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RESEARCH ARTICLE

Soil physicochemical factors as environmental filters for spontaneous plant colonization of abandoned tailing dumps

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Abstract Abandoned tailing dumps (ATDs) offer an opportunity to identify the main physicochemical filters that determine colonization of vegetation in solid mine wastes. The current study determined the soil physicochemical factors that explain the compositional variation of pioneer vegetal species on ATDs from surrounding areas in semiarid Mediterranean-climate type ecosystems of north-central Chile (Coquimbo Region). Geobotanical surveys—including physicochemical parameters of substrates (0–20 cm depth), plant richness, and coverage of plant species—were performed on 73 ATDs and surrounding areas. A total of 112 plant species were identified from which endemic/native species (67%) were more abundant than exotic species (33%) on ATDs. The distribution of sampling sites and plant species in canonical correspondence analysis (CCA) ordination diagrams indicated a gradual and progressive variation in species composition and abundance from surrounding areas to ATDs because of variations in total Cu concentration (1.3%) and the percentage of soil particles <2 μm (1.8%). According to the CCA, there were 10 plant species with greater abundance on sites with high total Cu concentrations and fine-textured substrates, which could be useful for developing plant-based stabilization programs of ATDs in semiarid Mediterranean-climate type ecosystems of north-central Chile.

Keywords Primary succession · Abiotic filters · Mine waste · Pioneer plants · Metal mining · Recolonization

Introduction

Mineral residues from metal mine operations, such as mine tailings, are discharged into the environment, becoming a source of hazardous metals that are transported to soils and surface waters, affecting the surrounding ecosystem (Johnson et al. 2016; Yu et al. 2016). Mine tailings are disposed of in artificial dumps. Once they enter the post-operational phase, surface tailings dry out at a speed that is dependent on the climatic conditions of the site, leaving a fine and non-cohesive material that is exposed to wind and water erosion and dispersion (Dold and Fontboté 2001). The erosion of abandoned tailing dumps (ATDs) is accentuated in arid and semiarid environments because of the high rate of water evaporation, which rapidly dries out surface tailings, resulting in the risk of metal pollution in surrounding areas (Conesa et al. 2007; Mendez and Maier 2008).

A range of physical, chemical, and biological remediation techniques are available for ATDs for different mining systems (Li 2006). Among them, well-developed revegetation (i.e., assisted or natural phytostabilization) can assure long-term and self-sustainable remediation (Tordoff et al. 2000; Mendez and Maier 2008). Once plants have successfully

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established on ATDs, they can readily accumulate organic matter, aid nutrient cycling (Ottenhof et al. 2007), improve the physical properties of the soil, and add nutrients to the mineral substrate (Verdugo et al. 2011). Spontaneous vegetation cover developed on metal-enriched substrates and ATDs offers a valuable ecological opportunity to look for plants capable of growing in such stressful environments, which could reduce both the erosive processes and the risks of environmental metal pollution (Salt et al. 1995). For example, diverse plant species that spontaneously colonize metal-enriched substrates have been identified, studied, and tested in different metalliferous habitats worldwide for plant-based remediation purposes (Whiting et al. 2004; Baker et al. 2010; Solís-Domínguez et al. 2012; Cuevas et al. 2013; Tapia et al. 2013). In particular, spontaneous pioneer plant species represent key stress-tolerant genetic resources that can be used in the remediation of ATDs in semiarid environments (Salt et al. 1995; Ginocchio and Baker 2004).

Abandoned tailing dumps are similar to strongly natural disturbed sites, such as lava fields, rockslides, and landslides, where spontaneous primary successional processes begin following disturbance (Pickett and White 1985). Particularly, primary succession occurs on mineral substrates that lack in situ plant propagules (Tilman 1988) and correspond to long-term vegetation changes and the transformation of mineral substrates into soil (Pickett and White 1985; Tilman 1988). After primary spontaneous plant colonization and establishment, pioneer plants modify the microenvironment so as to reduce the frequency and/or intensity of some physical disturbances or stresses, allowing further colonization by less-tolerant species; this creates habitats for other organisms and eventually increases biological diversity with time (Parraga-Aguado et al. 2014). In the case of ATDs, spontaneous colonization is limited, generally with small patches of vegetation distributed mainly on their edges (dump walls) (Conesa et al. 2007; Das and Maiti 2007). Therefore, a large portion of them remained bare and exposed to erosion agents. For example, it was reported that even 18 years after abandonment plant cover only accounts for <3% of the total area (Shu et al. 2005).

The study of the early stages of primary vegetational succession on mineral substrates of ATDs could identify the physicochemical characteristics that determine their spontaneous colonization (Conesa et al. 2006; Horáčková et al. 2016; Żołnierz et al. 2016). ATD substrate is characterized as being toxic and unsuitable for plant growth because of its elevated metal (i.e., Cu, Ni, Pb, Cd, and Zn) concentrations (Ginocchio et al. 2006), low organic matter content (Ottenhof et al. 2007), low soil nutrients availability (Verdugo et al. 2011), restrictive soil cation exchange capacity (CEC), and limited microbiological activity (De La Iglesia et al. 2006). Their poor soil physical properties, such as low porosity and a fine homogeneous texture, reduce water infiltration and root development and promote compaction (Mendez and Maier 2008; Verdugo et al. 2011). Depending on their metal sulfide content and the climatic conditions of the site, secondary acidification of ATD substrate can also occur (Dold and Fontboté 2001), further increasing toxicity (Ginocchio et al. 2009). Therefore, it has been assumed that metal toxicity, extreme acidity, and/or low nutritional availability of the substrate are the main factors restricting plant colonization and establishment in ATDs (Mendez and Maier 2008; Schippers et al. 2000; Li and Huang 2015). Hence, it is generally thought that plants able to colonize and establish on ATDs are metal-tolerant species or metallophytes (Whiting et al. 2004; Baker et al. 2010). However, in water-limited environments, such as semiarid Mediterranean-climate type ecosystems, the establishment of a plant cover on ATDs could be more difficult because of extreme temperatures at the tailing surface and low precipitation throughout the year, resulting in high salt concentrations (up to 18 dS m^{-1}) and high compaction levels (Pérez-Sirvent et al. 2015). Therefore, physical, chemical, nutritional, and/or microbiological limiting conditions of tailings would be other edaphic factors controlling plant colonization on ATDs at early successional stages, in addition to acidity and/or metal toxicity.

Although several studies have reported the occurrence of spontaneous pioneer plant species on metal-enriched soils and ATDs in different semiarid Mediterranean-climate type regions worldwide (Conesa et al. 2006; Mendez and Maier 2008; Cuevas et al. 2013; Tapia et al. 2013), the soil physicochemical factors that restrict spontaneous vegetation early establishment in ATDs are still poorly understood. Therefore, in the current study, we carried out an edaphic and botanical survey of 73 ATDs in a semiarid Mediterranean-climate type area of north-central Chile (Coquimbo Region, latitude 29° 00′ to 32° 10′ S and longitude 70° 00′ to 71° 50′ W) to explore the physicochemical factors of tailings that determine the compositional variation in pioneer plant species growing on ATDs. We used the Coquimbo Region as a case study area, as it holds 67% (Casale et al. 2011) of ATDs registered in north and central areas of Chile (SERNAGEOMIN 2015).

