Int. J. Environ. Sci. Technol. (2017) 14:2591–2602
DOI 10.1007/s13762-017-1342-y

ORIGINAL PAPER

Multi-matrix environmental monitoring to assess heavy element distribution around a municipal solid waste landfill in Italy

F. Nannoni[1] · R. Mazzeo[2] · R. Santolini[2] · G. Protano[1]

Received: 19 December 2016 / Revised: 23 April 2017 / Accepted: 26 April 2017 / Published online: 8 May 2017

Abstract Multi-matrix environmental monitoring was used to evaluate the influence of a municipal solid waste landfill (Ginestreto, Emilia Romagna, Italy) on the level and distribution of heavy elements in the surrounding environment (air, soil and soil biota). Concentrations of As, Cd, Co, Cr, Cu, Hg, Ni, Pb, Sb, Tl and Zn were measured by inductively coupled plasma-mass spectrometry in transplanted lichens, topsoils and isopods. The highest accumulation levels found for Cd, Cr, Pb, Sb and Zn in lichens transplanted within the Ginestreto landfill. However, similar concentrations of these heavy elements were also found in lichens exposed in monitoring sites influenced by other man-made sources, such as vehicle traffic and truck movements. The fallout of heavy elements emitted by the landfill had low impact on their levels in topsoil: Cd, Cr, Pb, Sb and Zn showed higher contents in topsoil collected close to the landfill and a slight decrease in concentrations with increasing distance from the landfill. There was no variation in heavy element accumulation in isopods in relation to distance from the landfill. The results of this study indicate that the Ginestreto municipal solid waste landfill had limited impact on the environmental distribution of heavy elements, since accumulation and enrichment in lichens and topsoils were only detected close to the landfill, up to about 100 m from its border.

Editorial responsibility: H.N. Hsieh.

Keywords Heavy elements · Isopods · Lichens · Multi-matrix environmental monitoring · Municipal solid waste landfill · Topsoil

Introduction

The monitoring of physico-chemical properties and inorganic and organic chemical species in air, water, soil and biota is a common way to assess the chemistry and quality of the surface environment, to establish local natural background levels, to determine and characterize contamination phenomena and to evaluate risk to ecological and/or human health (Mitchell 2002; Wiersma 2004). However, a more accurate study of the distribution, behaviour and fate of contaminants (e.g. heavy elements) in the surface environment can be achieved using a number of suitably disposed abiotic and biotic matrices. In biogeochemical research, this approach is useful to reconstruct the pathways of contaminants in the surface environment, to evaluate their transfer between the environmental compartments and to establish the main targets involved in contamination processes.

In the presence of point and diffuse contamination sources (e.g. industrial plants, smelters, vehicle traffic, waste incinerators and landfills), air quality may be monitored measuring the concentrations of gases such as NO_x, SO_2 and volatile organic compounds (VOCs), and levels and composition of particulate matter (PM_{10} and $PM_{2.5}$), as well as using bioindicator organisms such as lichens. Indeed, lichens are widely used as bioindicators of air quality and environmental contamination (e.g. Loppi et al. 1997; Conti and Cecchetti 2001; Nimis et al. 2002; Wolterbeek 2002). By virtue of their morphological and physiological features, lichens absorb and accumulate

✉ F. Nannoni
nannoni@unisi.it

[1] Department of Physical, Earth and Environment Sciences, University of Siena, Via del Laterino 8, 53100 Siena, Italy

[2] Department of Earth, Life and Environmental Sciences, University of Urbino "Carlo Bo", Via Cà le Suore 2/4, 61029 Urbino, Italy

contaminants such as heavy elements, intercepting airborne materials and atmospheric gases. Lichens are "early-warning" indicators of environmental changes and widely used in monitoring spatial patterns and temporal trends of heavy elements in the air environment (Bennett and Wetmore 1999, 2000).

The lichen transplantation is an effective technique widely used for the determination of heavy element accumulation by these organisms (Sloof 1995; Mikhailova 2002; Conti et al. 2004; Ayrault et al. 2007; Godinho et al. 2008; Pacheco et al. 2008). The use of lichen transplants in place of native lichens (lichens grown in situ) is mainly due to the following reasons: absence/scarcity of native lichens in the study area, uniformity of the lichen species utilized in biomonitoring and of the exposure period, possibility to choose the monitoring sites and their number, knowledge of the concentration of chemical elements before exposure, possibility to evaluate the accumulation trend of chemical elements. Moreover, several authors showed that lichens transplanted from uncontaminated areas close to contamination sources uptake noteworthy amounts of heavy elements (Bargagli 1998; Garty et al. 2001; Conti et al. 2004; Paoli et al. 2011).

Topsoils are useful to define fallout and enrichment of air contaminants on the ground. Soil may be a sink for air contaminants, mainly through sorption, precipitation and co-precipitation reactions. These processes govern the behaviour of heavy elements in soil and rule their partitioning in soil fractions, determining the mobility and availability of heavy elements for soil biota (Chuan et al. 1995; Peijnenburg 2002; Harmsen 2007; Violante et al. 2010).

Soil organisms such as terrestrial isopods may be exploited to evaluate soil quality and to define the transfer of contaminants to biota (Hopkin and Martin 1982; Dallinger and Prosi 1988; Witzel 1998). These detritivorous organisms are mainly exposed to air contaminants through their food sources and microhabitat in the upper layer of soil. Isopods are also used as useful bioindicators of environmental contamination by heavy elements, which they uptake and accumulate (Witzel 1998; Paoletti and Hassall 1999; Odendaal and Reinecke 2004a; Vijver et al. 2006).

Multi-matrix environmental monitoring was used to evaluate the influence of emissions from a municipal solid waste landfill (MSWL) in central Italy on levels and distribution of heavy elements in the land around the dump. The monitoring was carried out from September to December 2012. The concentrations of 11 heavy elements (As, Cd, Co, Cr, Cu, Hg, Ni, Pb, Sb, Tl and Zn) were determined in transplanted lichens, topsoil and isopods. As a potential contamination source, municipal solid waste landfills have been relatively less investigated in biogeochemical studies. To our knowledge, few studies have dealt with the environmental impact of landfills using singly transplanted lichens, soils or isopods (Paoli et al. 2012, 2015; Barbieri et al. 2014; Protano et al. 2014) and even fewer using these matrices simultaneously (Nannoni et al. 2015a, b).

Materials and methods

Study area

The study area includes about 25 km^2 of land around the Ginestreto municipal solid waste landfill in the municipality of Sogliano al Rubicone (FC, Emilia Romagna, Italy; Fig. 1).

The Ginestreto MSWL is situated in a hilly area characterized by small parallel valleys separated by high and steep hills. This morphological structure is typical of impermeable and easily fragmented soil and forms by erosive action of weathering. The area is sparsely developed, and the main land uses are pasture, agriculture and woodlands as well as pig and sheep breeding. As shown in Fig. 1, the prevalent direction of winds is from SW.

The geology of the study area is mainly characterized by Pliocene marine sediments belonging to the Argille azzurre formation. This lithostratigraphic unit mainly consists of blue-grey clays and marly clays with interbedded conglomerates, sandstone and silty clays. Clayey, silty and calcareous marls of the Marne di Antognola formation crop out in the NE sector.

The municipal solid waste landfill of Ginestreto is in two batches, denominated Ginestreto 1 (G1) and Ginestreto 2 (G2), in two adjacent gullies. According to Italian law (Italian Legislative Decree no. 36/2003), batch G1 is classified as "*landfill for municipal and not hazardous waste*". It was active from 1990 to 2005, covers an area of about 112,000 m^2 and contains about 2.5 million tons of solid waste. It is now closed and end capped. Ginestreto 1 was also subject to environmental restoration as required by law.

