used in numerous studies to detect vegetation stress and damage (Pu et al. 2008; Romer

et al. 2012; Rathod et al. 2013; Sanches et al. 2013). Whereas vegetation is rooted in the soil substrate, a change in their morphological and physiological properties due to environmental variables can indicate the ecological, geochemical and hydrological situation (Zinnert et al. 2013). As the attributes of vegetation influence its spectral properties, imaging spectroscopy is nowadays an alternative and near real-time method for monitoring plant changes, and such analysis can indirectly serve as a proxy for soil and atmospheric conditions.

The aim of this study is to compare two new methods to indirectly assess the quality of air, which overcomes the abovementioned limitations of most commonly used air quality measurement stations. Both methods are used in this study to indirectly measure air quality around open-pit lignite mine, but they can be applied also in other areas. The first is based on evaluating forest health conditions using optical indices derived from aerial hyperspectral image data (Mišurec et al. 2012; Kopačková et al. 2014), while the second is based on collecting and measuring the chemical composition of atmospheric dust deposited on paved hard surfaces. The study formed part of the EO-MINERS project which aimed at developing new remote sensing and in situ measurement techniques to address the impacts of the mining industry on the environment and society. The study area is located in the Sokolov basin, in the NW part of the Czech Republic, where several potential sources of atmospheric dust exist, including open-pit coal mining, coal-firing power plants, chemical industry, traffic and urbanisation.

MATERIALS AND METHODS

The study area is located in NW Czech Republic in the area of Sokolov (Fig. 1). This part of the country, located close to the Czech-German border, is characterised by a large open-pit lignite mine and the presence of different industries: power and heat-producing plants, petrochemical industries, metallurgical processing, wood processing and others. Larger towns in the area include Sokolov (28 000 inhabitants) and Karlovy Vary (50 000 inhabitants). The area is drained by the River Ohře, which flows towards E into the Labe (Elbe) River. The study area has relatively uniform climate, so authors do not believe that variations in climate (except wind) is an important influential factor.

The basement of the Sokolov Basin is formed from pre-Variscan and Variscan metamorphic complexes (recorded metamorphism from Devonian to Lower Carboniferous periods) of the Eger, Erzgebirge, Slavkov Forest, Thuring-Vogtland Crystalline Units and granitoids of the Karlovy Vary Pluton. The upper portions of these rocks are frequently weathered to kaolinitic residue. The basal late

Fig. 1 The study area. 1—quaternary deposits; 2—consolidated Cenozoic sedimentary rocks; 3—mafic igneous rocks; 4—felsic igneous rocks; 5—volcanic- and quartz-rich metamorphic rocks; 6—highly metamorphic rocks; 7—low metamorphic rocks; 8—populated areas; 9—open-pit lignite mines (active and abandoned); 10—highway; 11—rivers; 12—larger industrial facilities; 13—street-dust sampling points; 14—area of Norway Spruce health status measurements

Eocene Staré Sedlo Formation is formed from well-sorted fluvial sandstones and conglomerates and is overlaid by a volcano–sedimentary complex up to 350 m thick, which contains three lignite seams with variable sulphur content. These lignite seams were exploited in the past in several open-pit mines in the N area of the Czech Republic, while the active Jiří open-pit lignite mine (next to the Sokolov town) was used in our case study.

For the purposes of this study, 81 mapped geological units of the area were divided into 7 lithological classes according to their main mineral and geochemical characteristics:

- (1) Unconsolidated quarternary sediments: clay, sand, gravel, silt.
- (2) Consolidated cenozoic sedimentary deposits and rocks: breccia, conglomerate, sandstone, siltstone, claystone, lignite and similar.
- (3) Mafic igneous rocks: gabbro, basalt, gabbrodiorite, tephrite, augite, basanite, etc.
- (4) Felsic igneous rocks: granite, granodiorite, diorite, porphyry, quartz veins, analcimite, albitite, tonalite, etc.
- (5) Volcanic- and quartz-rich metamorphic rocks: andesite, trachyte, phonolite, nephelinite, tuff, volcanic breccia, pyroclastic flows, quartzite, phyllite, migmatite, gneiss.
- (6) Highly metamorphic rocks: hornfels, eclogite, amphibolite, serpentinite, metagabbro, etc.
- (7) Low metamorphic rocks where source layers were originally sedimentary rocks: phyllite, quartzite, schist, soapstone, skarn, etc.

Street-dust sampling

Street dust was selected as sampling material, because it is easy to collect on many different public surfaces in the study area. Street dust was swept from hard surfaces in the study area with a polyethylene brush from an area of approximately 2–3 m² between August 2010 and March 2012. Areas with visible accumulation of soils, construction materials or plant remains were avoided. Between 200 and 300 g of street fine-grained dust was collected at each of the 113 sampling points from the wider area of the Sokolov lignite mine area (as far as 20 km away). The sampled street dust was then air-dried and sieved through a 0.125 mm sieve to remove possible stones, soil aggregates and plant remains. Thereafter, 5 g of < 0.125 mm street-dust fraction was digested by the near-total (4 acids) digestion method. A 0.25 g sample split is heated in HNO₃, HClO₄ and HF to fuming and dried. The residue is dissolved in HCl and analysed by the means of ICP-ES/MS. Laboratory quality control was ensured by conducting 17

repetition analyses (precision tests, parameter average relative percent difference—*RPD*), 14 analyses of 4 standard materials OREAS24P, OREAS45CA, DS8 and DS9 (accuracy control, parameter recovery rate—*%R*) and 6 analyses of blank samples (bias control), which were mixed randomly within the other 113 samples. The results of the chemical analysis of 19 elements are presented in this study: Al, As, Ba, Cd, Ce, Cr, Cu, Fe, Hf, La, Li, Na, Ni, Pb, Sr, Th, U, Y and Zn. In this way, we obtained an indication of the composition of deposited atmospheric dust on 113 locations around Sokolov lignite open-pit mine.