Methods

Study area

Climate of the Coquimbo Region ranges from arid Mediterranean-type in the north (Elqui province) to semiarid Mediterranean-type towards the southern end (Limarí and Choapa provinces). Mean annual temperatures and precipitation vary from 14.8 °C and 127.4 mm in the north to 14.2 °C and 334.3 mm in the south, respectively (Di Castri and Hajek 1976). Plant communities are characterized by high endemism and diversity of xerophytic shrubs, cacti, and a seasonal herbaceous cover. Small and medium-sized Cu and Au mine operations have been common in the area since the nineteenth century, leaving more than 300 ATDs scattered throughout the region (Casale et al. 2011). Cu tailings in the region came from mines that processed porphyry Cu, characterized by a high mineral Cu (chalcopyrite) content, using alkaline foam flotation processes (Dold and Fontboté 2001).

Seventy-three ATDs throughout the Coquimbo Region were selected for the present study (Table 1), according to the following criteria: (1) minimal disturbance after abandonment; (2) no or low introduction of exotic plants (revegetation or forestation); (3) no incorporation of foreign substrates or soil amendments; and (4) year of abandonment ideally documented.

Geobotanical surveys

Geobotanical surveys were performed in selected ATDs (Table 1) and their surrounding areas according to Baker and Brooks (1989); each ATD was only visited for 1 week (spring for good representation of flora and vegetation) and all surveys were done from March 2005 to December 2007. At each ATD, composite samples were made of five subsamples of surface tailings (0–20 cm depth) collected both from dam walls and the consolidated tailings (Fig. 1). Composite soil samples (eight subsamples at 0–20 cm depth) were also collected up to 80–100 m away from each ATD. All substrate samples were transported to the laboratory to be physicochemically characterized, as described below.

Spontaneous vegetation established on ATDs and surrounding areas was characterized in terms of plant richness (number of plant species) and coverage (projection of aerial biomass of plants onto the ground, expressed as a fraction of the total area), according to methods described by Mueller-Dombois and Ellenberg (1974). All vascular plants were registered, herborized, and taxonomically identified; total plant coverage was estimated from five 30-m-long linear transects evenly and radially distributed along ATDs and selected sites in surrounding areas. Aerial tissue samples (last growth season for perennial plants and whole shoots for herbs and/or grasses) of dominant plant species were collected for at least three randomly selected individual plants. Tissue samples were stored in clean paper bags and transported to the laboratory for further processing, as described below. The Spatz index (Mueller-Dombois and Ellenberg 1974) was calculated from plant species composition and abundance to analyze the floristic similarity of vegetation present on ATDs and surrounding areas. It ranges from null (0%) to complete similitude (100%); this index is more sensitive to changes in plant abundance than other similarity indexes. The Spatz index was calculated using the Ginkgo program version 1.5.0 (Bouxin 2005).

Physicochemical characterization of substrates

Substrate samples were oven dried at 30 °C, sieved to 2 mm, and stored. Fractions less than 2 μm were determined by granulometry using the method of Bouyoucos (USDA 2004). The substrate pH, electrical conductivity (EC), CEC, organic matter (OM), and sulfate content were determined using USDA protocols (USDA 2004). Total concentrations of metals (Cu, Zn, and Fe) and Ca were determined by atomic absorption spectrophotometry, after acid ($HNO_3/HF/H_2O_2$) digestion and extraction in a microwave oven, using method 3051 of the US EPA (1995); duplicate samples, blank samples, and certified reference material (B-Loam from High-Purity Standard, Charleston, SC, USA) were also analyzed to meet the criteria for quality assurance and quality control.

Determination of metals in aerial tissues

Aerial tissue samples were sequentially washed with tap water and ultrapure water ($>18\ M\Omega\ cm^{-1}$) to eliminate external contamination. Shoots were air dried at 30 °C to a constant weight, pulverized in a grinder with stainless steel blade, and placed in clean polyethylene containers (US EPA 1995). Metals (Cu, Zn, and Fe) were analyzed as described previously. The standard reference material sample used was SRM 1573a tomato leaves (National Institute of Standards and Technology, Gaithersburg, MD, USA).

Statistical analyses

One- and two-way analyses of variance were used to test for differences in physicochemical characteristics and metal concentrations in aerial tissues among substrate types (soils from surroundings, consolidated tailings, dam wall tailings) and/or geographic location (Elqui, Limarí and Choapa provinces). Fisher's least-significant difference test was used for a posteriori comparison. When required, characteristics were corrected for non-normality using logarithmic transformations ($x' = \log10\ [x]$). Simple linear regressions were used to evaluate statistical relations between the physicochemical characteristics of tailings and floristic similarity of ATDs and surrounding soils with either time since abandonment or surface area. The InfoStat program (Grupo InfoStat, Universidad Nacional de Córdoba, Argentina), version 2010p, was used to perform the statistical analyses. Canonical correspondence analyses (CCAs; Leps and Šmilauer 2003) were conducted to determine whether selected physicochemical characteristics of substrates (soils and tailings) explained the compositional variation of vegetation on ATDs at a regional level. To obtain a CCA ordination model that only included those physicochemical characteristics of substrates that contribute significantly to species composition, a forward selection of explanatory variables was made. The statistical significance of the contribution

Table 1 Location and general characteristics of selected abandoned tailing dumps for geobotanical surveys performed in north-central Chile (Coquimbo Region)