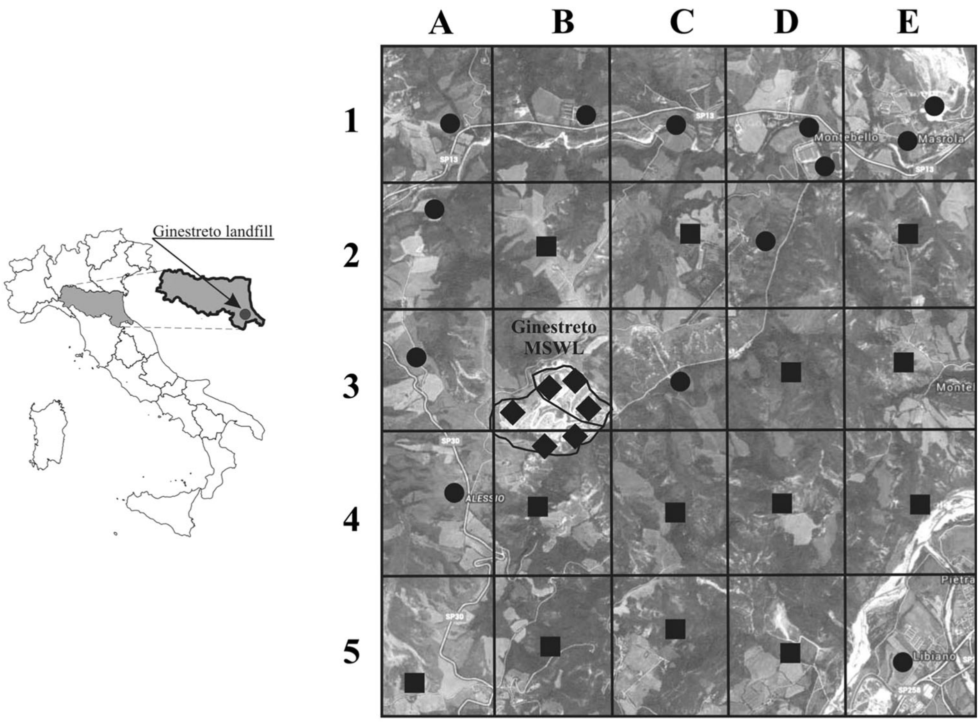
Ginestreto 2 opened in 2005 and was still active at the time of this research (2012). It covers an area of about 120,000 m^2 and has a storage capacity of about 2,500,000 m^3. It is classified as "*landfill for municipal and not hazardous waste, subcategory c: landfill for non-hazardous waste with high contents of organic or biodegradable and inorganic waste, with recovery of biogas*".

Besides the municipal solid waste landfill of Ginestreto, there are other potential sources of contamination in the study area: a composting plant and a quarry (henceforth Masrola quarry) in the NE, and the town of Pietracuta in the SE sector. Two provincial roads (SP13 and SP30) run through the study area.

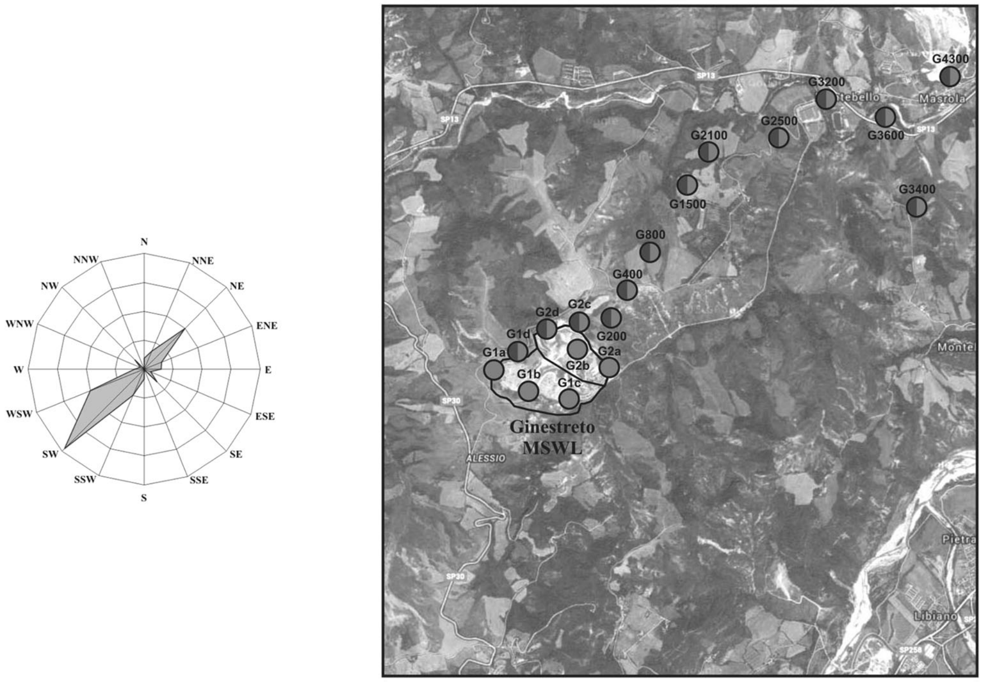
Lichen sampling, transplantation and laboratory treatment

Thalli of the *Evernia prunastri* (L.) Ach. lichen were harvested from a remote site of Siena province (Tuscany,

Fig. 1 Map of the study area showing the location of monitoring sites and the direction of prevailing winds. **a** Lichen sampling sites, **b** soil and isopod sampling sites



(a) Lichen: ● Anthropic sites ◆ Landfill sites ■ Rural sites



(b) ● Soil sampling sites ● Soil and isopod sampling sites

central Italy). This lichen species was selected because it is commonly utilized in biomonitoring studies (Garty et al. 2001; Loppi and Frati 2006; Guttova et al. 2011; Paoli et al. 2011).

In laboratory, lichens were cleaned with plastic tweezers and washed with ultra-pure water to remove extraneous particles deposited onto their surface. Then, thalli were stored in paper bags. The lichen samples ($n = 4$) utilized for analytical determinations were frozen at −20 °C.

To select the sites for lichen transplantation, the study area was divided into 25 square cells of 1 km of side (Fig. 1a). Based on the prevalent land use and the location of potential contamination sources, within each cell one suitable and representative site was selected for the lichen transplants. Two transplantation sites were individuated in cells D1 and E1 where the composting plant and Masrola quarry are found, respectively. In B3 and B4 cells which include the Ginestreto landfill, overall seven sites for transplantation were selected.

Lichen transplants were exposed in 32 monitoring sites that can be clustered into three groups (Fig. 1a): (1) landfill sites situated within the G1 and G2 batches ($n = 6$); (2) anthropic sites placed near the composting plant, Masrola quarry, town of Pietracuta and in proximity of the main roads ($n = 13$); (3) rural sites situated in agricultural, pasture and wooded zones not affected by the direct influence of the contamination sources ($n = 13$).

In each site, 3 lichen thalli fasten on the branches of a tree, at a height of about 2.5 m above ground. Lichen transplants were exposed for 4 months from September to December 2012 to minimize the effects of dry or hot periods on heavy element accumulation. In fact, these meteorological conditions may influence the viability of thalli and the process of chemicals uptake. Moreover, for periods of exposure longer than 4 months, transplanted lichens may either lose some biomass or become saturated with elements, significantly altering their surface structure and physiological performance. At the end of the 4 months of exposure, lichen transplants were removed from monitoring sites and stored in plastic bags. Each sample was a mixture of all thalli transplanted in the monitoring site.

In laboratory, the exposed lichens were placed in paper bags and frozen at −20 °C. After exposure, lichens were not washed in order not to alter their chemical composition (Bettinelli et al. 1996). Before the analysis, thalli were left 15 min at room temperature and cleaned with plastic tweezers to remove extraneous particles deposited onto lichen surface.

Native and exposed thalli were air-dried to constant weight and pulverized and homogenized in liquid nitrogen using a ceramic mortar and pestle. Only the peripheral parts of lichen (up to 2 cm from lobe tips) were selected for analysis.

About 200 mg of lichen powder were mineralized with a mixture of 6 mL HNO_3, 1 mL H_2O_2 and 0.2 mL HF (ultra-pure trace-grade reagents). Mineralization of samples was performed in a microwave digestion system (Milestone Ethos 900). A certified reference material and a blank of the utilized reagents were included in each mineralization batch.

Soil sampling and laboratory treatment

Topsoil samples were collected in 18 sites during June 2012. Topsoil sampling involved the upper 5 cm of soil profile to better assess the contribution of heavy elements from the landfill fallout and the other potential contamination sources. Topsoil samples were collected within 100 m from the border of landfill ($n = 8$) and at variable distance (from 200 to 4300 m) from Ginestreto MSWL along a SW-NE transect aligned with the direction of prevailing wind ($n = 10$; Fig. 1b). Each topsoil sample consisted of 3 sub-samples collected a few metres apart.

In laboratory, topsoils were dried at +40 °C, sieved through a 2-mm mesh and homogenized by quartering and pulverization. Mineralization of topsoils was carried out in a microwave laboratory station adding a mixture of 2 mL HNO_3, 2 mL HF and 1 mL H_2O_2 to 250 mg of powdered soil. A standard reference material and a blank of the employed reagents were included in each digestion batch.

Isopod sampling and laboratory treatment

Mature specimens of the isopod *Armadillidium vulgare* (Latreille 1804) were sampled in the litter layer by hand-sorting. This species was chosen because it is the most common in the study area. Isopods were collected in 15 sites out of 18 in which topsoils were sampled. These sites were situated within 100 m from the border of Ginestreto MSWL ($n = 3$) and along the SW-NE transect designed for soil sampling ($n = 12$; Fig. 1b). In each site, the individuals of *A. vulgare* were sampled within an area with a radius of about 5 m. A total of 150 isopods were sampled, 10 for each site.