Hyperspectral image data pre-processing and analysis

The second method was employed to process the aerial hyperspectral image data—HyMap (HyVista Corp., Australia), which were acquired during the HyEUROPE 2010 flight campaign using the HyMap (HyVista Corp., Australia) air-borne imaging spectrometer. The HyMap data were atmospherically corrected using ATCOR-4 (Richter 2009) and direct ortho-georectification was performed using the PARGE software (Schlapfer 1998).

To assess the vegetation-health status, two selected indicators of vegetation health, namely Red Edge Position (REP) (Curran et al. 1995) and exponential transformation of the Structure Insensitive Pigment Index (expSIPI) (Penuelas et al. 1995) were computed. REP, the inflection point of the spectral curve in the red edge region, is frequently used as an indicator of vegetation stress (Clevers et al. 2002; Sanches et al. 2013) as it shifts to shorter wavelengths under stress conditions (e.g. the presence of heavy metals in the soil). SIPI is sensitive to the ratio of bulk carotenoids to chlorophyll, whereas higher carotenoid and lower chlorophyll levels also indicate a vegetation stress. REP and expSIPI were further normalised using *z*-scores. After this transformation, values were comparable and independent of their physical dimensions (units). Finally, a raster combining the information from REP and expSIPI was created—both raster datasets were summarised and then reclassified into five classes using the standard deviation (σ) classification method (Class 1: values < mean – 1.0 σ , Class 2: mean – 1.0 σ < values < mean – 0.5 σ , Class 3: mean – 0.5 σ < values < mean + 0.5 σ , Class 4: mean + 0.5 σ < values < mean + 1.0 σ , Class 5: values > mean + 1.0 σ ; see detailed description in Mišurec et al. 2012). The classification results were further validated by ground truth data (foliar biochemistry: Cab, Car and Car/Cab) and were associated with the geochemical conditions of the forest stands (pH, macronutrient parameters, base saturation, exchangeable aluminium, Bc/Al ratio) (Kopačková et al. 2014). The method proved

suitable as the classification results were in accordance with the statistical assessment of all the ground truth data listed above. Here, we provide a general description of methods that were employed and then focus on the new data analysis that forms part of this study; however, a detailed description of the HyMap hyperspectral image data analysis as well as validation and interpretation is given in Kopačková et al. (2014).

As described above, the result of the hyperspectral image processing is the validated physiological status of the Norway spruce forest in the Sokolov basin presented in five classes: from 1 (worst health status) to 5 (best health status). To be able to conduct further statistical assessment, which was the main goal of this study, forest health map pixels (ground sampling of 4 m) were transformed to 3 085 473 points.

Statistical analysis

The impact of the lithology on the Norway Spruce health status was determined by calculating average Norway Spruce health status and corresponding standard deviation of the measurements in each of the seven lithological units. Student *t* test for comparing averages was used to compare means of all pairs to determine whether specific lithological unit is more or less favourable for the growth of Norway Spruce as the other units. The impact of the lithology on the composition of the street dust was assessed differently as in the Norway Spruce health status case, because we operated with much fewer street-dust measurements, and certain lithological units do not contain enough data for the Student *t*-test of means. Non-parametric statistics was applied instead, by comparing medians of subsets of samples collected on the seven lithological classes described above. Parameter $RT = md_max/md_min$ shows ratio (RT) between the maximum median (*md_max*) and minimum median (*md_min*) values. A high value of the *RT* parameter means that lithology might influence the street-dust composition with regard to a specific element, whereas low values mean it is very likely that the lithology has no influence on the street-dust composition concerning a specific element.

The comparison of the Norway Spruce health status and street-dust composition was made by calculating Pearson's correlation coefficients between 2 variables: the content of a specific element in street dust collected at a certain sampling point and the average class value of the Norway Spruce health status map around street-dust sampling point. The average health status was calculated from available measurements within a circle, the centre of which was the street-dust sampling location, and had a radius of 5000, 2000, 1000, 500, 200, 100 and 50 m. These ranges were selected in order to determine whether street-dust

composition can be linked to Norway Spruce health status locally, or over larger distances. In this way, different numbers of data pairs (elemental level in street dust and average Norway Spruce health status around) used for the correlation coefficient calculation were obtained: 86, 69, 42, 31, 21, 14 and 7, respectively.

The interpolated maps (kriging for elemental levels in street dust and the moving average method for Norway Spruce health status) were used for visual evaluations of the similarities and dissimilarities in elemental levels in street dust and Norway spruce health status. GS Surfer built-in Kriging was used to interpolate metal levels in street dust, and GS Surfer polynomial regression function (planar surface) to calculate general trend for Norway Spruce health status. The ENVI SW, QGIS, GS Surfer and MS Excel applications were used for data analysis and map preparation.

RESULTS AND DISCUSSION

The assessment of the Norway spruce forest health status using five classes, from 1 (worst status) to 5 (best status), reveals an average value of 2.83 with a standard deviation of 0.90. The general forest health status trend by using Surfer's built-in polynomial regression (planar surface) interpolation function shows that health status is improving from NE (average value 2.4) towards SW (average value 3.4). Lower vegetation-health status corresponds to the central parts of the Sokolov basin, while better vegetation-health status is generally observed at higher altitudes away from populated centres.

