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RESEARCH ARTICLE

Initial Soil Development Under Pioneer Plant Species in Metal Mine Waste Deposits

Joselito M. Arocena,^{1,2} Jan M. van Mourik,³ Madeleine L. M. Schilder,³ and Angel Faz Cano⁴

Abstract

Mine waste materials are often inhospitable to plants due to extreme pH, high salinity, very low organic matter, elevated metal contents, and poor physical conditions. We investigated initial soil development in three study areas under different pioneer plant species in degraded landscapes left behind by past mining activities in southeast Spain. Soil pH, electrical conductivity, cation exchange capacity, total carbon, nitrogen, and sulfur were determined, as well as micromorphology, using 12 soil thin sections prepared from materials collected under vegetated and unvegetated sites. Soils are alkaline or highly alkaline, whereas other parameters substantially vary between sites (e.g., C:N = 9–149). pH of waste materials ranges from 6.2 to 7.9 and higher than soil pH, whereas electrical conductivity and gypsum contents were lower in soils than waste materials except for the Portman Bay site. Mine waste materials are dominated by platy/laminated

microstructure, whereas incipient soils regardless of overlying pioneer species have granular structure of varying degrees of development. Roots of pioneer species break-up the dense laminae of waste deposits and initiate preferential water flow through root channels. These channels encourage biological activities, and hence enhanced the accumulation of soil organic matter. The variables we investigated are useful to assess the formation of soils in inhospitable environments in mined areas. For instance, mechanical alteration of laminated waste deposits can be initiated by plowing to encourage preferential flow paths, hence soil development. Amendment of mine wastes with organic materials can stimulate biological activities to hasten the formation of granular soil microstructure common in productive ecosystems.

Key words: degraded landscapes, fungal hyphae, granular soil microstructure, soil fauna, soil organic matter.

Introduction

Metal mining activities in the Sierra de Cartagena (SE Spain) after more than 2,500 years came to an end in early 1990s leaving behind large volumes (i.e., usually 700,000–900,000 m³/deposit) of mine wastes composed of overburden rocks, tailings, discarded infrastructures, and landscapes with very scarce vegetation. These waste materials are quite inhospitable to plant growth because of acidity (pH 2.0–7.6), high electrical conductivity (EC = 6–20 dS/m) and contain elevated contents of metals such as lead, Pb (5,000–8,000 mg/kg soil), and zinc, Zn (8,000–22,000 mg/kg soil) (Conesa et al. 2007).

Field observations in the Sierra de Cartagena showed that pioneer plant species such as *Hyparrhenia hirta* L. and *Zygochloa fabago* L. had colonized areas of low salinity in selected mine waste materials (Conesa et al. 2007). In highly saline areas, the dominant plant colonizers are *Phragmites australis* (Cavanilles), *Salicornia ramosissima* J. Woods, *Limonium carthaginens* (Boiss.) and *Tamarix boveana* Bunge. *Lygeum spartum* Loeff. ex L. is a minor species found in some saline areas. Pioneer plant species are known to tolerate unfavorable soil conditions and play a major role in reclamation of degraded mine soils (Freitas et al. 2003) by providing physical cover to minimize erosion.

In addition to physical protection, vegetation cover contributes to the pool of soil organic matter (SOM). Early plant colonizers like *L. spartum* contributed up to 11 kg SOM/kg soil in the Balsa Rosa site in southeast Spain since the mine closure in 1991 (Ottenhof et al. 2007). Soil organic matter increases water holding capacity and aeration, regulates temperature, contributes to cation exchange capacity, and promotes soil structure favorable to plants and organisms (Stevenson 1994; Sollins et al. 2006). In our earlier study (Ottenhof et al. 2007), we proposed that the addition of SOM to mine waste materials from pioneer species represents the early stages of soil formation, and with time, we expect

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the formation of well-developed Ah horizon on the surface of mine waste materials.