In laboratory, isopods were washed with deionized water to remove adhering soil particles. In order to allow gut emptying specimens were kept at +18 °C and with a photoperiod of 12 h in Petri dishes containing a filter paper and some drops of distilled water for 72 h. Daily filter paper was changed, and faeces were removed.

The 150 specimens were killed by freezing (−80 °C) and then freeze-dried for 48 h. The freeze-dried isopods were mineralized individually with a mixture of 3 mL HNO_3 and 1 mL H_2O_2 (ultra-pure trace-grade reagents) in a microwave digestion system. In each mineralization batch, a certified reference material and a blank of the reagents were included.

Lichen, soil and isopod analysis

The contents of As, Cd, Co, Cr, Cu, Hg, Ni, Pb, Sb, Tl and Zn in native and transplanted lichens, isopods and topsoils were determined by inductively coupled plasma-mass spectrometry (ICP-MS) (PerkinElmer Sciex Elan 6100 spectrometer) and expressed on a dry weight basis (mg/kg dw).

Analytical quality was checked by analysing the following standard reference materials: (1) IAEA 336 of the International Atomic Energy Agency for lichen; (2) NIST

2709 of the National Institute of Standards and Technology for soil; (3) NIST 2977 of the National Institute of Standards and Technology for isopod. The recoveries ranged from 89 to 106% for IAEA 336, from 91 to 108% for NIST 2709 and from 93 to 109% for NIST 2977.

The analytical precision, estimated by five replicate analyses of each sample and expressed as percent relative standard deviation (% RSD), was below 9, 6 and 5% for all the chemical elements in lichen, topsoil and isopod samples, respectively.

Data interpretation and statistical analysis

The ratio between the heavy element content in lichens after their exposure in the monitoring sites and that in non-exposed control lichen, defined as Exposed to Control (EC) ratio (Frati et al. 2005), was utilized to assess the accumulation of heavy metals in transplanted thalli. To evaluate the variations in accumulation or loss of heavy elements in transplanted lichens, the following 5-class interpretative scale was utilized: severe loss EC = 0.00–0.25, loss EC = 0.25–0.75, normal EC = 0.75–1.25, accumulation EC = 1.25–1.75 and severe accumulation EC > 1.75. These classes were based on progressive ±25% deviations from "normal" conditions.

Normal distribution and homoscedasticity of datasets were checked using the Shapiro–Wilk W-test and Fischer F-test, respectively. The significance of differences was verified by means of Student *t* test for data normally distributed and Mann–Whitney U test for data not normally distributed ($p < 0.05$).

Correlations among the heavy element contents in topsoils and isopods and the distance from landfill as well as among the heavy element contents in topsoils and isopods were checked using Spearman test ($p < 0.05$).

Results and discussion

Heavy elements in transplanted lichens

Table 1 shows the concentrations of As, Cd, Co, Cr, Cu, Hg, Ni, Pb, Sb, Tl and Zn in native specimens of *Evernia prunastri* sampled in an uncontaminated control site and in transplanted lichens exposed for 4 months in the landfill and in anthropic and rural sites in the Ginestreto MSWL area.

In transplanted lichens As, Cd, Co, Cr, Cu, Ni, Pb, Sb and Zn concentrations decreased in the monitoring sites in the following order: landfill ≥ anthropic > rural, whereas Hg and Tl concentrations were substantially homogeneous.

Statistical analysis indicated that there were significant differences ($p < 0.05$; Table 1) between: (1) concentrations of Cr, Cu, Pb, Sb and Zn in lichens exposed in all monitoring sites (landfill, anthropic and rural) and in control sites; (2) concentrations of Cd and Ni in lichens transplanted in anthropic and/or landfill sites and in control ones. Lichens exposed in landfill and anthropic sites had contents of Cd, Cr, Cu, Ni, Pb, Sb and Zn significantly higher than those in rural stations ($p < 0.05$; Table 1). Only Sb showed a statistically significant difference between concentrations in lichens transplanted in landfill and anthropic sites. There were no significant differences between the concentrations of As, Co, Hg and Tl in transplanted and control lichens.

The values of the EC ratio indicated that all heavy elements showed the highest levels of accumulation in lichens exposed in landfill and anthropic sites (Table 2).

Severe accumulation (EC > 1.75) of Cd, Cr, Pb, Sb and Zn was found in lichens from landfill and anthropic sites, and less accumulation (1.25 > EC > 1.75) in those transplanted in rural stations (except for Cd; Table 2). The highest EC values of these heavy elements distinguished thalli transplanted within the Ginestreto landfill. Cu accumulated in lichens exposed in all monitoring stations, Co and Ni in anthropic and landfill sites. Lichens transplanted in the study area did not accumulate As, Hg or Tl (EC from 0.75 to 1.25; Table 2).

For lichens exposed in the landfill sites, the highest accumulation was found for Sb ($EC_{mean} = 4.92$), followed by Cd (2.32), Cr (2.22), Pb (2.18) and Zn (2.17). Cu, Ni and Co accumulated in these lichen transplants with EC mean values of 1.50, 1.48 and 1.41, respectively. The highest EC ratios of Cr, Pb, Sb and Zn were detected in lichens transplanted in active batch (G2).

In anthropic sites, Cd, Cr, Pb, Sb and Zn were again the heavy elements that exposed lichens accumulated most of all, with EC mean values ranging from 1.8 (Zn) to 2.48 (Sb; Table 2). Cu also showed usually accumulation in lichens transplanted in anthropic sites, while As, Co, Hg, Ni and Tl were not accumulated at all or only moderately. Among anthropic sites, most of the heavy elements analysed achieved highest accumulation levels in lichens exposed close to Masrola quarry (site E1).

In lichens transplanted in rural sites, Cr, Cu, Pb, Sb and Zn accumulated, whereas accumulation of As, Cd, Co, Hg, Ni and Tl did not usually occur (Table 2).

Heavy elements in soil and isopods

Concentrations of Cd, Cr, Pb, Sb and Zn in topsoils sampled close to the landfill were significantly higher ($p < 0.05$; Table 3) than in those collected along the SW-NE transect (Fig. 1b), while the contents of As, Co, Cu, Hg, Ni and Tl were comparable (soil sites GS-3600 and GS-4300 were excluded from the statistical analysis for the reasons explained below).

Table 1 Concentrations and mean values of heavy elements (data expressed as mg/kg dry weight ± SD) in native lichens collected in the control site and in lichens transplanted in the monitoring sites of the Ginestreto MSWL area