The impact of the area's geological composition on the health status is evaluated according to mean Norway Spruce health status and corresponding standard deviations on different geological units. Average health status and corresponding standard deviation, separated by the symbol "±", are 2.82 ± 0.87 on Quaternary sediments, 2.78 ± 0.82 on sedimentary rocks, 3.07 ± 0.66 on mafic igneous rocks, 2.53 ± 0.87 on felsic igneous rocks, 3.18 ± 0.84 on volcanic- and quartz-rich rocks, 3.13 ± 0.90 on high metamorphic rocks and 2.82 ± 0.87 on low metamorphic rocks. Student *t* test for comparing averages shows that the average Norway Spruce health status values on all three types of metamorphic rocks and on mafic igneous rocks (groups 3, 5, 6 and 7) are similar between each other, and that the average values on quaternary sediments, sedimentary rocks and felsic igneous rocks differ (groups 1, 2 and 6) from all other groups. All calculations were done on the confidence level of 0.95. Yet it cannot be determined whether the areas of lower vegetation-health status found on sedimentary rocks, unconsolidated sediments and felsic igneous rocks are a

consequence of the less favourable geological background for forest growth or the negative impacts of anthropogenic activities, which are also concentrated in lowland flat areas where such rocks and sediments are situated. Oppositely, better Norway Spruce health status has been measured in the areas of high-grade metamorphic rocks, mafic igneous rocks, volcanic- and quartz-rich rocks and low-grade metamorphic rocks, which are predominantly situated in the less populated highland areas. Therefore, according to data in our study, it cannot be determined whether lithological composition or anthropogenic activities influences the Norway Spruce health status. Probably, both factors might have certain influence in the Sokolov case.

The descriptive statistical parameters of street-dust composition in the Sokolov basin ($N = 113$) are presented in Table 1. Table 2 compares the chemical composition of street dust in the Sokolov basin with the maximum detected levels of selected elements in other cities and towns around the globe, as well as with European soil standards and average values for soils. The results show that, compared to other areas, street dust in the Sokolov basin has elevated levels of Al, Ni, Sr and Th. These characteristics may be geogenic in origin and mainly come from the abundant silicate minerals in the area, or may be anthropogenic in origin, i.e. coal production and power production. On the contrary, levels of the most commonly mentioned anthropogenically emitted potentially toxic elements (Pb, Zn, Cd,

As, Cu, etc.) are generally lower than elsewhere in the world. This might be attributed to the fact the Sokolov basin is not densely populated and that there is no developed smelting or other metallurgical industry. Significant impacts of the area's lithological composition on the chemical composition of the street dust were not detected for most elements since the RT parameter is generally around 1 (Table 1). Increased values of the RT parameter (larger than 1.5) were detected for Th, Pb, Cu, As, Cd, U, La and Ce, while Cr, Hf, Y and Zn has the value of RT parameter 1.4. Therefore, we may assume that the changes in elemental levels in street dust with regard to the aforementioned elements are mainly driven by changes in lithology. For the remaining elements, changes in elemental levels concerning are probably not lithologically driven, and other sources of variations are present, including anthropogenic dust emissions.

Table 3 shows the correlation coefficients between the street-dust's chemical composition and the average Norway Spruce forest health status around the street-dust sampling points. A positive correlation coefficient means that a better Norway Spruce health status is observed around the street-dust samples with higher levels of specific element, while negative values mean the opposite. Significant positive correlations are observed for Ce La and Pb on the confidence level 0.95, and for Th and U on the confidence level of 0.90. The opposite effect is observed

Table 1 Descriptive statistics for 19 chemical elements in 113 samples of street dust collected in the Sokolov basin. *min* minimum value, *P25* 25th percentile, *md* median, *P75* 75th percentile, *max* maximum value, *avg* average value, *std* standard deviation, *RT* ratio between maximum and minimum median elemental levels in different lithological units, *RPD* average relative percent difference; *%R* recovery rate

	Unit	min	P25	md	P75	max	avg	std	RT	RPD	%R
Al	%	3.96	4.94	5.3	5.69	6.85	5.33	0.58	1.1	3	109
As	mg/kg	8	15.5	19	25	42	20.79	7.67	1.7	13	184
Ba	mg/kg	344	518	557	590	782	557.49	68.19	1.1	5	110
Cd	mg/kg	0.2	0.4	0.5	0.6	1.4	0.55	0.22	1.6	34	358
Ce	mg/kg	96	120	135	150	297	139.83	30.41	1.5	5	105
Cr	mg/kg	75	133	165	198	382.5	171.04	55.58	1.4	6	110
Cu	mg/kg	82.05	147.7	168.8	196.8	523.8	176.82	58.27	1.7	9	117
Fe	%	4.76	6.13	6.85	7.64	9.94	6.97	1.09	1.2	3	110
Hf	mg/kg	4	5.7	6.3	6.8	11	6.37	1.01	1.4	7	106
La	mg/kg	51.1	65.2	72.1	79.6	169.2	75.71	17.52	1.5	5	127
Li	mg/kg	22.6	37.6	47.4	57	116	49.58	16.94	1.3	5	96
Na	%	0.668	0.903	0.993	1.112	1.556	1.01	0.19	1.2	4	101
Ni	mg/kg	46.3	67.9	82.7	93.9	405.4	88.80	39.29	1.2	8	119
Pb	mg/kg	22.2	34.7	46.2	57.9	138.9	50.01	21.17	1.8	9	115
Sr	mg/kg	270	357	400.5	445.5	592	405.37	68.59	1.2	4	102
Th	mg/kg	9.1	16.4	19.6	25.2	69.6	21.80	8.50	1.8	8	117
U	mg/kg	2.8	4.8	6.3	7.9	23.6	7.01	3.45	1.5	12	104
Y	mg/kg	16.6	21.9	24.2	26.4	45.8	24.93	4.30	1.4	7	113
Zn	mg/kg	166	252	306	364	1545	333.92	165.16	1.4	5	100

Table 2 Descriptive statistics of the chemical composition of street dust collected in the Sokolov basin (113 samples) and comparison with street-dust composition elsewhere in the world