Formation of aggregated soil surface horizon rich in SOM can possibly transform mine waste materials into a functional ecosystem characterized by healthy soil capable of supporting diverse species of organisms. Aggregation is one of the best indicators for fertile soils because it bridges the physics and biochemistry of soil systems (Young & Crawford 2004). Soil scientists especially pedologists have been using the presence of structure to differentiate soils from nonsoil materials in addition to the contents of SOM.

The main objective of this study was to investigate the formation of soils in degraded mined sites. Specifically, we documented the different types of microstructure in soils under selected pioneer plant species such as *P. australis*, *T. boveana*, *Pinus halepensis* Mill., and *L. spartum*. The results have useful information to understand key ecosystem processes of soil formation in many degraded landscapes dominated by metal mine waste materials. We hope to provide the foundational knowledge to accelerate the formation of favorable soil conditions necessary to encourage the establishment of sustainable ecosystems in these otherwise derelict landscapes.

Methods

Study Area

The Sierra de Cartagena is situated in the province of Murcia (southeast Spain) (Fig. 1). The mining area is located on eastern side of the Cordillera Bética and is part of a wide volcano-tectonic and metallogenetic belt that extends from Cabo de Gata to Sierra de Cartagena. The climate is typically Mediterranean with average monthly temperature ranging from 9.3°C in January to 24.4°C in July and mean annual precipitation of 275 mm, mostly in autumn and spring. The potential evapotranspiration reaches 900 mm/year.

Figure 1. The geographical location of the study area in the Sierra de Cartagena, southeast Spain.

Sample Collection

We collected soil samples for chemical and micromorphological analyses from three representative mining deposits of different ages in the Sierra de Cartagena mining district: Portmán Bay, Balsa Galo, and Balsa Rosa. Portman Bay mine waste deposits consisted of more than 300 million tons of pyritic waste materials sedimented 30–35 years ago from the mineral wash facility that directly disposed wastes into the Mediterranean Sea (Departamento de Ciencias Sociales del I.E.S. Sierra Minera 2008). Balsa Galo site contained mine waste materials deposited approximately 20–25 years ago, whereas Balsa Rosa sites had mine waste materials accumulated approximately 12 or 13 years ago consisting mainly of mine residues from a zinc mine (Schilder 2003). Soil samples were taken in October 2003 from mine waste deposits at each mining areas to represent nonvegetated deposits and waste materials colonized by pioneer plant species. Because of variations in plant colonization, samples were taken from areas vegetated by the dominant pioneer plant species in each respective location. We collected soil samples under a perennial grass species (*Phragmites australis*) in Portman Bay, a deciduous shrub (*Tamarix boveana*) at Balsa Galo, a species of pine tree (*Pinus halepensis*), and a gray-green needlegrass (*Lygeum spartum*) in Balsa Rosa.

In each mining district, three plots of 5 m × 5 m were randomly selected to collect samples for chemical and micromorphological analyses. Composite bulk sample from three sampling points within each plot were collected from 0 to 12 cm depth for chemical analyses. Soil samples were stored in polyethylene bags and transported to the University of Amsterdam for chemical analysis. For microstructure analysis, Kubiena boxes (5 cm × 7.5 cm × 2.5 cm) were used to collect undisturbed soil samples from vegetated and nonvegetated plots in each sampling location.

Micromorphological Analysis

Thin sections from undisturbed soil samples were prepared according to the technique described by Jongerius and Heintzberger (1975). Twelve thin sections (5 cm × 7.5 cm) were described under an Olympus BH-2 polarizing microscope following the concepts and terminology in Brewer and Pawluk (1975) for microfabric, Brewer (1976) for plasma fabric, types of void and pedofeatures, and Bullock et al. (1985) for microstructure. There were four thin sections from Portman Bay (2[no vegetation] + 2[*P. australis*]), three from Balsa Rosa (1 each of no vegetation, *L. spartum*, and *P. halepensis*), and five thin sections from Balsa Galo (3[no vegetation] + 2[*T. boveana*]).