Abandoned tailing dump	Province	Ore processing	Location (UTM)		Altitude (m.s.l.)	Surface (ha)	Years since abandonment	Introduction of exotic plants	Total Cu (mg/kg)
			North	East					
Indey	Elqui	Gold	6.651.973	299.590	1070	1.91	26	No	1466
Nueva Esperanza	Elqui	Gold	6.651.297	300.501	1040	0.72	31	No	2875
Urquieta 1	Elqui	Gold	6.652.149	297.484	1064	1.76	18	No	2209
Urquieta 2	Elqui	Copper	6.651.926	297.489	1077	0.96	18	No	375
Victoria	Elqui	Gold	6.654.380	300.778	1045	0.57	26	No	1602
Carlos Valentín	Elqui	Copper/gold	6.657.257	287.133	283	0.53	9	No	673
Danae	Elqui	Gold	6.667.342	284.948	155	2.38	26	No	1724
Tambillos	Elqui	Copper/gold	6.657.364	284.121	204	3.58	24	No	1841
Blanquita	Elqui	Gold	6.733.669	285.257	496	0.27	31	No	10,431
Don Moisés	Elqui	Gold	6.749.244	298.284	318	0.45	9	No	3678
Enriqueta	Elqui	Copper	6.750.868	294.044	274	0.55	>5	No	4901
La Pajita	Elqui	Gold	6.732.882	285.417	542	0.65	13	No	2700
San Ramón	Elqui	Gold	6.751.532	293.011	264	0.67	15	No	1839
Tesoro	Elqui	Copper/gold	6.750.475	299.819	344	1.90	>5	No	3077
Aliaga	Elqui	Gold	6.678.250	303.495	286	1.47	31	No	5632
Esperanza	Elqui	Gold/copper	6.696.880	282.175	20	0.73	13	No	4121
La Estrella	Elqui	Gold	6.675.797	296.619	394	0.02	26	No	1007
Lambert	Elqui	Gold	6.696.615	295.035	190	0.55	26	No	7316
Las Rojas	Elqui	Gold/copper	6.681.953	301.996	235	1.63	>5	No	1468
Pajonales	Elqui	Copper	6.685.611	294.381	131	1.89	31	No	2316
Rolex	Elqui	Gold	6.680.127	302.043	241	0.23	8	No	1832
La Viñita	Elqui	Gold	6.702.958	330.174	1196	Undetermined	13	No	503
Marianita	Elqui	Gold	6.679.534	307.059	289	1.08	>5	No	552
San Luis (old)	Elqui	Gold	6.675.235	303.292	370	Undetermined	>5	No	486
San Luis	Elqui	Gold	6.676.579	303.839	332	0.41	>5	No	2064
El Bronce	Limarí	Gold	6.556.198	294.431	828	0.80	31	No	2999
El Huimo	Limarí	Copper	6.581.633	294.865	795	0.02	>5	No	3276
Flor del Valle	Limarí	Copper	6.545.212	303.992	840	2.21	14	No	2386
Quilitapia	Limarí	Gold	6.656.073	294.148	818	Undetermined	14	No	3587
Rosario	Limarí	Gold	6.558.512	317.103	922	1.20	>5	No	4301
San Antonio	Limarí	Gold	6.555.937	294.114	805	0.13	26	Yes	2916
San Martín	Limarí	Gold	6.550.212	308.627	820	Undetermined	8	No	2508
San Sebastián	Limarí	Gold	6.557.226	294.280	802	1.59	18	No	915
Yabú	Limarí	Copper	6.550.252	308.394	890	3.35	>5	No	3299
El Pingo	Limarí	Gold	6.586.470	348.864	1700	Undetermined	8	No	5653
Huana	Limarí	Copper	6.601.387	313.109	454	0.49	13	No	1166
San Miguel	Limarí	Gold	6.589.554	347.458	1315	Undetermined	13	No	3014
El Cobre	Limarí	Copper	6.638.187	294.559	555	0.32	14	No	12,930
El Incienso	Limarí	Copper	6.627.788	292.153	385	1.13	>5	No	7063
La Cabra - Talinay	Limarí	Gold	6.577.084	244.006	18	2.97	>5	Sí	255
Planta Ovalle (La Cocinera)	Limarí	Copper	6.618.667	291.524	315	10.66	>5	Yes	6136
Ariqueñita	Limarí	Gold	6.583.984	285.192	231	Undetermined	26	No	3368
Camila	Limarí	Gold/copper	6.583.648	285.534	265	4.06	>5	No	4879
Camila (old)	Limarí	Gold/copper	6.583.775	285.287	241	1.42	12	No	5224
Delirio	Limarí	Copper/gold	6.581.970	286.086	294	4.73	26	No	624
El Trinfo	Limarí	Gold	6.588.294	301.914	749	1.34	26	No	2474

Table 1 (continued)

Abandoned tailing dump	Province	Ore processing	Location (UTM)		Altitude (m.s.l.)	Surface (ha)	Years since abandonment	Introduction of exotic plants	Total Cu (mg/kg)
			North	East					
Los Mantos	Limarí	Gold/copper	6.584.124	285.924	247	0.10	>5	No	5431
Punitaqui (tranque 1)	Limarí	Copper	6.586.337	285.063	236	0.80	>5	No	5091
Punitaqui (tranque 2)	Limarí	Copper	6.586.337	285.063	236	0.96	>5	No	3715
Punitaqui 1 y 2	Limarí	Gold	6.585.366	284.750	218	0.55	31	No	6461
Segura	Limarí	Gold	6.579.976	292.721	705	0.32	26	No	2169
El Algarrobo	Limarí	Gold	6.629.716	308.523	584	0.77	14	No	1180
Las Palmas	Limarí	Copper	6.636.116	320.786	784	0.09	26	No	4111
Miriam	Choapa	Gold	6.524.489	268.331	315	0.42	16	No	304
Canela Baja	Choapa	Gold	6.522.995	265.628	267	0.04	7	No	974
El Maitén	Choapa	Gold	6.494.973	286.685	230	2.06	14	Yes	1318
Pluma de Oro	Choapa	Gold	6.497.821	294.309	306	1.18	>5	No	2256
California	Choapa	Gold/copper	6.498.376	296.615	372	1.82	6	No	2299
San Jorge	Choapa	Gold	6.498.488	295.157	316	1.19	>5	No	127
San Antonio	Choapa	Gold	6.499.174	296.269	304	0.39	14	No	3364
Anta Colla	Choapa	Copper	6.500.243	296.797	376	6.20	14	No	1373
Hernández	Choapa	Gold	6.501.469	298.318	400	3.05	20	No	5699
Santa Clara (ex Aucó)	Choapa	Copper	6.505.517	300.749	443	0.38	14	No	12,876
Don Roberto	Choapa	Copper	6.518.594	307.992	763	0.98	21	No	1820
Horizonte	Choapa	Copper	6.518.016	305.659	690	0.43	14	No	3935
El Canelillo	Choapa	Gold	6.523.082	302.078	870	0.83	11	No	3809
Esperanza 1	Choapa	Copper	6.524.981	304.745	1259	1.11	11	No	395
La Fortuna	Choapa	Gold	6.523.410	302.036	879	0.28	>5	No	2129
Los Canelos	Choapa	Gold/copper	6.528.566	300.299	1177	0.69	16	No	4507
Caimanes (ex Isamit)	Choapa	Gold	6.464.575	298.853	501	0.73	26	No	9211
Las Vacas	Choapa	Gold	6.472.175	280.713	200	6.11	8	Yes	44
Los Pelambres (El Chinche)	Choapa	Copper	6.476.107	349.547	1452	35.26	13	Yes	620
San Eliseo	Choapa	Copper	6.482.591	312.255	481	1.88	14	No	7217

of physicochemical variables of substrate was assessed using a partial Monte Carlo permutation test with 1000 permutations. In this test, the candidate physicochemical variable of the substrate was used as the only explanatory variable (ordination model with just one canonical axis), considering the other physicochemical variables already selected as co-variables. The statistical significance of the CCA model was evaluated using a permutation test of Monte Carlo based on the sum of all canonical eigenvalues and considering 1000 permutations. To isolate the effect of physicochemical variables of the substrate on species abundance from latitude, partial CCA tests were conducted, considering latitude as a co-variable. CANOCO 4.5 (Microcomputer Power, Ithaca, NY, USA) was used to conduct the CCA.

