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# **The Complex Nature of Pollution in the Capping Soils of Closed Landfills: Case Study in a Mediterranean Setting**

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Additional information is available at the end of the chapter

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## **1. Introduction**

### **1.1. Waste landfills capped with soil**

In most developed countries there is serious concern about the state of waste landfills that were closed towards the end of the past century. Economic growth and urban development during this period generated vast amounts of domestic and industrial waste, and this waste was deposited in landfills without its separation or prior treatment. Today, countries with emerging economies or countries in settings of poverty are facing a similar situation, whereby the uncontrolled disposal of waste has led to regions with worryingly high levels of pollutants that affect the atmosphere, soil and water resources.

In the Mediterranean setting, most landfills have been sealed simply by capping with soil from the surroundings. This soil has given rise to a plant cover emerging from the existing seed bank. Besides recovering the visual impacts on the landscape of mountains of rubbish, a plant cover will avoid the spread of pollutants to other ecosystems once the landfill has been closed. However, the implantation of such a cover is conditioned by interactions among several factors, which are responsible for the complex nature of soil pollution affecting closed landfills.

In the literature, there is a lack of work related to pollution of the capping soils of closed landfills. Bibliography concerning landfills is mostly focused on leachates and their effect on water. In case of soil-related works, they were not accomplished in Mediterranean environment. Specially, quantitative data of landfill soil pollution and its possible effects on colonizing plant population is not available.

For all these reasons, the purposes of this chapter are: i) to describe the profile of solid waste landfills sealed with soil in the Mediterranean setting; ii) to focus on the study of a given case in order to present a research methodology that can be used in other scenarios with a similar problem. In the sections detailing this case study, we describe the methods and techniques employed for studying landfill's remediation and discuss the data obtained to give an overview of the topic examined.

## 2. Profile of solid waste landfills in the Mediterranean region

Numerous waste tips in the central Iberian Peninsula capped with soil over the 1980s and 90s have been widely described from an interdisciplinary perspective in [1]. Research efforts have focused on the pollutants present in the soils used to seal 20 of these landfills and on factors inducing the spread of pollutants. These studies have been aimed at designing measures to remediate the visual impacts of solid waste landfills (Figure 1).

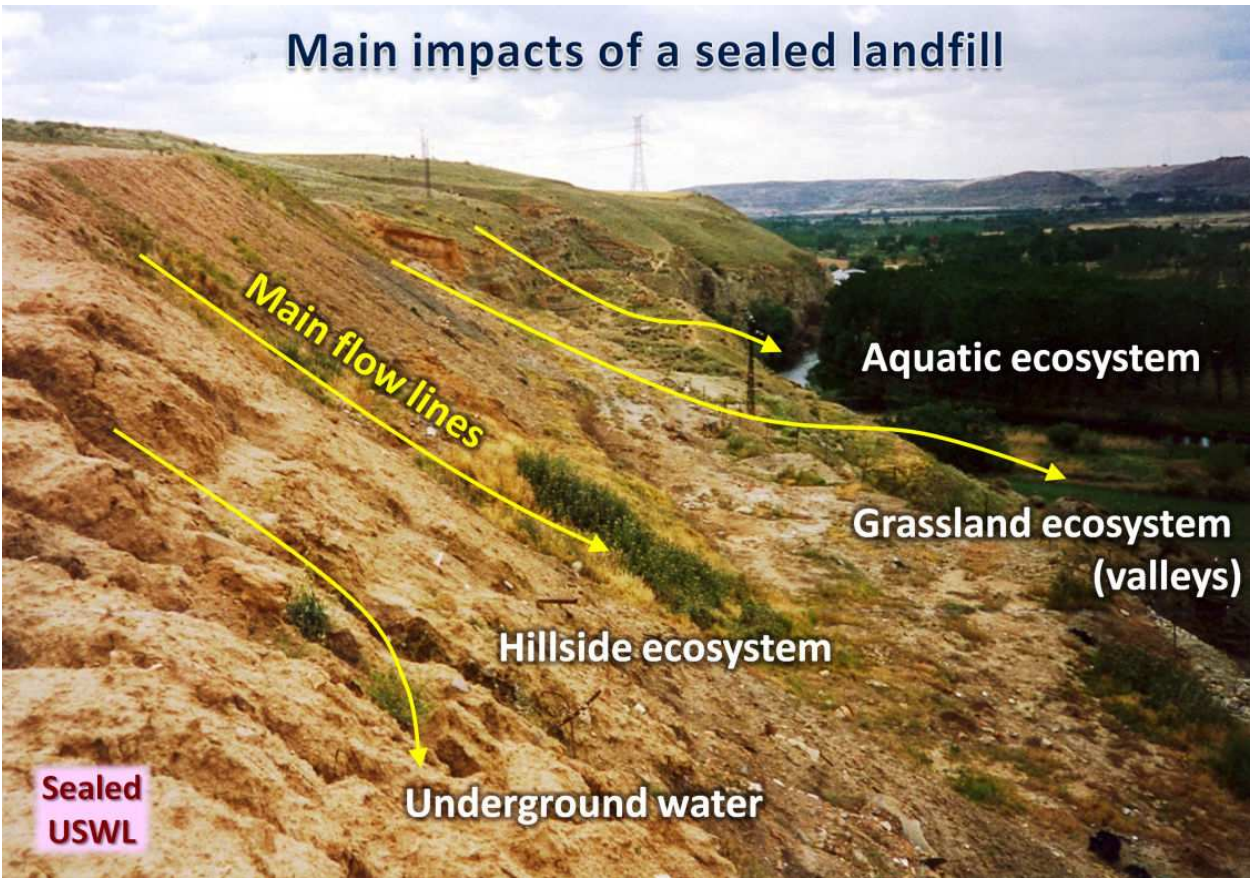


Figure 1. Based on [7]

The figure shows the main impacts (not only visual) produced by a landfill sealed with soil. The most important impact is pollution produced by surface and deep leachates of polluting

substances generated by surface run off and rainwater infiltration [2-6]. This type of pollution especially affects ecosystems in the main areas of leachates discharge i.e., the foots of landfill slopes grazed by domestic and wild animals [5]. Effects are nevertheless also produced on crops, particularly cereals such as barley, which are sometimes grown on the landfill itself (usually on its platforms). We have noted that this cereal accumulates heavy metals (unpublished data). In addition, soil pollution may spread to nearby rivers, on which these mountains of waste seem to hang, or to streams, which transport pollutants to areas beyond the landfill.

Table 1 summarizes the main plant communities detected at the 20 landfill sites examined, along with a summary of their main characteristics according to [8]. Despite the 20 years passed since the landfills were closed, plant cover generally lacks a bush stratum. Existing communities are those classified as ruderals and nitrophiles with a dominance of annual species whose life cycle is typical of the Mediterranean region. Many of these landfills still show large expanses of soil unable to sustain plant growth while other areas boast good plant cover, though with a low diversity. In general, all landfill sites are grazed by itinerant herds of sheep.