Chemical Analyses

Soil samples were dried for at least 48 hours and passed through a 2-mm sieve prior to chemical analyses. The total amounts of C, N, and S were measured using an Elementar VarioEL CNS analyzer (Hanau, Germany) with sulphanic

acid as the reference material, and with detection limits of 0.001% for both C and N, and 0.012% for S. Electrical conductivity (EC_{25}) and pH_{CaCl_2} and pH_{H_2O} were determined using a Consort C832 multi parameter analyser. We determined the total gypsum using the procedure recommended by Nelson et al. (1978). A modified $BaCl_2$ method (Hendershot & Duquette 1986; Gillman 1987; Bodem NEN 5738 1996) and NaOAc, pH 8.3 (Polemio & Rhoades 1977) were used to estimate the cation exchange capacity (CEC) in waste materials and incipient soils under selected pioneer plant species. Samples were dialyzed to remove excess gypsum prior to CEC determination.

Results

Microstructure of Nonvegetated Mine Waste Deposits

The nonvegetated mine waste deposits were dominated by either massive (or compacted), platy or single grain microstructures (Figs. 2–4). Large areas (>80%) of thin section from nonvegetated mine waste deposits at Portman Bay exhibited dense reddish- and yellowish-colored massive microstructure with the rest of the slide showed cracks of about 80–200 μm wide (Fig. 2A). Some of the coarse components

(>5 μm) were composed of pyrite. We observed few planar voids (or voids that are planar in appearance according to the ratio of principal axes, the edges of corresponding planes are generally accommodating) and vugh type of pore (or largely isolated voids, spherical to elongate, or irregular, and not normally connected to voids of comparable size) about 400 μm long diameter $\times$ 100 μm short diameter in some parts of the thin section. Visual estimate of the total porosity was approximately 5–10%. The related distribution pattern (RDP) of the coarse and fine components is closed porphyric where some coarse materials embedded in fine materials were close enough to touch each other.

Platy microstructure in mine waste materials at Balsa Galo site was moderately developed with planar voids from 50 to 150 μm in width in-between plates with sizes from 250 to greater than 1,000 μm in width (Fig. 3A). The porosity was estimated at about 25–35% of the thin section. The coarse and fine limit was 5 μm and the RDP was closed porphyric. The platy microstructure in Balsa Rosa site was weakly developed where planar pores were not as continuous as in Balsa Galo site (Fig. 4A). Some of the voids appeared as vugh type in a mass of dense groundmass characterized by coarse components (>5 μm) embedded in fine materials (or open porphyric RDP).

Figure 2. Soil microstructure at Portman Bay dump (30–35 years old), (A) laminated structure with platy structure in mine waste (dump) materials, (B) cross section of *Phragmites australis* root and initial soil aggregation, (C) cross section of *P. australis* root (up arrow) and centipede (down arrow), and (D) close-up aggregated structure promoted by fungal hyphae (arrows) and the presence of compound packing void around *P. australis* root; micrographs were taken at plain polarized light. Micrographs are oriented upward toward the surface of the soil.

Figure 3. Soil microstructure at Balsa Galo (20–25 years old), (A) laminated structure with dominantly platy structure in mine waste materials stored in the balsa, (B) cross section of *Tamarix boveana* root growing through the laminated layer, (C) initial aggregation of mineral and organic materials and the development of compound packing voids, (D) soil aggregates composed of inorganic and organic materials and promoted by fungal hyphae (arrow) from the decomposition of *T. boveana* roots, (E) initial bacterial attack on *T. boveana* roots (arrows), and (F) microbial fecal materials, cross-polarized light; micrographs were taken at plain polarized light unless specified otherwise. Micrographs are oriented upward toward the surface of the soil.

We visually estimated the porosity at approximately 20–30% at Balsa Rosa site.

Microstructure of Mine Waste Deposits Under Pioneer Plant Species

Mine waste deposits colonized by pioneer plant species showed remarkable differences compared with nonvegetated materials. The surface layer (0–10 mm) of vegetated mine waste deposits exhibited granular (or aggregated) microstructures of varying degrees of development irrespective

of the species of pioneer colonizers (Figs. 2–4) and age of the deposits. However, we cannot compare the influence of time in the development of granular structure because each site is dominated by different pioneer species and mine waste materials. The aggregates were concentrated in the inter-phase between the laminated mine waste deposits and growing and/or decomposing roots of pioneer plant species. We observed that roots of pioneer plant species grew perpendicular into the layers (or plates) of mine waste deposits (Figs. 2B, 3B, & 4B).