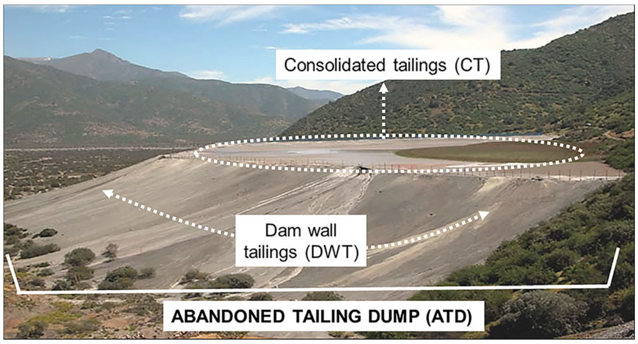

Fig. 1 Photograph of an abandoned tailing dump (ATD) in north-central Chile, indicating location of consolidated tailings and dam wall tailings considered for the geobotanical surveys (Photo by Rosanna Ginocchio)

Results

Physicochemical characteristics of substrates

Physicochemical characteristics of consolidated tailings, dam wall tailings, and surrounding soils by provinces (Elqui, Limarí, and Choapa) are shown in Table 2. A significant difference according to geographic location was only found for OM while significant differences according to substrate type were found for texture, CEC, OM, sulfate, total Cu, and total Fe. The interaction factor among geographic location × substrate type was only significant for OM and textural fractions <2 μm and 50–2000 μm (Table 2). OM significantly increased from north to south of the study area (0.3% Elqui < 0.5% Limarí < 0.6% Choapa), following the arid to semiarid gradient; it was also an order of magnitude higher in soils than in tailings (1.0 ± 0.8% soils and 0.3 ± 0.3% tailings). According to the USDA textural classification chart for soil (Soil Survey Staff 1993), both soils and dam wall tailings were sandy loam, whereas consolidated tailings were silt loam. The CEC was one order of magnitude lower in tailings than in soils, whereas sulfate, total Cu, and total Fe were one order of magnitude higher in tailings than in soils. No significant differences were found for these characteristics among consolidated tailings and dam wall tailings, with the exception of sulfate content, which was 1.8 times higher on consolidated tailings. Even though total Cu and Fe concentrations were higher in tailings than in surrounding soils, there was high variability among ATDs for these characteristics (Table 2).

Flora and vegetation

A total of 195 plant species were identified on both ATDs and surrounding soils, belonging to 50 families. For ATDs, mean plant richness was 7 and a total of 112 spontaneous plant species, belonging to 37 families, were found. Native/endemic species were more abundant than exotics (67 and 33%, respectively) and the main families were Asteraceae (27%) and Poaceae (11%). Most plant species (80%) were only present in less than 10% of ATDs, but 10 plant species were frequently (>20% of ATDs) found on ATDs. A mean plant coverage of 4 ± 6% was found in ATDs, with a range of 0.1–26%; there was a significant and positive ($R = 0.82$, $P < 0.01$) relation between coverage of plant species and percentage of occurrence on ATDs (Fig. 2). Dominant species (coverage >10% and percentage of occurrence >20%) on ATDs were *Baccharis linearis*, *Baccharis marginalis*, *Bromus berterianus*, *Erodium cicutarium*, *Muehlenbeckia hastulata*, *Pleocarphus revolutus*, *Schinus molle*, *Schinus polygama*, *Schismus arabicus*, and *Tessaria absinthioides*. On surrounding areas, the same general trends were found; most species belonged to the Asteraceae (25%) and Poaceae (11%), and native/endemic species were more abundant than exotics (68 versus 32%). However, plant richness and coverage of dominant species were higher than on ATDs. Floristic similarities among ATDs and surrounding areas varied from 0 to 36%, with a mean of 3.3%. Therefore, pioneer plants on ATDs represented a subgroup of the plant species present in surrounding areas. Floristic similarity significantly increased ($R = 0.49$, $P < 0.01$) with time of abandonment of ATDs (Fig. 2), but was independent of surface area ($R = 0.02$, $P = 0.863$). Plant changes with time were slow and variable; after 31 years of abandonment, the floristic similarities of vegetation on tailings versus the surrounding area ranged from 1.6 to 13.3% (Fig. 2).

Metal concentrations in aerial tissues

Table 3 shows the shoot metal concentrations (Cu, Zn, and Fe) of pioneer plants (percentage of occurrence >5%) growing on both ATDs and surrounding soils. Mean Cu, Zn, and Fe concentrations in aerial tissues broadly varied among plant species, and in general, no significant differences were found among substrates (Table 3). The exceptions were *Haplopappus parvifolius* and *Senecio bridgesii* for Cu, *H. parvifolius* and *S. molle* for Zn, and *B. linearis*, *B. marginalis*, *Haplopappus macraeanus*, and *P. revolutus* for Fe, which showed higher metal concentrations when they were on tailings than on soils (Table 3). Mean shoot Cu and Zn concentrations of common spontaneous plant species growing on tailings ranged from 11 mg to 804 mg Cu kg^{-1} (dry weight basis) and from 17 mg to 191 mg Zn kg^{-1}, respectively (Table 3). However, metal concentrations in aerial tissues of plants growing on tailings and surrounding soils did not differ statistically (Table 3), even though total metal concentrations were higher in tailings than in surrounding soils (Table 2). Only Cu concentrations were significantly and positively correlated to Zn and Fe levels in tissues of plants growing on tailings ($R = 0.22$ for $P = 0.01$ and $R = 0.64$ for $P = 0.01$, respectively) and on surrounding soils ($R = 0.33$ for $P = 0.01$ and $R = 0.62$ for $P = 0.01$, respectively).