Reference	Area	Method Analytical methods\units	Al %	As mg/ kg	Ba mg/ kg	Cd mg/ kg	Ce mg/ kg	Cr mg/ kg	Cu mg/ kg	Fe %	Ni mg/ kg	Pb mg/ kg	Sr mg/ kg	Th mg/ kg	Zn mg/ kg
Li et al. (2017a, b)	Chengdu, China	< 0.063 mm, 65% HNO ₃ , ICP-OES				6.4		463	331		69.8	164			607
Tang et al. (2017)	Coal mining area, China	< 0.1 mm, HNO ₃ + HF + HClO ₄ , ICP-MS, CVAFS		9.58		0.45		129				71.5			
Dehghani et al. (2017)	Teheran, Iran	< 0.063 mm, AQ, ICP-MS	1.8	11.5		2.9		128	799		267	571			1210
Keshavarzi et al. (2015)	Shiraz, Iran	< 0.063 mm, ICP-MS		8.6		0.85		31.6	49.9	16.3	39.4	36.8			161
Ordóñez et al. (2015)	Avilés, Spain	< 0.147 mm, AQ, ICP-MS	1.12	110	640	139		214	966	6.56	69.3	1482	422	8	45 700
Wei et al. (2015)	Beijing, China	< 0.125 mm, HNO ₃ + HF, ICP-MS				5.01		227	623		60.0	2450			908
Li et al. (2013)	Zhuzhou, China	< 0.149 mm, AQ, CVAFS, ICP-MS		1194		691		59	1020		20	17 600			35 400
Christoforidis and Stamatis (2009)	Kavala, Greece	< 0.063 mm, HNO ₃ , AAS		180		1.3		692	508		267	2500			658
Žibret et al. (2013)	eMalahleni, South Africa	< 0.125 mm, total dig., ICP-MS	5.76	21	1840	0.90	185	43 000	300	17.4	366	835	204	39.1	1330
Žibret (2012)	Celje, Slovenia	< 0.125 mm, AQ, ICP-MS	0.48	22.8		7.2		740	295	12.7	173	352			2220
This study—maximum value	Sokolov, Czech Republic	< 0.125, total dig., ICP-MS	6.85	42	782	1.4	297	383	524	9.94	405	139	592	693.6	1545
This study—median	Sokolov, Czech Republic	< 0.125, total dig., ICP-MS	5.30	19	557	0.5	135	165	167	6.85	83	46	401	19.6	306
This study—minimum value	Sokolov, Czech Republic	< 0.125, total dig., ICP-MS	3.96	8	344	0.2	96	75	82	4.76	46	22	270	9.1	166
MHSPE (2014)	Intervention values for soil and sediment			55	625	12		380	190		210	530			720
Salminen et al. (2005)	European topsoil median	< 0.063 mm, AQ, ICP-QMS and ICP-AES	5.82	7.03	375	0.145	48.2	60	13	2.46	18	22.6	89	7.24	52

Table 3 Pearson correlation coefficients between street-dust elemental levels and average Norway Spruce forest health status around street-dust sampling points. Positive correlation values mean that a better health status of the Norway spruce forest is found around street-dust samples containing a higher elemental level. dist (m)—radius of the circle around street-dust sampling point, where average Norway spruce forest health status was calculated. *N*—the number of street-dust composition and Norway spruce average health status data pairs. ¹Sources of variations in elemental levels in street dust are probably changes in lithology; *significant non-directional correlations at a confidence level of 0.90; **significant non-directional correlations at a confidence level of 0.95

dist (m)	5000	2000	1000	500	200	100	50
N	86	69	42	31	21	14	7
Al	− 0.15	− 0.06	− 0.09	− 0.31*	− 0.28	− 0.58**	− 0.65
As ¹	− 0.06	− 0.15	0.07	− 0.04	0.01	− 0.09	− 0.07
Ba	− 0.02	− 0.03	0.21	− 0.18	− 0.01	− 0.20	− 0.48
Cd ¹	− 0.08	− 0.10	− 0.03	− 0.07	0.05	0.22	0.28
Ce ¹	0.29**	0.22*	0.19	0.30	0.17	0.58**	0.69*
Cr	− 0.08	− 0.07	− 0.25	− 0.06	− 0.11	0.17	0.53
Cu ¹	0.03	0.03	0.09	0.10	0.16	0.42	0.46
Fe	− 0.02	0.03	− 0.19	− 0.05	− 0.11	0.23	0.59
Hf	0.07	0.09	0.01	0.21	0.13	0.34	0.64
La ¹	0.26**	0.20*	0.19	0.30	0.18	0.56**	0.68*
Li	− 0.18*	− 0.15	0.00	− 0.28	− 0.30	− 0.32	− 0.61
Na	− 0.16	− 0.03	− 0.23	− 0.23	− 0.35	− 0.73**	− 0.55
Ni	0.04	0.12	− 0.19	− 0.04	− 0.10	0.21	0.34
Pb ¹	0.20*	0.14	0.37**	0.29	0.48**	0.50*	0.64
Sr	− 0.10	0.00	− 0.27*	− 0.32*	− 0.31	− 0.52*	− 0.30
Th ¹	0.18	0.08	0.11	0.25	0.10	0.51*	0.67*
U ¹	0.09	− 0.12	0.08	0.26	0.11	0.48*	0.44
Y	0.15	0.12	0.06	0.09	0.02	0.40	0.71
Zn	− 0.11	− 0.20	0.18	0.29	0.27	0.40	0.18

for Al and Na on the confidence level of 0.95, and for Li and Sr on the confidence level of 0.9. The highest number of statistically significant correlations is observed within distances of 100 m. It was established (Table 1, parameter RT) that changes in elemental levels for the elements being positively correlated with the Norway Spruce health status in street dust probably correspond to changes in lithology. Natural changes in lithology, which affects soil quality in a way that soil on certain lithological units is more suitable for the Norway Spruce growth, could explain that observation (Kopačková et al. 2015).