Lichen sites	As	Cd	Co	Cr	Cu	Hg	Ni	Pb	Sb	Tl	Zn
Control											
Native 1	0.21 ± 0.02	0.022 ± 0.004	0.2 ± 0.01	1.4 ± 0.06	3.2 ± 0.26	0.06 ± 0.005	2.2 ± 0.07	1.4 ± 0.04	0.09 ± 0.03	0.006 ± 0.001	12 ± 0.17
Native 2	0.21 ± 0.02	0.029 ± 0.008	0.18 ± 0.03	1.3 ± 0.02	2.9 ± 0.3	0.066 ± 0.011	1.7 ± 0.1	1.2 ± 0.01	0.09 ± 0.06	0.007 ± 0.001	9.9 ± 0.11
Native 3	0.29 ± 0.02	0.025 ± 0.005	0.3 ± 0.06	0.93 ± 0.03	2.7 ± 0.24	0.057 ± 0.008	1.6 ± 0.07	1.5 ± 0.09	0.11 ± 0.08	0.009 ± 0.003	10.8 ± 0.14
Native 4	0.37 ± 0.04	0.036 ± 0.008	0.19 ± 0.04	1.1 ± 0.05	3.4 ± 0.28	0.069 ± 0.014	2.3 ± 0.15	1 ± 0.03	0.07 ± 0.02	0.014 ± 0.004	6.1 ± 0.11
Mean	0.27 ± 0.08	0.028 ± 0.006	0.22 ± 0.05	1.2 ± 0.23	3.1 ± 0.31	0.063 ± 0.005	1.9 ± 0.34	1.3 ± 0.2	0.09 ± 0.02	0.009 ± 0.004	9.7 ± 2.5
Rural											
A5	0.28 ± 0.02	0.03 ± 0.007	0.23 ± 0.06	1.5 ± 0.02	3.4 ± 0.03	0.05 ± 0.007	1.6 ± 0.04	1.7 ± 0.04	0.15 ± 0.05	0.006 ± 0.002	14.7 ± 0.25
B2	0.27 ± 0.02	0.042 ± 0.008	0.28 ± 0.06	1.7 ± 0.04	4.3 ± 0.06	0.069 ± 0.014	2.1 ± 0.02	1.5 ± 0.02	0.12 ± 0.03	0.007 ± 0.001	15.5 ± 0.31
B4/B	0.31 ± 0.04	0.043 ± 0.003	0.26 ± 0.05	2.1 ± 0.04	3.6 ± 0.04	0.064 ± 0.005	1.9 ± 0.04	2.2 ± 0.04	0.12 ± 0.01	0.009 ± 0.001	19.6 ± 0.21
B5	0.32 ± 0.03	0.036 ± 0.005	0.24 ± 0.04	1.6 ± 0.01	4.1 ± 0.04	0.074 ± 0.004	2.1 ± 0.04	1.6 ± 0.02	0.12 ± 0.02	0.011 ± 0.003	14.2 ± 0.18
C2	0.32 ± 0.01	0.036 ± 0.003	0.31 ± 0.08	1.8 ± 0.03	4.2 ± 0.07	0.065 ± 0.006	1.8 ± 0.04	1.9 ± 0.01	0.11 ± 0.02	0.01 ± 0.001	12.6 ± 0.2
C4	0.28 ± 0.02	0.03 ± 0.009	0.28 ± 0.06	1.5 ± 0.05	4.3 ± 0.04	0.095 ± 0.008	2 ± 0.02	1.8 ± 0.02	0.11 ± 0.03	0.008 ± 0.001	14.7 ± 0.4
C5	0.32 ± 0.02	0.039 ± 0.004	0.23 ± 0.05	1.9 ± 0.03	3.7 ± 0.04	0.07 ± 0.003	2 ± 0.03	1.6 ± 0.02	0.12 ± 0.01	0.008 ± 0.001	15 ± 0.19
D3	0.29 ± 0.03	0.024 ± 0.007	0.21 ± 0.05	1.7 ± 0.02	3.8 ± 0.06	0.062 ± 0.005	2 ± 0.04	1.2 ± 0.01	0.14 ± 0.04	0.008 ± 0.001	14.1 ± 0.22
D4	0.35 ± 0.03	0.039 ± 0.005	0.22 ± 0.09	1.8 ± 0.05	4.4 ± 0.04	0.07 ± 0.006	1.8 ± 0.06	1.7 ± 0.01	0.13 ± 0.02	0.008 ± 0.001	12.6 ± 0.19
D5	0.29 ± 0.02	0.03 ± 0.002	0.26 ± 0.07	1.6 ± 0.03	4.2 ± 0.06	0.056 ± 0.005	2.6 ± 0.04	1.9 ± 0.02	0.12 ± 0.02	0.01 ± 0.001	14.5 ± 0.24
E2	0.29 ± 0.03	0.035 ± 0.005	0.27 ± 0.08	1.4 ± 0.02	5.4 ± 0.06	0.062 ± 0.005	2 ± 0.02	2.9 ± 0.04	0.27 ± 0.05	0.008 ± 0.001	18.1 ± 0.2
E3	0.24 ± 0.02	0.034 ± 0.005	0.24 ± 0.06	1.6 ± 0.06	4.4 ± 0.04	0.06 ± 0.004	2.2 ± 0.04	2 ± 0.05	0.12 ± 0.01	0.008 ± 0.001	15.8 ± 0.25
E4	0.28 ± 0.01	0.038 ± 0.002	0.27 ± 0.07	1.5 ± 0.03	4.2 ± 0.08	0.064 ± 0.011	1.9 ± 0.03	1.8 ± 0.03	0.12 ± 0.02	0.007 ± 0.001	13 ± 0.21
Mean	0.29 ± 0.03	0.035 ± 0.005	0.25 ± 0.03	1.7^{a} ± 0.21	4.2^{a} ± 0.5	0.066 ± 0.011	2 ± 0.23	1.8^{a} ± 0.39	0.13^{a} ± 0.04	0.008 ± 0.001	14.9^{a} ± 2
Anthropic											
A1	0.35 ± 0.03	0.065 ± 0.008	0.25 ± 0.04	1.9 ± 0.04	4.6 ± 0.05	0.085 ± 0.006	2 ± 0.05	2.1 ± 0.02	0.2 ± 0.04	0.008 ± 0.001	19.6 ± 0.36
A2	0.24 ± 0.01	0.054 ± 0.011	0.24 ± 0.07	2.1 ± 0.03	4.1 ± 0.04	0.046 ± 0.013	1.9 ± 0.04	1.6 ± 0.02	0.18 ± 0.03	0.006 ± 0.001	15.8 ± 0.14
A3	0.38 ± 0.02	0.062 ± 0.005	0.36 ± 0.07	3 ± 0.02	4.9 ± 0.04	0.065 ± 0.009	2.4 ± 0.05	2.8 ± 0.05	0.37 ± 0.08	0.011 ± 0.002	17.9 ± 0.25
A4	0.4 ± 0.02	0.055 ± 0.003	0.37 ± 0.03	2.4 ± 0.04	5.5 ± 0.07	0.1 ± 0.005	5.4 ± 0.06	2.7 ± 0.04	0.27 ± 0.06	0.012 ± 0.002	19.7 ± 0.19
B1	0.32 ± 0.03	0.048 ± 0.006	0.28 ± 0.04	1.7 ± 0.03	4.7 ± 0.05	0.085 ± 0.008	2.1 ± 0.03	2.2 ± 0.02	0.19 ± 0.05	0.008 ± 0.001	16.6 ± 0.32
C1	0.29 ± 0.01	0.069 ± 0.006	0.27 ± 0.09	2.3 ± 0.02	3.9 ± 0.05	0.061 ± 0.005	2.4 ± 0.04	2.5 ± 0.03	0.17 ± 0.04	0.008 ± 0.001	17.1 ± 0.24
C3	0.37 ± 0.02	0.062 ± 0.005	0.29 ± 0.05	2.4 ± 0.03	4.9 ± 0.02	0.084 ± 0.013	2.7 ± 0.04	2.9 ± 0.02	0.22 ± 0.04	0.013 ± 0.001	15.9 ± 0.26
D1/A	0.29 ± 0.03	0.06 ± 0.004	0.33 ± 0.09	2.7 ± 0.08	4.9 ± 0.03	0.083 ± 0.008	2.3 ± 0.05	2.8 ± 0.04	0.21 ± 0.03	0.011 ± 0.002	19.3 ± 0.32
D1/B	0.3 ± 0.03	0.048 ± 0.009	0.31 ± 0.08	2.1 ± 0.03	3.9 ± 0.05	0.066 ± 0.009	2.1 ± 0.06	2.5 ± 0.05	0.15 ± 0.02	0.01 ± 0.001	14.8 ± 0.19
D2	0.24 ± 0.01	0.027 ± 0.006	0.3 ± 0.02	1.8 ± 0.03	4.1 ± 0.08	0.056 ± 0.004	2.8 ± 0.09	1.7 ± 0.03	0.13 ± 0.02	0.008 ± 0.001	14.8 ± 0.18
E1/A	0.44 ± 0.02	0.096 ± 0.009	0.69 ± 0.15	3.4 ± 0.04	5.5 ± 0.03	0.081 ± 0.006	4 ± 0.09	2.8 ± 0.03	0.32 ± 0.01	0.02 ± 0.003	22.9 ± 0.37
E1/B	0.23 ± 0.01	0.064 ± 0.006	0.4 ± 0.02	2.9 ± 0.04	4.8 ± 0.03	0.048 ± 0.009	2.1 ± 0.03	2.7 ± 0.04	0.19 ± 0.02	0.007 ± 0.001	16.5 ± 0.25

Table 1 continued

Lichen sites	As	Cd	Co	Cr	Cu	Hg	Ni	Pb	Sb	Tl	Zn
E5	0.3 ± 0.03	0.041 ± 0.004	0.21 ± 0.08	1.7 ± 0.02	4.1 ± 0.05	0.095 ± 0.008	2.4 ± 0.03	1.9 ± 0.02	0.15 ± 0.04	0.008 ± 0.001	13.1 ± 0.32
Mean	0.32 ± 0.06	0.058^{ab} ± 0.016	0.33^{b} ± 0.12	2.3^{ab} ± 0.53	4.6^{ab} ± 0.54	0.073 ± 0.018	2.7^{b} ± 0.99	2.4^{ab} ± 0.45	0.21^{ab} ± 0.07	0.01 ± 0.004	17.2^{ab} ± 2.6
Landfill											
B3/A	0.35 ± 0.01	0.065 ± 0.004	0.43 ± 0.09	3.1 ± 0.04	4.8 ± 0.07	0.069 ± 0.008	4.1 ± 0.08	3.7 ± 0.05	0.8 ± 0.09	0.009 ± 0.001	23 ± 0.24
B3/B	0.39 ± 0.01	0.072 ± 0.007	0.34 ± 0.07	3.7 ± 0.05	5 ± 0.05	0.069 ± 0.003	2.7 ± 0.05	3.4 ± 0.03	0.48 ± 0.07	0.012 ± 0.002	17.3 ± 0.34
B3/C	0.32 ± 0.03	0.062 ± 0.003	0.3 ± 0.05	3.3 ± 0.03	4.8 ± 0.06	0.078 ± 0.008	2.8 ± 0.03	3.2 ± 0.02	0.41 ± 0.06	0.007 ± 0.001	27.5 ± 0.29
B3/D	0.27 ± 0.02	0.048 ± 0.004	0.28 ± 0.06	2.1 ± 0.04	4.2 ± 0.05	0.061 ± 0.005	2.6 ± 0.04	1.7 ± 0.05	0.35 ± 0.05	0.008 ± 0.002	18.3 ± 0.27
B4/A	0.34 ± 0.03	0.075 ± 0.005	0.24 ± 0.06	1.8 ± 0.03	4.6 ± 0.03	0.095 ± 0.007	2.1 ± 0.06	2 ± 0.03	0.15 ± 0.02	0.01 ± 0.003	17 ± 0.25
B4/C	0.26 ± 0.01	0.067 ± 0.006	0.25 ± 0.07	2.3 ± 0.04	4.1 ± 0.06	0.078 ± 0.006	2.8 ± 0.06	2.5 ± 0.01	0.44 ± 0.06	0.011 ± 0.001	23.2 ± 0.26
Mean	0.32 ± 0.05	0.065^{ab} ± 0.009	0.31 ± 0.07	2.7^{ab} ± 0.75	4.6^{ab} ± 0.35	0.075 ± 0.012	2.9^{ab} ± 0.65	2.7^{ab} ± 0.83	0.44^{abc} ± 0.21	0.01 ± 0.002	21.1^{ab} ± 4.2