Relations among physicochemical characteristics of substrates and abundance of plant species

Only 2 (total Cu concentration and the percentage of particles in the substrate that were <2 μm; Fig. 3) out of the 12 physicochemical parameters considered (Table 2) significantly contributed to the CCA ordination model ($P \leq 0.05$; partial Monte Carlo permutation test; Table 4). The relation between the variation in floristic composition and the total Cu concentration and the percentage of particles <2 μm was statistically significant (*F* ratio = 2.010, $P = 0.001$). The CCA ordination diagram (Fig. 3) shows the distribution of sites (ATDs and surrounding areas) according to the weighted average of species present in each site, in direct relation to the substrate characteristics determined for each site. A 100% of the total variation of the species–substrate relation was explained by the first two axes of the ordination model (Fig. 3) and the total inertia that was constrained corresponded to 3.1%. The percentage of particles <2 μm (canonical $r = 0.78$) was the variable most correlated with the first canonical ordination axis,

Table 2 Physicochemical characteristics of substrates located at consolidate tailings (CT), dam wall tailings (DWT), and surrounding soils (SS) per zone of the Coquimbo Region, north-central Chile

Zone	Subs.	Number	pH	EC	CEC	OM (%)	Texture (%)			Sulfate	Total (mg/kg)			
				(dS/m)	(cmol+/kg)		<2 μm	2–50 μm	50–2000 μm	(mg/L)	Cu	Zn	Fe	Ca
Elqui	CT	26	7.1 ± 1	5.2 ± 4.5	8.7 ± 4.9b	0.2 ± 0.2a	14 ± 10.4cd	44 ± 12.6c	43 ± 19a	2927 ± 3936bc	2217 ± 2039bc	590 ± 1581	97,112 ± 99,080b	17,152 ± 16,314
	DWT	24	7.3 ± 1	3.1 ± 3.0	7.2 ± 3.6ab	0.2 ± 0.1a	9.0 ± 8.9ab	24 ± 11.4ab	67 ± 16.6def	1710 ± 2692ab	3217 ± 3564cd	339 ± 595	98,083 ± 92,116b	18,935 ± 18,209
	SS	22	7.7 ± 0.6	3 ± 4.3	12.9 ± 4.6cd	0.6 ± 0.4b	12 ± 4.9bcd	17 ± 5.5a	71 ± 9.2f	373 ± 498a	810 ± 1601ab	119 ± 81	52,736 ± 16,477a	15,086 ± 6383
Limarí	CT	28	7.5 ± 1.5	7.2 ± 20.1	6.7 ± 3.1ab	0.2 ± 0.2a	10 ± 4.9abc	37 ± 18.5c	53 ± 20.9bc	1728 ± 2634ab	3616 ± 2619cd	934 ± 2432	77,826 ± 70,288ab	12,685 ± 11,080
	DWT	28	7.8 ± 1.1	7.1 ± 24.0	6.2 ± 2.9a	0.2 ± 0.1a	10 ± 3.5ab	29 ± 14.6b	61 ± 16.3cde	1638 ± 2997ab	4036 ± 2724d	584 ± 2432	77,970 ± 60,807ab	14,193 ± 17,241
	SS	25	7.1 ± 0.7	1.7 ± 1.6	14.7 ± 5.1d	1.1 ± 0.8c	17 ± 5.8e	22 ± 8.5a	61 ± 11.3cd	321 ± 851a	803 ± 669a	133 ± 128	52,300 ± 17,155a	9620 ± 5683
Choapa	CT	20	7.5 ± 1.7	5.3 ± 6.8	7.8 ± 5ab	0.4 ± 0.4ab	13 ± 10.1bcd	41 ± 20.9c	46 ± 26.7ab	4268 ± 6908c	3296 ± 4737cd	128 ± 208	86,689 ± 63,996ab	19,605 ± 27,023
	DWT	20	7.7 ± 0.1	2.4 ± 1.7	6 ± 4a	0.3 ± 0.2a	7 ± 10.1a	23 ± 13.3ab	70 ± 14.4ef	1538 ± 1521ab	3132 ± 2674cd	92 ± 121	92,534 ± 65,715b	13,203 ± 20,717
	SS	20	7.5 ± 0.6	2.2 ± 1.7	12.2 ± 3.3c	1.1 ± 0.8c	15 ± 5d	21 ± 7.2a	64 ± 10.1def	893 ± 920a	1103 ± 983ab	99 ± 77	50,142 ± 16,945a	17,233 ± 12,195
P-zone			0.639	0.553	0.452	<0.05	0.568	0.85	0.678	0.151	0.236	0.109	0.446	0.131
P-subs.			0.452	0.198	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	0.122	<0.05	0.685
P-zone × subs.			0.224	0.773	0.061	<0.05	<0.05	0.074	<0.05	0.334	0.433	0.649	0.926	0.66

Mean and standard deviation values are given. Different letters in columns indicate significant differences

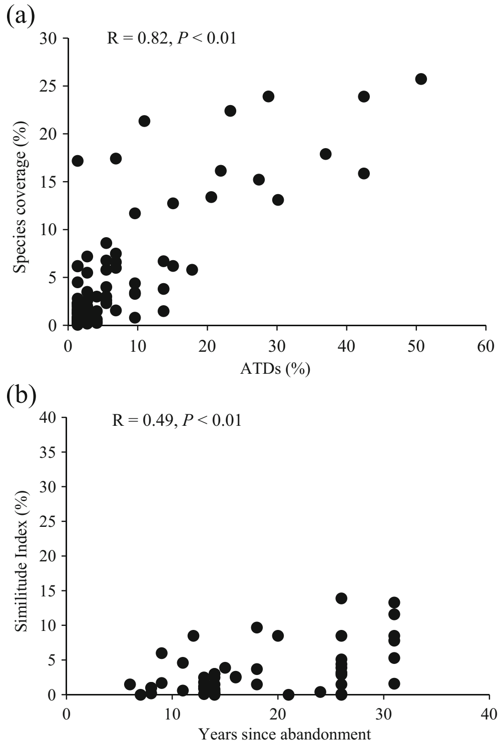

Fig. 2 Variation of species coverage on abandoned tailing dumps at the Coquimbo Region, north-central Chile (**a**) and variation of floristic similitude of abandoned tailing dumps with surrounding soils according to time since tailings abandonment (**b**). Coefficient of regression and significance of linear regression are given, excluding the outlier point (La Estrella tailings dump) for graph **b**

whereas total Cu concentration (canonical $r = 0.72$) was the variable most correlated to the second canonical ordination axis (Table 4), both of which explained the distribution of sites in the study area. The distribution of sites in the CCA ordination diagram (Fig. 3) indicated that there was a gradual and progressive variation in species composition from surrounding areas to ATDs because of variation in total Cu concentrations of substrates and percentage of particles <2 μm. Plant species present at the sites (tailings plus surrounding areas) are displayed in the ordination diagram of Fig. 4. In this diagram, the orthogonal projection of the plant species (stars) on any physicochemical vector indicates approximately the relative value on a weighted average for each species regarding the vector. Thus, the plant species *Haplopappus bezanillanus*, *Baccharis paniculata*, *Sphacele salviae*, *Atriplex numularia*, *Rapistrum rugosum*, *Bromus catharticus*, *Gymnophyton robustum*, and *Senecio adenotrichius* had the highest weighted averages in terms of the total Cu concentration and the percentage of particles <2 μm, suggesting that their greater coverage (%) occurred in sites with the highest total Cu concentration and finer substrates. Latitudinal variation of the study area was large; therefore, a partial CCA was conducted considering latitude as a co-variable, for determining the contribution to the model of every physicochemical parameter that could not be explained by latitude (Table 5). Total Cu concentration in the substrate explained 1.3% of the total variation in plant species abundance, whereas the percentage of particles <2 μm explained 1.8% of the total variance. When latitude was considered as a co-variable in the CCA ordination model, constrained inertia was only reduced by 1.8% and the significance of the model remained (F-ratio = 1.995; $P = 0.001$). This suggested that the effect of both physicochemical parameters selected on plant species composition was independent of latitude (Table 1).