Negative correlations, indicating that higher elemental levels in street dust correspond to lower Norway Spruce forest health status, were detected for Al, Li, Sr and Na (Fig. 2). However, this link cannot be explained by changes in lithology (Table 1, low RT value), therefore we assume such variations may be explained with some anthropogenic factors like emissions of Al, Li, Sr and Na-enriched dust particles into the atmosphere. Spatial patterns in forest health status and levels of the aforementioned elements in street dust have been compared to reveal the underlying cause of that phenomena.

The spatial distributions of Al, Li and Na levels in street dust (Fig. 3), which are negatively correlated with vegetation-health status (Table 3), show that the highest levels of aforementioned elements are detected in the central-east part of the research area, between the towns of Karlovy Vary and Nová Role, as well as around the lignite open-pit mines, in the town of Sokolov and around the Vřesová industrial facilities, while lower levels are generally observed in the W part of the study area. A similar trend is observed with vegetation-health status which generally decreases from SW towards NE, with the lowest health scores in NE parts of the area between the Vřesová plant and the town of Nejdek. Localised areas of decreased health status can also be found near the town of Sokolov, around the open-pit lignite mine and in the NE areas where felsic igneous rocks prevail. It has been revealed that all four of the mentioned spatial trends are in agreement. This may support the idea that anthropogenic emissions of Al-, Na-, Sr- and Li-containing substances can influence the street-dust composition, as well as the Norway Spruce forest health status in the area under study. Such emissions might be connected to coal extraction, processing and

Fig. 2 Scaling of Al and Na levels in street dust and average Norway Spruce Health status 100 m around street-dust sampling points in the Sokolov basin

combustion (Querol et al. 1995; Vejehati et al. 2010), especially to emissions of impurity particles (i.e. kaolinite particles) contained in the lignite. Further studies, like those entailing the observation of individual particles under the SEM-EDS, are required to confirm this assumption. The results of this study are also in the agreement with the studies of Kopačková et al. (2014, 2015), where Al was identified as a phytotoxic element, because increased Al levels in Norway Spruce needles corresponded to decreased chlorophyll contents and a higher carotenoid-to-chlorophyll ratio (Car/Cab), thus indicating stress in plants.

Some discussion about the role played by lithology is needed at this point. It can be argued that lithology is the factor which influences the elemental levels in street dust as well as vegetation-health status. Combining data from Table 1 (RT parameter) and Table 3, two specific groups of elements emerge. The first group of elements consists of Ce, La, Pb, U and Th. Their increased levels in street dust are very likely a consequence of natural lithological enrichment, and their elemental levels in street dust are positively correlated with forest health status. The highest levels of Pb and Th in street dust were found on volcanic- and quartz-rich metamorphic rocks predominately found in the S part of the area, and this area also corresponds with the best Norway Spruce forest health status. Numerous studies show that lithology certainly plays a significant role in vegetation-health status (Borůvka et al. 2005; Egli et al. 2010; Harraz et al. 2012; Kopačková et al. 2015).

Therefore this phenomenon is probably completely natural in its origin and these elements don't have any impact on vegetation-health status in Sokolov case. The second group of elements consists of Al, Na, Li and Sr. No distinctive differences in elemental levels in street dust collected in different lithological units were observed. On the contrary, Al, Na, Li and Sr levels in street dust are negatively correlated with the average Norway Spruce forest health status in the area of the street-dust sampling. Therefore, anthropogenic influences are the most likely cause of these phenomena.

The spatial patterns in street-dust elemental levels and Norway Spruce forest health status indicate that the local variations are larger than the general (regional) trends, and the variations generally do not follow lithological changes but more likely follow anthropogenically induced ones (Fig. 3). The best example is Al, whose levels in street dust are indifferent to the lithological changes, but increased Al levels are found close to the open-pit mine, urbanised and industrial areas (around the open-pit lignite mine, Vřesová industrial area and town of Sokolov). Street-dust Al-level variations are thus more likely a result of the local atmospheric anthropogenic dust emissions from one or several sources (Fig. 3), rather than a reflection of lithological changes, or a result of different regional dust depositional variations.

Data from this study also show that the strongest links between the Norway Spruce health status and specific

Fig. 3 Spatial distribution of Norway Spruce health status with general trend (polynomial regression), Na, Al and Li levels in street dust. 1—populated areas; 2—abandoned and active lignite open pits; 3—highway; 4—rivers; 5—street-dust sampling points; 6—larger industrial facilities; 7—Norway Spruce health status measurement area

elemental levels in the street dust are observed within distance of 100 m (Table 3). Over distances above or below 100 m this link is no longer so clearly present. This shows that negative anthropogenic effects in the Sokolov basin are locally limited. These results also indicate that street dust is a sampling media that can also reveal localised, small-scale pollution sources, and that chemical anomalies are only locally limited since are no distinctive regional trends and large-scale anomalies, like those which can be found in many other contaminated study areas around the world.

Despite a fact, that temporal factor has not been taken into account in this study, previous studies shows that it should not have a significant impact to the results here. The study of Allot et al. (1990) determined the environmental

half-life time of radiocaesium after Chernobyl reactor accident. Radioactive Cs has half-life radioactive decay rate of 30.17 years, while the half-life of Cs linked to radioactivity in street dust was determined between 150 and 250 days, and this value can be considered as characteristic of any pollutant (Allot et al. 1990). This means that street dust could potentially show the history of atmospheric deposition at least over a year (less than two half-life times). Our results also support this hypothesis, as we found statistically significant correlations between Al, Na, Li and Sr levels in street dust and Norway Spruce health status, as a consequence of anthropogenic activities. Spruce needles were confirmed to be well suited for detection of contamination (Suchara et al. 2011). In this study, the forest health status was assessed using indicators of

vegetation health—REP and expSIPI—which are sensitive to photosynthetic pigment contents (chlorophyll and carotenoids), and changes in these pigments can be detected shortly after the stress (Kirchgeßner et al. 2003). However, as discussed in Kopačková et al. (2014), the main gradients found in the Sokolov basin very likely correspond to long-term stress rather than short-term inter-seasonal changes. As this test site is primarily affected by long-term lignite mining (open-pit mines, the Vřesová plant), the main pollution sources stay the same at a year time-scale. Taking into account that anthropogenic dust emissions in Sokolov area are more or less continuous on the annual scale, the results of both methods, used here to indirectly assess the quality of air, very likely reflect mainly long-term anthropogenic impacts, rather than short-term variations.