In Portman Bay, weak aggregates of approximately 100–500 µm in size were observed around decomposing roots

Figure 4. Soil microstructure at Balsa Rosa (12–15 years old), (A) laminated structure of mine waste materials stored in Balsa, (B) cross section of *Pinus halepensis* root growing through the laminated waste materials, (C) soil aggregates composed of inorganic and organic materials around *P. halepensis* root, (D) close-up micrograph of strongly aggregated structure with compound packing voids under *P. halepensis*, (E) decomposing roots of *Lygeum spartum*, and (F) close-up micrograph of moderately aggregated structure under *L. spartum*; micrographs were taken at plain polarized light. Micrographs are oriented upward toward the surface of the soil.

of *Phragmites australis* (Fig. 2D). The weakly developed aggregates had an open porphyric RDP (where coarse materials embedded in fine materials do not touch each other) and significantly higher porosity (~50%) especially around the *P. australis* roots; the pores appeared as cracks created by the growing and/or decomposing roots. The fine materials (<50 µm) embedding the coarse minerals were dark in color. Euhedral crystals of gypsum (up to 1,000 µm × 300 µm) dominated the coarse materials.

A strongly developed aggregated structure was observed in mine waste deposits colonized by *Tamarix boveana* at Balsa Galo site (Fig. 3D). The aggregates ranged in sizes from 100 to 500 µm in diameter and were composed of a mixture of dark, brown, and birefringent materials. The well-developed aggregates especially in the top 1 mm of the inter-phase between roots and laminated mine waste deposits had high porosity (40–50%) composed mostly of simple and compound packing void (or voids resulting from packing of compound

individuals, such as aggregates, which may [simple] or do not [compound] accommodate each other) (Fig. 3C). The RDP of the coarse and fine component was open porphyric.

The microstructures of mine wastes under *Pinus halepensis* and *Lygeum spartum* in Balsa Rosa site were granular although less developed in the latter compared with the former (Fig. 4D–F). Well-developed aggregates under *P. halepensis* were from 100 to 500 μm in diameter and were observed around growing and/or decomposing roots (Fig. 4D). The aggregated structure dominated the top 50% of the thin section and where porosity was estimated at 50–60% composed mostly of simple packing voids. The RDP was open porphyric. The weakly developed aggregates in the inter-phase between *L. spartum* roots and mine waste materials were 500–1,000 mm in diameter and were still connected with each other and showed open porphyric RDP (Fig. 4F). The voids were compound packing voids and estimated at approximately 30–40% of the area in the inter-phase.

Pedological Features

We did not observe any pedological features in nonvegetated mine waste deposits; however, biological features were abundant in waste deposits colonized by pioneer plant species. A cross section of centipede was captured in Fig. 2C; the internal features of the organism showed organic matter and mineral matter. In Fig. 2D, fungal hyphae were observed around the surface of the decomposing root as well as on some weakly developed soil aggregates. In Balsa Galo site, fungal hyphae seemed to originate from the surface of soil aggregates (Fig. 3D). Initial bacterial attack was observed on otherwise intact *T. boveana* roots (Fig. 3E). Oblate-shaped faunal fecal materials about 20 μm in diameter were present near decomposing organic materials (Fig. 3F).

Soil Chemical Properties

We summarized the mean (and standard error) of selected soil chemical properties of tailings and soil samples in Table 1. pH in waste materials and incipient soils was alkaline to highly alkaline, whereas EC values and gypsum contents were generally lower in soils under pioneer plant species except for the site at Portman Bay. Incipient soil under *P. australis* had EC value (mS/cm) of 27.8 compared with 5.8 in waste materials. Total N in waste materials and soils was very low (<0.1%), whereas C/N ratios ranged from 9 in waste at Balsa Galo to 149 in waste materials at Balsa Rosa. CEC measured in BaCl_2 and NaOAc methods showed similar results with values (cmolc/kg) from as low as 32 in soils under *T. boveana* in Balsa Galo to as high as 149 in waste materials at Portman Bay.