Phytosociological class	Main characteristics
9. ISOETO-NANOJUNCETEA Br.-Bl. & Tüxen ex Westhoff, Dijk & Passchier 1946	Pionner annual and dwarf perennial ephemeral isoetid communities on periodically flooded bare soils
12. PHRAGMITO-MAGNOCARICETAE Klika in Klika & V. Novák 1941	Swampy, fenny, lacustrine and riverine helophyte communities dominated by perennial graminoids, sedges, forbs and herbs of fresh and brackish waters
20. JUNCETEA MARITIMI Br.-Bl. in Br.-Bl. Roussine & Nègre 1952	Perennial grasslands growing on coastal and inland temporary wet or inundated salt marshes
34. ARTEMISIETEA VULGARIS Lohmeyer, Preising & Tüxen ex von Rochow 1951	Perennial and tall biennial forbs, grasses and thistle pioneer ruderal and nitrophilous sunny communities growing on rich soils.
37. PEGANO-SALSOLETEA Br.-Bl. & O. Bolós 1958	Nitrophilous or halo-nitrophilous dwarf scrub communities, including anthropogenic alloctonous shrubby vegetation
38. POLYGONO-POETEA ANNUAE Rivas Martinez 1975	Annual pioneer ephemeral and exceptionally small creeping perennial nitrophilous anthropozoogenic heavy trodden communities of urban and rural paths
39. STELLARIETEA MEDIAE Tüxen, Lohmeyer & Preising ex von Rochow 1951.	Annual ephemeral weeds, ruderal, nitrophilous and semi-nitrophilous communities
39A. Stellarienea mediae	-Cultivated field weed communities
39B. Chenopodio-Stellarienea Rivas Goday 1956	-Ruderal, nitrophilous and seminitrophilous communities.
39e. Thero-Brometalia (Rivas Goday&Rivas Martinez-Subnitrophilous Mediterranean annual ephemeral grassland-like ex Esteve 1973) O. Bolós 1975	spring blooming communities.
39f. Sisymbrietalia officinalis J. Tüxen in Lohmeyer & al. 1962 em. Rivas-Martinez, Fernández-González & Loidi 1991	Nitrophilous and temperate annual ephemeral grassland-like. Path, roadside and rural often trampled communities

Phytosociological class	Main characteristics
40. GALIO-URTICETEA Passarge ex Kopecký	Perennial hemycryptophyte and climbing tall herbs of nitrified wood fringes and other semi-shaded anthropogenic biotope communities.
41. CARDAMINO HIRSUTAE-GERANIETEA PURPUREI (Rivas-Martínez, Fernández-González & Loidi 1999) Rivas-Martínez, Fernández-González & Loidi classis nova, stat. Nov.	Annual spring and summer ephemeral internal and external shrub fringes slightly nitrified semi-shaded communities, growing on rich organic nutrient soils.
43. TRIFOLIO-GERANIETEA Müller 1962	Semi-shaded perennial herb communities of scarce moisture external fringe woodlands. Calcareous or mesoeutrophic rich soils in temperate submediterranean central Iberian territories.
50. TUBERARIETEA GUTTATAE (Br.-Bl. in Br.-Bl., Roussine & Nègre 1952) Rivas Goday & Rivas Martínez 1963 nom. mut. Propos.	Therophytic grasslands. Pioneer spring and early summer ephemeral plant acidophilous or calcifugous communities, dominated by non nitrophilous annual short herbs and grasses, but localized only in dry or initial soils, mostly in submediterranean or step territories.
51. FESTUCO-BROMETEA Br.-Bl. & Tüxen ex Br.-Bl. 1949	Perennial xerophytic and mesophytic grasslands. Anthropogenic grazed baso-neutrophilous or slightly acidophilous mesophytic or slightly xerophytic nutrient rich-pastures largely covered by perennial grasses.
54. POETEA BULBOSAE Rivas Goday & Rivas Martínez in Rivas-Martinez 1978	Western Mediterranean oceanic thermo- to supramediterranean upper semiarid to humid pastures, grazed and manured, dominated by dwarf perennial grasses and other nutritious prostrate chamaephytes.....
56. LYGEO-STIPETEA Rivas-Martinez 1978 nom. Conserv. Propos.	Mediterranean perennial basophilous xerophytic tall bunchy dense or short open grasslands.
57. STIPO GIGANTAE-AGROSTIETEA CASTELLANAE Rivas-Martínez, Fernández-González & Loidi 1999	Silicicolous perennial grasslands rich in endemics, serial of <i>Quercus rotundifolia</i> and other <i>Quercus</i> natural potential forest communities.
59. MOLINIO-ARRHENATHERETEA Tüxen 1937	Mesophile to wet often manured meadows and pasture communities on deep and moist soils, widely spread by grazed and anthropic activities

**Table 1.** Phytosociological classes and mean characteristics of the main species found at the landfills.

Most of the capped landfills are mixed dumps containing both domestic and industrial waste. Besides mitigating the visual impacts of a landfill, the plant cover prevents its collapse and the pollution of other ecosystems by deposited waste materials.

However, in such scenarios the stability of plant communities that become established from the seed bank of the capping soil layer is threatened. Among others, the factors that give rise



to this situation are continued waste disposal after the landfill's initial sealing, the scarce volume of capping soil present and land use projects implemented without a priori planning.

### 3. Case study: The Getafe landfill (Madrid)

#### 3.1. Geomorphological characterization

Here we examine the case of a closed landfill in the Madrid Autonomous Community. This site can be described as one of the most complex scenarios observed among the soil-capped solid waste landfills of the central Iberian Peninsula despite its many features common to all the landfills examined in this region [1]. Located in the municipal district of Getafe (Madrid), this landfill was first described by [9], when it occupied an area of around 70,000 m<sup>3</sup>. Fifteen years later (in 2009), the site covered some 95,000 m<sup>2</sup> of land.

Continuous waste dumping and subsequent capping with soil from the surroundings has determined the complex morphology of this landfill. In the photo in Figure 2, the landfill appears as a flattened hill rising out of a plain.



**Figure 2.** Picture of the whole landfill in spring of 2009

The landfill site has three main zones: a zone (western) mostly containing solid domestic waste, and two zones (central and eastern) mainly accommodating industrial waste and some inert compounds. We have designated these latter zones “rubble tips” to distinguish them from the landfill proper (Figure 3).

The flatted tops of the landfill correspond to platforms, yet more outstanding are its 12 slopes showing a high variety of exposures (across their 360°). Slope heights are 10-20 m and gradients are 50%. Their profiles are straight and many slopes overlap one another. Many slopes show signs of erosion, especially in troughs, often exposing their waste materials. Leachate surface runoff may be observed in three main discharge areas. The westernmost discharge area occupies a wetland. The other two areas, south of the rubble tips form shallow water sheets in the wettest months and quickly dry when rain ceases at the end of spring. In all these discharge zones and at the foots of the slopes, sheep herds may be found grazing. What is more, these and other animals drink any water that accumulates in these areas in 5 to 6 months of the year.

### 3.2. Composition of the capping soil layer: Factors linked to fertility, salinity, metal toxicity, organic compounds and erosion

To identify the soil factors that mainly determine the landfill's vegetation, mostly arising from the seed bank of the capping soil, we used a stratified sampling procedure (platforms, adjacent rubble tips and main surface leachate discharge zones). At each site, samples were collected using a hoe from the top soil layer (0-10 cm) to give an average soil sample. 57 of such samples were transported to the laboratory, where they were air-dried and sieved (< 2 mm). These samples were then subjected to each of the techniques mentioned in the following sections. Sampling sites 27 to 31 correspond to piles of waste deposited directly in the easternmost discharge zone with no type of cover at all. Although these samples do not correspond to the capping soil, they were collected to assess the possible effect of these waste materials on the soils of the discharge zone in future studies. Corresponding results do not appear in the tables provided below.



**Figure 3.** Main areas of the landfill and sites where capping soil samples were collected. 03/08/2009 Google Earth Image. UTM coordinates: X=442599 Y=4459459, 30T.

#### a. Soil fertility indicators

In the 57 soil samples, we examined several variables related to soil fertility with consequent impacts on the vegetation. The procedures described in [10] were used to determine: pH in water and in a saturated soil paste, percentage organic matter by potassium dichromate reduction, Kjeldahl total nitrogen, pseudototal (by extraction with nitric and perchloric acids at 4:1) and exchangeable (by extraction with ammonium acetate, pH 7) concentrations of Ca, K, Na and Mg, and pseudototal and bioavailable P and  $P_2O_5$  concentrations, analyzed by plasma emission spectroscopy (ICP-OES).