Since the remote sensing is gaining focus in the European Union, especially with the launch of new Sentinel Satellites with freely access datasets, such studies are very important towards establishing remote sensing as relevant methods to determine anthropogenic and natural impacts on the environment. This might yield also an implication on the future improvement of policies by the EU and member states in a way to promote the use of opportunities the remote-sensing methodology provides, and to make information obtained by remote-sensing methodology a relevant one for different legal processes.

CONCLUSIONS

In relation to the Sokolov lignite basin, two different datasets were statistically analysed in this study, namely street-dust composition (point dataset) and Norway Spruce health status derived from hyperspectral image data (a continuous dataset). The results show that the areas with increased levels of Al, Sr, Li and Na in street dust correspond to the areas of decreased Norway Spruce health status. Highest number of significant correlations were found within 100 m radius from the street-dust sampling points. Differences in the study's geological background could be one factor affecting the Norway Spruce health status and street-dust composition, yet they cannot satisfactorily explain all the links between decreased forest health status and elemental levels in street dust. Areas of decreased Norway Spruce health status and increased Al, Sr, Li and Na levels in street dust are found around urbanised areas, around open-pit lignite mine and around some of the larger factories in the area. Anthropogenic emissions of Al-, Na-, Li- and Sr-containing substances could be linked to the coal production and combustion and may be suspected to play a role in these phenomena. Further studies are needed to confirm this assumption. Nevertheless, the study results confirm a statistically significant

linear relationship that may be established between hyperspectral data-based classifications and in situ data collection. The results also show that such a relationship can be established over distances of up to 100 m. The results of combined multidisciplinary studies could be used to develop novel in situ and remote-sensing-based methods for the high-resolution determination of air quality.

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REFERENCES

- Allot, R.W., C.N. Hewitt, and M.R. Kelly. 1990. The environmental half-lives and mean residence times of contaminants in dust for an urban environment: Barrow-in-Furnes. *Science of the Total Environment* 93: 403–410. [https://doi.org/10.1016/0048-9697\(90\)90131-D](https://doi.org/10.1016/0048-9697(90)90131-D).
- Almeida, S.M., C.A. Pio, M.C. Freitas, M.A. Reis, and M.A. Trancoso. 2006. Source apportionment of atmospheric urban aerosol based on weekdays/weekend variability: Evaluation of road re-suspended dust contribution. *Atmospheric Environment* 40: 2058–2067.
- Balabanova, B., T. Stafilov, R. Šajn, and K. Bačeva. 2014. Comparison of response of moss, lichens and attic dust to geology and atmospheric pollution from copper mine. *International Journal of Environmental Science and Technology* 11: 517–528. <https://doi.org/10.1007/s13762-013-0262-8>.
- Balabanova, B., T. Stafilov, R. Šajn, and C. Tănăsolia. 2017. Long-term geochemical evolution of lithogenic versus anthropogenic distribution of macro and trace elements in household attic dust. *Archives of Environmental Contamination and Toxicology* 72: 88–107. <https://doi.org/10.1007/s00244-016-0336-y>.
- Bavec, Š., M. Gosar, M. Miler, and H. Biester. 2017. Geochemical investigation of potentially harmful elements in household dust from a mercury-contaminated site, the town of Idrija (Slovenia). *Environmental Geochemistry and Health* 39: 443–465. <https://doi.org/10.1007/s10653-016-9819-z>.
- Borůvka, L., O. Vacek, and J. Jehlička. 2005. Principal component analysis as a tool to indicate the origin of potentially toxic elements in soils. *Geoderma* 128: 289–300. <https://doi.org/10.1016/j.geoderma.2005.04.010>.
- Christoforidis, A., and N. Stamatis. 2009. Heavy metal contamination in street dust and roadside soil along the major national road in Kavala's region, Greece. *Geoderma* 151: 257–263.
- Clevers, J.G.P.W., S.M. De Jong, G.F. Epema, F.D. Van der Meer, W.H. Bakker, A.K. Skidmore, and K.H. Scholte. 2002. Derivation of the red edge index using the MERIS standard band setting. *International Journal of Remote Sensing* 23: 3169–3184. <https://doi.org/10.1080/01431160110104647>.
- Curran, P.J., W.R. Windham, and H.L. Gholz. 1995. Exploring the relationship between reflectance red edge and chlorophyll concentration in Slash Pine Leaves. *Tree Physiology* 15: 203–206.
- Dehghani, S., F. Moore, B. Keshavarzi, and B.A. Hale. 2017. Health risk implications of potentially toxic metals in street dust and surface soil of Tehran, Iran. *Ecotoxicology and Environmental Safety* 136: 92–103.

