EnvironmentAsia
The international journal by the Thai Society of Higher Education Institutes on Environment

EnvironmentAsia 13(2) 2020 101-113
DOI 10.14456/ea.2020.33
ISSN 1906-1714; ONLINE ISSN: 2586-8861

Ecological Succession in Areas Covered by Rock Mine Wastes in Benguet, Northern Philippines

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Received: February 8, 2019; Revised: October 1, 2019; Accepted: December 4, 2019

Abstract

This study analyzed the vegetation in the three sites covered by Cu-rich rock mine wastes in Mankayan, Benguet, Philippines. Site 1 is a topsoil amended tailings pond, site 2 is an unamended tailings pond with only about 10%–24% vegetation cover, and site 3 is an agricultural land that was inundated in 1986 by mine rock wastes. Soil samples were analyzed for pH; texture; and Cu, organic matter (OM), available phosphorus, and exchangeable potassium contents. Results show that site 2 had mean soil Cu level of 220 mg/kg, site 1 had 100 mg/kg, and site 3 had 174 mg/kg. Site 2 had mean soil pH value of 4. Sites 1 and 3 had 66%–75% vegetation cover and soil pH of 6.5 and 5.65, respectively. This study proposes a hypothesis on ecological succession as follows: *Digitaria sanguinalis* and *Paspalum conjugatum* community constituted the pioneer stage observed in site 2. Improvement in soil environment led the pioneers to be replaced by *Cynodon dactylon* and *P. conjugatum* community in site 1, followed by *C. dactylon*, *P. conjugatum*, and *Mimosa pudica* community in site 3. The increase in soil OM increased the number of species and vegetation cover in the study sites. The soil environments (i.e., texture, OM, high Cu, and low soil pH) of each site determine the plant communities present in each site. Low soil pH increases Cu solubility.

Keywords: Copper; Pioneer species; Ecological succession; Rock mine wastes

1. Introduction

The Philippines is endowed with abundant mineral resources, and the extraction of these minerals has become the backbone of the country's mining industry. In the past decades, foreign investments in large-scale mining operations have become one of the sources of foreign exchange of the Philippine economy. In addition, the government derives revenues from the sale of mineral and metal products.

There are also big benefits from the industry at the local level. For one, it provides employment to the local people. For another, the industry serves as an impetus for developing the local economy where the mining areas are located and for building infrastructures (e.g. school buildings, scholarships, hospitals, etc.) in the host communities. Moreover, the mining industry also supplies minerals and metals that are essential components of equipment and gadgets, especially in the electronic industry. However, the economic benefits gained from the mining industry are negated by the long-term effects of the environmental destruction and degradation resulting from mining activities, and the local communities in the mine sites are the main recipients of these impacts.

Mining operations impose varying levels of environmental impacts. Cooke *et al*. (2002) and Li (2006) cite that mine tailings (wastes from pulverized rocks after the essential ores have been extracted) cause a series of environmental problems due to the high levels of heavy metals in the tailings They also usually generate large volumes of sulfuric acid due to the oxidation of the sulfidic mineral pyrite. Thus, they pose threats to human health and well-being and the environment.

Soil with tailings provides a very harsh environment for plants. For one, the texture of tailings can vary from very coarse to intermediate (similar to sand wastes), or it can be very fine (similar to milled tailings) since the component rock materials have not had enough time to weather. For another, tailings are generally deficient in clay-sized particles due to the absence of colloidal materials. They also behave much like a sandy loam and can be prone to moisture deficiency (Peters, 1984). On the other hand, fine-textured materials with no organic matter (OM) can lead to high-bulk densities, extreme compaction, low water infiltration rates, and surface waterlogging. They also have very low levels of macronutrients, i.e. nitrogen (N), phosphorus (P), and potassium (K) (Cooke *et al*., 2002).

Very few plant species with tolerant ecotypes or populations colonize areas covered with mine tailings. Moreover, they may form an open vegetation cover that represents an arrested succession. Plants are also prevented from further developing under such soil conditions due to the toxicity of the heavy metals present and due to the infertility and high acidity of pyritic mine wastes (Cooke *et al*., 2002). These open areas are also prone to wind and water erosion, thereby making the surrounding areas prone to water and air pollution (Chen *et al*., 2016).

The revegetation process in the areas covered with mine tailings is slow due to the disturbances in the soil characteristics (as described above) and due to the absence of topsoil, which removes the soil seed bank and root stocks. Thus, there is a need to reestablish the microflora and microfauna communities responsible for nutrient cycling or the breakdown of organic matter that would release the nutrients needed to enable diverse plant species to proliferate (Peters, 1984). Accordingly, redeveloping these advanced communities may take a century or more (Singh *et al*., 2002).