Discussion

Acidity, metal toxicity, and/or low nutritional availability (Mendez and Maier 2008; Schippers et al. 2000; Li and Huang 2015) have been generally considered the main factors restricting spontaneous plant colonization and establishment on ATDs. However, our study demonstrate that from 12 physicochemical characteristics considered (Table 2), content of fine particles (percentage of particles <2 μm) and total Cu content of tailings are the main factors restricting spontaneous colonization of ATDs in semiarid Mediterranean-climate type ecosystems in north-central Chile. Under both conditions, high percentage of fine particles and total Cu concentration found in tailings (particularly on consolidated tailings), only a subset of plant species (*H. bezanillanus*, *B. paniculata*, *S. salviae*, *A. nummularia*, *R. rugosum*, *B. catharticus*, *G. robustum*, and *S. adenotrichius*) was able to establish and growth, as shown by the CCA ordination model obtained in the present study (Fig. 4). On one hand, elevated content of fine particles in ATDs results in substrate compaction (high bulk density) with time (Lottermoser 2007), which may restrict root growth and therefore plant establishment as it has been shown for soils (Chen et al. 2014). On the other hand, total Cu content strongly varied among ATDs (range of 100 to 18,127 mg kg^{-1}) and with surrounding soils (mean values of 3252 and 905 mg kg^{-1}, respectively), as expected from literature (Lottermoser 2007). However, Cu toxicity to plants in tailings is only expected under high bioavailability of this element. Previous studies of our research group have demonstrated that Cu bioavailability in alkaline tailings is low as metals occurs in mineral form which are rather insoluble (Badilla-Ohlbaum et al. 2001; Ginocchio et al. 2006; Ginocchio et al. 2009; Verdugo et al. 2011). Weathering of tailings occurs when exposed to external environmental conditions (e.g., rain, presence of iron- and sulfur-oxidizing bacteria), leading to substrate acidification and dissolution of metals from primary minerals (Dold and Fontboté 2001; Lottermoser 2007). However, secondary acidification of tailings was a rare phenomenon in studied ATDs (Table 2), particularly due to semiarid climatic conditions of the area and elevated calcium contents of tailings (Table 2). Under

Table 3 Shoot metal concentration of common spontaneous plant colonizers (percentage of occurrence >5%) of abandoned tailing dumps in the Coquimbo Region, north-central Chile

Plant species	Copper (mg/kg)		Zinc (mg/kg)		Iron (mg/kg)	
	Tailings	Surrounding soils	Tailings	Surrounding soils	Tailings	Surrounding soils
Acacia caven	207 ± 324.9 (7)a	158 ± 399.8 (16)a	97 + 100.3 (6)a	69 ± 99.3 (16)a	1062 ± 758.4 (7)a	1221 ± 1600.4 (16)a
Baccharis linearis	53 ± 41.9 (33)a	93 ± 183.6 (22)a	88 ± 82.6 (33)a	58 ± 42.6 (22)a	651 ± 412.2 (33)a	409 ± 249.0 (20)b
Baccharis marginalis	75 ± 79.0 (14)a	36 ± 35.3 (9)a	85 ± 66.6 (14)a	43 ± 31.8 (9)a	815 ± 682.4 (14)a	366 ± 187.4 (9)b
Baccharis pingraea fma. *angustissima*	557 (1)	nd	60 (1)	nd	12,488 (1)	nd
Cestrum parqui	78 (1)	41 (2)	45 (1)	24 (2)	522 (1)	293 (2)
Cortaderia rudiuscula	11 (2)	30 (2)	35 (2)	18 (2)	202 (2)	317 (2)
Erodium moschatum	nd	21 (1)	nd	50 (1)	nd	485 (1)
Haplopappus cerberoanus	167 (2)	45 (2)	31 (2)	15 (2)	1851 (2)	1193 (2)
Haplopappus macraeanus	106 ± 53.5 (3)a	40 ± 32.5 (3)a	89 ± 53.5 (3)a	31 ± 2.6 (3)a	1490 ± 422.5 (3)a	630 ± 327.2 (3)b
Haplopappus parvifolius	804 ± 124.4a	69 ± 43.7 (6)b	191 ± 110.2 (3)a	51 ± 44.0 (6)b	3584 ± 2648.7 (3)a	2034 ± 2003.7 (6)a
Lithraea caustica	37 (2)	15 ± 3.8 (3)	17 (2)	12 ± 1.6 (3)	446 (2)	248 ± 18.4 (3)
Muehlenbeckia hastulata	30 + 24.6 (16)a	51 ± 114.0 (12)a	33 ± 14.7 (16)a	26 + 9.7 (12)a	694 ± 915.8 (16)a	608 ± 615.2 (11)a
Nicotiana glauca	78 ± 19.2 (4)	351 (1)	105 ± 76.1 (4)	68 (1)	359 ± 158.9 (4)	711 (1)
Nolana albescens	1316 (1)	624 (1)	41 (1)	45 (1)	25,287 (1)	21,103 (1)
Ophryosporus paradoxus	nd	91 ± 95.7 (3)	nd	33 ± 11.5 (3)	nd	1761 + 1166.1 (3)
Pleocarphus revolutus	434 ± 325.3 (6)a	281 ± 447.9 (17)a	56 ± 30.9 (7)a	44 ± 44.3 (17)a	11,015 ± 8813.7 (7)a	4355 ± 6064.7 (17)b
Schinus molle	55 ± 47.4 (17)a	70 ± 112.9 (13)a	45 ± 44.1 (17)a	22 ± 11.7 (13)b	602 ± 449.7 (17)a	633 ± 763.1 (13)a
Schinus polygama	38 ± 2502 (10)a	23 ± 29.8 (14)a	19 + 7.4 (11)a	17 + 6.4 (13)a	482 ± 275.9 (10)a	314 ± 209.5 (14)a
Schkuhria pinnata	93 (2)	61 ± 46.6 (12)	37 (2)	34 ± 36.9 (12)	1816 (1)	979 ± 341.0 (12)
Scirpus asper	150 ± 111.3 (4)	9 (1)	50 ± 40.0 (4)	11 (1)	3241 ± 4996.4 (4)	242 (1)
Senecio bridgesii	63 ± 35.0 (3)a	14 ± 6.4 (3)b	39 + 24.0 (3)a	45 + 41.8 (3)a	265 ± 153.8 (3)a	125 ± 102.9 (3)a
Solanum pinnatum	124 (1)	18 (1)	84 (1)	18 (1)	745 (1)	313 (1)
Tessaria absinthioides	105 ± 99.9 (16)a	171 ± 302.5 (10)a	91 ± 86.3 (16)a	50 ± 30.0 (10)a	1159 ± 1433.2 (16)a	905 ± 1138.0 (10)a
Typha angustifolia	16 ± 9.7 (3)	nd	43 ± 36.3 (3)	nd	176 ± 57.4 (3)	nd

Mean, standard deviation, and number of sites sampled are given. Different letters among sites per metal and plant species indicate significant differences (*T*-student, $P = 5\%$). nd indicates not determined due to scarce availability of aerial plant tissues

semiarid climatic conditions, high evapotranspiration rates contribute to the development of calcium carbonate (gypsum) and metal carbonate forms at tailings surface (Lottermoser 2007), thus reducing metal solubility (Dold and Fontboté 2001). Therefore, further studies on Cu bioavailability and thus phytotoxicity have to be performed in selected tailings, as Cu speciation studies were not included in the present study.