[a] Significant differences among the mean contents of heavy elements in rural, anthropic and landfill lichens compared to control ones ($p < 0.05$)

[b] Significant differences among the mean contents of heavy elements in anthropic and landfill lichens compared to rural ones ($p < 0.05$)

[c] Significant differences among the mean contents of heavy elements in landfill lichens compared to anthropic ones ($p < 0.05$)

Along the SW-NE transect As, Cd, Cr and Pb concentrations in topsoil decreased slightly, but not statistically significant ($p < 0.05$), with distance from the landfill.

The highest concentrations of Cd, Cu, Pb, Zn and the lowest of As, Co, Cr, Hg, Ni, Tl were found in topsoil samples collected near road SP13 (GS-3600) and Masrola quarry (GS-4300). The geochemical features of these soils were presumably influenced by the nature of the parent rock (marly-clay lithologies of the Marne di Antognola formation) and anthropogenic input from vehicle traffic and truck movements.

With regard to isopods, statistical analysis indicated: (1) no differences between heavy element concentrations in isopods collected close to Ginestreto MSWL and in sites along the SW-NE transect (Table 4); (2) no significant variation in heavy element concentrations in isopods with increasing distance from the landfill. Conversely, statistically significant positive correlations ($p < 0.05$) were found between Pb and Sb concentrations in *A. vulgare* specimens and those in living soils.

Lichens

The severe accumulation found for Cd, Cr, Pb, Sb and Zn in lichens transplanted within the Ginestreto MSWL suggested that these heavy elements were the main contaminants. It seems likely that these heavy elements were mostly associated with airborne particulate matter produced by landfilling activities, such as waste handling in batch G2 and re-suspension of dust from the landfill surface. The fact that the highest concentrations of Cd, Cr, Pb, Sb and Zn were measured in lichens exposed in G2 demonstrates that waste management operations increased production and dispersal of these contaminants.

Waste management is a source of particulate matter, the concentration and composition of which are influenced by mechanical and chemical factors. These includes: nature of the waste, characteristics of the soil used to stabilize the landfill surface, action of tipping and compaction of waste and meteorological conditions that in turn influence wind erosion, re-suspension and dispersion from landfill and road surfaces (Fitz and Bumiller 2000; Chalvatzaki et al. 2010; Han et al. 2011; Paoli et al. 2015). About composition, high contents of Cd, Cr, Cu, Ni, Pb and Zn were found in the particulate matter emitted by a municipal UK landfill (Koshy et al. 2009). Several studies (Prudent et al. 1996; Slack et al. 2004, 2005) indicated that these heavy metals are mainly associated with rubber, electronic equipment, plastics and non-ferrous metal accumulated in the municipal landfills.

Other authors revealed accumulation of Cd, Cr, Cu, Ni, Pb, Sb and Zn in lichens transplanted in some Italian municipal solid waste landfills (Paoli et al. 2012; Protano et al. 2014; Nannoni et al. 2015b). On the other hand,

Table 2 Mean values of EC ratio of *Evernia prunastri* lichens transplanted in the monitoring sites of the Ginestreto MSWL area and relative accumulation/loss (A/L) scale

Monitoring sites	As		Cd		Co		Cr		Cu		Hg		Ni		Pb		Sb		Tl		Zn	
Rural ($n = 14$)	1.09	N	1.23	N	1.18	N	1.38	A	1.36	A	1.04	N	1.07	N	1.43	A	1.49	A	0.92	N	1.54	A
Anthropic ($n = 12$)	1.22	N	2.15	SA	1.53	A	1.96	SA	1.52	A	1.19	N	1.37	A	1.94	SA	2.44	SA	1.13	N	1.80	SA
Landfill ($n = 6$)	1.20	N	2.32	SA	1.41	A	2.22	SA	1.50	A	1.19	N	1.48	A	2.18	SA	4.92	SA	1.06	N	2.17	SA

Accumulation/loss scale: *L* loss, *N* normal, *A* accumulation, *SA* severe accumulation

lichens are able to head off heavy elements from both wet depositions and airborne particles.

In the study area, high concentrations of Cd, Cr, Pb, Sb and Zn were also accumulated by lichens transplanted in anthropic sites, presumably due to input from: (1) vehicle traffic; (2) activities collateral to landfill management, such as truck emissions and suspension of dust from the road surface; (3) activities of Masrola quarry. On this question, the moderate to severe accumulation of Cd, Cr, Pb, Sb and Zn in lichens transplanted near the roads SP13 and SP30 (cells A1, A2, A3, A4, B1, C1, D1 and E1) was attributed to vehicle circulation, by virtue of co-occurrence of these heavy elements traditionally linked to traffic contamination. The contribution of vehicle traffic to levels of Cd, Cr, Pb, Sb and Zn in urban areas is well known and recognized in various studies (e.g. Madrid et al. 2002; Manta et al. 2002; Imperato et al. 2003; Bretzel and Calderisi 2006).

Enrichments in Cd, Cr, Pb, Sb and Zn also occurred in lichens transplanted close to the landfill access road, constantly used by trucks (cells D2 and C3). This finding is mainly related to the movement and emissions of trucks (e.g. diesel exhaust fumes, tyre wear dust and brake wear dust) transporting waste materials over unpaved roads and previously deposited waste and suspension of dust from the road surface.

Among the anthropic sites, the highest accumulation levels of various heavy elements (As, Cd, Co, Cr, Cu, Ni, Tl and Zn) were found in lichens transplanted near the entrance to Masrola quarry (sample E1; Fig. 1a). Again, heavy element enrichment in exposed lichens can be attributed to truck emissions and dust raised by their passage.

As a whole, there were no significant differences between the concentrations of heavy elements in lichens transplanted in the landfill and anthropic sites (except for Sb). This result testifies that landfill activities and vehicle/truck circulation both contributed to atmospheric emissions of certain heavy elements in the study area.

The moderate accumulation of Cr, Pb, Sb and Zn in lichens exposed in rural monitoring sites is evidence of wide distribution of these heavy elements in the study area, while Cu accumulation was probably due to agricultural pesticides and fertilizers.

Lastly, As, Co, Hg, Ni and Tl indicate prevalently natural (geogenic) origin in the study area, as they did not usually accumulate in lichens exposed in the monitoring sites.

Soils and isopods

The analytical data of this research indicate that the 25-year activity of the Ginestreto MSWL has had a low impact on levels of heavy elements in topsoil of the study area. In fact, the concentrations of all heavy elements analysed in topsoil samples were: (1) comparable to the respective contents in uncontaminated soils formed by clayey and carbonate sedimentary rocks (Reimann and de Caritat 1998; Kabata-Pendias 2001); (2) constantly below the contamination thresholds for green public, private and residential areas set by the Italian guidelines (Italian Legislative Decree no. 152/2006; Table 3). Only Zn concentration in sample GS-4300 (156 mg/kg) collected near Masrola quarry was slightly above the contamination threshold of 150 mg/kg.

Among the heavy elements analysed, only Cd, Cr, Pb, Sb and Zn showed higher contents in topsoils collected close the Ginestreto MSWL and a slight, albeit non-significant, decrease in concentrations with increasing distance from the landfill (expect Zn). These findings are in line with the data of transplanted lichens and confirm that Cd, Cr, Pb, Sb and Zn are the main airborne contaminants of Ginestreto landfill. The results also suggest that dispersal of these contaminants from landfill is affected by meteorological conditions, such as prevailing winds.