Mankayan, Benguet, Philippines is the host municipality of the 83-year-old Lepanto Consolidated Mining Company (LCMCo). Currently, LCMCo produces gold as its main product, with copper as a by-product. Since 1936, the company has produced four filled-up or decommissioned tailings ponds (Term used by the Philippine Department of Environment and Natural Resources (DENR) to refer to abandoned tailing ponds as per Memorandum Order 99-32, series of 1999). In this study, these ponds are labeled as tailing ponds 1, 2, 3, and 4 (TP1, TP2, TP3, and TP4). The first three ponds have minimal vegetation, whereas TP4 is covered with vegetation. At the time of the study, the local community was using TP4 as a pasture land.

In 1986, a section of TP3's dam wall collapsed, which caused the mine tailings to overflow and settle into the low-lying and accessible areas near the dam. These Cu-laden mine tailings were then carried downstream through the Comillas River (referred to by the locals as Mankayan/ Lepanto River), and consequently inundated the productive lowland rice paddies along the riverbank of two barangays (district) in the municipalities of Mankayan and Cervantes, Ilocos Sur province. Accordingly, soil productivity in these areas significantly decreased as the agricultural fields got contaminated with Cu (Cuevas *et al*., 2014).

TP4 was amended with topsoil after the mining company ceased dumping tailing wastes at the site in 1990. However, in 1991, the area was covered by tons of trash coming from a municipal garbage open dump site located on the upper slope of TP4. The trash slide was triggered by super typhoon Trining (International name Ruth) that passed through Northern Luzon in October of that year. This accident contributed to the soil amendment of the area, which allowed its slow revegetation. By 2001, the area started to become a pasture area for the community (personal communication with the community).

The local communities in Mankayan are currently facing the negative impacts of the mining activities. Agriculture, which is the principal means of livelihood in most barangays, is severely affected as the soil has become considerably less fertile due to heavy metal contamination. Against this back drop, this study aimed to achieve the following:

1. To determine the plant species composition of lands covered or affected by mine tailings, and
2. To gather basic information on the soil conditions in the areas affected by mine tailings in Mankayan.

Ecologists refer to the process of the gradual increase in vegetation as primary succession (Cooke *et al*., 2002) Accordingly, identifying and studying the plant species present in the area and determining how these plant species contribute to the succession process is important in order to establish baseline information. Ultimately, the succession process in the mined sites is important to understand how the study sites and other mined areas can be rehabilitated. Generally, the results of the study can provide information on the process or strategy for rehabilitating those areas in the country that are affected by mine wastes.

This article is a condensed version of a published Agriculture and Development Discussion Paper Series 2014-4 of Southeast Asian Regional Graduate Study and Research in Agriculture (SEARCA) entitled "Ecological Succession in Three Copper Contaminated Mine Tailings Pond in Mankayan, Benguet Province, Cordillera Administrative Region, Philippines". The discussion paper has limited circulation. This condensed article aims to reach wider audience.

2. Materials and Methods

2.1 Study area

Mankayan is one of the 13 municipalities of Benguet province, Philippines. Mankayan is rich in copper and gold. Mining is an activity that the local community has been engaged in since the precolonial period. Two companies, namely, Suyoc Mines and Lepanto Mining Company (LCMCo), were formally established in 1933 and 1936, respectively, and have been mining the area since then. During the Second World War, mining operations in Mankayan were limited. The reestablished LCMCo and Itogon Suyoc Mines then resumed their mining activities during the post-war period (DILG-CAR, 2015). Most of the local residents are either employed in the agriculture sector or in the two large mining companies, whereas some continue their small-scale mining activities. Figure 1 shows the river systems and tailing ponds in Mankayan and the study sites.

Ever since mining activities have started more than 80 years ago, LCMCo have accumulated four decommissioned ponds. Three study sites were selected in this study, two of which were in the decommissioned tailing ponds.

Study sites 1 and 2 are located in Brgy. Paco, Mankayan, Benguet. Study site 1 is located in TP4, which is used as pasture land for cattle by the local community at the time of the study. Meanwhile, study site 2, which is located along the dirt road, is a smaller pond and an extension of TP3. Lastly, study site 3 is an agricultural land along the Lepanto riverbank in Brgy. Cabiten that was inundated by Cu contaminated mine wastes in 1986. This area is at a lower elevation than the other two sites and is directly behind the pond that was breached. Therefore, it received high amounts of Cu-filled mine wastes.