Sampling point	pH	OM.	N	Ca		K		Na		Mg		P		P <sub>2</sub> O <sub>5</sub>
				T	E	T	E	T	E	T	E	T	E	
Platform														
G-23	8.5	2.9	0.09	61566	6	1729	5	923	2	7111	3	205	0	130
G-24	8.0	1.2	0.06	5483	66	8855	4	244	5	4869	6	598	7	240
G-45	8.1	1.3	0.08	7345	30	6892	4	223	4	7085	4	553	3	100
G-46	7.8	1.4	0.08	15253	28	11362	7	276	6	22144	4	542	8	260
G-47	8.3	1.8	0.10	14890	22	10051	3	257	5	11553	4	569	4	110
G-48	7.9	1.5	0.10	9818	34	9400	5	218	7	11036	5	462	7	150
Slope														
G-6	7.5	4.0	0.05	6627	27	2495	5	86	16	1316	7	70	0	40
G-8	8.1	0.9	0.05	42871	9	3600	7	355	6	10842	2	32	0	50
G-11	8.2	2.5	0.12	42156	12	6790	12	337	16	7992	4	542	4	300
G-16	7.8	2.2	0.12	46571	14	4478	14	502	12	5795	5	317	0	110
G-17	8.0	2.3	0.06	57028	8	2524	10	604	6	6123	6	132	0	45
G-18	8.2	2.8	0.18	38558	9	3262	9	760	15	6124	7	113	0	15
G-19	7.6	1.2	0.19	11643	27	8270	4	241	15	6617	8	441	0	60
G-20	7.8	1.4	0.09	4051	59	11010	5	243	6	6765	9	547	9	240
G-21	7.9	0.6	0.05	8366	41	7671	4	222	7	5506	8	494	8	200
G-22	8.1	0.9	0.06	7296	53	9209	4	254	5	5810	5	590	6	190
G-39	8.1	1.1	0.05	25150	8	4800	4	350	6	8250	3	50	0	20
Foot of slope														
G- 3 A	7.9	0.9	0.06	3969	53	6902	7	221	27	6222	7	258	10	140
G- 3 F	7.6	2.1	0.09	5922	46	7492	6	214	18	10126	5	258	14	200
G-9	8.2	1.2	0.06	42176	10	3206	7	467	5	4391	4	106	0	60
G-10	8.2	0.9	0.03	29893	9	4759	4	339	5	5086	5	137	0	20
G-37	7.8	3.7	0.17	10122	41	8360	8	224	9	4598	7	429	19	320
G-38	7.8	2.3	0.11	14063	35	5774	5	215	32	4861	11	444	9	200
Discharge zone														
G- 2 A	7.7	6.2	0.29	13490	39	7245	10	324	52	9071	6	279	9	140
G- 2 B	7.8	7.8	0.37	28560	21	6702	9	252	34	8336	7	366	12	220
G- 4 A	7.5	3.8	0.13	12337	20	3570	12	162	26	3884	5	10	0	1050
G- 4 B	7.8	3.8	0.10	11135	19	3468	8	177	32	3577	8	8	0	70
G-7	7.5	5.6	0.25	37831	33	7442	3	308	32	7953	10	276	0	115

**Table 2.** pH, organic matter (OM, %), nitrogen (N, %), pseudo-total concentration (T) of nutrient elements (mg kg<sup>-1</sup>) and percentage of exchangeable fraction (E) in soil samples collected from landfill proper.



The results of these determinations in each soil sample are provided in Tables 2 and 3. All results are provided to highlight the huge variation existing for each factor. pH varied from 7.0 to 8.5, given the alkaline nature of the surrounding soils used to cap the landfill. The distributions of all variables failed to vary significantly between the landfill proper and rubble tips.

#### **b. Heavy metals and trace elements toxic for plants**

Although some preliminary results regarding soil pollution due to heavy metals, organic compounds and salinity have been already described [1, 7, 11, 12] here we examine this issue in detail. All 57 soil samples were subjected to inductively coupled plasma optical emission spectrometry (ICP-OES) to determine pseudototal (after prior extraction with nitric and perchloric acids, 4:1 [13]) and bioavailable (after prior extraction with ammonium acetate + EDTA using the method [14]) concentrations of Al, Mn, Zn, Cu, Pb, Cr and Ni. In addition, total As concentrations were determined by X-ray fluorescence in 48 samples. Total Hg levels were determined using an Advanced Mercury Analyser (AMA-254, LECO Company, Czech Republic) according to the procedure described by [15] in 34 selected samples of the 57 soil samples collected [16].

Tables 4 and 5 provide the metal and trace element concentrations detected in the capping soil and discharge area samples. We also examined total Al and Mn levels: Al concentrations in the landfill ranged from 8123 to 50747 mg kg<sup>-1</sup>, and Mn concentrations from 205 to 7432 mg kg<sup>-1</sup>. In the rubble tips, concentration ranges were higher for Al and lower for Mn. Given the alkaline nature of the soils, these elements are not considered hazardous for plant populations and are therefore not included in the tables.

The sites showing the highest levels of all elements occurred on the landfill's slopes and these showed an uneven spatial distribution. However, the most contaminated sites were simultaneously polluted by all elements. The percentage of a metal found in its bioavailable form was also highly variable. Despite being poorly mobile, Pb showed high bioavailability percentages. Cd was also highly bioavailable. Most variation was shown by Zn and Cu. The metals appearing in lowest concentrations were Cr and Ni.

Apart from the trace element bioavailability study conducted according to the method of [14], we performed a more exhaustive analysis of metal bioavailability in the soil samples. To this end, we undertook sequential extraction by the BCR method optimized by [17]. Sequential extraction serves to indicate the fractions of each metal that are bioavailable (F1: exchangeable), reducible (F2: bound to oxyhydroxides), oxidizable (F3: bound to organic matter) and residual (F4). Given that it is the landfill proper that shows the higher concentrations of these metal pollutants, 5 sites were selected representing platform, slope and discharge zones showing variable concentrations of these types of pollutant. The sites were selected according to their known distributions of metals; we have preserved the numbers assigned to their collection sites. Table 6 provides total concentrations of each metal in each sample calculated as the sum of all fractions. The reader may find the percentages of each metal found in each fraction in Figure 4.

Sampling point	pH	OM.	N	Ca		K		Na		Mg		P		P <sub>2</sub> O <sub>5</sub>
				T	E	T	E	T	E	T	E	T	E	
Platform														
G- 49	8.1	1.7	0.11	13588	24	7139	7	102	15	10111	5	613	3	18
G- 50	7.6	1.6	0.12	10910	38	7464	7	120	11	9279	4	297	11	1171
G- 51	7.8	2.2	0.10	14428	23	9093	5	134	8	10778	2	873	6	66
G- 52	7.8	0.8	0.04	5342	42	6711	3	106	11	6411	4	283	4	12
G- 53	7.7	2.3	0.10	15831	21	7671	8	97	12	7853	3	580	12	54
Slope														
G- 13	8.3	1.5	0.08	26245	16	2653	16	187	11	3343	6	106	21	30
G- 15	7.7	1.2	0.09	16589	50	7331	5	198	8	4009	7	249	4	8603
G- 32	7.8	0.7	0.05	63966	14	6989	33	238	12	7583	5	261	3	4008
G- 40	8.1	1.0	0.04	14200	28	7550	3	250	6	10350	2	350	4	264
G- 42	8.2	0.2	0.03	9617	35	3704	4	158	16	4643	4	289	12	26
Foot of slope														
G- 12	7.9	1.4	0.07	10790	37	7968	4	214	7	7278	9	423	4	144
G- 14	8.0	1.0	0.06	17651	27	3658	7	127	11	3126	9	68	0	159
G- 33	7.9	1.4	0.09	17519	27	7125	6	190	7	5067	6	536	6	72
G- 34	7.0	2.5	0.13	31469	17	7942	5	248	22	6187	7	469	5	790
G- 35	7.9	1.2	0.08	25913	19	8208	5	173	12	7176	7	428	5	44
G- 41	7.9	1.1	0.10	24281	20	8442	4	246	6	8838	1	593	19	25903
G- 43	8.0	0.8	0.05	72211	6	7503	3	246	6	10099	3	362	8	993
G- 44	7.9	1.3	0.07	17827	19	7959	3	315	13	5894	5	253	4	287
Discharge zone														
G- 1 A	7.7	4.2	0.20	72005	34	4234	5	1281	74	8466	22	177	10	5918
G- 1 B	7.7	2.0	0.11	43501	21	7456	4	292	19	7316	3	265	6	3830
G- 5	7.3	5.8	0.24	25041	30	8150	8	412	40	11338	3	449	6	3305
G- 25	8.0	2.6	0.12	15164	28	8552	6	310	27	5753	10	407	5	74
G- 26	7.8	1.1	0.07	64650	9	6624	3	198	15	6081	5	240	4	819
G- 36	7.5	5.6	0.30	34429	25	9961	5	306	27	8024	8	498	3	4245

**Table 3.** pH, organic matter (OM, %), nitrogen (N, %), pseudo-total concentration (T) of nutrient elements (mg kg<sup>-1</sup>) and percentage of exchangeable fraction (E) in soil samples collected from rubble tips.

