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Effects of Soil Amelioration and Vegetation Introduction on the Restoration of Abandoned Coal Mine Spoils in South Korea

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Abstract: In order to ecologically restore coal mine spoils, tolerant species were selected through vegetation surveys on the abandoned coal mine spoils and natural forests established on the poor environment similarly to there. In addition, tolerant species were selected through cultivation experiments in the laboratory. Many C_4 plants were included among the tolerant species selected through cultivation experiments. Soil was ameliorated by applying commercial organic fertilizer that can improve both physical and chemical properties of soil at the same time. Vegetation introduced for restoration was prepared by combining plant species tolerant to the degraded environment of coal mine spoils and the reference information. The treatment with a soil ameliorator improved the chemical properties of soil, such as the pH and nutrient contents, and promoted the growth of sample plants significantly. However, additional improvements were required compared with the chemical properties of healthy forest soil. The sites restored by ameliorating soil and introducing tolerant species showed a more similar species composition to the reference sites compared with the afforested and non-restored sites in both lowland and upland areas. However, such restoration did not play a significant role in increasing species diversity or excluding exotic plants. In this respect, more active restoration is recommended.

Keywords: coal mine spoils; ecological restoration; reference information; restoration effect; soil amelioration; tolerant species

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1. Introduction

Coal mining activities in Korea have been conducted through deep mining processes, because coal deposits are deep underground. Therefore, coal mining activities usually lead to the production of large quantities of waste material, or spoils. Such coal mining debris has been piled up on mountains or discarded in mountain valleys. Therefore, acid mine drainage, barren unvegetated areas, and steep unstable piles of mining waste are frequently left behind after mining. Even when the damaged areas are re-vegetated, exotic or non-local species are usually employed for the rehabilitation of those areas. Consequently, most rehabilitated mine areas form an ecological space dissimilar to the surrounding habitat [1].

This problem has occurred because the ecology of the mined area is not well-understood by rehabilitation practitioners. In reality, untreated deep mining debris does not function as soil by itself because it does not include sufficient organic matter and nutrients. Therefore, ecosystem development in these areas must progress in the same manner as primary succession: the process of ecosystem development on barren surfaces where severe disturbances have removed most vestiges of biological activity. Succession progresses as a result of interactions among plants growing in a given area. The facilitation of growth of new plant species by early colonizers promotes species compositional change to the next successional stage [2–4].

A properly planned restoration project attempts to fulfill clearly stated goals that reflect important attributes of the reference ecosystem. Goals are attained by pursuing specific objectives, which are evaluated on the basis of performance standards, also known as design criteria or success criteria. These standards or criteria are largely conceived from an understanding of the reference ecosystem [5–7].

Three strategies exist for conducting an evaluation: direct comparison, attribute analysis, and trajectory analysis. In direct comparison, selected parameters are determined or measured in the reference and restoration sites. The parameters considered include aspects of both the abiotic environment and the biota. In attribute analysis, attributes such as species composition, percentage of indigenous species, stability of the system, the physical environment, the presence of normal developmental processes, harmony with the larger ecological matrix, potential threats to the habitat, resilience, and capacity for self-sustenance are used to judge the degree to which each goal has been achieved. Trajectory analysis is an evaluation of trends in restoration area to determine whether the restoration is following its intended trajectory towards the reference condition [5–7].

The trajectory of a restoration project may be viewed in terms of ecosystem structure and functioning. A change in both dimensions occurs when habitat is degraded. The fundamental goal of restoration is to return a habitat or ecosystem to a condition as close as possible to its pre-degraded state. Complete restoration would involve a return or a partial return to the original state, whereas other trajectories would result in rehabilitation of the system, or replacement with a different system [8].

To effectively restore degraded areas or to protect existing high-quality areas, we must be able to define the attributes of "normal" and undegraded or "healthy," habitats as a model. One way of setting a baseline and measuring restoration success is to define the normal "biological integrity" of a system and then measure deviations from this norm. Biological integrity is defined as "the ability to support and maintain a balanced, integrated, adaptive biological system having the full range of elements and processes expected in the natural habitat of a region" [9]. To evaluate the integrity of a site, ecological attributes of the site are compared with those of an "undisturbed" reference.

Many species have been introduced, deliberately and accidentally, into areas where they are not native [10,11]. Often, these exotic species subsequently expand their ranges beyond the place of initial establishment because of advantageous life history strategies [12]. Disturbed lands often provide favorable microhabitats for exotic species equipped with opportunistic or ruderal life history strategies [12–15]. Unlike in their original habitat, these exotic species can become very aggressive in their newly settled habitat. Therefore, experts in this field view the spread of exotic species as one of the most serious environmental problems, and also consider it a major contributor to biodiversity loss [16]. Restoration practices are recommended as a measure to inhibit the invasion of exotic species [15,17,18]. Restorative treatment reduces the relative coverage of exotic plants, which implies that restoration practices can contribute to conserving and restoring the biological integrity of damaged riverine ecosystems [9,19,20].

Although the restoration projects should be scientifically assessed, most projects are still unevaluated, and conducted evaluations lead to ambiguous results [21–27]. Furthermore, a consensus on what constitutes a successful restoration project is still lacking. In addition, although restoration programs are being incorporated widely into natural resource strategies from the local to the global level, uncertainty remains as to how to effectively and efficiently execute these efforts [6,28]. However, without an adequate evaluation of restorations, lessons cannot be learned from successes and failures, and the restoration field will not advance [6,22,26,27,29]. Moreover, evaluating the success of restoration projects is crucial to adaptive management, improving the effectiveness of future projects and collaborative learning [30,31].

Evaluating restoration is not straightforward, and what characterizes successful restoration and how best to measure it are highly debated [27,32]. Hobbs and Norton [33] provided a framework to delineate the practice of ecological restoration, including the aims and methodologies that can be used, the expansion of targets for restoration beyond ecology, and the inclusion of historical, social, cultural, political, aesthetic, and moral aspects [34]. However, since then, debates over the goals of restoration [35,36], the influence of climate change [37–39], and socioeconomic circumstances [40–43] have continued. All of these issues affect the definition and evaluation of restoration success, and synthesizing these debates has led to the development of useful indicators [32].

This study was carried out to restore coal mine spoils ecologically and evaluate the effects after restoration. The aim of this study was to restore the coal mine spoils to a level similar to the natural forest by introducing plants. To realize this goal, we applied a soil ameliorator and introduced a selection of tolerant plants that can withstand the degraded environment of coal mine spoils. The restoration effects, first of all, were evaluated based on the effect of the soil ameliorator in terms of improving the chemical properties of soil and promoting the growth of specimen plants. Furthermore, the effects were also evaluated based on vegetation quality. Vegetation quality was evaluated based on species composition, biodiversity, and exotic species rate.

2. Materials and Methods

2.1. Site Description

Sites for carrying out this study were selected in two areas of Dogye-eup (the first area) and Taebaek-si (the second area) in Gangwon province (Figure 1). The first area, ranging vertically from 200 m to 400 m above sea level, was chosen to obtain information for the restoration of coal mining spoils in lowland areas. Exposed outcrops appeared frequently, and soil development was usually poor in forests around the first area. The environmental conditions led to the establishment of a Korean red pine (*Pinus densiflora* Siebold & Zucc.) forest. Ecological restoration of the coal mine spoils located in this area was practiced by imitating this Korean red pine forest as a reference site. There were two sorts of reclaimed sites in the first area. One site was reclaimed by introducing black locust (*Robinia pseudoacacia* L.) about 30 years ago, and the other one was afforested by introducing birch (*Betula schmidtii* Regel.) 10 years ago.

The second area, ranging vertically from 800 to 1000 m above sea level, was chosen to obtain information for the restoration of coal mining spoils in upland areas. Four kinds of reclaimed sites were found in the second area. *Alnus incana* subsp. *Hirsute* Turcz. ex Spach., *Betula platyphylla* var. *japonica* H. Hara., *Lespedeza cyrtobotrya* Miq., and *Robinia pseudoacacia* were introduced to rehabilitate the coal mine spoils of this area 30 years ago. The other site was reclaimed by introducing *Lespedeza cyrtobotrya* 10 years ago. Surrounding forests chosen as reference site were usually covered with Mongolian oak (*Quercus mongolica* Fisch. ex Ledeb.) forest.

2.2. Soil Amelioration

Coal waste is severely deficient in nutrients due to its low organic matter content and low pH, and it is not hospitable for plants to establish due to physical defects of the substrate as a planting bed. Organic fertilizer replenishes nutrients in natural organic materials and is considered to be a soil ameliorator that can improve the physical and chemical properties of such coal waste at the same time [1,44]. Therefore, commercial organic fertilizers were adopted and applied as soil ameliorators in this study.

2.3. Selection of Tolerant Species

The tolerant species to realize ecological restoration of coal mine spoils were selected through field surveys on vegetation established on the mountainous land with exposed outcrops and talus with similar environments to coal spoils (the first criterion). In addition, the species that were naturally established flourished in the coal mine spoils as species that does not exist or rarely appear, and especially flourished in the coal mine spoils in comparison with the species composition of reference sites and coal mine spoils (the second criterion).