Three subsites, namely, 1A, 1B, and 1C, were established in site 1 in accordance with the vegetation and soil texture of the area (Figure 2). Site 2 is small, spanning an area of 1.5 ha; thus, no subsite was established (Figure 3). Site 3 is a terraced rice field; accordingly, two subsites were designated depending on land use. Subsite 3A is closest to the river bank, and is the most Cu-contaminated site owing to the mine waste disaster in 1986; hence, the area has not been able to grow rice since then. This paddy field underwent natural attenuation process, and was also being used as pasture land at the time of the study. The next lower-tier rice paddy was designated as subsite 3B. Figure 4 show the relative location of site 3.

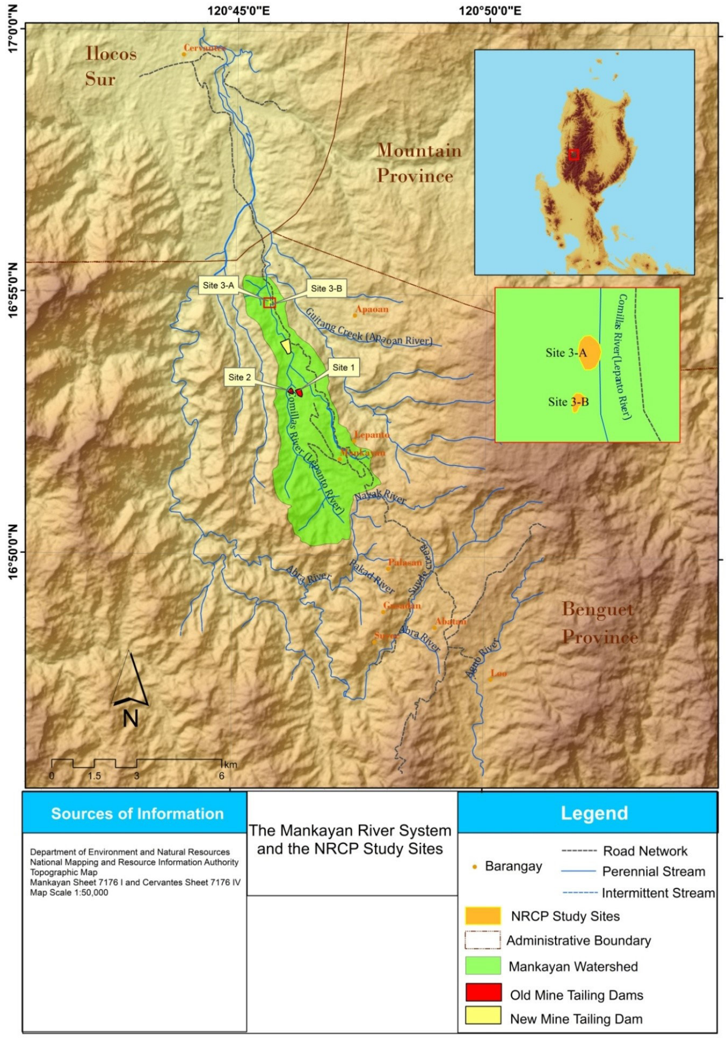

Figure 1. Map of river system of Mankayan relative to the location of tailing ponds of Lepanto Consolidated Mining Co. and the study sites of the project.

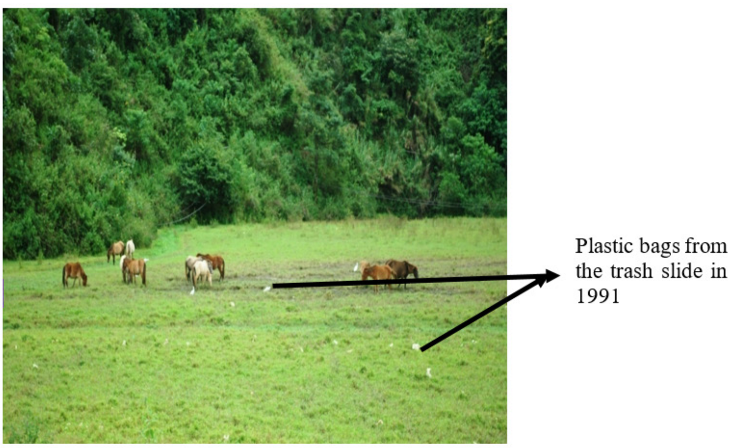

Figure 2. Animals grazing in TP 4 -site 1 C – pasture land.

Figure 3. Close up of the substratum of site 2 showing patchy vegetation cover.