Discussion

Pioneer Plant Species Initiate Soil Formation in Mine Waste Materials

The growth of pioneer plant species seems to initiate the formation of soils in mine waste materials. In Balsa Galo, the

root growth of deciduous shrub (*Tamarix boveana*) is forceful enough to break through the dense and laminated waste materials. Roots of a species of pine tree (*Pinus halepensis*) similarly ruptured the layered structure of waste materials in Balsa Rosa. Cracks developed from the breakage of dense materials can initiate preferential flow of water (e.g., Mooney & Morris 2008). In arid environment similar to the study area, roots of *Larrea tridentate* increase the downward water flux to deeper soil depths via preferential flow in root channels (Devitt & Smith 2002). With the scattered patches of pioneer plant species in the study areas, significant increases in infiltration of water in the mine waste deposits especially in the vicinity of root crowns through rainfall interception, throughfall and stemflow favor the formation of soils.

The consequence of preferential flow paths to soil processes is quite significant. Except for Portman Bay, the lower EC in incipient soils compared with mine wastes might have been due to higher rate of electrolyte removal in places of preferential flow paths (i.e., root channels). Bundt et al. (2001) referred to highly conducting water conduits such as root channels as biological “hot spots” in their study of forested soils in Switzerland. They reported higher organic C contents (10–70%), total N, microbial biomass (9–92%) in the preferential flow paths compared with the soil matrix. Decomposition of root biomass in root channels could lead to SOM build up in the waste materials. The presence of fungal hyphae and bacterial colonies are other indicators for high intensity of biological activities in waste materials where incidence of root penetration is present. Soil organic matter improves water holding capacity and aeration, regulates temperature, and promotes soil structure favorable to plants and organisms (Stevenson 1994; Sollins et al. 2006). Although we did not observe higher CEC in incipient soils than waste materials, the eventual consequence of SOM build up is to increase CEC, hence fertility of the soils. Our earlier results in Balsa Rosa (Ottenhof et al. 2007) showed that *Lygeum spartum* significantly increased exchangeable Ca and K due to increase in CEC resulting from the accumulation of SOM high in lignin-derived compounds (e.g., guaiacols and syringols).

Our data further show the more advanced development of granular microstructure under *T. boveana* and *P. halepensis* than *Phragmites australis* and *L. spartum*. The differences might be related to the extensive root development, as well as to longer time of colonization by these pioneer species into the waste materials. In Balsa Galo, deeper root penetration by *P. halepensis* than *L. spartum* might have been responsible for the well-developed granular structure in the former. Deep and wide root penetration may have enhanced the intensity of biological activities, hence high rate of SOM accumulation.

Soil Fauna and Soil Structure Development

The development of granular microstructure in soils is significantly influenced by the presence of mesofauna (e.g., Brewer & Pawluk 1975). Earthworms change soil microstructure

Table 1. Mean (and standard error) chemical composition of wastes and incipient soils under selected pioneer species at Balsa Galo, Portman Bay, and Balsa Rosa sites, ($n = 3$).