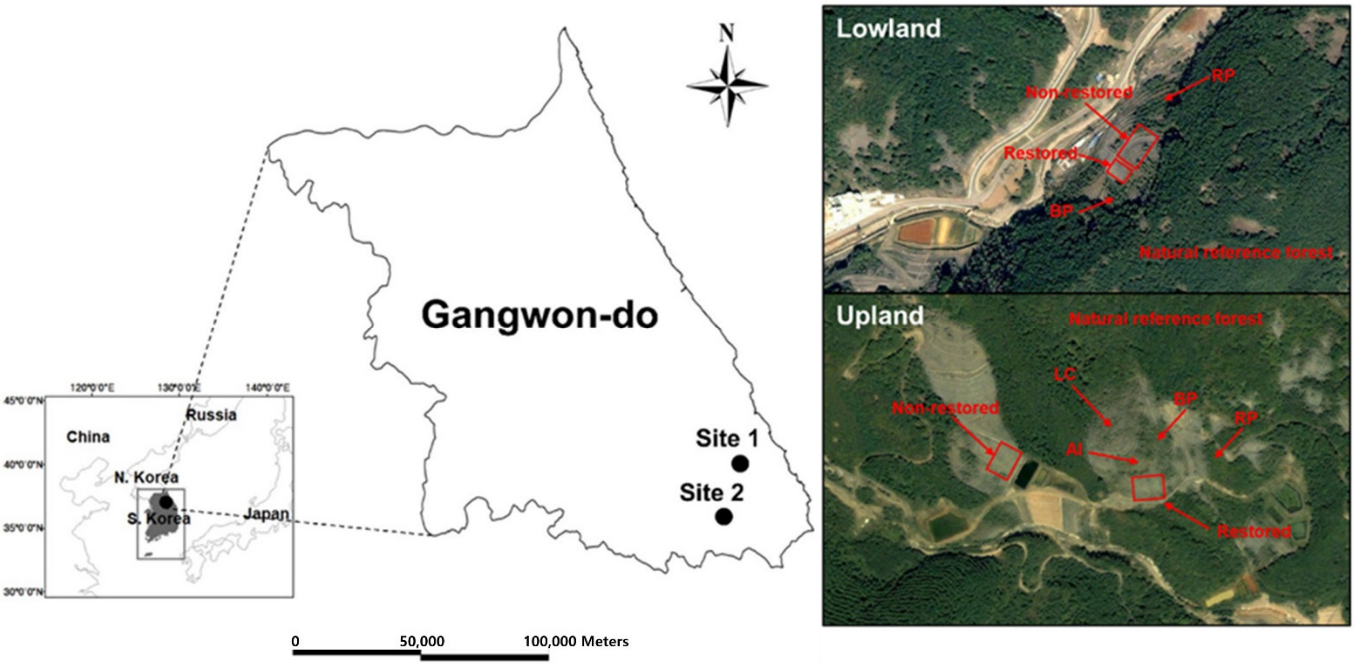

Figure 1. A map showing the study sites of the abandoned coal mine. Do indicates the administrative unit corresponding to the province. BP: *Betula platyphylla* var. *japonica*, RP: *Robinia pseudoacacia*, LC: *Lespedeza cyrtobotrya*, AI: *Alnus incana* subsp. *hirsuta*.

The tolerant species from laboratory experiments were selected by comparing the growth of sample plants cultivated in the ameliorated pots by adding organic fertilizer and forest soil to pots containing raw coal mine debris (Table 1).

Table 1. The chemical properties of soil contained in pots prepared to select tolerant species in the laboratory experiment. Raw: coal mine debris, FS: ameliorated by adding forest soil on the coal mine debris, OF: ameliorated by adding organic fertilizer in the coal mine debris.

Plot	pH	OM	TN	AP (ppm)	Ca^{2+}	Mg^{2+}	K
		(%)				($cmol_c$/kg)	
Raw	3.40 (0.08)	7.85 (0.69)	0.15 (0.02)	0.02 (0.01)	0.31 (0.04)	0.12 (0.03)	0.05 (0.03)
FS	4.94 (0.06)	7.93 (0.47)	0.32 (0.03)	6.96 (3.02)	2.11 (0.04)	0.75 (0.03)	0.35 (0.04)
OF	4.95 (0.10)	16.1 (0.96)	0.38 (0.03)	2.15 (1.36)	1.05 (0.06)	0.48 (0.03)	0.14 (0.03)

Numbers in parenthesis indicate standard deviations.

2.4. Restorative Treatment

Our restoration goal was to cover these damaged mountains with vegetation and restore them similarly to existing forests. Barren coal mine debris needs to be ameliorated by introducing a proper soil ameliorator to the level that the introduced plants can survive to realize ecological restoration through the successful settlement of plants. Ecological restoration was carried out by applying a soil ameliorator and introducing tolerant plants to the coal mine spoil dump. The coal mine spoil dump was reshaped to maintain a slope similar to that of the surrounding mountain to ensure stability. Then, coal mine debris was ameliorated by applying an organic fertilizer, which was selected as a suitable ameliorator through the preliminary study. Organic fertilizer was supplied as 6.4 ton/ha and 12.8 ton/ha. Chemical properties of the organic fertilizer are given in Appendix A.

The planting bed was prepared in a size of 5 m × 5 m. Each treatment plot of soil had five replicates for the lowland site and three for the upland site. Sample plants were introduced at 1 m intervals for trees and 50 cm intervals for shrubs and herbaceous plants. The control plot of the soil involved a fresh coal mine debris plot that was not treated with any soil ameliorator. No plants were introduced for restoration to the non-restored plot of vegetation (Figure 2).

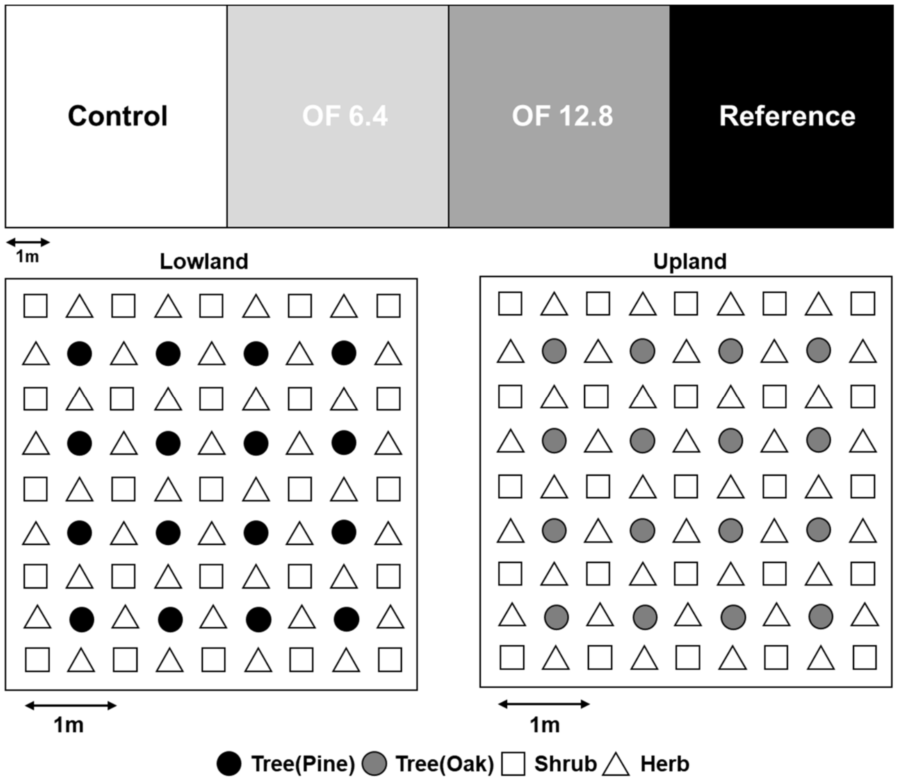

Figure 2. A conceptual diagram of a restoration design that carried out soil improvement and vegetation introduction. The soil amelioration plots were composed of control plots with fresh coal mine debris, OF 6.4 plot ameliorated with the treatment of organic fertilizer of 6.4 ton/ha, and OF 12.8 plot ameliorated with the treatment of organic fertilizer of 12.8 ton/ha. In addition, natural forest soil was selected as the reference plot for comparison. The model for vegetation restoration in the lowland was prepared by imitating the *Pinus densiflora* forest as a reference site, and the upland was prepared by imitating the *Quercus mongolica* forest as a reference site. This diagram depicts one full replicate of the experimental design, with five replicates for the lowland site and three replicates for the upland site.