In agreement with the results of this research, several studies found no accumulation of heavy elements in soils close to municipal waste dumpsites (Jain et al. 2005; Amadi and Nwankwoala 2013; Nannoni et al. 2015a).

Among the heavy elements analysed, only Pb and Sb, reported as contaminants of the Ginestreto MSWL, showed a significant correlation between their concentrations in soil and isopods. For the other heavy elements, the lack of correlation was presumably due to: (1) the fact that isopod *A. vulgare* can regulate its assimilation and uptake of Cd, Cu and Zn (e.g. Hopkin and Martin 1982; Zidar et al. 2003; Odendaal and Reinecke 2004b); (2) the geochemical

Table 3 Concentrations and mean values of heavy elements (data expressed as mg/kg dry weight ± SD) in topsoil samples collected close the Ginestreto landfill and at variable distances along a SW-NE transect

Soil sites	As	Cd	Co	Cr	Cu	Hg	Ni	Pb	Sb	Tl	Zn
Landfill											
GS-1a	6 ± 0.24	0.22 ± 0.04	11 ± 0.04	104 ± 1.8	28.2 ± 0.84	0.028 ± 0.023	54.5 ± 0.52	9.7 ± 0.3	0.32 ± 0.02	0.31 ± 0.005	89.2 ± 2.5
GS-1b	5.1 ± 0.14	0.38 ± 0.02	9.3 ± 0.24	109 ± 2	14.4 ± 0.26	0.026 ± 0.02	48.3 ± 0.56	25.6 ± 0.26	1.3 ± 0.02	0.24 ± 0.004	73.2 ± 1.7
GS-1c	5.6 ± 0.35	0.32 ± 0.04	11.8 ± 0.18	69.9 ± 1.6	27.9 ± 0.51	0.03 ± 0.02	56.7 ± 1.2	18.8 ± 0.21	1.1 ± 0.06	0.23 ± 0.007	102 ± 1.5
GS-1d	5.2 ± 0.19	0.22 ± 0.03	10.9 ± 0.1	93.3 ± 1.4	31.1 ± 0.52	0.032 ± 0.021	51.8 ± 0.72	10.0 ± 0.25	0.33 ± 0.02	0.31 ± 0.007	82.7 ± 1.1
GS-2a	5 ± 0.23	0.44 ± 0.02	10.4 ± 0.33	83.6 ± 1.3	21.7 ± 0.28	0.029 ± 0.018	49.7 ± 0.63	28.4 ± 0.14	1.3 ± 0.03	0.31 ± 0.008	78.7 ± 1.6
GS-2b	6.2 ± 0.15	0.22 ± 0.04	11.8 ± 0.12	86.5 ± 1.9	29.1 ± 0.21	0.033 ± 0.023	63.9 ± 0.55	34 ± 0.18	0.9 ± 0.04	0.28 ± 0.009	99.1 ± 1.4
GS-2c	6 ± 0.23	0.38 ± 0.04	11.1 ± 0.1	89.7 ± 1	22.2 ± 0.16	0.035 ± 0.014	53.9 ± 0.52	30.5 ± 0.1	1 ± 0.02	0.31 ± 0.007	81.9 ± 1.8
GS-2d	5.9 ± 0.18	0.32 ± 0.05	13.1 ± 0.28	82.9 ± 1.5	29.3 ± 0.41	0.031 ± 0.021	59.8 ± 1.1	24.3 ± 0.18	0.99 ± 0.02	0.38 ± 0.011	91 ± 1.8
Mean	5.6 ± 0.47	0.31* ± 0.08	11.2 ± 1.1	89.9* ± 12.4	25.5 ± 5.6	0.031 ± 0.003	54.8 ± 5.2	22.7* ± 9.1	0.9* ± 0.38	0.3 ± 0.047	87.2* ± 9.9
Transect											
GS-200	6.6 ± 0.15	0.26 ± 0.03	12.7 ± 0.26	88.9 ± 0.93	42.8 ± 0.47	0.012 ± 0.002	57.5 ± 0.94	19.2 ± 0.29	0.48 ± 0.017	0.4 ± 0.009	90.8 ± 1.1
GS-400	6.6 ± 0.14	0.27 ± 0.02	12.3 ± 0.18	75.6 ± 0.92	49.9 ± 0.45	0.027 ± 0.009	56.8 ± 1	23.2 ± 0.25	0.71 ± 0.024	0.38 ± 0.006	69 ± 0.95
GS-800	5.4 ± 0.07	0.29 ± 0.04	12.9 ± 0.12	79.9 ± 1.3	32.8 ± 0.54	0.049 ± 0.019	65.9 ± 0.64	18.8 ± 0.11	0.72 ± 0.082	0.29 ± 0.011	70.6 ± 1.4
GS-1500	6.3 ± 0.25	0.17 ± 0.02	10 ± 0.2	74 ± 0.85	21.5 ± 0.34	0.026 ± 0.013	56.2 ± 0.62	8.8 ± 0.14	0.72 ± 0.053	0.23 ± 0.008	68.4 ± 0.53
GS-2100	5.7 ± 0.13	0.21 ± 0.05	11.9 ± 0.12	76.1 ± 1.1	29.0 ± 0.71	0.045 ± 0.012	72.7 ± 1.3	11.1 ± 0.05	0.48 ± 0.037	0.25 ± 0.005	73.9 ± 1.5
GS-2500	4 ± 0.17	0.11 ± 0.05	9.9 ± 0.14	44 ± 0.45	21.2 ± 0.36	0.015 ± 0.005	55.2 ± 1	7.5 ± 0.13	0.7 ± 0.053	0.27 ± 0.006	79.1 ± 1.5
GS-3200	5.6 ± 0.41	0.28 ± 0.06	12.8 ± 0.23	83.1 ± 1.2	28.7 ± 0.3	0.013 ± 0.005	53.4 ± 0.98	11.6 ± 0.1	1 ± 0.029	0.26 ± 0.009	85.5 ± 0.77
GS-3400	2.8 ± 0.17	0.12 ± 0.04	8.4 ± 0.22	38.9 ± 0.66	25 ± 0.44	0.039 ± 0.013	31.8 ± 0.76	6.6 ± 0.08	0.31 ± 0.045	0.21 ± 0.008	83.9 ± 0.56
Mean	5.4 ± 1.3	0.21* ± 0.07	11.3 ± 1.7	70.1* ± 18.3	31.3 ± 10.2	0.028 ± 0.015	56.2 ± 11.8	13.4* ± 6.2	0.65* ± 0.22	0.29 ± 0.069	77.6* ± 8.4
Other											
GS-3600	2.4 ± 0.14	0.5 ± 0.05	5.6 ± 0.14	25.4 ± 0.53	51.4 ± 0.43	0.009 ± 0.003	31.9 ± 0.62	12 ± 0.13	0.91 ± 0.03	0.27 ± 0.012	90 ± 0.75
GS-4300	2 ± 0.19	0.59 ± 0.07	6.7 ± 0.09	12.5 ± 0.3	33.3 ± 0.23	0.005 ± 0.001	45.9 ± 1.1	50.8 ± 0.25	1.2 ± 0.028	0.17 ± 0.007	156 ± 1.5
Contamination threshold in soils for public, private and residential green areas (Italian Legislative Decree no. 152/2006)											
	20	2	20	150	120	1	120	100	10	1	150

* Significant differences among the mean contents of heavy elements in isopods collected in landfill sites and along the transect ($p < 0.05$)

Table 4 Concentrations and mean values of heavy elements (data expressed as mg/kg dry weight ± SD) in specimens of *Armadillidium vulgare* collected close the Ginestreto landfill and at variable distances along a SW-NE transect (*n* = number of isopods per site)