Study Areas	pH H_2O	pH $CaCl_2$	EC (mS/cm)	Gypsum (%)	Tot S (%)	Tot C (%)	Tot N (%)	C/N	CEC $BaCl_2$ (cmolc/kg)	CEC $NaOAc$ (cmolc/kg)
Balsa Galo										
Wastes	6.20 (0.22)	6.14 (0.23)	31.6 (6.38)	18.30 (2.10)	3.50 (0.051)	0.36 (0.003)	0.038 (0.002)	9 (0.72)	65 (9.7)	55 (11)
<i>Tamarix boveana</i>	4.68 (1.35)	4.63 (1.34)	11.9 (4.15)	8.02 (2.02)	9.34 (3.32)	0.413 (0.331)	0.024 (0.012)	12 (5.1)	46 (28)	32 (19)
Portman Bay										
Wastes	6.38 (0.87)	6.25 (0.84)	6.3 (1.35)	5.83 (1.31)	6.58 (4.26)	0.814 (0.396)	0.037 (0.015)	18 (6.6)	54 (22)	43 (17)
<i>Phragmites australis</i>	5.8 (0.21)	5.71 (0.22)	14.5 (2.90)	27.8 (3.03)	8.16 (1.31)	0.957 (0.260)	0.083 (0.022)	11 (0.26)	214 (42)	88 (21)
Balsa Rosa										
Wastes	7.94 (0.064)	7.8 (0.078)	19.2 (5.24)	21.4 (0.85)	5.19 (0.32)	2.06 (0.126)	0.016 (0.001)	130 (12)	149 (5.7)	95 (7.7)
<i>Lygeum spartum</i>	7.56 (0.084)	7.43 (0.081)	2.61 (0.074)	12.3 (0.327)	3.89 (0.261)	1.04 (0.168)	0.025 (0.005)	41 (3.2)	114 (8.0)	99 (8.5)
<i>Pinus halepensis</i>	7.59 (0.099)	7.34 (0.029)	1.54 (0.63)	7.44 (0.63)	2.33 (0.161)	1.56 (0.102)	0.058 (0.005)	27 (0.96)	139 (2.1)	140 (23)

through the re-organization of materials (and void spaces) from the deposition of granule-shaped excrements. Jones et al. (1994) referred to earthworms as “ecosystem engineers” because they transform massive soil to favorable habitats for other organisms. Bioturbation by earthworms alters soil drainage properties (Davidson et al. 2002). The aggregated microstructure is likely products of earthworm fecal materials similar to those reported by van Mourik (2003). The presence of centipede in Portman Bay samples is another indicator for the presence of mesofauna because centipede is a known predator of earthworm and collembola (Salmon et al. 2005). Frouz et al. (2007) observed significant accumulation of earthworm coprolites, millipedes, and dipteran larvae in afforested coal mine spoils in north Bohemia, Czech Republic. The presence of mesofaunal activities improved properties of mine spoils such as decreased laminar structure in favor of more humified surface layer, increased microbial respiration, and water holding capacity (Frouz et al. 2006, 2007).

Development of Packing Type of Pores

The formation of granular structure from laminated/platy microstructures corresponds to the development of packing type of pores from planar type voids. Root penetration from pioneer species initially breaks down the laminae and the subsequent increase in biological activities resulted in the formation of packing voids from the granular microstructure. Packing type pores are often responsible for adequate soil aeration, water infiltration, and root distribution. Biological activities (e.g., earthworm) rearrange soil components into well-organized granular units composed of intimately mixed organic and mineral matter arrange in such a way to create continuous pore system conducive to plant growth. Physical process such as wetting and drying can also initiate soil aggregation (Pires et al. 2008). The estimated 30–50% pore space in the aggregated structure corresponds to a porous soil (Pagliai 1988).

Conclusions

We conclude that growth of pioneer plants, regardless of species, initiates the development of soils in mine waste deposits through SOM accumulation and increased biological activities. Our results indicate possibilities to enhance the development of soil in mine waste deposits. For instance, mechanical break-up of laminated structure of mine wastes can produce preferential flow paths of water that can eventually lead to increase biological activities observed in the study. Second, addition of organic materials (e.g., manure) in waste materials can enhance biological activity that can eventually lead to the formation of granular structure.

Implications for Practice

- Pioneer plant species are effective sources of soil organic matter and should be included in restoration strategies in mined areas.

- Increased biological activities often establish with pioneer plant species and enhance the transformation of laminated and platy structures in mine wastes to aggregated soil microstructure.
- The presence of granular soil microstructure is a reliable indicator for the presence of good and productive soil. The establishment of functional system (or restoration) in any disturbed environment should aim for the formation of soil with granular structure.
- The formation of good soil structure in degraded landscapes can be accelerated by addition of organic matter such as those from pioneer plant species (and organic amendments).
- The key to soil formation in mine wastes is to accelerate soil organic matter build up to improve soil properties such as water holding capacity, CEC, microbial and mesofaunal populations.

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