The arrangement of tolerant plants to realize ecological restoration was harmoniously planned considering the distribution range of plants in the natural environment, based on the topography and the tolerance ranking for the polluted soil obtained from experimental study. Our restoration plan placed plants for restoration by considering both natural and artificial elements [45–48]. Upland and lowland restoration models were prepared assuming a Mongolian oak forest and a Korean red pine forest, respectively, by reflecting the spatial distribution patterns of natural vegetation of the corresponding region. In order to create a Mongolian oak forest, *Q. mongolica*, *Betula platyphylla* var. *japonica*, *B. schmidtii*, *Albizia julibrissin* Durazz., *Styrax japonicas* Siebold & Zucc., *Acer pseudosieboldianum* (Pax) Kom., *Rhododendron schlippenbachii* Maxim., and *Spodiopogon sibiricus* Trin. were introduced. *P. densiflora*, *R. mucronulatum*, *Lespedeza cyrtobotrya*, *Miscanthus sinensis* Andersson., and *Arundinella hirta* (Thunb.) Tanaka. were introduced to create a Korean red pine forest. Both plots were prepared by hypothesizing a forest with canopy tree, shrub, and herb layers in the future (Figure 3). Each restoration model should avoid heterogeneous choices that do not match the surroundings, considering natural vegetation around the coal mine spoils and exotic plant species which should be thoroughly excluded when tolerant plants are introduced. Among the plants introduced for restoration, three-year-old seedlings were used in the case of woody plants, whereas one-year-old seedlings were used in the case of herbaceous plants.

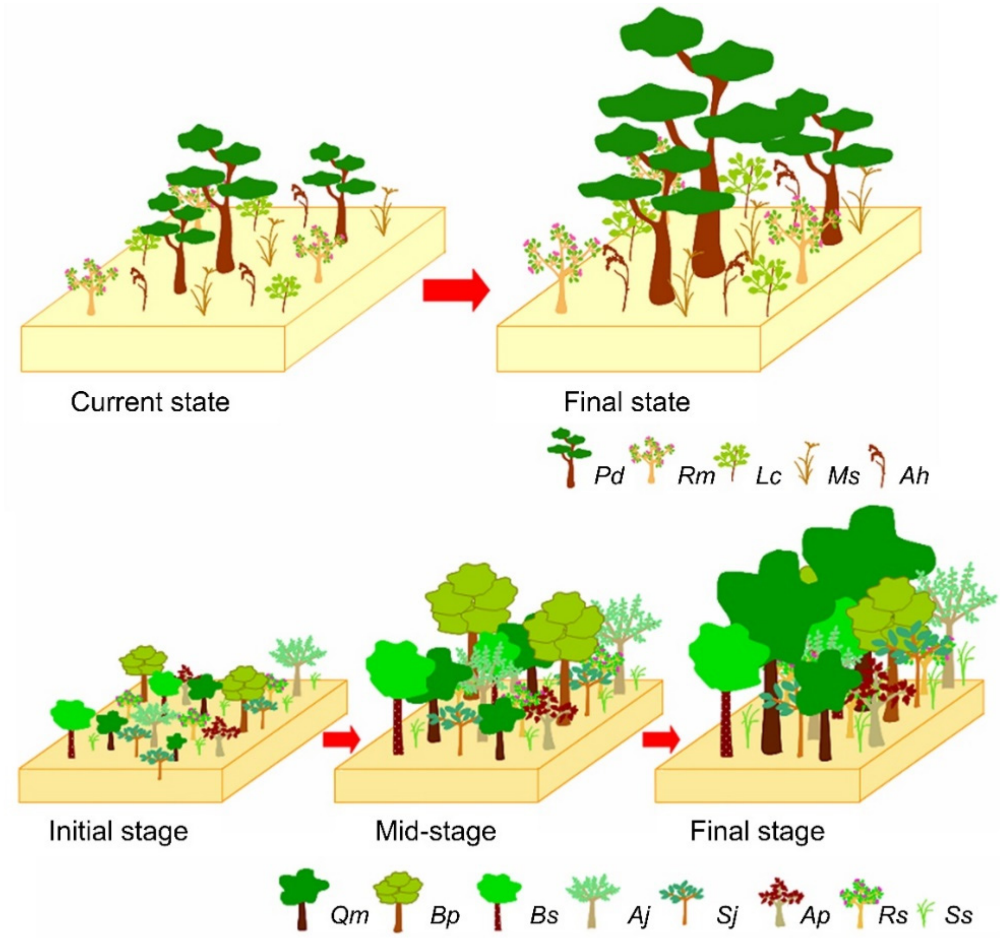

Figure 3. Restoration design prepared to realize true restoration in lowland (upper) and upland (lower) areas, by hypothesizing *Pinus densiflora* forest (upper) *Quercus mongolica* forest (lower) in the future. Pd: *Pinus densiflora*, Rm: *Rhododendron mucronulatum* Turcz., Lc: *Lespedeza cyrtobotrya*, Ms: *Miscanthus sinensis*, Ah: *Arundinella hirta*, Qm: *Quercus mongolica*, Bp: *Betula platyphylla* var. *japonica*, Bs: *Betula schmidtii*, Aj: *Albizzia julibrissin*, Sj: *Styrax japonicus*, Ap: *Acer pseudosieboldianum*, Rs: *Rhododendron schlippenbachii*, Ss: *Spodiopogon sibiricus*.

2.5. Evaluation on Restoration Effects

The restoration effect in soil was evaluated for pH, organic matter, N, P, K, Ca, and Mg contents, and cation exchange capacity (CEC). Soil characteristics (pH, organic matter, Total-N, P, K^+, Ca^{2+}, and Mg^{2+} content and CEC) in the three treatment plots (control, OF 6.4 and OF 12.8) were compared with one-way analysis of variance (ANOVA) and Tukey's honestly significant difference (HSD) test at $\alpha = 0.05$ (SAS 2001).

The restoration effect of vegetation was evaluated by comparing species composition, species diversity, and exotic plant ratio with natural reference forests and artificial plantation.

2.6. Soil Analysis

Soil samples were collected in September 2017 from the top 10 cm after removing the litter at five random points in each plot; after which, they were pooled, air-dried at room temperature, and sieved through 2 mm mesh.

Soil properties were diagnosed for pH, and organic matter, Total-N, P, K^+, Ca^{2+}, and Mg^{2+} contents. Soil pH was measured with a bench top probe after mixing the soil with distilled water (1:5 ratio, w/v) and filtering the extract (Whatman No. 44 paper). Organic matter content was obtained by measuring the loss after ignition for four hours in a muffle furnace of 400 °C. Total nitrogen was measured with the micro-Kjeldahl method [49]. Available P was extracted in 1 N ammonium fluoride (pH = 7.0) and exchangeable K^+, Ca^{2+}, and Mg^{2+} contents were measured from the extract by 1 N ammonium acetate (pH = 7.0 for K, Ca and Mg and pH = 4.0 for Al) by ICP (inductively coupled plasma atomic emission spectrometry; Shimadzu ICPQ-1000, Shimadzu Cor., Kyoto, Japan) [50].

2.7. Vegetation Analysis

In the restoration site located in the lowland area, a vegetation survey was carried out for 72 plots. A total of 16 ecologically restored plots were chosen for vegetation survey and 18 reference stands, 5 non-restored plots, and 33 afforested plots by introducing *Betula schmidtii* (15 plots) and *Robinia pseudoacacia* (18 plots) were investigated for comparison with the restored plots.

In the other restoration site located in upland, 49 plots were chosen for the vegetation survey. A total of 5 ecologically restored plots were chosen for vegetation survey and 10 reference stands, 3 non-restored plots, and 31 afforested plots by introducing *Alnus incana* subsp. *hirsuta* (12 plots), *Betula platyphylla* var. *japonica* (9 plots), *Lespedeza cyrtobotrya* (5 plots), and *Robinia pseudoacacia* (5 plots) were investigated for comparison with the restored plots.

Plots 10 m × 10 m in size were used for the reference stands and the afforested plots, which are reached mature forest and 5 m × 5 m plots were used for the restored plots and the young, afforested plots (*Betula schmidtii* plots and *Lespedeza cyrtobotrya* plots).

The purpose of designation of reference plots was to compare them, as a target community, with the restored plots. Neither soil amelioration nor planting was conducted in the reference plots.

Vegetation data were collected in the restored stands and the reference plots in 2017. All the plant species which occurred in each plot were identified following KPNI [51]. The dominance of each species in each plot was estimated with an ordinal scale (1 for <5% to 5 for >75%), and each ordinal scale was converted to the median value of percentage cover range in each cover class [52]. Importance value of each species was then determined by multiplying the fraction of each species cover to the summed cover of all species in each plot by 100. A matrix of importance values for all species in all plots was constructed and imputed to detrended correspondence analysis (DCA) for ordination [53].

As a measure of species diversity and dominance, a rank abundance curve [54–56] was constructed. Percentages of native and alien species to endemic species were also determined for each stand type.

We measured the height and diameter growths of sample plants and compared between the ameliorated and the untreated plot. Plant height and diameter were measured with a measuring tape with 0.5 mm precision and Vernier calipers (NTD12, Mitutoyo Cor., Kanagawa, Japan) with 0.05 mm precision and averaging five randomly chosen stems in each subplot. The height and diameter of sample plants among plots were compared with ANOVA and HSD at $\alpha = 0.05$ [57].