- Dotzler, S., J. Hill, H. Buddenbaum, and J. Stoffels. 2015. The potential of EnMAP and Sentinel-2 data for detecting drought stress phenomena in deciduous forest communities. *Remote Sensing* 7: 14227–14258.
- Egli, M., G. Sartori, A. Mirabella, D. Giaccari, F. Favilli, D. Scherrer, R. Krebs, and E. Delbos. 2010. The influence of weathering and organic matter on heavy metals lability in silicatic Alpine soils. *Science of the Total Environment* 408: 931–946. <https://doi.org/10.1016/j.scitotenv.2009.10.005>.
- Everitt, J.H., C. Yang, D.E. Escobar, R.I. Lonard, and M.R. Davis. 2002. Reflectance characteristics and remote sensing of a riparian zone in south Texas. *The Southwestern Naturalist* 47: 433–439.
- Fernández-Manso, A., O. Fernández-Manso, and C. Quintano. 2016. SENTINEL-2A red-edge spectral indices suitability for discriminating burn severity. *International Journal of Applied Earth Observation and Geoinformation* 50: 170–175.
- Gould, W. 2000. Remote sensing of vegetation, plant species richness, and regional biodiversity hotspots. *Ecological Applications* 10: 1861–1870.
- Harraz, H.Z., M.M. Hamdy, and M.H. El-Mamoney. 2012. Multi-element association analysis of stream sediment geochemistry data for predicting gold deposits in Barramiya gold mine Eastern Desert Egypt. *Journal of African Earth Sciences* 68: 1–14. <https://doi.org/10.1016/j.jafrearsci.2012.03.009>.
- Keshavarzi, B., Z. Tazarvi, M.A. Rajabzadeh, and A. Najmeddin. 2015. Chemical speciation, human health risk assessment and pollution level of selected heavy metals in urban street dust of Shiraz, Iran. *Atmospheric Environment* 119: 1–10.
- Kirchgeßner, H.D., K. Reichert, K. Hauff, R. Steinbrecher, J.P. Schnitzler, and E.E. Pfundel. 2003. Light and temperature, but not UV radiation, affect chlorophylls and carotenoids in Norway spruce needles (*Picea abies* (L.) Karst.). *Plant, Cell and Environment* 26: 1169–1179. <https://doi.org/10.1046/j.1365-3040.2003.01043.x>.
- Knorn, J., A. Rabe, V.C. Radeloff, T. Kuemmerle, J. Kozak, and P. Hostert. 2009. Land cover mapping of large areas using chain classification of neighboring Landsat satellite images. *Remote Sensing of Environment* 113: 957–964.
- Kolb, E.C., and D.R. Worsnop. 2012. Chemistry and composition of atmospheric aerosol particles. *Annual Review of Physical Chemistry* 63: 471–491. <https://doi.org/10.1146/annurev-physchem-032511-143706>.
- Kopačková, V., Z. Lhotáková, F. Oulehle, and J. Albrechtová. 2015. Assessing forest health via linking the geochemical properties of a soil profile with the biochemical parameters of vegetation. *International Journal of Environmental Science and Technology* 12: 1987–2002. <https://doi.org/10.1007/s13762-014-0602-3>.
- Kopačková, V., J. Mišurec, S. Lhotáková, F. Oulehle, and J. Albrechtová. 2014. Using multi-date high spectral resolution data to assess the physiological status of macroscopically undamaged foliage on a regional scale. *International Journal of Applied Earth Observation and Geoinformation* 27: 169–186. <https://doi.org/10.1016/j.jag.2013.09.009>.
- Lamb, D.W., and R.B. Brown. 2001. Remote-sensing and mapping of weeds in crops. *Journal of Agricultural Engineering Research* 78: 117–125.
- Laurin, G.V., N. Puletti, W. Hawthorne, V. Liesenberg, P. Corona, D. Papale, Q. Chen, and R. Valentini. 2016. Discrimination of tropical forest types, dominant species, and mapping of functional guilds by hyperspectral and simulated multispectral Sentinel-2 data. *Remote Sensing of Environment* 176: 163–176.
- Li, H.H., L.J. Chen, L. Yu, Z.B. Guo, C.Q. Shan, J.Q. Lin, J.G. Gu, Z.B. Yang, et al. 2017a. Pollution characteristics and risk assessment of human exposure to oral bioaccessibility of heavy metals via urban street dusts from different functional areas in Chengdu, China. *Science of the Total Environment* 586: 1076–1084.
- Li, X., T. Wu, H. Bao, X. Liu, C. Xu, Y. Zhao, D. Liu, and H. Yu. 2017b. Potential toxic trace element (PTE) contamination in Baoji urban soil (NW China): Spatial distribution, mobility behavior, and health risk. *Environmental Science and Pollution Research* 24: 19749–19766. <https://doi.org/10.1007/s11356-017-9526-z>.
- Li, Y., Y. Yu, Z. Yang, S. Zhenyao, W. Xuan, and C. Yanpeng. 2016. A comparison of metal distribution in surface dust and soil among super city, town, and rural area. *Environmental Science and Pollution Research* 23: 7849–7860. <https://doi.org/10.1007/s11356-015-5911-7>.
- Li, Z., X. Feng, G. Li, X. Bi, J. Zhu, H. Qin, Z. Dai, J. Liu, et al. 2013. Distributions, sources and pollution status of 17 trace metal/metalloids in the street dust of a heavily industrialized city of central China. *Environmental Pollution* 182: 408–416.
- Lu, X.W., L.J. Wang, K. Lei, J. Huang, and Y.X. Zhai. 2009. Contamination assessment of copper, lead, zinc, manganese and nickel in street dust of Baoji, NW China. *Journal of Hazardous Materials* 161: 1058–1062.
- MHSPE. 2014. The New Dutchlist. In: Intervention values and target values—soil quality standards. Ministry of Housing, Spatial Planning, and the Environment, Directorate General for Environmental Protection, Department of Soil Protection, The Hague, The Netherlands. Retrieved January 16, 2014, from <http://www.contaminatedland.co.uk/stdguid/dutch-1.htm>.
- Miler, M., and M. Gosar. 2013. Assessment of metal pollution sources by SEM/EDS analysis of solid particles in snow: A case study of Žerjav, Slovenia. *Microscopy and Microanalysis* 19: 1606–1619. <https://doi.org/10.1017/S1431927613013202>.
- Mišurec, J., V. Kopačková, Z. Lhotáková, J. Hanuš, J. Weyermann, P. Entcheva-Campbell, and J. Albrechtová. 2012. Utilization of hyperspectral image optical indices to assess the Norway spruce forest health status. *Journal of Applied Remote Sensing* 6: 063545-1.
- Ordóñez, A., R. Álvarez, E. De Miguel, and S. Charlesworth. 2015. Spatial and temporal variations of trace element distribution in soils and street dust of an industrial town in NW Spain: 15 years of study. *Science of the Total Environment* 524–525: 93–103.
- Penuelas, J., F. Baret, and I. Filella. 1995. Semiempirical indexes to assess carotenoids:chlorophyll-a ratio from leaf spectral reflectance. *Photosynthetica* 31: 221–230.
- Pu, R.L., M. Kelly, G.L. Anderson, and P. Gong. 2008. Using CASI hyperspectral imagery to detect mortality and vegetation stress associated with a new hardwood forest disease. *Photogrammetric Engineering and Remote Sensing* 74: 65–75.
- Querol, X., J.L. Fernández-Turiel, and A. Lopez-Soler. 1995. Trace elements in coal and their behaviour during combustion in a large power station. *Fuel* 74: 331–343.
- Rathod, P.H., D.G. Rossiter, M.F. Noomen, and F.D. van der Meer. 2013. Proximal spectral sensing to monitor phytoremediation of metal-contaminated soils. *International Journal of Phytoremediation* 15: 405–426.
- Richter, R. 2009. *Atmospheric/topographic correction for airborne imagery*. Wessling: DLR German Aerospace Centre.
- Romer, C., M. Wahabzada, A. Ballvora, F. Pinto, M. Rossini, C. Panigada, J. Behmann, J. Leon, et al. 2012. Early drought stress detection in cereals: Simplex volume maximisation for hyperspectral image analysis. *Functional Plant Biology* 39: 878–890.
- Šajn, R., M. Aliu, T. Stafilov, and J. Alijagić. 2013. Heavy metal contamination of topsoil around a lead and zinc smelter in Kosovska Mitrovica/Mitrovica, Kosovo/Kosovo. *Journal of Geochemical Exploration* 134: 1–16. <https://doi.org/10.1016/j.gexplo.2013.06.018>.