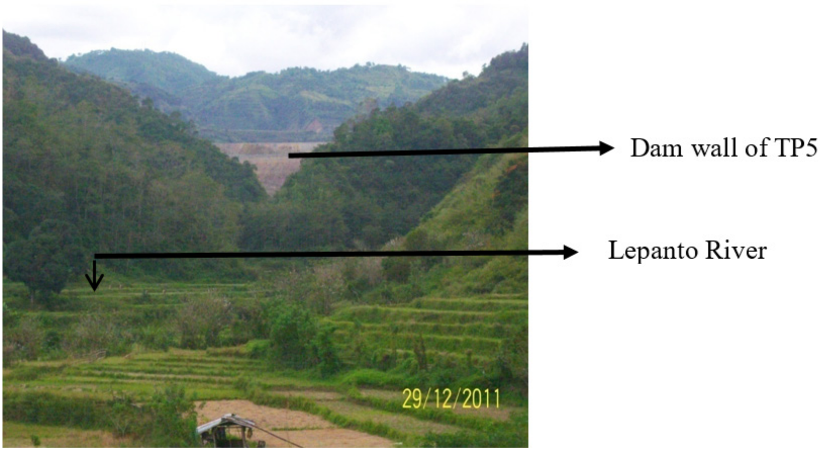

Figure 4. View of Site 3.

2.2 Vegetation analyses

The research team conducted nondestructive vegetation analysis from March to April 2013 for the dry season, and another set from September to October 2013 and August 2014 for the wet seasons. In subsite 3B, no wet season analysis was done since the area was planted to rice. In each of the subsites, three 50-meter transect lines (10 m apart) were laid from the north to south direction. The geographic location and elevation of the transect lines were determined using a GPS receiver. Ten 1 × 1 m quadrats at 5-meter intervals (total of 50) were nested along each transect line.

In each quadrat, the research team measured the percentage cover, frequency, and density of each plant species. The importance value of each species was computed by adding the percentage cover, frequency, and density of each species. Plant samples were collected and herbarium specimens were prepared following the standard protocols. The team identified the plants through the taxonomic literatures and by comparing the collected plant samples with the previously identified specimens at the University of the Philippines (UP) Baguio Herbarium.

2.3 Soil analyses

Soil samples were also collected during the dry season sampling and were accordingly analyzed for soil pH, soil texture, Cu, OM, available phosphorus, and exchangeable potassium contents. Soil pH was analyzed at the Biology Department of UP Baguio using the standard pH meter (1 soil: 1 water [w/v] ratio). All soil Cu analyses were analyzed as extractable Cu through the flame atomic absorption spectrophotometry method using HNO_3, HF, and $HClO_4$ for the extraction. The samples were analyzed at the Natural Science Research Unit of St. Louis University, Baguio City. The methods of Recel *et al.* (1988) were used in this study to analyze the soil fertility parameters. Percentage OM was analyzed using the Walkley-Black method, available P through the Bray method, and the exchangeable K by ammonium acetate extraction. Lastly, soil texture was analyzed using the hydrometer method. All these soil analyses were conducted at the Soil Analytical Chemistry Laboratory, Agricultural Systems Cluster, College of Agriculture and Food Science, UP Los Baños.

2.4 Statistical analyses

The statistical analyses to analyze for the differences in vegetation composition during the wet and dry season were done using the Statistical Package for the Social Science, and the matrices were encoded in MS Excel 2013. Correlation analysis between soil parameters and plant species was also done in the study using Minitab®17.

3. Results and Discussion

3.1 Soil properties of the study sites

Table 1 shows that the soil in the three sites are way above the normal level of 30 mg/kg, which implies that Cu present in the soil samples are toxic (Kebata-Pendias *et al*., 2001). Site 2 had the highest concentration at 220 mg/kg, followed by site 3 at 163–184 mg/kg. Site 1 had the lowest at 90–116 mg/kg. Subsites 1A, 1B, and 1C had different levels of Cu. Likewise, the soil physical and chemical properties vary in the study sites. Site 3 had the highest soil OM at 1.9%–2.2%, whereas site 2 had the lowest at 0.03%. Site 2 also had the lowest pH at 4.0. The soil pH content in subsites 1A, 1B, 3A, and 3B are optimal for plant growth, with soil pH ranging from 6.25–6.8. In subsite 1C, the soil pH was relatively lower at 5.69. The soil texture in sites 1 and 2 were loamy sand to sandy loam, showing its mine tailing origin. These two sites used to be tailing ponds, wherein the main constituent was pulverized rocks, and thus explains the sandy texture. Meanwhile, the presence of soil organic matter gives the loamy texture. Site 3 is an agricultural land and its texture is loam to clay