2.8. Statistical Analysis

All statistical analyses were carried out using Statistical Analysis System (SAS) version 9.1 [57]. For all analyses, we assessed differences using a significance level of at least $p = 0.05$. Analysis of variance (ANOVA) was performed to compare any differences in the soil environmental factors among pitch pine stands with different stand ages and with the reference oak stand. Tukey's honestly significant difference method was employed when making multiple comparisons among means.

Detrended correspondence analysis (DCA) is an eigenvector ordination technique based on correspondence analysis (CA or RA). It is especially suited to the analysis of ecological datasets based on sample units and species [53,58]. The differences in species composition among stands restored ecologically (restoration), rehabilitated by applying the silvicultural method, and reference stands were analyzed using DCA.

3. Results

3.1. Selection of Tolerant Species by Field Survey

Tolerant plant species to be introduced for restoration were selected as species which appeared as more than III in constancy (frequency 40–60%) in the reference site to ensure a similar species composition to the reference site (the first criterion). The reference site was selected in the rocky mountain with similar environmental conditions. In addition, species which presented as particularly as high frequency and coverage of more than 60% on the abandoned coal mine spoils were selected as tolerant species additively (the second criterion) (Table 2).

Table 2. Tolerant species selected by field survey in the abandoned coal mine spoils and nearby mountainous land with similar environmental condition.

Layer	Species	Criteria Rank
Canopy tree	*Pinus densiflora*	2
	Quercus variabilis Blume.	1
	Q, mongolica	1
	Q. serrata Murray.	1
	Q. dentate Thunb.	1
	Betula davurica Pall.	1
	B. schmidtii	2
	B. platyphylla var. *japonica*	2
	Fraxinus rhynchophylla Hance.	1
	Kalopanax pictus Nakai.	2
Understory tree	*Lindera obtusiloba* Blume.	1
	Maackia amurensis Rupr.	1
	Euonymus oxyphyllus Miq.	1
	Styrax obassia Siebold & Zucc.	1
Shrub	*Corylus sieboldiana* Blume.	1
	Fraxinus sieboldiana Blume.	1
	Juniperus rigida Siebold & Zucc.	1
	Lespedeza cyrtobotrya	2
	L. maximowiczii	2
	Rhododendron mucronulatum	1
	Rhus trichocarpa Miq.	1
	R. chinensis	1
	Salix hulteni Flod.	2
	Smilax china L.	1
	Tripterygium regelii Sprague & Takeda.	1
	Zanthoxylum schinifolium Siebold & Zucc.	1

Table 2. *Cont.*

Layer	Species	Criteria Rank
Herb	*Spodiopogon sibiricus*	2
	Arundinella hirta	2
	Potentilla freyniana Bornm.	1
	Pteridium aquilinum var. *latiusculum* Underw.	1
	Vitis coignetiae Pulliat ex Planch.	1
	Miscanthus sinensis	2
	Themeda triandra var. *japonica* Forssk.	1
	Cymbopogon tortilis var. *goeringii* Hand.-Mazz.	1
	Echinochloa Crus-galli var. *oryzicola* Ohwi.	1
	Echinochloa crus-galli P.Beauv.	1
	Aster scaber Thunb.	1
	Actinidia rufa Siebold & Zucc.	1
	Polygonatum odoratum var. *pluriflorum* Ohwi.	1
	Saussurea grandifolia Maxim.	1

As a result of the field survey, the most tolerant species were selected based on the first criterion rather than the second. This is because most plant species established naturally on the abandoned coal mine spoils showed very low coverage and frequency. In this respect, soil amelioration is urgently required to restore the coal mine area with more stability.

3.2. Selection of Tolerant Species by Cultivation Experiment in Laboratory

Initially, we planned to select species that grew in the control plot with coal mine debris larger than that in the experimental plot with ameliorated substrate as the tolerant species. However, there were no plants that showed such a response. Therefore, we compared the tolerance order of sample plants based on the ratios of growth coefficients of sample plants in the control plot with both plots ameliorated by applying organic fertilizer (OF) and forest soil (FS) (Table 3).

Table 3. Growth coefficient in each plot, ratio of growth coefficient to the ameliorated plot, and the order of tolerance to the raw coal mine debris. Coal: raw coal mine debris plot, OF: plot ameliorated treating organic fertilizer of 12.8 ton/ha, FS: plot ameliorated covering forest soil of 10 cm depth.

Scientific Name (Genus)	Coal	OF	FS	Coal/OF (%)	Coal/FS (%)	Order of Tolerance [1]	Order of Tolerance [2]	Synthetic Order	Remarks
Pinus	1.32	1.80	1.60	73.3	82.5	1	1	1	Tree
Miscanthus	0.55	0.94	0.71	77.5	58.5	1	4	2	C_4
Quercus	1.00	1.50	1.48	66.7	67.6	2	2	3	Tree
Echinochloa	0.51	0.87	0.79	64.6	58.6	5	3	4	C_4
Themeda	0.49	0.91	0.71	69.0	53.8	3	7	5	C_4
Cymbopogon	0.33	0.60	0.52	63.5	55.0	6	5	6	C_4
Amaranthus	0.23	0.42	0.39	59.0	54.5	7	6	7	C_4
Spodiopogon	0.38	0.81	0.68	55.8	46.9	8	8	8	C_4
Lespedeza 1	0.27	0.59	0.49	55.1	45.8	9	9	9	Legume
Melica	0.31	0.72	0.57	54.4	43.1	10	10	10	C_4
Lespedeza 2	0.27	0.65	0.51	52.9	41.5	11	11	11	Legume
Lespedeza 3	0.19	0.51	0.43	49.3	37.3	12	12	12	Legume
Albizzia	0.23	0.65	0.48	47.9	35.4	13	13	13	Legume
Artemisia	0.11	0.35	0.28	39.3	31.4	14	14	14	C_3
Rumex	0.12	0.52	0.33	36.4	23.1	15	15	15	C_3

[1] Order of tolerance of compared growth in substrate ameliorated by organic fertilizer. [2] Order of tolerance of compared growth in forest soil.

As a result of the comparison on the tolerance levels of 15 sample plants, trees of *Pinus densiflora* and *Quercus mongolica* showed the highest and the third highest tolerance order, respectively. *Miscanthus sinensis* showed the next highest tolerance, followed by *Echinochloa*, *Themeda*, *Cymbopogon*, etc. Overall, C_4 plants showed higher tolerance order, legumes were the next, and C_3 plants showed the lowest tolerance level.

Meanwhile, trees such as *P. densiflora* and *Q. mongolica* could not be compared directly with other sample plants because the measuring items were different from each other. However, compared based on the tolerance index obtained in this study, *P. densiflora* and *Q. mongolica* ranked first and third among the total sample plants, respectively. Compared with the two plants with the same life form, the tolerance of *P. densiflora*, which was the early successional species, was higher than *Q. mongolica*, the late successional species.

3.3. Soil Amelioration Effect

Soil amelioration effects were evaluated based on pH, OM, TN, AP, CEC, Ca, Mg, and K contents. The treatment of soil ameliorators showed significant differences among treatment plots with different supplies, such as non-treatment, OF 6.4 ton/ha, and OF 12.8 ton/ha plots (Figure 4). However, the evaluation results showed that the contents were lower compared with those of the reference sites, except for the organic matter content and nitrogen content of some plots.