- Salminen, R., M.J. Batista, M. Bidovec, A. Demetriades, B. De Vivo, W. De Vos, M. Duris, A. Gilucis, et al. 2005. Geochemical Atlas of Europe. Part 1—background information, methodology and maps. Geological Survey of Finland, Espoo.
- Sanches, I.D., C.R. Souza Filho, L.A. Magalhaes, G.C.M. Quiterio, M.N. Alves, and W.J. Oliveira. 2013. Assessing the impact of hydrocarbon leakages on vegetation using reflectance spectroscopy. *ISPRS Journal of Photogrammetry and Remote Sensing* 78: 85–101.
- Schlapfer, D., 1998. Parametric Geocoding, PARGE Using Guide, Version 2.3. ReSe Applications Schlapfer & Remote Sensing Laboratories, University of Zurich, Zurich.
- Suchara, I., J. Sucharova, M. Hola, C. Reimann, R. Boyd, P. Filzmoser, and P. Englmaier. 2011. The performance of moss, grass, and 1- and 2-year old spruce needles as bioindicators of contamination: A comparative study at the scale of the Czech Republic. *Science of the Total Environment* 409: 2281–2297. <https://doi.org/10.1016/j.scitotenv.2011.02.003>.
- Tang, Z., M. Chai, J. Cheng, J. Jin, Y. Yang, Z. Nie, Q. Huang, and Y. Li. 2017. Contamination and health risks of heavy metals in street dust from a coal-mining city in eastern China. *Ecotoxicology and Environmental Safety* 138: 83–91.
- Vejahati, F., Z. Xu, and R. Gupta. 2010. Trace elements in coal: Associations with coal and minerals and their behavior during coal utilization: A review. *Fuel* 89: 904–911. <https://doi.org/10.1016/j.fuel.2009.06.013>.
- Vogelmann, J.E., G. Xian, C. Homer, and B. Tolk. 2012. Monitoring gradual ecosystem change using Landsat time series analyses: Case studies in selected forest and rangeland ecosystems. *Remote Sensing of Environment* 122: 92–105.
- Wei, X., B. Gao, P. Wang, H. Zhou, and J. Lu. 2015. Pollution characteristics and health risk assessment of heavy metals in street dusts from different functional areas in Beijing, China. *Ecotoxicology and Environmental Safety* 112: 186–192.
- Yu, Y., Y. Li, B. Li, and M.K. Stenstrom. 2017. Profiles of lead in urban dust and the effect of the distance to multi-industry in an old heavy industry city in China. *Ecotoxicology and Environmental Safety* 137: 281–287. <https://doi.org/10.1016/j.ecoenv.2016.11.031>.
- Žibret, G. 2012. Impact of dust filter installation in ironworks and construction on brownfield area on the toxic metal concentration in street and house dust (Celje, Slovenia). *Ambio* 41: 292–301. <https://doi.org/10.1007/s13280-011-0188-7>.
- Žibret, G., D. Van Tonder, and L. Žibret. 2013. Metal content in street dust as a reflection of atmospheric dust emissions from coal power plants, metal smelters, and traffic. *Environmental Science and Pollution Research* 20: 4455–4468. <https://doi.org/10.1007/s11356-012-1398-7>.
- Zierold, K.M., and C.G. Sears. 2015. Community views about the health and exposure of children living near a coal ash storage site. *Journal of Community Health* 40: 357–363. <https://doi.org/10.1007/s10900-014-9943-6>.
- Zinnert, J.C., S.M. Via, and D.R. Young. 2013. Distinguishing natural from anthropogenic stress in plants: Physiology, fluorescence and hyperspectral reflectance. *Plant and Soil* 366: 133–141.

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