Sampling point	Zn		Cu		Pb		Cd		Cr		Ni		As	Hg
	T	B	T	B	T	B	T	B	T	B	T	B		
Platform														
G-23	9491	23	4593	3	4421	50	93	35	531	0.9	231	1.1	271	11
G-24	137	20	14	18	19	70	0.0		3.2	2.2	8.7	1.5	n.d	0.0
G-45	148	2.1	8.9	13	28	8.2	0.0		7.3	0.6	5.6	4.1	14	-
G-46	147	2.1	38	17	35	48	0.0		2.2	2.3	12	4.0	22	-
G-47	126	3.8	12	14	11	43	0.0		4.7	1.1	9.9	3.4	n.d	-
G-48	175	5.3	43	16	22	40	0.0		18	0.6	21	3.4	n.d	-
Slope														
G-6	640	22	1916	21	132	29	0.0		256	0.1	35	2.5	119	0.3
G-8	13029	27	1055	8.1	12689	23	185	34	269	1.7	86	1.9	282	4.0
G-11	3247	20	240	11	579	51	10	67	154	0.6	43	2.0	n.d	0.5
G-16	10777	25	748	9.3	5734	38	142	41	150	3.0	42	2.6	n.d	3.0
G-17	17416	26	1313	8.5	12612	28	308	37	242	1.5	60	2.2	n.d	4.9
G-18	22992	28	1804	9.4	18136	30	306	36	298	1.8	80	3.7	685	4.2
G-19	5190	25	125	14	1198	47	29	52	40	3.3	15	2.6	n.d	0.2
G-20	1085	2.6	18	9.4	106	12	0.3	64	9.8	0.5	9.0	0.9	12	0.0
G-21	129	9.0	11	21	18	37	0.0		3.5	1.4	7.0	1.7	13	0.0
G-22	168	9.3	14	20	25	53	0.0		9.1	0.8	8.8	1.8	23	0.0
G-39	17830	76	1445	20	12555	68	190	60	587	2.2	210	2.5	492	-
Foot of slope														
G- 3 A	61	2.2	9.1	14	18	59	0.0		2.3	12	5.1	9.2	-	-
G- 3 F	69	4.6	31	6.2	8.1	40	0.0		9.2	3	5.2	7.0	-	-
G-9	12632	25	1181	10	7179	37	257	48	236	2.4	90	2.1	306	2.4
G-10	15184	33	1493	13	10085	48	155	42	504	2.2	206	2.2	n.d	3.3
G-37	559	66	20	25	28	61	0.0		3.8	4.7	8.5	5.9	15	0.0
G-38	108	18	15	24	23	65	0.0		15	1.0	7.4	6.7	19	0.0
Discharge zones														
G- 2 A	528	17	36	27	117	36	0.0		6.6	6.1	8.6	5.1	-	-
G- 2 F	366	14	35	18	64	28	0.0		5.7	4.9	7.3	5.5	-	-
G- 4 A	577	19	882	27	149	29	0.0		110	0.1	156	1.5	-	-
G- 4 F	477	19	1260	26	139	19	0.0		153	0.2	213	1.5	-	-
G-7	2417	33	151	27	290	48	2.5	86	9.5	3.4	34	8.9	54	0.3
Ref. (pH"/>7)	450		210		300		3		150		112		29*	1.5

**Table 4.** Pseudo-total concentration (T) of trace elements (mg kg<sup>-1</sup>) and percentage of bioavailable fraction (B) in soil samples collected from landfill proper. nd: not detected; -: not analyzed. Reference levels for alkaline soils according to Spanish law (RD1310/1990), \*As Dutch reference level.

Sampling point	Zn		Cu		Pb		Cd		Cr		Ni		As	Hg
	T	B	T	B	T	B	T	B	T	B	T	B		
<i>Platform</i>														
G-49	10	0.0	13	21	0.0		0.0		1.8	0.0	5.4	0.0	n.d	-
G-50	17	0.0	21	23	22	54	0.0		3.4	0.0	7.8	0.0	n.d	-
G-51	13	0.0	17	19	0.0		0.0		2.4	0.0	6.5	0.0	n.d	-
G-52	9	0.0	14	18	0.0		0.0		3.6	0.0	8.0	0.0	12	-
G-53	13	0.0	14	29	0.0		0.0		6.8	0.0	7.7	0.0	15	-
<i>Slope</i>														
G-13	1261	18	783	7.0	164	35	0.0		378	0.1	223	1.2	42	0.8
G-15	159	15	34	14	28	48	0.0		17	0.7	12	3.3	29	0.0
G-32	166	11	40	54	24	42	0.0		14	3.8	11	3.4	26	0.1
G-40	120	35	15	14	15	86	0.0		3.5	3.4	5.0	6.6	14	-
G-42	72	12	10	9.2	10	43	0.0		6.7	1.5	4.1	7.1	n.d	-
<i>Foot of slope</i>														
G-12	1123	2	83	14	129	10	0.0		10	1.2	25	2.6	25	0.0
G-14	341	16	266	11	64	32	0.0		94	0.1	75	1.6	22	0.2
G-33	146	19	29	14	26	56	1.2	90	7	2.5	8.8	3.5	22	0.0
G-34	224	18	28	22	48	40	1.5	3.6	10	1.9	12	4.4	37	0.1
G-35	76	4.8	14	18	11	33	0.9	24	13	1.2	9.1	3.2	31	0.0
G-41	1259	1.3	38	13	148	7.6	1.4	26	9.1	1.2	11	4.1	21	-
G-43	226	2.8	22	5.4	24	12	0.0		1.1	9.1	10	2.2	100	-
G-44	1869	10	73	21	215	54	3.5	67	18	0.9	22	3.6	30	-
<i>Discharge zone</i>														
G- 1 A	238	23	18	32	57	43	0.0		2.9	12	4.6	9.0	-	-
G- 1 F	74	4.0	13	19	17	22	0.0		1.5	18	6.4	5.2	-	-
G-5	252	65	56	31	66	41	0.0		10	0.1	8.3	5.2	31	0.2
G-25	171	13	25	19	44	45	0.0		5.7	3.3	10	4.0	27	0.4
G-26	126	8.1	63	8.5	83	32	0.0		24	1.0	16	2.0	36	0.2
G-36	904	35	68	41	152	62	1.7	11	9.2	2.8	14	7.5	40	0.6
Ref. (pH"/>7)	450		210		300		3		150		112		29*	1.5