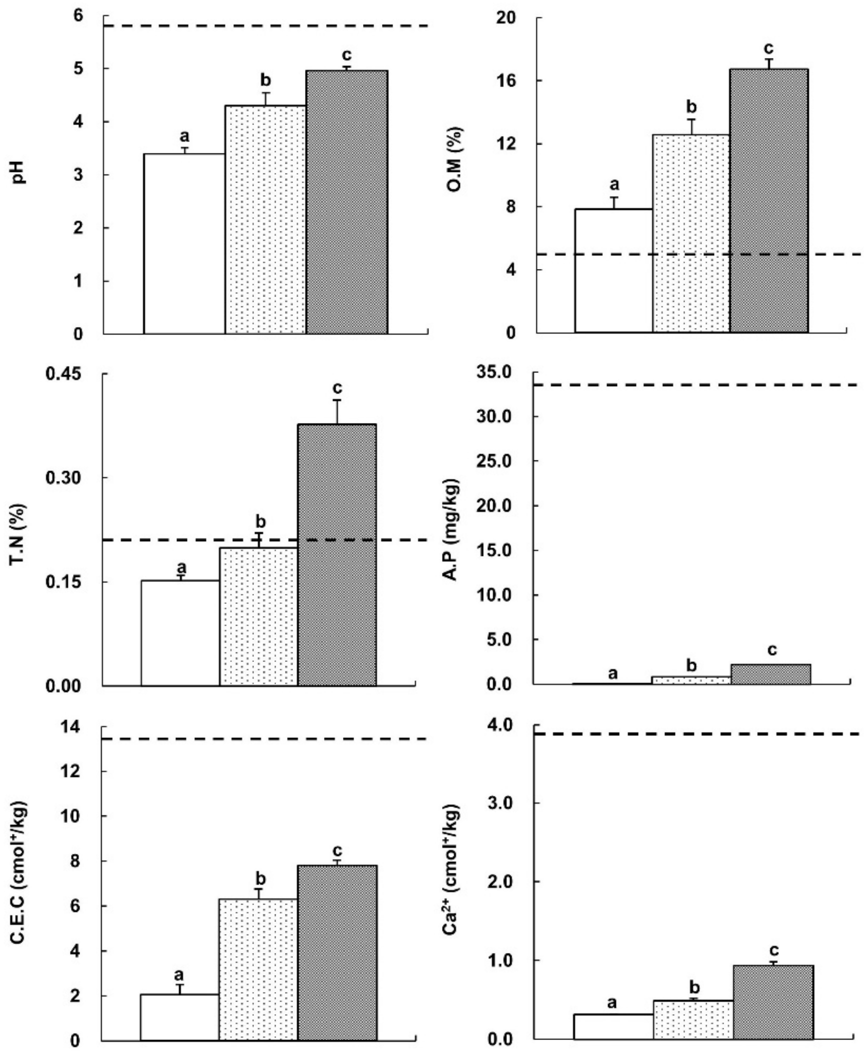

Figure 4. *Cont.*

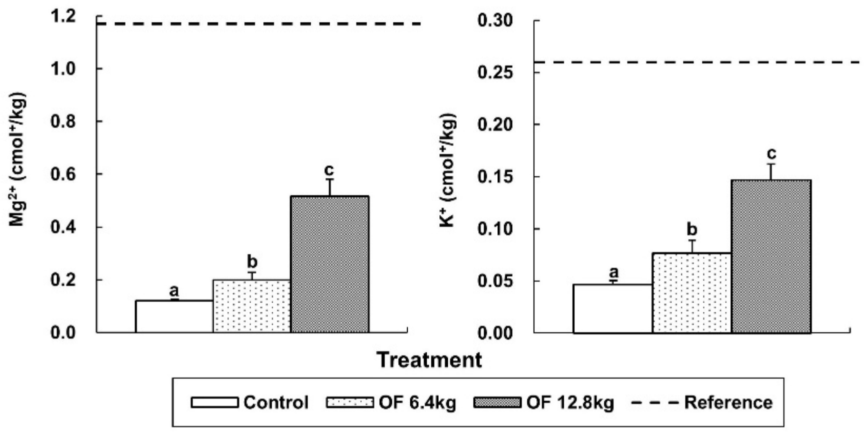

Figure 4. Effect of organic fertilizer as a soil ameliorator on soil characteristics. Control: fresh coal mine debris plot, OF 6.4 ton: plot ameliorated treating organic fertilizer of 6.4 ton/ha, OF 12.8 ton: plot ameliorated treating organic fertilizer of 12.8 ton/ha, Reference: natural forest soil. Each bar is expressed as the mean and standard error of mean. Tukey's honestly significant difference (HSD) test was conducted on each of the parameters that showed a statistically significant difference among the three types of treatments at $\alpha = 0.05$; the means with the same alphabetical character (in superscript) for each parameter are not different from each other.

3.4. Growth of Sample Plants

Plant growth showed significant differences among treatment plots with different amounts of soil ameliorators in all sample plants. From these results, the soil amelioration effect on the plant growth was identified from all sample plants (Figure 5).

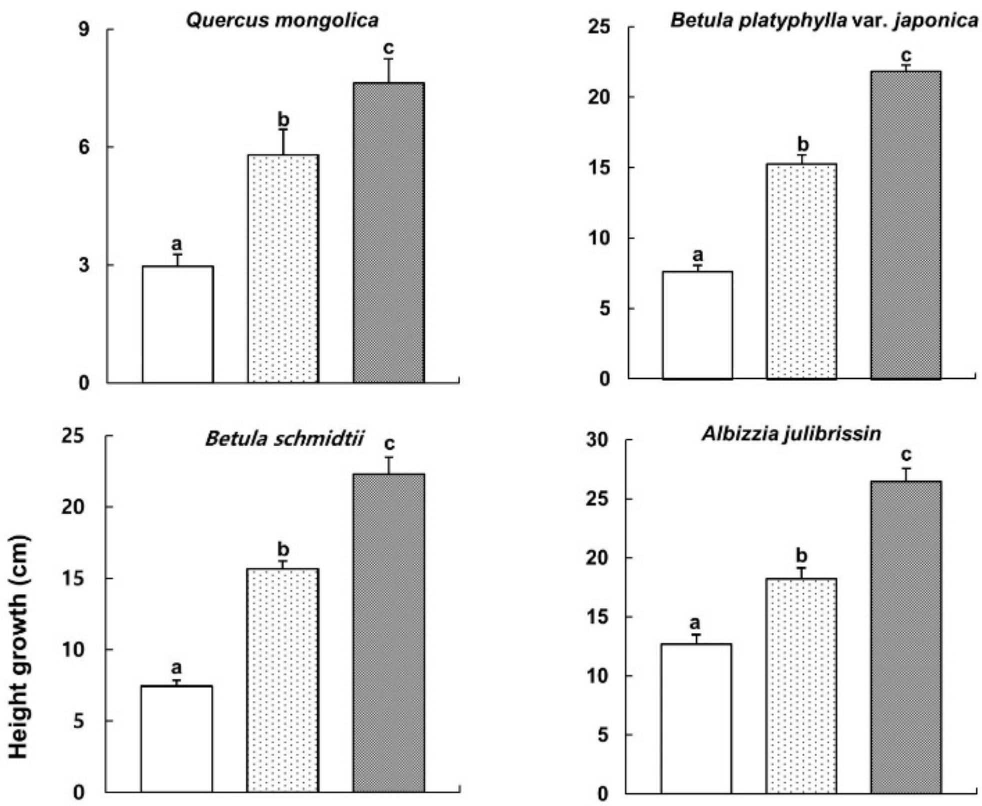

Figure 5. *Cont.*

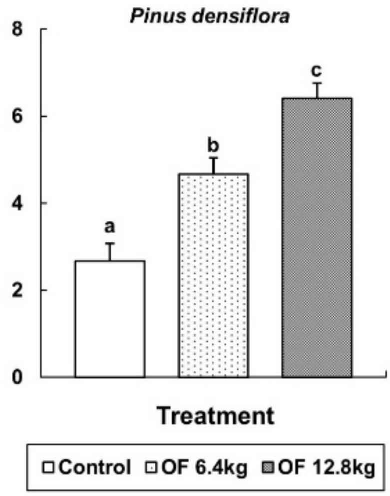

Figure 5. Height growth response of sample plants in control (fresh coal mine debris) and ameliorated plots (OF 6.4 ton and OF 12.8 ton). Control: fresh coal mine debris plot, OF 6.4 ton: plot ameliorated treating organic fertilizer of 6.4 ton/ha, OF 12.8 ton: plot ameliorated treating organic fertilizer of 12.8 ton/ha, Reference: natural forest soil. Each bar expresses the mean and standard error of the mean. Tukey's honestly significant difference (HSD) test was conducted on each of the parameters that showed a statistically significant difference among the three types of treatments at $\alpha = 0.05$; the means with the same alphabetical character (in superscript) for each parameter are not different from each other.

3.5. Species Composition

The restoration site located in the lowlands consisted of an ecologically restored site, two afforested sites by introducing *Betula schmidtii* and *Robinia pseudoacacia*, and non-restored sites, respectively. As a result of stand ordination, the non-restored sites were located far from the reference sites and the restored and afforested sites, showing a large difference in species composition (Figure 6). The restored sites were located closer to the reference sites than the sites afforested through the introduction of *Robinia pseudoacacia*, along with the sites afforested through the introduction of *Betula schmidtii* on Axis I. Meanwhile, the restored sites were located closer to the reference sites than the sites afforested through the introduction of *Betula schmidtii* along with the sites afforested through the introduction of *Robinia pseudoacacia* on Axis II. Synthesizing the results, the restored sites tended to be located closer to the reference sites than the non-restored sites as well as the afforested sites; thus, it was judged that they had a more similar species composition to the reference sites.

As a result of stand ordination, compared with the lowland sites, the upland sites were located relatively close to each other, indicating that the difference in species composition between the sites was not large (Figure 7). However, the distance varied depending on the site. The restored sites tended to be located closer to the reference sites, along with the non-restored and sites afforested through the introduction of *Betula platyphyla* var. *japonica* than the sites afforested, through the introduction of *Alnus incana* subsp. *hirsuta*, *Lespedeza cyrtobotrya*, and *Robinia pseudoacacia*.