Isopod sites	*n*	As	Cd	Co	Cr	Cu	Hg	Ni	Pb	Sb	Tl	Zn
Landfill												
GS-1d	10	0.77 ± 0.02	0.26 ± 0.01	1 ± 0.01	1.9 ± 0.03	202 ± 1.8	0.071 ± 0.007	8.5 ± 0.19	0.73 ± 0.01	0.023 ± 0.003	<0.001	104 ± 1.2
GS-2d	10	1 ± 0.02	0.22 ± 0.01	1 ± 0.01	2.8 ± 0.04	155 ± 1.1	0.068 ± 0.01	8.2 ± 0.15	1.1 ± 0.03	0.048 ± 0.002	<0.001	107 ± 1.1
GS-2c	10	0.36 ± 0.05	0.18 ± 0.02	0.87 ± 0.03	0.87 ± 0.04	262 ± 1.6	0.08 ± 0.009	7 ± 0.13	1.3 ± 0.01	0.045 ± 0.002	<0.001	113 ± 0.6
Mean		0.71 ± 0.33	0.22 ± 0.04	0.97 ± 0.09	1.9 ± 0.97	207 ± 53.4	0.073 ± 0.006	7.9 ± 0.78	1.1 ± 0.3	0.039 ± 0.014	108 ± 4.7	
Transect												
GS-200	10	0.88 ± 0.03	0.18 ± 0.03	1.1 ± 0.05	2.3 ± 0.04	241 ± 2	0.064 ± 0.005	9.1 ± 0.29	1.2 ± 0.02	0.038 ± 0.005	0.004 ± 0.001	106 ± 0.94
GS-400	10	0.37 ± 0.06	0.15 ± 0.02	0.71 ± 0.03	0.87 ± 0.05	225 ± 2.4	0.11 ± 0.021	10.2 ± 0.29	1.1 ± 0.01	0.035 ± 0.003	0.005 ± 0.002	127 ± 1.2
GS-800	10	0.96 ± 0.04	0.23 ± 0.04	1.3 ± 0.01	3.1 ± 0.04	220 ± 1.3	0.055 ± 0.008	9.7 ± 0.25	1.1 ± 0.01	0.032 ± 0.003	0.005 ± 0.002	140 ± 2
GS-1300	10	0.78 ± 0.04	0.49 ± 0.02	0.95 ± 0.01	1.9 ± 0.03	152 ± 1.5	0.046 ± 0.008	10.6 ± 0.35	0.85 ± 0.02	0.039 ± 0.005	<0.001	99 ± 0.64
GS-1500	10	0.73 ± 0.02	0.2 ± 0.01	0.95 ± 0.02	1.7 ± 0.07	153 ± 1.8	0.045 ± 0.008	11 ± 0.21	1 ± 0.03	0.03 ± 0.003	<0.001	94.4 ± 0.78
GS-3000	10	0.84 ± 0.06	0.3 ± 0.04	0.92 ± 0.03	2.1 ± 0.04	102 ± 1	0.005 ± 0.001	11.4 ± 0.43	0.79 ± 0.02	0.031 ± 0.005	<0.001	101 ± 0.79
GS-2100	10	0.79 ± 0.03	0.18 ± 0.01	1.1 ± 0.01	2.4 ± 0.03	281 ± 3.4	0.093 ± 0.008	8.8 ± 0.2	0.97 ± 0.02	0.024 ± 0.003	<0.001	190 ± 1.6
GS-2500	10	0.61 ± 0.02	0.28 ± 0.01	1.2 ± 0.01	1.1 ± 0.01	158 ± 1.3	0.037 ± 0.007	7.5 ± 0.12	0.79 ± 0.01	0.017 ± 0.002	<0.001	111 ± 1
GS-3200	10	0.83 ± 0.04	0.3 ± 0.02	1.2 ± 0.01	2.4 ± 0.02	197 ± 1.5	0.058 ± 0.013	7.7 ± 0.22	0.91 ± 0.01	0.03 ± 0.002	<0.001	140 ± 1.3
GS-3400	10	0.82 ± 0.06	0.25 ± 0.03	0.85 ± 0.02	1.6 ± 0.06	101 ± 1.3	0.021 ± 0.009	9.5 ± 0.11	0.73 ± 0.01	0.015 ± 0.001	<0.001	94.7 ± 0.67
Mean		0.76 ± 0.17	0.26 ± 0.1	1 ± 0.17	1.9 ± 0.66	183 ± 59.6	0.053 ± 0.031	9.5 ± 1.3	0.94 ± 0.16	0.029 ± 0.008	0.005 ± 0.001	120 ± 30
Other												
GS-3600	10	0.69 ± 0.02	0.39 ± 0.02	1.1 ± 0.01	2.3 ± 0.03	330 ± 4.5	0.065 ± 0.01	9.4 ± 0.27	0.84 ± 0.01	0.023 ± 0.003	<0.001	183 ± 1.2
GS-4300	10	0.66 ± 0.03	0.15 ± 0.04	1.3 ± 0.02	1.5 ± 0.03	149 ± 1.8	0.058 ± 0.006	9.4 ± 0.33	1 ± 0.02	0.053 ± 0.002	<0.001	151 ± 1.7

uniformity of As, Co, Hg, Ni and Tl in the surface environment (air and soil) of the study area. As regards the first point, Cu and Zn are essential elements for isopods; their storage and excretion depend on physiological requirements and excess avoidance in contaminated soils (Witzel 2000; Zödl and Wittmann 2003; Gál et al. 2008). Moreover, some authors (e.g. Hopkin 1990; Hames and Hopkin 1991) reported that Isopoda even have regulation mechanisms for Cd, although demonstrations of the ability of these organisms to eliminate this element have so far been contradictory.

Conclusion

The results of this study show that the Ginestreto municipal solid waste landfill has little influence on heavy element levels in the surrounding environment, restricted to about 100 m from the landfill boundary.

Accumulation in *Evernia prunastri* transplanted for 4 months within and around the landfill revealed that: (1) airborne emissions from the landfill affected air concentrations of heavy elements in lichens within the landfill mainly for Cd, Cr, Pb, Sb and Zn; (2) landfill activities and other anthropic sources, such as vehicle traffic and truck movements, likewise contributed to the air levels of heavy elements in the study area.

The fallout of particulate-bound heavy elements had little influence on their enrichment in topsoil. This finding is probably due to limited and discontinuous release of these contaminants from the landfill and erosion and leaching processes occurring at the top of the soil profile. Likewise, there was no variation in heavy element accumulation in isopods in relation to distance from the landfill. This finding presumably reflects the rather uniform concentrations of heavy elements in topsoils of the study area, as well as physiological mechanisms of regulation and excretion of isopods for some heavy elements.

The multi-matrix environmental monitoring conducted around the Ginestreto landfill highlighted the sensitivity of transplanted lichens to air levels of heavy elements from landfill emissions.

Finally, the results of this study suggest that sustainable and appropriate landfilling management, as in the case of Ginestreto landfill, is associated with low environmental risk due to heavy element contamination.

References

Amadi AN, Nwankwoala HO (2013) Evaluation of heavy metal in soils from Enyimba dumpsite in Aba, southeastern Nigeria using contamination factor and geo-accumulation index. Energy Environ Res 3:125–134

Ayrault S, Clochiatti R, Carrot F, Daudin L, Bennett JP (2007) Factors to consider for trace element deposition biomonitoring surveys with lichen transplants. Sci Total Environ 372:717–727

Barbieri M, Sappa M, Vitale S, Parisse B, Battistel M (2014) Soil control of trace metals concentrations in landfills: a case study of the largest landfill in Europe, Malagrotta, Rome. J Geochem Explor 143:146–154

Bargagli R (1998) Trace elements in terrestrial plants: An ecophysiological approach to biomonitoring and biorecovery. Springer, Heidelberg

Bennett JP, Wetmore CM (1999) Changes in element contents of selected lichens over 11-years in northern Minnesota, USA. Environ Exp Bot 41:75–82

Bennett JP, Wetmore CM (2000) 16-Years trends in elements of lichens at Theodore Roosevelt National Park, North Dakota. Sci Total Environ 263:231–241

Bettinelli M, Spezia S, Bizzarri G (1996) Trace element determination in lichens by ICP-MS. At Spectrosc 17:133–141

Bretzel F, Calderisi M (2006) Metal contamination in urban soils of coastal Tuscany (Italy). Environ Monit Assess 118:319–335

Chalvatzaki E, Kopanakis I, Kontaksakis M, Glytos T, Kalogerakis N, Lazaridis M (2010) Measurements of particulate matter concentrations at a landfill site (Crete, Greece). Waste Manag 30:2058–2064

Chuan MC, Shu GY, Liu JC (1995) Solubility of heavy metals in a contaminated soil: effects of redox potential and pH. Water Air Soil Pollut 90(543):556

Conti ME, Cecchetti G (2001) Biological monitoring: lichens as bioindicators of air pollution assessment—a review. Environ Pollut 114:471–492

Conti ME, Tudino M, Stripeikis J, Cecchetti G (2004) Heavy metal accumulation in the lichen *Evernia prunastri* transplanted at urban, rural and industrial sites in Central Italy. J Atmos Chem 49:83–94

Dallinger R, Prosi F (1988) Heavy metals in terrestrial isopod *Porcellio scaber* Latr. II. Subcellular fractionation of metal accumulating lysosomes from hepatopancreas. Cell Biol Toxicol 4:97–109

Fitz DR, Bumiller K (2000) Evaluation of watering to control dust in high winds. J Air Waste Manag Assoc 50:570–577

Frati L, Brunialti G, Loppi S (2005) Problems related to lichen transplants to monitor trace element deposition in repeated surveys: a case study from Central Italy. J Atmos Chem 52:221–230

Gál J, Markiewicz-Patkowska J, Hursthouse A, Tatner P (2008) Metal uptake by woodlice in urban soils. Ecotoxicol Environ Saf 69:139–149