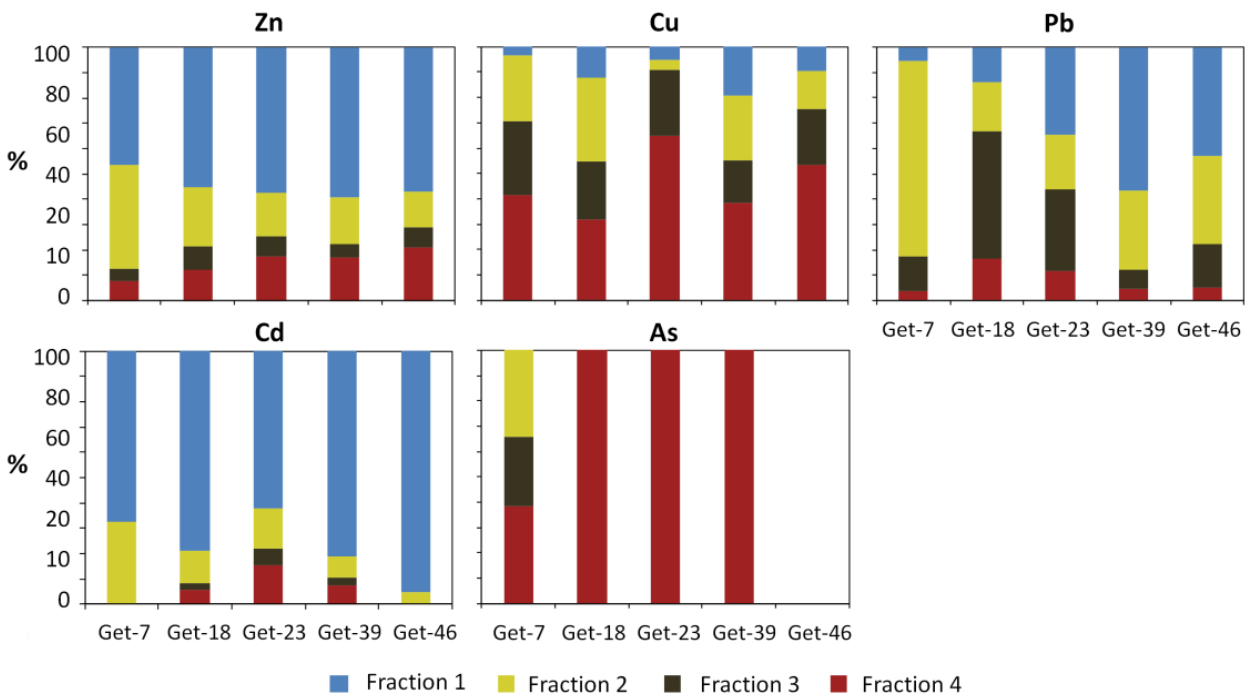
**Table 5.** Pseudo-total concentration (T) of trace elements (mg kg<sup>-1</sup>) and percentage of bioavailable fraction (B) in soil samples collected from rubble tips. nd: not detected; -: not analyzed. Reference levels for alkaline soils according to Spanish law [18], \*As Dutch reference level.



The results of these tests prompt the following conclusions. Cd and Zn showed highest percentages in the bioavailable fraction. In the case of Cd, this finding is of major concern given its high concentration in the soils examined and this situation has been also described by [19]. Arsenic shows the highest residual percentage and thus its available levels are low. The bioavailable fraction of Cu is fairly low, while remaining fractions vary according to the soils. The behavior of Pb was more irregular among the different soils. In general, the residual fraction was low. The organic matter fraction was variable being greatest at site 18. Its bioavailable fraction was very high at site 39, which is worrying given the high concentration of this heavy metal at this site.

Sample		Zn	Cu	Pb	Cd	As
G-7	wetland	1425	102	278	3	16
G-18	slope	127529	1441	19500	364	32
G-23	platform	33446	2042	11057	106	10
G-39	slope	76120	1272	20032	223	14
G-46	platform	610	41	182	2	0

**Table 6.** Total concentration of trace elements (mg kg<sup>-1</sup>) in soils selected for conducting the sequential fractionation



**Figure 4.** Percentage of metal content that is in each fraction

Clearly the presence of very high concentrations of trace elements and heavy metals is a problem for the establishment of plant populations, worsened by the fact that the sites of

highest concentrations coincide with zones of intense slope. In effect, zones corresponding to samples 17 and 18, along with 10 and 39, are naked slopes with practically no plant cover in comparison with surrounding zones.

### c. Salinity

Salinity has been described as one of the main impacts on the plant populations and animals of the closed landfills of the Iberian Peninsula's central region [5, 12, 20, 21] as well as landfills in other environments [22-25]. This problem is therefore closely examined in the case of the Getafe landfill. Electrical conductivity was determined in all the soil samples collected, along with  $F^-$ ,  $Cl^-$ ,  $NO_2^-$ ,  $NO_3^-$ ,  $PO_4^{3-}$  and  $SO_4^{2-}$  anion concentrations by ion chromatography. These results may be found in Tables 7 and 8. As for the other chemical properties of the soil, points showing greatest salinity were unevenly distributed throughout the capping soil.

By comparing soils from the landfill and rubble tips by principal components analysis (PCA) (Statgraphics 15), we were able to observe that electrical conductivity was related to the  $Cl^-$  and  $SO_4^{2-}$  contents of the landfill cap and also to  $F^-$ ,  $Na$ ,  $NO_3^-$  concentrations in the case of the rubble tips. The distribution of sites appearing on the new coordinate axes seems to indicate higher salinity in discharge areas. To confirm this observation, we conducted an analysis of variance (ANOVA) of the factors electrical conductivity and  $Cl^-$  level in the different landfill areas. Our findings indicate that both variables were significantly higher in the soils of the wetlands where the landfill's runoff is deposited.

### d. Organic compounds

Pollution by organic compounds is also a concern emerging from studies designed to address the topic of sealed landfills, as many recently banned compounds, dumped in landfills and numerous affected ecosystems, have been detected [26]. The organic compounds determined in the soil samples and the techniques used for this purpose were: total hydrocarbons by infrared spectrometry (UNE 77307); organochlorine insecticides and polychlorinated biphenyls (PCBs) by gas chromatography (ISO 10382); and polycyclic aromatic hydrocarbons (PAHs) (ISO 18287) and phenols (U.S. E.P.A 3550B, U.S. E.P.A 3650B and U.S. E.P.A 8401) by gas chromatography. The reader is referred to [1] for descriptions of these techniques and their modifications for the present purposes.

Table 9 shows the great variety of organic pollutants that may be found in the Getafe landfill. Those detected at concentrations higher than permitted levels and widely distributed at the site were total hydrocarbons, PCBs, the PAHs with a greater number of rings and some organochlorine insecticides. In general, the sites showing most pollution of this type were those also showing most heavy metal pollution.

Given that total hydrocarbons were detected at all the sites in which these were examined (N=43), Table 10 presents the differences detected.

Landfill samples	EC	F <sup>-</sup>	Cl <sup>-</sup>	NO <sub>2</sub> <sup>-</sup>	NO <sub>3</sub> <sup>-</sup>	PO <sub>4</sub> <sup>3-</sup>	SO <sub>4</sub> <sup>2-</sup>
<i>Platform</i>							
G- 23	132	5.5	4.6	1.4	5.4	0.0	26
G- 24	107	1.8	8.1	1.6	52	2.1	11
G- 45	114	2.6	12	1.5	3.3	2.1	8.5
G- 46	161	7.4	8.5	1.1	5.3	2.3	31
G- 47	116	2.4	8.9	1.7	7.6	1.6	10
G- 48	113	2.6	13	1.6	3.7	3.1	8.0
<i>Slope</i>							
G- 6	175	2.8	6.4	0.7	3.0	0.0	147
G- 8	317	19	6.0	1.4	17	0.0	398
G- 11	159	7.6	7.7	1.0	3.6	0.0	41
G- 16	1853	10	38	1.3	70	0.0	4063
G- 17	587	14	10	1.4	22	0.0	592
G- 18	985	31	121	2.6	193	0.0	635
G- 19	1329	13	32	2.0	1152	0.0	691
G- 20	154	1.6	5.2	1.3	38	2.2	15
G- 21	171	2.5	6.3	0.9	94	0.9	91
G- 22	157	1.7	4.9	1.1	15	1.1	123
G- 39	366	18	8.6	3.0	41	0.0	214
<i>Foot of slope</i>							
G- 3 A	270	3.2	33	1.2	28	0.0	96
G- 3 F	340	1.6	30	1.5	110	5.4	67
G- 9	212	18	8.7	1.3	13	0.0	139
G- 10	237	17	5.3	1.1	12	0.0	194
G- 37	391	1.5	27	1.0	112	0.0	65
G- 38	369	4.2	60	1.3	7.3	0.0	656
<i>Discharge zones</i>							
G- 2 A	1490	3.8	135	2.9	93	2.0	1938
G- 2 F	1960	1.6	77	1.5	0.0	0.0	3322
G- 4 A	1490	3.7	125	1.9	148	2.9	1647
G- 4 F	1500	2.9	43	1.0	34	0.0	1729
G- 7	1878	10	85	1.3	20	1.0	4866

**Table 7.** Electrical conductivity (EC,  $\mu\text{S cm}^{-1}$ ) and anion concentration ( $\text{mg kg}^{-1}$ ) in soil samples collected from landfill proper.