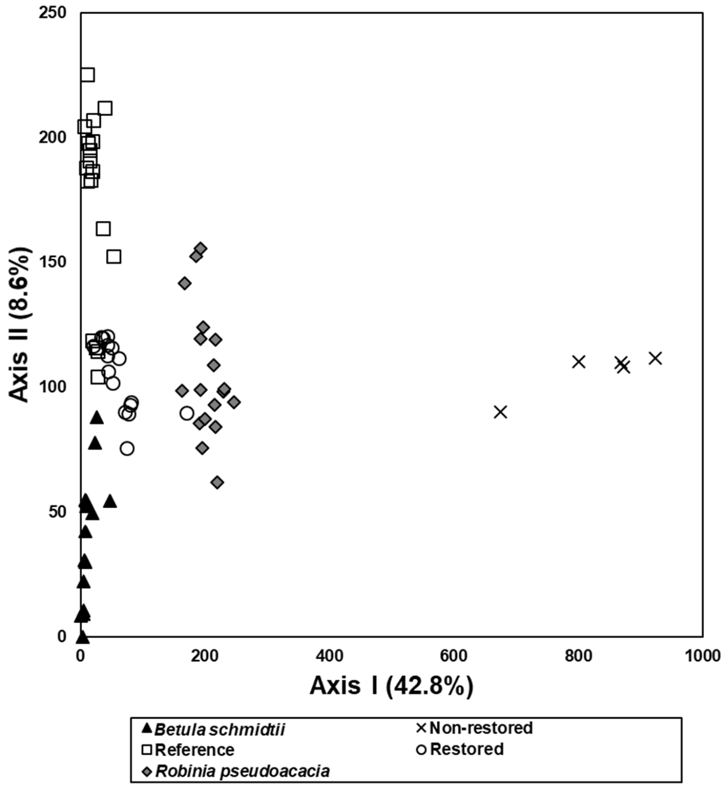

Figure 6. DCA ordination of vegetation including sites restored ecologically (restoration), rehabilitated applying silvicultural method (*Betula schmidtii* and *Robinia pseudoacacia*), and reference stands dominated by *Pinus densiflora*.

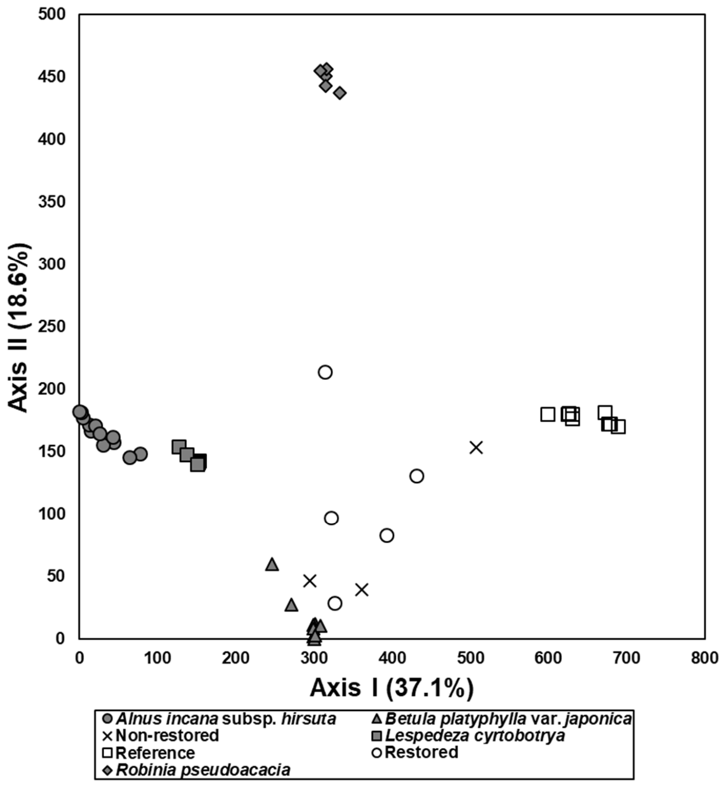

Figure 7. DCA ordination of vegetation including sites restored ecologically (restoration), rehabilitated applying silvicultural method (*Alnus incana* subsp. *hirsuta*, *Betula platyphylla* var. *japonica*, *Lespedeza cyrtobotrya*, and *Robinia pseudoacacia*), and reference stands dominated by *Quercus mongolica*.

3.6. Species Diversity

In the restoration site located in the lowlands, the species diversity of each treatment site was compared with the reference site based on the species rank–dominance curves; species diversity of all treatment sites, including ecologically restored sites, was lower than that of the reference sites except, for the site afforested through the introduction of *Robinia pseudoacacia* (Figure 8). However, the restored site showed higher species diversity than the non-restored site.

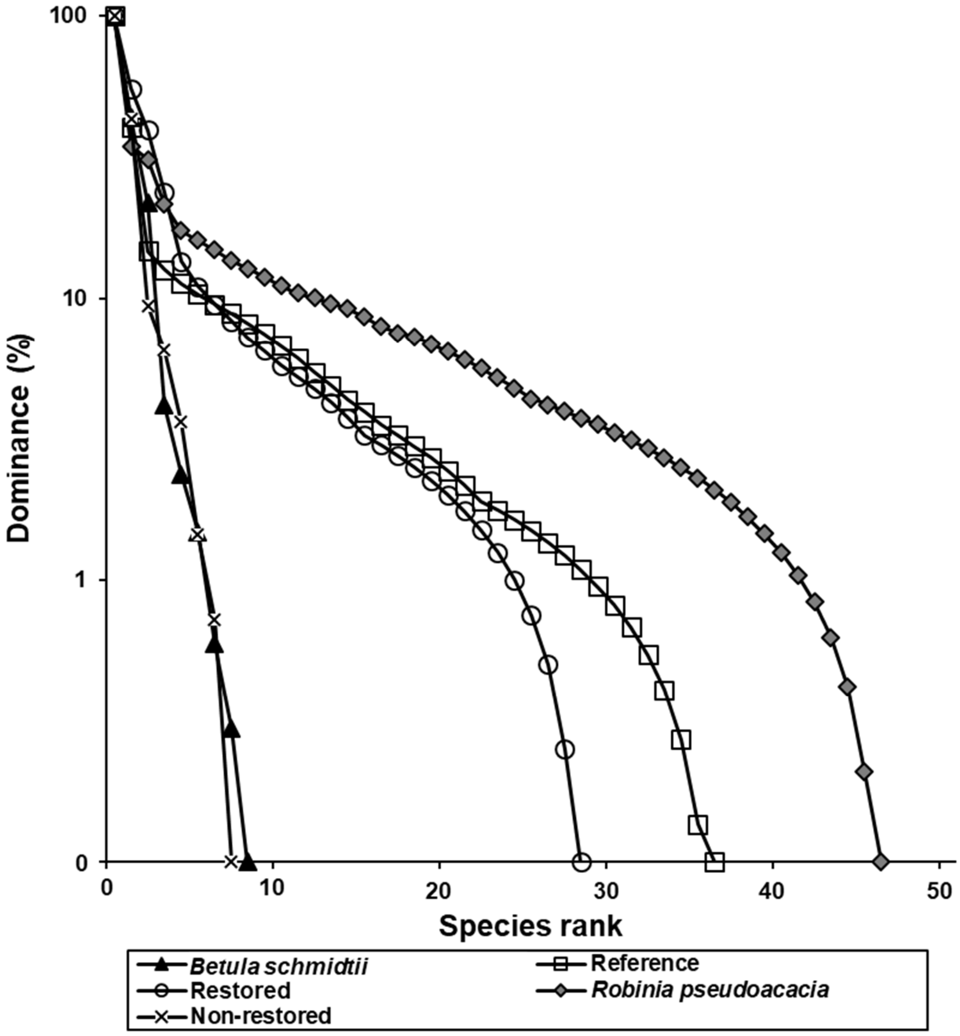

Figure 8. Rank–abundance curves of vegetation including sites restored ecologically (restoration), rehabilitated applying silvicultural method (*Betula schmidtii* and *Robinia pseudoacacia*), and reference stands dominated by *Pinus densiflora*.

In the restoration site located in the uplands, the species diversity of each treatment site was compared with the reference site based on the species rank–dominance curves; species diversity of all treatment sites, including ecological restored sites, was lower than that of the reference sites (Figure 9). However, even here, the restored site showed higher species diversity than the non-restored site.