Table 1 shows that subsite 1C has the lowest pH and highest Cu level within site 1. Phosphorus level in site 1C is also lower than those of subsites 1A and 1B. Soil pH is a critical factor affecting Cu and P solubility. O'dell *et al*. (2007) commented that pH is often the main factor that determines the availability of metals in plants—lower pH indicates higher metal content. Thus, low pH increases Cu solubility. Acidic pH lowers the availability of phosphorus for plant absorption (USDA, 1995). This phenomenon is clearly shown in Table 1, where the data show that site 2, with the lowest pH at 4.0, have the highest Cu level and the lowest P available of 1.89 mg/kg. Soil pH in subsites 1A and 1B ranged from 6.25 to 6.8, whereas available P ranged from 9 mg/kg to 10 mg/kg. Cu soil content is also much lower at 90–94 mg/kg. Subsite 1C has soil pH of 5.69, Cu content of 116 mg/kg, and available P of 4.75 mg/kg.

Soil texture is significantly correlated with site. Table 1 shows that site 2 has loamy sand (50% – 80% sand, 0% – 50% silt, 0% – 20% clay), whereas site 1 has sandy loam to silt loam texture. In silt loam, sand comprises 0% – 50%, silt 50% – 100%, and clay 0% – 20%. In site 3A, soil texture is loamy and is composed of 30% – 50% sand, 30% – 50% silt, and 0% – 20% clay. Site 3B has clay texture composed of 0% – 50% sand, silt 0% – 50%, and clay 30% – 100%. (Classification was based on the table of textural names and composition developed by USDA and US Bureau of Soils). The soil type in Mankayan belongs to the Guinaoang clay series as exemplified by site 3B. The sandy texture in site 2

Table 1. Soil physical and chemical properties in the study sites

Sites	Elevation (m)	Soil texture	Mean Soil pH*	Cu** (mg/kg)	% OM*	P* (mg/kg)	K* (me/100 g soil
Site 1 – Brgy. Paco							
Subsite 1A	869	Silt loam	6.25	94.41	0.235	10.00	0.170
Subsite 1B	867	Sandy loam	6.81	90.64	0.600	9.40	0.155
Subsite 1C	875	Loamy sand to sandy loam	5.69	116.17	0.690	4.75	0.230
Site 2 – Brgy Paco							
Site 2	866	Loamy sand	4.05	220.73	0.035	1.85	0.025
Site 3 – Brgy Cabiten							
Subsite 3A	589	Loam	6.53	163.30	1.900	5.60	0.160
Subsite 3B	581	Clay	6.31	184.53	2.280	2.37	0.340

Note: Values with * refers to the mean of two replicates. Those with ** are the mean of 30 replicates, in which the samples were taken during 2013 dry season sampling.

and subsites 1A, 1B, 1C, and 3A come from the mine tailings (pulverized rock wastes) dumped in the study sites. The change in the soil texture (from sandy loam to loamy sand) in the three sites may be due to the OM contributed by the plants that have colonized the area.

The results of the study show that texture and % soil OM content (r = 0.671, p = 0.024) are significantly correlated. This indicates that as OM increases, soil texture likewise improves, as indicated by the change in soil texture in each site from sandy to sandy-loam to loamy-sand. Soil texture greatly affects the water and nutrient retention capacity of the soil. A sandy texture has low water and nutrient retention capacity, and this increases as soil texture improves from light to heavy—from sandy loam, silt, to clay (Peters, 1984).

3.2 Species composition

Table 2 presents the dominant species monitored in site 1 during the three-season vegetation survey. The three plant species dominant in all three subsites were *Cynodon dactylon*, *Paspalum conjugatum* (Fam. Poaceae) and *Cuphea carthagenensis* (Fam. Lythraceae). They constituted around 75% of the mean importance values (IV) of all the species present. The most represented species family in site 1 is Poaceae. Wang *et al*. (2004) had similar results in their study that examined the vegetation composition of a deserted land with copper tailings. Subsites 1A and 1B had high moisture content during the 2013 rainy season, which increased the number of species in the subsites. However, the same did not happen during the 2014 wet season due to the six months of dry period prior, which heavily affected vegetation. Thus, there were fewer species encountered in each site compared to the 2013 surveys. Despite this, the dominant species remained the same.