Tip samples	EC	F <sup>-</sup>	Cl <sup>-</sup>	NO <sub>2</sub> <sup>-</sup>	NO <sub>3</sub> <sup>-</sup>	PO <sub>4</sub> <sup>3-</sup>	SO <sub>4</sub> <sup>2-</sup>
<i>Platform</i>							
G-49	135	1.5	6.6	0.0	0.0	5.2	18
G-50	826	1.1	3.2	2.4	0.0	0.0	1171
G-51	169	1.7	8.3	0.0	0.0	5.0	66
G-52	60	2.4	2.9	2.6	0.0	2.8	12
G-53	206	1.2	5.1	2.6	0.6	8.0	54
<i>Slope</i>							
G- 13	170	7.3	7.2	0.8	18	0.0	30
G- 15	1719	3.7	4.4	0.8	12	0.0	8603
G- 32	2360	9.4	6.9	1.0	67	0.0	4008
G- 40	299	2.8	5.1	1.0	3.8	0.0	264
G- 42	99	3.0	7.9	1.5	4.3	1.8	26
<i>Foot of slope</i>							
G- 12	90	0.0	1.1	0.0	0.0	0.0	144
G- 14	193	4.2	15	1.9	13	0.0	159
G- 33	327	2.5	13	1.0	143	0.0	72
G- 34	744	3.8	56	1.5	21	1.5	790
G- 35	198	2.7	13	2.1	37	2.8	44
G- 41	1716	1.9	4.8	1.2	19	0.0	25903
G- 43	877	2.1	3.6	1.0	11	0.0	993
G- 44	384	4.4	46	1.4	5.0	0.0	287
<i>Discharge zones</i>							
G- 1 A	8220	8.6	7570	0.0	495	0.0	5918
G- 1 F	2350	2.9	199	2.3	29	0.0	3830
G- 5	2180	3.8	260	2.0	201	0.0	3305
G- 25	280	3.3	35	1.9	24	0.0	74
G- 26	709	6.0	12	1.5	60	0.0	819
G- 36	2500	5.2	69	3.6	43	0.0	4245

**Table 8.** Electrical conductivity (EC,  $\mu\text{S cm}^{-1}$ ) and anion concentration ( $\text{mg kg}^{-1}$ ) in soil samples collected from rubble tips.



Pollutant	Max conc.	Ref*	Pollutant	Max conc.	Ref*
<i>PAHs</i>			<i>Insecticides</i>		
Naphthalene	0.23	1	Alfa-HCH	0.01	0.01
Acenaphthene	0.04	6	Beta-HCH	0.27	0.01
Fluorene	0.09	5	Gamma-HCH	0.48	0.01
Anthracene	0.46	45	Hexachlorobenzene	0.04	0.01
Fluoranthene	2.59	8	Endosulfan	0.07	0.6
Pyrene	2.03	6	p.p'-DDE	0.02	0.6
1,2-benzanthracene	0.99	0.2	<i>Hydrocarbons</i>		
Chrysene	1.11	20	Total concentration	3408	50
Benzo(b)fluoranthene	1.85	0.2	Conc. of aromatics	335	
Benzo(k)fluoranthene	0.89	2	Conc. of aliphatics	3073	
Benzo(a)pyrene	1.56	0.02	<i>Phenols</i>		
Indene-1,2,3-(cd)pyrene	1.63	0.3	Phenol	0.05	7
Dibenzo(a,h)anthracene	0.14	0.03	Cresols	0.02	4
			2,4,6-trichlorophenol	0.01	0.9
<i>PCBs</i>	3.05	0.01	Pentachlorophenol	0.01	0.01

**Table 9.** Maximum concentration of organic pollutants found in soils of Getafe landfill (mg kg<sup>-1</sup>) and maximum allowed values according to Spanish law (\*Ref, [27])

**e. Factors linked to soil erosion**

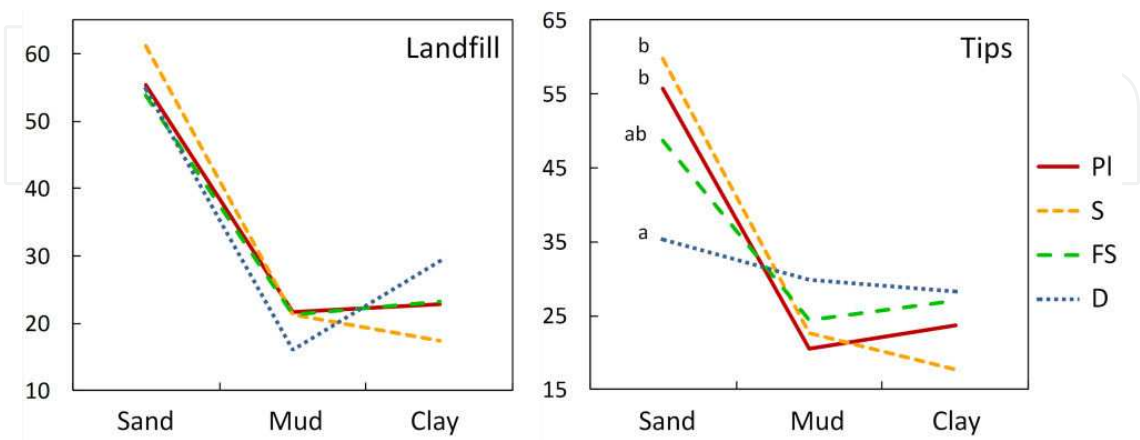
Signs of soil erosion observed on the landfill’s slopes prompted us to address this matter, given the significant effect that soil particle size and the loss of certain fractions can have on the ability of plant species to take root.

The traditional method of Bouyoucos to determine sand, mud and clay fractions was used on all 57 soil samples. In addition, the Mastersizer-S was used to assess particle size by the dispersion and diffraction of a laser light beam as it crosses a suspension of the sample. This technique and the sample preparation method are described in [1]. Particle size was determined in 43 of the samples to establish the type of particle that may be lost through erosion. Significant differences in this variable were detected in several fractions of fine sand between soil from the landfill cap and soil from the rubble tips. These results are provided in Figure 5 and table 11. The high standard deviation of the data determined that only differences in the sand fraction of the rubble tip soil were significant.

Although the results obtained using both granulometric techniques are not comparable since the first method gives a percentage weight while the second procedure provides percentage volumes, both revealed that the most marked differences among the higher zones, slopes and lower zones occur in the rubble tips adjacent to the landfill. Table 11 shows the different

Landfill		Landfill		Tips	
Sampling point	HC	Sampling point	HC	Sampling point	HC
<i>Platform</i>		<i>Foot of slope</i>		<i>Slope</i>	
G-23	901	G- 3 A	13	G-13	215
G-24	78	G- 3 F	13	G-15	52
<i>Slope</i>		G-9	92	G-32	33
G-6	2423	G-10	154	<i>Foot of slope</i>	
G-8	93	G-37	33	G-12	174
G-11	230	G-38	26	G-14	169
G-16	62	<i>Discharge zone</i>		G-33	52
G-17	63	G- 2 A	5.1	G-34	19
G-18	3408	G- 2 F	5.1	G-35	22
G-19	95	G- 4 A	854	<i>Discharge zone</i>	
G-20	33	G- 4 F	854	G- 1 A	7.5
G-21	42	G-7	123	G- 1 F	7.5
G-22	78			G-5	67
G-39	87			G-25	24
				G-26	18
				G-36	36
Ref.	50	Ref.	50	Ref.	50

**Table 10.** Total concentration of hydrocarbons (HC, mg kg<sup>-1</sup>) in points of landfill proper and rubble tips and maximum allowed values according to Spanish law (Ref, [27])



**Figure 5.** Mean percentage of each textural fraction determined by Bouyoucos technique in samples from platforms (P), slopes (S), foots of slopes (FS) and discharge zones (D) in landfill proper and tips. Different letters mean significant differences between means in the same area (Bonferroni, 95%)

granulometric fractions analyzed. For the rubble tips, results indicate the dragging of fine sands from slopes towards the lower zones accompanied by the consequent build-up of coarse sands. Although with a lack of significance, differences were also observed in the remaining fractions.