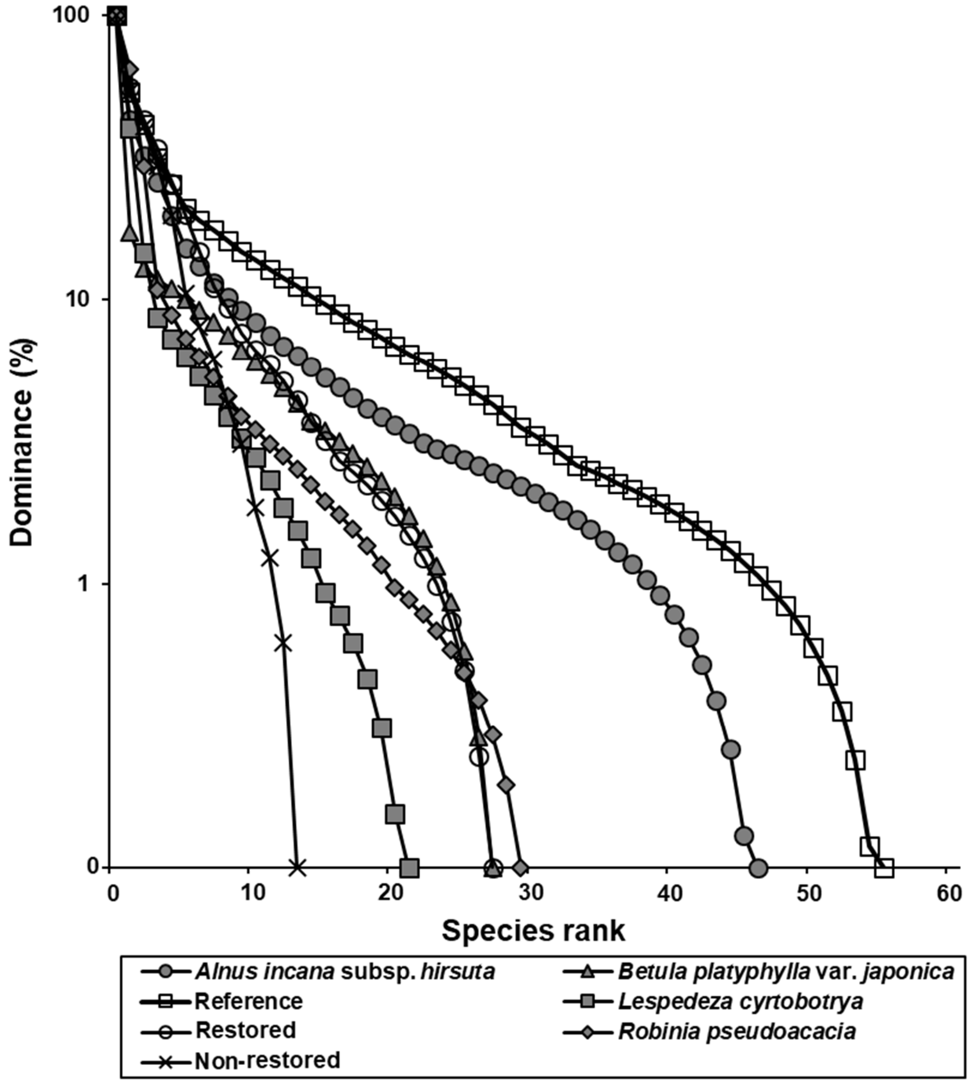

Figure 9. Rank–abundance curves of vegetation including sites restored ecologically (restoration), rehabilitated applying the silvicultural method (*Alnus incana* subsp. *hirsuta*, *Betula platyphylla* var. *japonica*, *Lespedeza cyrtobotrya*, and *Robinia pseudoacacia*), and reference stands dominated by *Quercus mongolica*.

Considering that the afforestation site had a stand age of more than 30 years, species diversity tended to increase in proportion to the time elapsed after restoration rather than the restoration method.

3.7. Evaluation Based on Exotic Species

Many exotic plants, including *Ambrosia artemisiifolia* var. *elatior* Desc., which the Korea Ministry of Environment has designated as a harmful plant disturbing the ecosystem, appeared in the restored coal mine spoils. Deliberately introduced species such as *Robinia pseudoacacia*, *Pinus rigida* Mill., *Larix kaempferi* Carrière., *Amorpha fruticose* L., *Festuca arundinacea* Schreb., *Rudbeckia bicolor* Nutt., and *Trifolium pratense* L. are included among them. However, there were more species that had naturally been established, represented by *Ailanthus altissima* Swingle., *Ambrosia artemisiifolia* var. *elatior*, *Oenothera biennis* L., *Bidens frondosa* L., *Taraxacum officinale* F.H. Wigg., etc. The percentage of exotic species was higher in all treatment sites than in reference sites, except for the non-restored site in the upland area (Figure 10). Comparing the exotic plant ratio between the restored and non-restored sites, there was no significant difference between both sites in both lowland and upland areas. However, in the upland area, the proportion of exotic plants in the restored site was considerably lower than that of the restored site. When comparing the ratio of exotic plants between the restored and afforested sites, the proportion of the former was higher in the lowland, but vice versa in the upland.

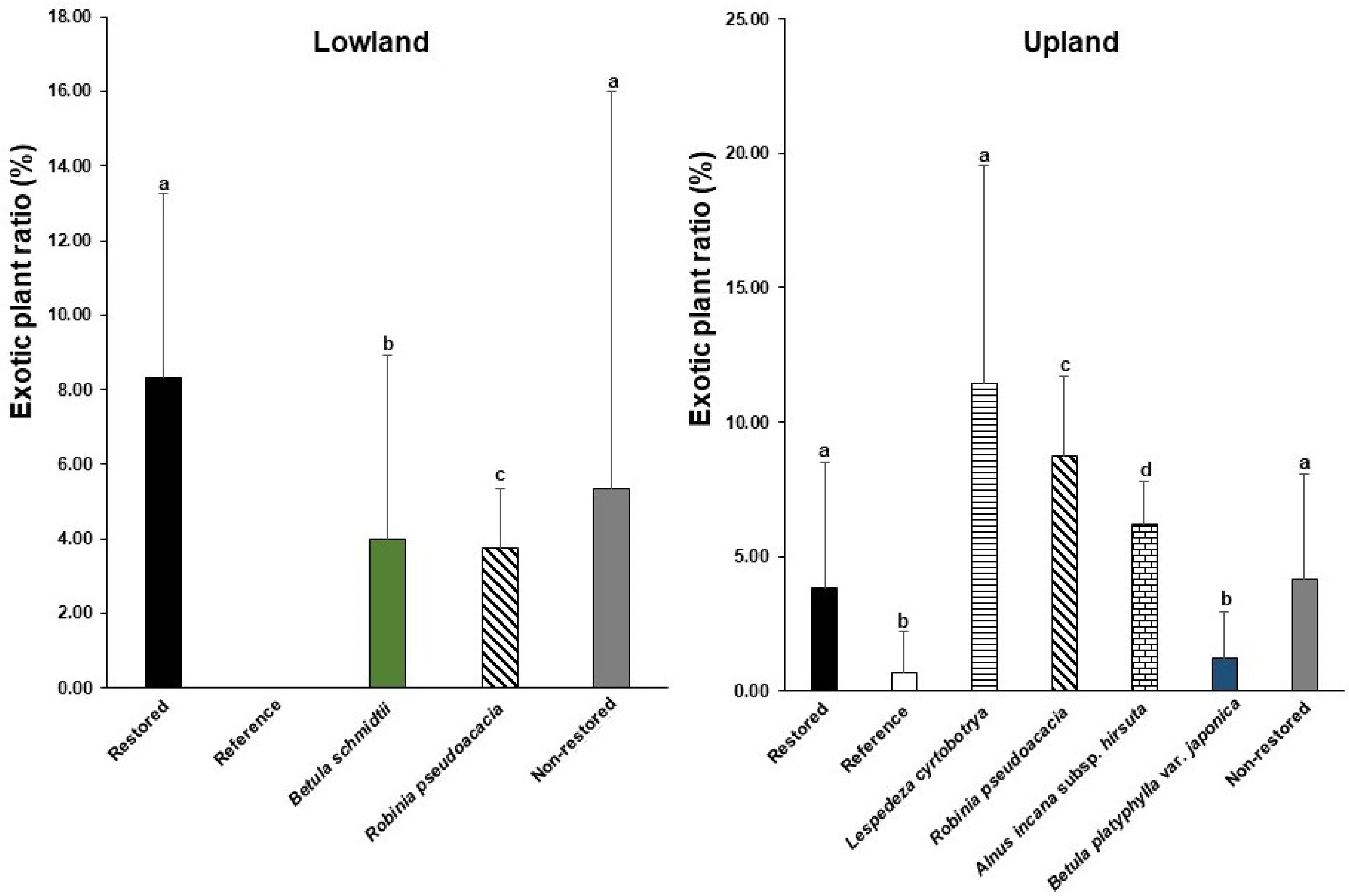

Figure 10. A comparison of the percentage of exotic plants among the treatment sites including the reference site in restoration sites located inn lowland (left) and upland (right) areas, respectively. Each bar expresses the mean and standard error of mean. Tukey's honestly significant difference (HSD) test was conducted on each of the parameters that showed a statistically significant difference among the three types of treatments at $\alpha = 0.05$; the means with the same alphabetical character (in superscript) for each parameter were not different from each other.