A number (112) of spontaneous plant colonizers were found in selected ATDs of north-central Chile, 10 of them being dominant (coverage >10% and percentage of occurrence on ATDs >20%). None of them was exclusively established on ATDs, unlike metalliferous habitats where strongly distinctive plant communities resulting from deterministic species selection by environmental filters have been described (Conesa et al. 2007; Parraga-Aguado et al. 2013). It is interesting to note that some dominant pioneer species (e.g., *B. linearis*) found on selected ATDs has been already described as pioneer and nurse plant species in highly disturbed sites of north-central Chile (Bustamante 1991), including abandoned mine tailings (Cuevas et al. 2013). Native/endemic plants were more successful (67%) than exotics (Table 5) as pioneer species. This response could be explained by the adaptation of native/endemic plant species to local site conditions (e.g., drought, high radiation, nutrient availability, soil depth) and conditions of semiarid Mediterranean-climate type environments. For example, low-nutrient soils are commonly found in semiarid Mediterranean-climate type areas, whereas exotic weedy species have higher nitrogen requirements (Dallman 1998). Low colonization success by exotic weedy species has been also described on primary successions on disused gravel-sand pits (Rehounková and Prach 2010;

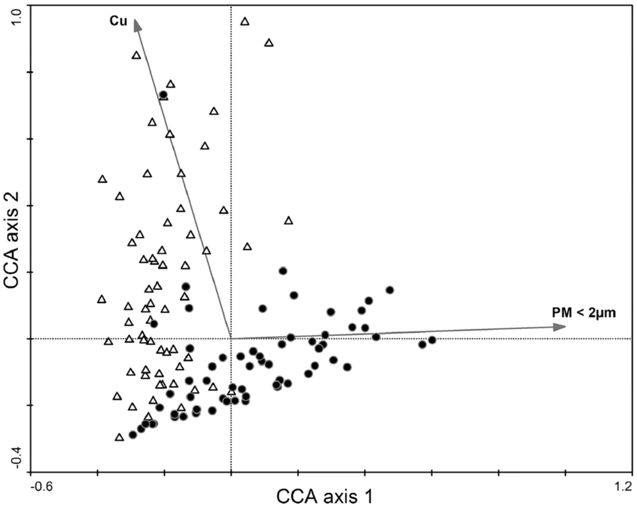

Fig. 3 Canonical ordination diagram illustrating the distribution of study sites (*open triangles*, abandoned tailing dumps; *solid circles*, surrounding soils) for vegetation (*n* = 127) and physicochemical parameters of substrates (*arrows*, *n* = 2). The first two axes explain 100% of total variance of the species physicochemical characteristics relationship. Percentage of total inertia that is constrained is 3.1

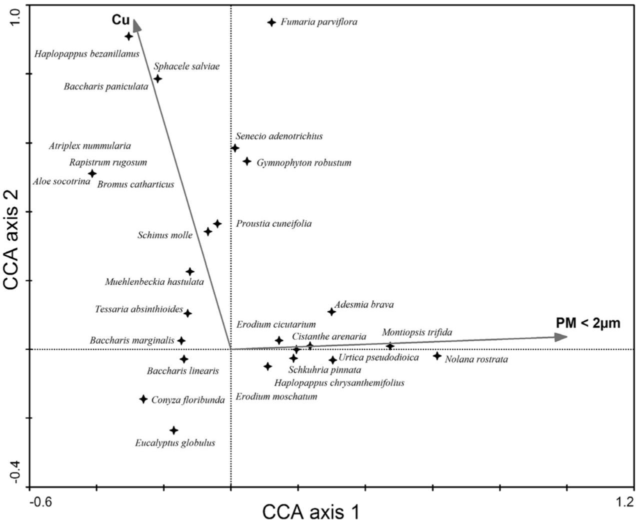

Fig. 4 Canonical ordination diagram illustrating the distribution of vascular plant species (*stars*; *n* = 27) and physicochemical parameters of substrates (*arrows*, *n* = 2). Distribution of plant species (*stars*) is shown according to their weighted average values for total Cu concentration and the percentage of particles <2 µm of substrates. Only the plant species well related to the ordination axes are included (5% of minimal adjust)

Šebelíková et al. 2016). In agreement with our results, Asteraceae and/or Poaceae have been described as the most represented families on ATDs in other places like southern China (Shu et al. 2005), southern Spain (Conesa et al. 2007), and India (Das and Maiti 2007). Initial plant colonization success is related to seed traits that determine the dispersal ability of the species, such as anemochory and wind dispersal, common in Asteraceae (Table 5) and the production of light diasporas (small seeds, common in Poaceae), which are generally advantageous for long-distance dispersal (Rehounková and Prach 2010).

Species richness increased with time since abandonment in studied ATDs of north-central Chile. However, plant changes with time were slow and variable among ATDs of similar abandonment time, leading to a maximum coverage of 26% after 31 years after abandonment. Changes in ATDs have been described as being very slow and very limited in terms of species richness and plant colonization (Shooner et al. 2015). For example, after 18 years, ATDs might still have limited plant colonization, with total plant covers being <3% (Shu et al. 2005). It is interesting to note that an increment of species richness with time was independent of the surface area of ATDs (Fig. 2). It has been reported that the succession process can depend more on the physicochemical parameters of tailings than on their surface area, at least during the early revegetation stages (Shu et al. 2005). In the present study, percentage of fine particles (<2 µm) and total Cu concentration in the substrate were found to be the main physicochemical parameters that explained the changes in spatial variation of plant species across ATDs and surrounding soils (31% of variation was explained by these factors). However, a large percentage of variation (69%) of the plant species–substrate relation remained unexplained, indicating the need to explore other environmental (e.g., microtopography of tailings, precipitation, wind speed) and microenvironment (substrate aggregation, presence of heterotrophic microbial communities) parameters in future studies, as it has been stated in the literature (Mendez and Maier 2008; Moreno-de las Heras 2009). For example, spontaneous plant colonization of ATDs has been described to be limited and unevenly distributed, being generally restricted to small patches in dam walls and on the edges of platforms on consolidated tailings (Conesa et al. 2007; Das and Maiti 2007; Moreno-de las Heras et al. 2008). Spontaneous plant colonization is also found in favorable microsites of consolidated tailings, such as cracks and manure deposits or sites below nurse pioneer shrubs with relatively higher OM and nutrient contents, and better water retention and infiltration (Shu et al. 2005; Cuevas et al. 2013). For ATDs in north-central Chile, this pattern could be