Garty J, Weissman L, Cohen Y, Karnieli A, Orlovsky L (2001) Transplanted lichens in and around the Mount Carmel National Park and the Haifa Bay industrial region in Israel: physiological and chemical responses. Environ Res Sect 85:159–176

Godinho RM, Wolterbeek H, Verburg T, Freitas MC (2008) Bioaccumulation behaviour of transplants of the lichen *Flavoparmelia caperata* in relation to total deposition at a polluted location in Portugal. Environ Pollut 151:318–325

Guttova A, Lackovicova A, Pisut I, Pisut P (2011) Decrease in air pollution load in urban environment of Bratislava (Slovakia) inferred from accumulation of metal elements in lichens. Environ Monit Assess 182:361–373

Hames CAC, Hopkin SP (1991) Assimilation and loss of 109Cd and 65Zn by the terrestrial isopods *Oniscus asellus* and *Porcellio scaber*. Bull Environ Contam Toxicol 47:440–447

Han S, Youn JS, Jung YW (2011) Characterization of PM_{10} and $PM_{2.5}$ source profiles for resuspended road dust collected using mobile sampling methodology. Atmos Environ 45:3343–3351

Harmsen J (2007) Measuring bioavailability: from a scientific approach to standard methods. J Environ Qual 36:1420–1428

Hopkin SP (1990) Species specific differences in the net assimilation of zinc, cadmium, lead, copper and iron by the terrestrial isopods *Oniscus asellus* and *Porcellio scaber*. J Appl Ecol 27:460–474

Hopkin SP, Martin MH (1982) The distribution of zinc, cadmium, lead and copper within the woodlouse *Oniscus asellus* (Crustacea, Isopoda). Oecologia 54:227–232

ILD (2003) Italian Legislative Decree n° 36, January 13, 2003, Implementation of Directive 1999/31/EC on the waste landfill, Official Italian Gazette n° 59, March 12, 2003 **(in Italian)**

ILD (2006) Italian Legislative Decree n° 152, April 3, 2006 and Subsequent Amendments, Environmental Regulations, Official Italian Gazette n° 88, April 14, 2006 **(in Italian)**

Imperato M, Adamo P, Naimo D, Arienzo M, Stanzione D, Violante P (2003) Spatial distribution of heavy metals in urban soils of Naples city (Italy). Environ Pollut 124:247–256

Jain P, Kim H, Townsend TG (2005) Heavy metal content in soil reclaimed from a municipal solid waste landfill. Waste Manag 25:25–35

Kabata-Pendias A (2001) Trace elements in soils and plants. CRC Press, Boca Raton, p 413

Koshy L, Jones T, Berube K (2009) Characterization and bioreactivity of respirable airborne particles from a municipal landfill. Biomarkers 14:49–53

Loppi S, Frati L (2006) Lichen diversity and lichen transplants as monitors of air pollution in a rural area of central Italy. Environ Monit Assess 114:361–375

Loppi S, Giovannelli L, Pirintsos SA, Putortì E, Corsini A (1997) Lichens as bioindicators of recent changes in air quality (Montecatini Terme, Italy). Ecol Mediterr 23:53–56

Madrid L, Diaz-Barientos E, Madrid F (2002) Distribution of heavy metal content of urban soils in parks of Seville. Chemosphere 49:1301–1308

Manta DS, Angelone M, Bellanca A, Neri R, Sprovieria M (2002) Heavy metals in urban soils: a case study from the city of Palermo (Sicily), Italy. Sci Total Environ 300:229–243

Mikhailova I (2002) Transplanted lichens for bioaccumulation studies. In: Nimis PL, Scheidegger C, Wolseley PA (eds) Monitoring with lichens—monitoring lichens. Kluwer Academy Publishers, Berlin, pp 301–304

Mitchell B (2002) Resource and environmental management, 2nd edn. Prentice Hall, Harlow, p 367

Nannoni F, Santolini R, Protano G (2015a) Heavy element accumulation in *Evernia prunastri* lichen transplants around a municipal solid waste landfill in central Italy. Waste Manag 43:253–362

Nannoni F, Mazzeo R, Protano G, Santolini R (2015b) Bioaccumulation of heavy elements by *Armadillidium vulgare* (Crustacea, Isopoda) exposed to fallout of a municipal solid waste landfill. Ecol Ind 49:24–31

Nimis PL, Scheidegger C, Wolseley PA (2002) Monitoring with lichens—monitoring lichens. Kluwer Academic Publishers, Berlin

Odendaal JP, Reinecke AL (2004a) Bioaccumulation of cadmium and zinc, and field validation of a histological biomarker in terrestrial isopods. Bull Environ Contam Toxicol 72:769–776

Odendaal JP, Reinecke AJ (2004b) Effect of metal mixture (Cd and Zn) on body weight in terrestrial isopods. Arch Environ Contam Toxicol 46:377–384

Pacheco AMG, Freitas MC, Baptista MS, Vasconcelos MTSD, Cabral JP (2008) Elemental levels in tree-bark and epiphytic-lichen transplants at a mixed environmental in mainland Portugal, and comparisons with an in situ lichen. Environ Pollut 151:326–333

Paoletti MG, Hassall M (1999) Woodlice (Isopoda Oniscidea): their potential for assessing sustainability and use as bioindicators. Agr Ecosyst Environ 74:157–166

Paoli L, Pisani T, Guttová A, Sardella G, Loppi S (2011) Physiological and chemical response of lichens transplanted in and around an industrial area of south Italy: relationship with the lichen diversity. Ecotoxicol Environ Saf 74:650–657

Paoli L, Corsini A, Bigagli V, Tannini J, Bruscoli C, Loppi S (2012) Long-term biological monitoring of environmental quality around a solid waste landfill assessed with lichens. Environ Pollut 161:70–75

Paoli L, Grassi A, Vannini A, Maslaňáková I, Bil'ová I, Bačkor M, Corsini A, Loppi S (2015) Epiphytic lichens as indicators of environmental quality around a municipal solid waste landfill (C Italy). Waste Manag 42:67–73

Peijnenburg WJGM (2002) Bioavailability of metals to soil invertebrates. In: Allen HE (ed) Bioavailability of metals in terrestrial ecosystems: importance of partitioning for bioavailability to invertebrates, microbes, and plants. SETAC, Pensacola, USA, pp 89–112

Protano C, Guidotti M, Owczarek M, Fantozzi L, Blasi G, Vitali M (2014) Polycyclic aromatic hydrocarbons and metals in transplanted lichen (*Pseudovernia furfuracea*) at sites adjacent to a solid-waste landfill in central Italy. Arch Environ Contam Toxicol 66:471–481

Prudent P, Domeizel M, Massiani C (1996) Chemical sequential extraction as decision-making tool: application to municipal solid waste and its individual constituents. Sci Total Environ 178:55–61

Reimann C, de Caritat P (1998) Chemical elements in the environment. Springer, Berlin, p 397

Slack RJ, Gronow JR, Voulvoulis N (2004) Hazardous components of household waste. Crit Rev Environ Sci Technol 34:419–445

Slack RJ, Gronow JR, Voulvoulis N (2005) Household hazardous waste in municipal landfills: contaminants in leachate. Sci Total Environ 337:119–137

Sloof JE (1995) Lichens as quantitative biomonitors for atmospheric trace-element deposition, using transplants. Atmos Environ 29:11–20

Vijver MG, Vink JPM, Jager T, Van Straalen NM, Wolterbeek HT, Van Gestel CAM (2006) Kinetics of Zn and Cd accumulation in the isopod Porcellio scaber exposed to contaminated soil and/or food. Soil Biol Biochem 38:1554–1563

Violante A, Cozzolino V, Perelomov L, Caporale AG, Pigna M (2010) Mobility and bioavailability of heavy metals and metalloids in soil environments. J Soil Sci Plant Nutr 10:268–292

Wiersma GB (2004) Environmental monitoring. CRC Press, Boca Raton, p 792

Witzel B (1998) Uptake, storage and loss of cadmium and lead in the woodlouse *Porcellio scaber* (Crustacea, Isopoda). Water Air Soil Pollut 108:51–68

Witzel B (2000) The influence of zinc on the uptake and loss of cadmium and lead in the woodlouse *Porcellio scaber* (Isopoda, Oniscidea). Ecotoxicol Environ Saf 47:43–53

Wolterbeek B (2002) Biomonitoring of trace element air pollution: principles, possibilities and perspectives. Environ Pollut 120:11–21

Zidar P, Drobne D, Strus J, Blejec A (2003) Intake and assimilation of zinc, copper, and cadmium in the terrestrial isopod *Porcellio scaber* Latr. (Crustacea, Isopoda). Bull Environ Contam Toxicol 70:1028–1035

Zödl B, Wittmann KJ (2003) Effects of sampling, preparation and defecation on metal concentrations in selected invertebrates at urban sites. Chemosphere 52:1095–1103