These data do not seem to clearly indicate the signs produced by the in situ transport of particles from the higher to the lower zones of slopes and discharge areas. No distinguishing factors were revealed in a discriminatory analysis (figure 6). The findings of such a study also indicate the heterogeneity of the situations arising on even a single slope and increase the complexity of understanding the plant colonization pattern, which may vary as small patches depending on these variations produced on a small scale.

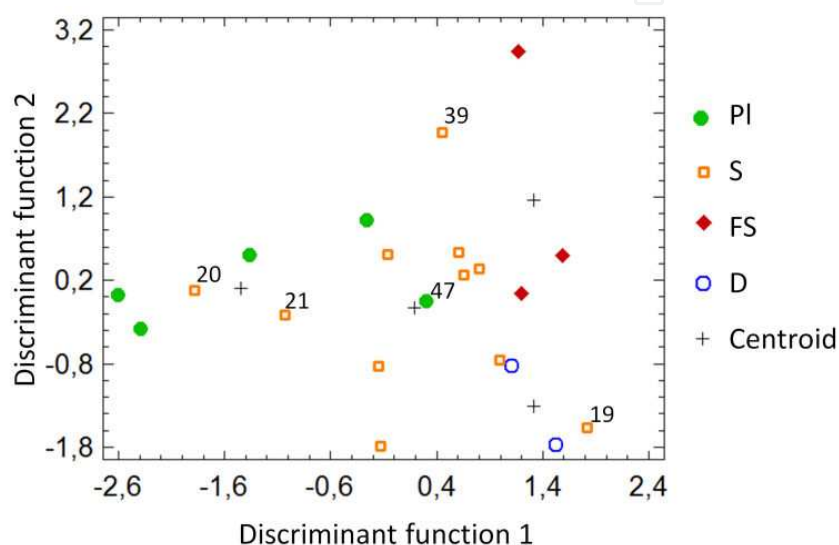
Area		Range of particle size (mm)							
		Clay	Mud	Fine sand A	Fine sand B	Fine sand C	Medium sand	Coarse sand	Very coarse sand
		<0.002	0.002-0.02	0.02-0.05	0.05-0.1	0.1-0.2	0.2-0.5	0.5-1	1-3.2
Landfill									
Platform	M	0.34	1.93	2.69	7.64	13.7	16.4	23.8	33.4
	SD	0.23	0.65	1.39	4.28	6.72	3.10	9.05	14.5
Slope	M	0.46	3.12	3.32	8.85	14.0	14.8	16.7	38.6
	SD	0.50	2.28	0.64	2.06	3.4	3.51	7.65	13.9
Foot of Slope	M	0.76	3.87	3.59	9.15	14.3	16.2	13.8	38.4
	SD	0.65	2.81	0.64	1.87	1.81	3.95	1.55	3.84
Discharge zone		0.35	2.30	4.43	11.9	17.6	15.6	13.0	34.8
Tips									
Slope	M	0.20	1.72	3.10	8.89 a	14.5 a	13.3	14.2 b	44.1
	SD	0.25	0.62	1.37	4.14	6.21	3.8	2.92	15.8
Foot of Slope	M	0.34	2.30	4.45	12.9 ab	20.1 ab	16.7	12.9 ab	30.4
	SD	0.23	0.45	1.02	3.27	5.03	5.4	1.79	14.5
Discharge zone	M	0.26	2.76	5.78	16.0 b	22.9 b	17.8	9.73 a	24.8
	SD	0.21	1.08	2.30	4.95	3.42	1.30	2.20	10.2

**Table 11.** Mean (M) and standard deviation (SD) of percentages of each granulometric fraction in different areas of landfill and tips. Different letters in the same range of particle size mean significant differences between means (Bonferroni, 95%)

3.3. Heterogeneous distribution of pollutants

Through PCA, we tried to gain insight into the structure of the soil cap used to seal the landfill. In Figure 7A, it may be seen that the first axis, or component, is closely and positively linked

to heavy metal and organic compound pollution although Na and F also appeared in this group of variables, and negatively related to soil fertility due to the presence of K and P. The second component was more related to soil salinity, represented by electrical conductivity, chlorides, sulfates, nitrates and nitrites. When organic components and the trace elements Hg and As were excluded, results failed to vary significantly and the first component continued to be positively and closely linked to the presence of heavy metals and negatively linked to that of K (Figure 7B). The second component, more related to salinity or electrical conductivity, this time was linked more to chlorides than the other anions.



**Figure 6.** Representation of discriminant functions calculated with Mastersizer results of landfill soil samples, grouped in platforms (P), slopes (S), foots of slopes (FS) and discharge zones (D).

These findings confirm our previous results indicating that despite the uneven distribution of pollutants, at the most polluted sites all pollutants contribute to this contamination. The PCA plot of points on the new axes (Figures 7C and 7D) serves to visually identify the sites showing highest heavy metal pollution as the landfill slopes and those with the greatest salinity as the rubble tips. The platforms emerged as the least polluted sites both in terms of heavy metals and salts contents.

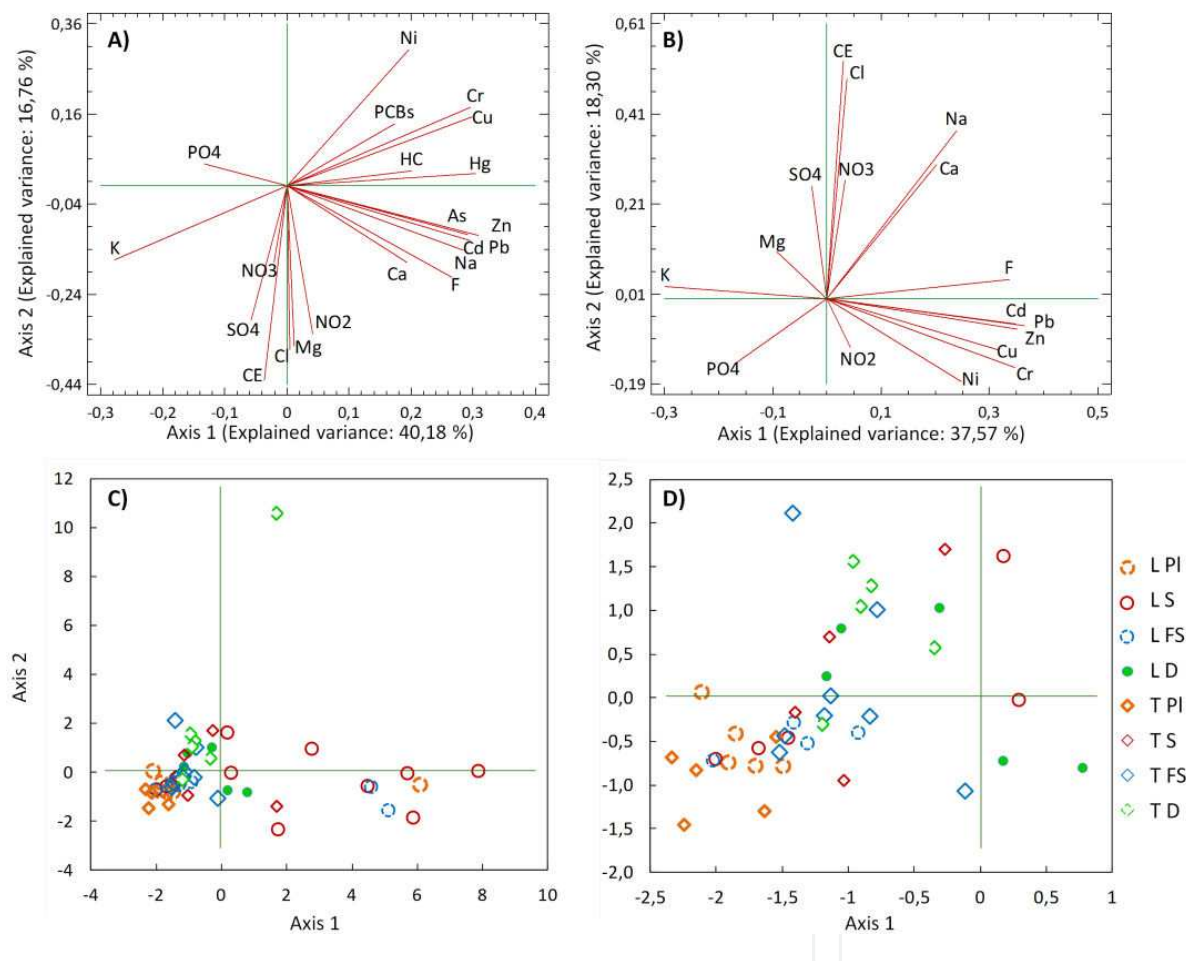
The chemical analysis results reveal great heterogeneity in both the distributions and concentrations of pollutants. As an example of the complexity of the problem addressed, Zn concentrations range from 9 mg kg<sup>-1</sup> to 23000 mg kg<sup>-1</sup>; maximal Cd concentrations are 308 mg kg<sup>-1</sup> (of which 85% represents the easily soluble fraction) and the maximal concentration of total hydrocarbons is 3408 mg kg<sup>-1</sup>.