Table 4 Correlation coefficients among the first two axes of a canonical correspondence analysis and two selected physicochemical characteristic of substrates

Physicochemical parameter	Correlation coefficients		*F* ratio (*P* value)
	Axis 1	Axis 2	
Total Cu concentration	−0.23	0.72	1.61 (0.010)
Percentage of particles <2 µm	0.78	0.03	2.40 (0.001)

Significance *P* value and *F* ratio of a partial Monte Carlo permutation test (forward selection) are given

Table 5 Variance of the plant species data explained by the physicochemical characteristics of substrate total copper concentration and percentage of particles <2 μm in a canonical ordination model where latitude is considered as co-variable of the physicochemical factors

Physicochemical parameter	Percentage of total variance* explained by physicochemical variable	Percentage of total variance* explained by latitude	Percentage of total variance* explained by physicochemical variable and latitude	Percentage of total variance* that is not explained by physicochemical variable
Total Cu concentration	1.8	1.8	0.06	96.3
Percentage of particles <2 μm	1.3	1.9	0	96.8

Percentage of total variance of plants species data only explained by latitude is also given (second column)

*Total inertia = 19.912

explained in part by changes in the physicochemical parameters across dam wall tailings and consolidated tailings. Indeed, consolidated tailings appear to be harsher substrates than dam wall tailings for plant establishment and growth, because the percentage of particles <2 μm, sulfate concentration, and EC values were higher for the former. Mean EC values for consolidate tailings (provincial level) were all above 4 dS m^{-1}, rendering them saline substrates. Elevated sulfate concentrations in consolidated tailings (and, consequently, high EC values) could be explained by the occurrence of secondary metal sulfide oxidation (i.e., pyrite and FeS_2), with the formation of sulfuric acid and reduction in pH (acid mine drainage) (Dold 2017). In arid and semiarid climates, where evaporation exceeds precipitation, the secondary sulfide oxidation phenomenon is restricted to upper tailings (oxidation zone); therefore, because the migration of water is upwards via capillary forces, super saturation controls the precipitation of mainly water-soluble secondary sulfates and strong salt enrichment at the top of consolidated tailings (Dold and Fontboté 2001).

Shoot metal concentrations of pioneer plants on ATDs have been frequently described as elevated (Shu et al. 2005; Conesa et al. 2007; Das and Maiti 2007). However, this was not a general finding in the current study; with few exceptions (*H. parvifolius*, *H. macraeanus*, *S. bridgesii*, *S. molle*, *B. linearis*, *B. marginalis*, *and P. revolutus*) (Table 6), the shoot metal concentrations of pioneer species were similar to concentrations found for the same species in surrounding soils. This finding could be interpreted as a shoot metal exclusion strategy (Baker et al. 2010), a positive characteristic expected for the phytostabilization of ATDs (Solís-Domínguez et al. 2012); however, we did not determine root metal concentrations. This finding might also result from shoot exposure to air-borne tailing particulates. Plant tissues were thoroughly washed before metal determination, but the possibility exists that persistent external contaminants on the aerial tissues could not be completely removed, particularly because of the presence of trichomes and/or resin glands in the leaves of these drought-tolerant plants (Dallman 1998). By contrast, similarities in terms of the lowest metal levels might also result from the low bioavailability to plants of these metals on tailings (Ginocchio et al. 2006; Das and Maiti 2007).

Our findings highlight the interesting potential of native/endemic species for use in plant-based remediation technologies (phytostabilization or phytoextraction) for stabilizing ATDs located in semiarid Mediterranean-climate type environments of north-central Chile. Dominant plant species identified on studied ATDs are able to tolerate multiple environmental stresses, both substrate (e.g., poor nutritional content,

Table 6 Dominant plant species growing on abandoned tailing dumps at Coquimbo Region, north-central Chile

Species	Growth form	Seed dispersal syndrome	Origin
Baccharis linearis (Asteraceae)	Shrub	Anemochorous	Native
Baccharis marginalis (Asteraceae)	Shrub	Anemochorous	Native
Bromus berterianus (Poaceae)	Herbaceous annual	Anemochorous	Exotic
Erodium cicutarium (Geraniaceae)	Herbaceous annual	Zoochorous	Exotic
Muehlenbeckia hastulata (Polygalaceae)	Shrub	Not determined	Native
Pleocarphus revolutus (Asteraceae)	Shrub	Anemochorous	Native
Schinus molle (Anacardiaceae)	Tree	Zoochorous	Native
Schinus polígama (Anacardiaceae)	Tree	Zoochorous	Native
Schismus arabicus (Poaceae)	Herbaceous annual	Anemochorous	Exotic
Tessaria absinthioides (Asteraceae)	Shrub	Anemochorous	Native

low OM content) and climate (e.g., water stress) based. However, further studies are needed to determine the metal tolerance of pioneer plant species and their propagation requirements, among other autecological characteristics.

Conclusions

The present study showed that acidity, metal toxicity, and/or low nutrient levels are not the only and/or the main factors limiting spontaneous plant colonization of ATDs. From all physicochemical characteristics evaluated in the present study (e.g., pH, OM, EC, sulfate), content of fine particles (percentage of particles <2 μm) and total Cu concentration of tailings are the main factors restricting spontaneous colonization of ATDs in semiarid Mediterranean-climate type areas of north-central Chile. However, further studies are needed to verify Cu bioavailability and thus plant toxicity of these tailings. Unlike other studies that stated tailing acidity as a relevant factor restricting spontaneous plant colonization, secondary acidification of tailings was rare on studied ATDs due to semiarid climatic conditions and their elevated Ca content.

Ten plant species were identified as dominant pioneer species of ATDs in semiarid Mediterranean-climate type areas of north-central Chile (*B. linearis*, *B. marginalis*, *B. berterianus*, *E. cicutarium*, *M. hastulata*, *P. revolutus*, *S. molle*, *S. polygama*, *S. arabicus*, and *T. absinthioides*). None of them is exclusively found on ATDs, but most of them are native/endemic species adapted to local climatic and edaphic conditions of semiarid environments, in which seeds are spread out at large distances by the wind or animals. Few (e.g., *B. linearis*) have been previously described as pioneer and nurse species of highly disturbed sites in the area. These findings highlight the interesting potential of pioneer native/endemic species for being used in plant-based remediation technologies (phytostabilization or phytoextraction) for proper stabilization of ATDs located in north-central Chile.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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