The dominant species in site 2 was *Digitaria sanguinalis* in all three-season sampling, followed by *P. conjugatum* during the 2013 dry season and 2014 wet season. *Paspalum scrobiculatum* was the dominant species during the wet seasons. The combined importance values of the two species account for about 50%–70% of the vegetation (Table 3). *Cynodon dactylon*, the most dominant species in sites 1 and 3, was only a minor species during the dry season and was not encountered during the wet season. Ten other species had important values of 1–8. The site had low vegetation cover and only had 10% during the 2013 dry season sampling. This increased to 24% during the 2014 wet season and had more bare ground than cover (Figure 3).

In contrast, site 1 had about 66% cover, whereas site 3 had 75% cover. These results show that the soil conditions in site 2 were unfavorable for plant growth (Table 1). Only those species that can tolerate stressful conditions can grow in this site. The results of the percentage cover and number of species present indicate the soil properties in the study sites inasmuch as the factors that influence the available ions essential or toxic to plant growth.

Table 2. Dominant plant species present to site 1 during the 2013 dry and 2013 and 2014 wet season survey

Species	Importance Value (IV) %									Mean IV %
	Subsite 1A			Subsite 1B			Subsite 1C			
	Dry 2013	Wet 2013	Wet 2014	Dry 2013	Wet 2013	Wet 2014	Dry 2013	Wet 2013	Wet 2014	
Cynodon dactylon	19.40	48.86	54.88	51.190	64.35	46.47	31.87	21.11	18.91	39.67
Paspalum conjugatum	20.05	8.98	13.72	12.110	9.28	20.63	26.52	36.97	53.42	22.41
Cuphea carthagenensis	7.77	10.45	20.77	10.370	7.60	19.69	22.07	15.88	24.57	15.46
Commelina diffusa	4.52	7.87	3.05	5.390	6.17			18.27		7.54
Cyperus kyllingia	0.38	3.53		4.628	2.30	5.76		2.12	**2.94**	
Axonopus compressus		2.11	4.82			6.89	0.73		4.93	
Ageratum conyzoides	5.19			3.330	0.77		1.47			
Cyperus rotundus	0.76			4.480			0.66			
Digitaria sanguinalis							12.58			
Lantana camara		1.92			0.71			0.70		
Ludwigia octovalvis		1.34			2.41			1.45		
Cyperus sanguinolentus		2.94			1.76			0.68		
Eupatorium triplinerve	1.38	1.31			0.77		1.28			
Cyperus exaltatus		2.80			0.73					

Table 3. Plant species composition of site 2: 2013 dry season and 2013 and 2014 wet season survey

Species	Importance Value (IV) %			Mean IV %
	Dry 2013	Wet 2013	Wet 2014	
Digitaria sanguinalis	63.23	29.80	2.79	31.94
Paspalum conjugatum	10.70		45.82	28.26
Paspalum scrobiculatum		27.80	17.53	22.66
Axonopus compressus	2.23	6.96		4.60
Chromolaena odorata	1.89	2.19	9.87	4.65
Eragrostis unioloides	4.69	1.48		3.10
Mimosa pudica	2.12	2.21	8.82	4.38
Chromolaena odorata	1.89	2.19	9.87	4.65
Desmodium triflorum		8.22	1.45	4.84
Fimbristylis cymose		6.35		
Fimbristylis tomentosa		5.76		
Cynodon dactylon	5.75			
Cyperus kyllingia	2.57			
Cuphea carthagenensis	1.23		2.23	
Lantana camara			3.30	
Sporobolus indicus			4.12	
Hyptis suaveolens			0.73	

Site 3 was dominated by *C. dactylon* and *P. conjugatum*, with *Mimosa pudica* coming third (Table 4). These species can tolerate high level of Cu in the soil. Note that four shrubs belonging to the legume family (Fabaceae), namely, *Mimosa pudica*, *M. invisa*, *Cassia occidentalis*, and *C. tora* and the tree sapling *Gmelina arborea* were present in site 3. These shrubs were absent in sites 1 and 2. The available Cu ions in the soil in site 3 were higher than that in site 1. Site 3 also had higher percent soil OM content. The soil texture was also different in both sites, with site 3 having clay and loam soil. Thus, it is possible that the improvement in the soil OM content and better soil texture enabled the shrubs to grow site 3. Their presence can indicate the regeneration of the land contaminated by mine tailings.