The spatial distributions of these factors determined using a Geographical Information System (ArcMap™ software, v. 9.3.1., ESRI) are depicted in Figure 8.



4. Understanding the complex nature of landfill soil caps with the view of restoring the impacts of pollution

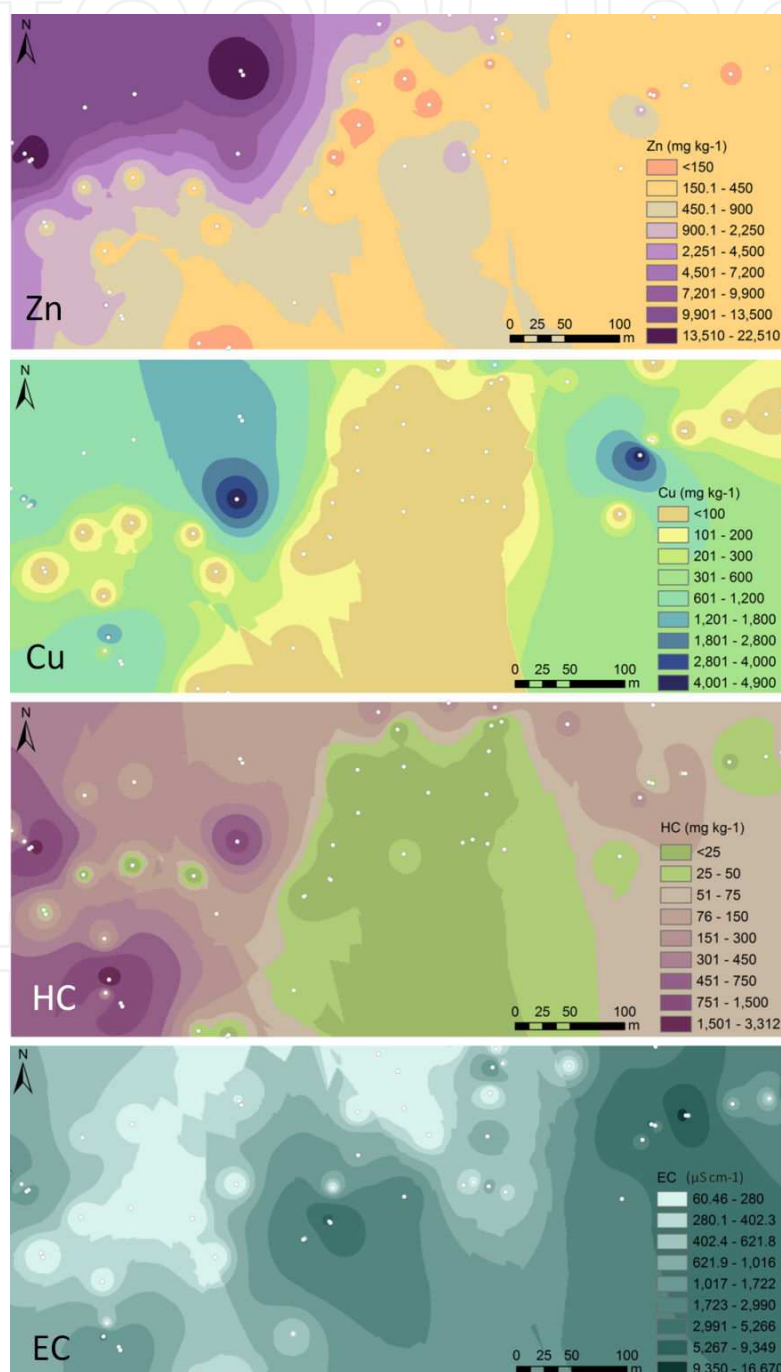
The mountains of waste and rubble we have created are new landscape features that most often emerge in areas around cities. These scenarios can be viewed as laboratories for research into the environmental impacts of landfills that were capped without prior treatment of the deposited waste. Even considering that the restoration of degraded ecosystems is a systemic topic, the functionality of this epistemological approach arises from the fact that ecosystems are dynamic systems that evolve and co-evolve with human activity.



**Figure 7.** Principle components analysis of the soil chemical variables showing points appearing on the new coordinate axes. A) PCA of the whole set of variables, N = 29, B) PCA excluding As, Hg, hydrocarbons and PCBs increasing the number of cases to N = 52, C) representing the 52 points on the new axes created by the PCA in Figure B), D) expansion of plot C) from -2.5 to 1 abscissa and -2 to 2.5 ordinate. L, landfill proper; T, rubble tips; PI, platforms; S, slopes; FS, foot of slopes; D, discharge zone.

The complexity of the problem faced arises from questions related to the secondary ecological succession (from the capping soil's seed bank), which interacts with the primary succession that is possible in this new ecosystem in the landscape. Besides restoring its impacts, efforts need to also focus on revegetating the landfill system itself.

Hence, these landfills may be considered a new type of ecosystem in which primary and secondary successions coincide. They are thus of great interest for ecological science since they provide a real scenario for investigating the measures we should install to restore a degraded and polluted ecosystem and help us identify the plant species related to their varied forms of pollution. This will enable researchers to select the most appropriate plant species for revegetation efforts rather than simply establishing a green cover once a landfill has been capped.



**Figure 8.** Spatial distribution of Zn, Cd, total hydrocarbons and electrical conductivity

The ecological theory that is most applicable to the restoration of the environmental impacts of capped landfills addresses the stress and ecological strategies of herbaceous species.

The classification of plant life cycle strategies described by Grime combines the stress intensity with the perturbation intensity [7, 28]. Thus, “competing species” are more appropriate for landfills with a low intensity of perturbation and stress, “ruderal” species adapt better to conditions of low stress and intense perturbation, and “stress-tolerants” are ideal for settings of intense stress and scarce perturbation. When both these factors are excessive, this approach is ineffective.

It should not be forgotten, however, that different types of ecosystem respond differently to a given perturbation, and vice-versa, that a given ecosystem can respond in many different ways to different perturbations. We also need to be aware of the vast environmental variability and randomness that exists along with other associated forms of uncertainty [29].

## 5. Conclusions

If a sealed landfill needs to be revegetated, it will be necessary to study the fertility of its soil cover, heavy metals and trace elements that can cause plant toxicity, salinity and organic compounds in the capping soil layer. The research methodology used in the landfill case study can be followed in other scenarios with a similar problem.

The analysis of all considered parameters and the heterogeneous distribution of pollutants indicate that a single-species cover should be avoided. It will be necessary to create a multi-species cover that will adapt to the heterogeneous distribution of the organic and inorganic pollutants present in capping soils and to the morphological features of the landfill's slopes.

From a scientific viewpoint, the scenario of the closed waste landfill has enabled the in depth study of what we have called the erosion-pollution binomial. This is the complex situation found in the capping soils of closed landfills in the Mediterranean setting. The plant species used for their revegetation should have the capacity to show an adequate response to this biome. To find such species, there is an urgent need for autecological studies and studies designed to assess native and commercial plant species that are able to adapt to these particular conditions. This is the reason why these results should not be extrapolated to other non-Mediterranean settings.

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