Table 4. Dominant species in site 3, 2013 dry season and 2013 and 2014 wet seasons

Species	Importance Value (IV) %					
	Site 3A: Pasture Land			Site 3B: Rice Paddy		
	Dry 2013	Wet 2013	Wet 2014	Dry-on Fallow	Mean IV %	Wet 2013–14
Cynodon dactylon	34.45	14.94	13.08	33.75	24.00	
Paspalum conjugatum	24.21	2.93	41.06	3.77	18.00	No vegetation analysis done because site 3B was planted to rice crop during the wet season
Axonopus compressus		40.48	6.18		23.33	
Mimosa pudica	16.81	16.51	16.93	29.41	20.00	
Eleusine indica		13.26	1.44		7.35	
Cassia occidentalis		5.70	8.72		7.21	
Paspalum distichum	4.05			3.51	3.78	
Acalypha indica	3.78			0.89	2.33	
Cassia tora	2.47			2.37	2.42	
Cyperus rotundus	2.56			0.44	1.5	
Gmelina arborea	2.16			3.59	2.88	
Mimosa invisa	0.83			1.93		
Cyperus kyllingia			2.33			
Cuphea carthagenensis			1.04			

The principal component statistical analysis (Eigen analysis of the correlation matrix) performed on the different soil parameters were measured and correlated with the 2013 samples. Accordingly, results show that site characteristics and Cu content explain 42% of all the variations. In the second component, layer and pH have the highest coefficients. This mean that the combination of site characteristics and Cu content is further modified or strengthened by pH and variation in the different layers. Therefore, the following factors determine the plant community present in each site: (1) characteristics of the soil environment of each site (e.g., soil texture, soil OM content) and their consequent effects on the water holding capacity (WHC) and cation exchange capacity (CEC), and (2) toxic levels of Cu and soil pH .

Based on these findings, the authors concluded that the soil environment rate of improvement in the three sites proceeded in the following manner in an increasing hierarchy:

Site 2 → Site 1 → Site 3

Site 2 had the worst soil environment, whereas site 3 improved the most. The changes in the soil environment likewise changed the plant species composition, and this process is known as ecological succession.

3.3 Plant succession in the three abandoned mine tailing ponds

Ecologists consider those areas covered with mine tailings to be undergoing primary ecological succession. Such areas have complete absence of soil since the original soil has been lost or has been buried by wastes (Singh *et al*., 2002). Moreover, these areas have compaction, surface crusting, changes in soil texture, loss of soil structure, and reduced water infiltration (Mendez *et al*., 2007). A succession is a directional change in the species structure of an ecological community over time.

The original living organisms are destroyed, and seed germination and plant growth are suppressed due to the harsh physical environment resulting from the mine tailings present in the soil. Consequently, the disturbance created is exceedingly disastrous such that a new habitat is created. Thus, plant colonizers that start in areas contaminated by mine tailings are virtually starting at "point zero" (Picaud *et al*., 2007). Ecologically, plants that slowly colonize the area have tolerant ecotypes or populations that can adapt to the harsh soil environment (Cooke *et al*., 2002). Ecologists consider this process of gradual increase in vegetation as primary succession, in which the soil slowly develops. This process takes a long period of time (sometimes century-long) before the area is completely covered with vegetation (Singh *et al*., 2002).

A hypothesis can be formulated based on the results of the present vegetation surveys with regard to the serial stages of plant succession on lands contaminated with Cu in Mankayan, Benguet. The changes in soil properties due to increase in soil OM content and to the diminishing amount of available Cu became the main factor that changed the species composition in the study sites over time.

The pioneer stage can be observed in site 2, where the plant community is dominated by *Digitaria sanguinalis* and *P. conjugatum* during the dry season and *D. sanguinalis* and *P. scrobiculatum* during the wet season. These species are small-statured creepers. As described above, the conditions in this site is so harsh that only those that can withstand the soil environment thrive. With the increasing OM content and soil pH, essential nutrients (e.g., P and K) become more available such that more species were able to colonize the area.

The presence of legumes is essential in adding nitrogen to the soil. In site 2, *Desmodium triflorum* and *M. pudica* were the tolerant legume species present during the wet season. These pioneer species were eased out, probably due to shading and the rapid growth of the invading species. These invading species are represented by the plant community in site 1C, which is the next seral stage. *Digitaria sanguinalis*, which used to be dominant in site 2, became a minor species in subsite 1C; the minor species *C. dactylon* and *P. conjugatum* became more dominant. *P. scrobiculatum* used to be dominant in site 2 during the rainy season; however, this species was encountered only once in subsite 1A, and with only very small importance value. The third seral stage was observed in subsites 1A and 1B, which were still dominated by *C. dactylon* and *P. conjugatum* with *Cuphea carthagenensis*. The importance value of *Commelina diffusa* increased, whereas that of *P. conjugatum* decreased.

Site 3 represents the more advanced stage in the succession. Although *C. dactylon* - *P. conjugatum* still dominated the community, the legume shrubs (i.e., *Mimosa pudica*) present in site 3 indicate the advancing stage of succession. These shrubs were absent in subsites 1A and 1B. Soil OM is the key factor responsible for the changes in seral stage. Although site 3 had a much higher available Cu, it had much higher soil OM than subsites 1A and 1B. This accordingly encouraged the shrubs to grow. All sites were surrounded by secondary forest; therefore, they all have the chance to get colonized by these species if conditions are favorable.

3.4 Similarity levels of plant species composition among the different sites

The similarity indexes of the plant species composition present in the sites are additional evidence that support the hypothesis proposed in this study. Site 2 represents the pioneer stage in the ecological succession, site 3 is the advance stage, whereas site 1 is the transition stage between the sites 2 and 3. Figure 5 presents the dendogram cluster analysis of the plant species composition based on the 2013 dry and wet season survey. The dendogram also presents the similarity levels between sites. Site 2 is the most different and has the greatest dissimilarity with site 3. The three subsites in site 1 have the highest similarity levels, which show that they are at the same stage. Site 1 is more similar to site 3 than site 3 is to site 2. Sites 1 and 2 have similarity levels that are higher than those of sites 2 and 3. Therefore, site 1 is the transition between sites 2 and 3.

Another evidence corroborates this successional pattern is the index of similarity shown in the dendogram. Site 2 (4 in the dendogram) has very minimal similarity (8%) with site 3 (5, 6 in the dendogram). This is mainly because site 3 is more advanced than site 2, which is at the 1st seral stage of succession. Site 1 (1, 2, 3 in the dendogram) and site 2 (4) have 34% similarity, whereas sites 1 and 3 have 27% similarity. These data illustrate that site 1 is the transitional stage between sites 2 and 3.

Ecological succession is a very slow process. Site 2 was established in 1986; 28 years later (2013–2014), it was still at the pioneer stage of succession. As such, it can be inferred that with soil OM content of 0.03% at the beginning of this study, there was already a slow build-up of OM, assuming it had zero OM at the start and had much higher amount of Cu. Thus, it shows that the soil environment has already improved since 1986. The topsoil amendment and the accidental trash slide in 1991 may have significantly improved the OM content in site 1, which accelerated the succession process by several decades. This may be due to greatly diminished level of Cu (100 mg/kg at the time of the study) from a level that maybe higher than or equal to the 220 mg/kg shown in site 2. Site 3 has no baseline data; thus, it can be hypothesized that the level of Cu may be as high as in site 2 before succession started. Accordingly, the Cu level was already reduced at the time of sampling.

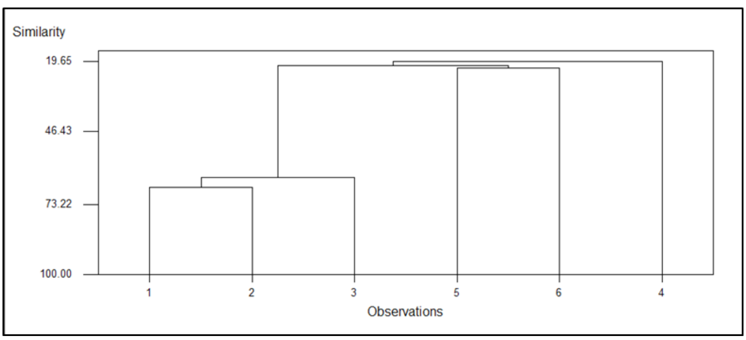

Figure 5. Dendrogram of cluster analysis by Minitab® 17 of plant species composition in the three study sites.Note: 1 = site 1A, 2 = site 1B, 3 = site 1C, 4 = site 2, 5 = site 3A, 6 = site 3B

4. Conclusion and Recommendation

The data on vegetation analyses shows the stages of plant succession in the decommissioned tailings ponds. Site 2 represents the 1st stage of ecological succession, site 1 is the next seral stage, and site 3 is the most advanced stage of succession. The succession in the three study sites was driven by the Cu content, pH, texture and OM content of the soil. This was shown by the principal component statistical analysis (Eigen analysis of the Correlation Matrix) discussed above that site and Cu content explain 42% of all the variations and that (texture) layer and pH have the highest coefficients. The characteristics of the soil environment of each of site such as soil texture, soil organic matter content and its consequent effects on water holding capacity (WHC) and cation exchange capacity (CEC) coupled with the toxic levels of Cu and soil pH are responsible or are the determinant factors for the plant community present in each site. Conversely, the best strategy to rehabilitate the Cu-contaminated land is through organic matter amendment. Municipal solid biowastes are important resources that can be composted and applied in these damaged lands

Acknowledgment

The funds for this research was provided by the National Research Council of the Philippines.

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