4. Discussion

4.1. Restoration Effects Based on Chemical Properties of Soil

Abiotic conditions in coal mine spoils are very similar to those of an early successional stage habitat. Coal mine debris excavated from deep mining does not function as soil by itself because it does not contain sufficient organic matter. Therefore, ecosystem development in these areas must progress in the same manner as primary succession: the process of ecosystem development on barren surfaces where severe disturbances have removed most vestiges of biological activity [4]. Succession progresses as a result of interactions between plants growing in a given area and their habitat and soil. The amelioration of soil by early colonizers facilitates the establishment of new species and promotes species compositional change to the next successional stage [2,3]. In this respect, soil amelioration is a preparatory stage which is necessary in the restoration of coal mine spoils.

Coal mine spoils generally comprise the bare stripped area, loose soil piles, waste rock and overburden surfaces, subsided land areas, and other land degraded by mining facilities, among which waste rocks often pose extreme stressful conditions for restoration. Mining disrupts the aesthetics of the landscape, and also disrupts soil components such as soil horizons and structure, soil microbe populations, and nutrient cycles that are crucial for sustaining a healthy ecosystem, hence resulting in the destruction of the existing vegetation and soil profile [59]. Overburdened dumps include adverse factors such as the elevated bioavailability of metals, elevated sand content, lack of moisture, increased compaction, relatively low organic matter content, and high surface temperature. Acidic dumps may release salt or contain sulfidic material, which can generate acid mine drainage [60]. The effects of mine wastes can be multiple, such as soil erosion, air and water pollution, toxicity, geo-environmental disasters, loss of biodiversity, and ultimately, a loss of ecosystem service [61,62].

It is imperative from the above that mineral extraction processes must ensure a return of productivity of the affected land. An increase in the concerns for environment has made concurrent post-mining reclamation of the degraded land as an integral feature of the whole mining spectrum [63]. Conservation and reclamation efforts to ensure the continued beneficial use of land resources are essential. Reclamation is the process by which derelict or highly degraded lands are returned to productive land, and by which some measures of biotic function and productivity are restored. Long-term mine spoil reclamation requires the establishment of stable nutrient cycles from plant growth and microbial processes [64–66]. Soil provides the foundation for this process; thus, its characteristics directly affect the future stability of the restored vegetation. The restoration of vegetation cover on overburden dumps can fulfill the objectives of stabilization, pollution control, visual improvement, and removal of threats to human beings [61]. Restoration strategies must address soil amelioration in order to return the land as closely as possible to its pristine condition and continue as a self-sustaining ecosystem. Therefore, adding additional organic matter to the soil in the early stages of reclamation would likely improve restoration success. In particular, organic fertilizer might be an excellent soil ameliorator because it contains high levels of available phosphorus as well as organic matter [67].

Soil amelioration usually represents a major challenge to most restoration programs [1,44–46]. In industrial areas, soil amelioration through the application of dolomite or sludge, a sort of organic fertilizer, contributes to successful restoration of the forest ecosystem degraded due to severe air and soil pollution through the neutralization of acidic soil, the enhancement of fertility, or reduction in Al^{3+} toxicity [1,20,67–69]. In this study, soil amelioration contributed to enhancement of the chemical properties of soil (Figure 4) and plant growth (Figure 5). However, the nutrient contents were lower compared with those of the reference sites (Figure 4). This might be because of possible differences in pedology of the sites and partly because we examined the soil properties in 0–10 cm soil depth, which might not represent the whole root zones of the trees. Thus, further investigations of the soil properties along the soil horizon need to be conducted to reach a better conclusion of the ameliorating effect of organic fertilizers.

4.2. Selection of Tolerant Plant Species

Restoration of a vegetation cover can contribute to stabilization, pollution control, visual improvement, and the removal of threats to human beings. Ecological restoration of loose mine spoil dumps is crucial to minimize their negative impact on the environment in the watershed and in downstream catchment areas. The introduction of vegetation for restoration stabilizes the spoil and expedites the pedogenic processes influencing soil properties [70]. Such reclamation efforts can significantly alter soil particle distribution, organic carbon, total nitrogen, available potassium, and cation exchangeable capacity of open pit mine fields [71]. Proper restoration can also reap ecosystem services because the restored mining site serves as a habitat for other species to establish, reduce soil erosion, and improve edaphic conditions [72,73].

However, the successful vegetation restoration of coal mine spoils and reconstruction of their ecosystem faces obstacles of loose materials devoid of soil, poor spoil fertility, high heavy metal content, and extreme acidity. The organic matter content of coal mine spoils is very low, some of which is mineralized organic carbon that cannot easily be absorbed by plants [74]. Soil nutrients are the main factors affecting the distribution and growth of vegetation [75]. In fact, nutrient deficiency is identified as a major restrictor of the successful restoration of ecosystems on coal mine spoils [76], in addition to soil moisture [77]. Mining destroys topsoil, making the physical structure of the soil substrate unsuitable for plant growth. Excessive heavy metals in the spoils hinder plant metabolism and stunt vegetation growth. Extreme pH values or soil salinization are detrimental to the initial colonization of vegetation on the spoil heaps [78]. The other factors impeding plant growth are poor capillary structure and lack of moisture in the coal mine spoils. Their large particle size is not conducive to retaining water, and causes moisture to be easily evaporated at a high temperature [73]. Without the soil structure prior to weathering, the level of cation exchange in the coal mine debris is rather low. When the cation exchange rate falls below 3%, the coal mine debris will have poor fertility and water retention capabilities [79]. A higher coal mine debris content in the spoils causes infiltration rates and saturated hydraulic conductivity to decrease [80].

Coal mine debris is only made up of minerals; thus, is not a true soil where minerals are mixed with organic matter. The substrate is deficient of nutrients, contains toxic substances, has significantly lower effects of soil microorganism and animal activities, and has many physical disabilities; thus, where it is reclaimed, the plant's natural establishment progresses very slowly [81–83] and the plant's growth is limited [84,85]. Environmental pollutants act as a selection pressure in the evolutionary process at the species level of plants, resulting in evolutionary changes. This evolutionary change may take millions of years or more, although can take place within several years or a generation or two [86–88]. For example, the resistance of plants to heavy metal contamination and herbicides is obtained within several years [88–90], and ongoing climate change has affected the ecological dynamics of many species and is expected to impose natural selection on ecologically important traits [91]. Additionally, in recent years, evidence of rapid evolution has been identified [92–94] thanks to the development of computing capabilities [95]. In addition, there are reports that rapid evolution is due to the spread of exotic species or contribute to the spread of exotic species [96,97].

Coal mining activities accompany the occurrence of coal mine debris, and these activities have a history of more than 100 years; therefore, tolerant species are expected to occur in the meantime. In order to quickly establish vegetation, the right species suitable for the coal mine spoils should be selected. The ultimate goal of this study was to recover the coal mine spoils to the forest of level similar to natural forest by introducing plants. The restoration work of coal mine spoils is likened to a primary succession without any vegetation; therefore, a restoration plan should be established by imitating the primary succession. To realize this goal, selecting tolerant plants that can withstand coal mine spoils is an essential process. The species for restoration is usually selected based on the following criteria [46]: (1) species to restore the function of ecosystems; (2) species that can eventually become members of the ecosystem; and (3) species that can ensure high biodiversity in the future and create a complete ecosystem with their own efforts. The tolerant plant species serves as an important foundation for successful restoration. Planting tolerant species not only has the effect of enduring poor coal mine waste and increasing the vegetation coverage, but can also create a natural landscape that matches the surrounding vegetation. In addition, it is possible to create an ecologically sound vegetation by inhibiting the invasion of exotic species [98]. From the results of field survey and experimental study, C_4 plants and legumes were selected as plant species with higher tolerance level than C_3 plants (Tables 1 and 2); thus, we introduced *Albizia julibrissin* and *Miscanthus sinensis* var. *purpurascens* to our experimental restoration plot. C_4 plants usually prefer a bare ground where they can receive enough sunlight and are tolerant to high temperature. It is believable that C_4 plants showed higher tolerance due to their habitat preference and biological traits being more suited to the ecological condition of the coal mine spoils than C_3 plants [99–101]. Legumes with a higher tolerance level next to C_4 plants were judged to have a higher tolerance level compared with C_3 plants that did not have such functions; they can exploit poor environmental conditions on their own by fixing atmospheric nitrogen. Selecting the tolerant plant species by classifying vegetation layers can contribute to restoring coal mine spoil sites into a multilayered forest. If the site is restored to multilayered vegetation rather than to simple existing afforestation, it can increase biodiversity [46,102,103].

4.3. Restoration Effects Based on Species Composition

The trajectory of a restoration project may be viewed in terms of ecosystem structure and function [104,105], both of which are impacted greatly by degradation. The fundamental goal of restoration is to return a particular habitat or ecosystem to a condition close to its pre-degraded state. Complete restoration would involve a return to that state, while a partial return, or other trajectories would result in rehabilitation or replacement with a different system [6–8,106–108]. To effectively restore degraded areas, or to protect existing high quality areas, we must be able to define the attributes of "normal", undegraded (or "healthy") habitats as a model [5–7,108,109]. One way of setting a baseline from which to measure restoration success is to define the normal "biological integrity" of a system and then measure deviations from there. Integrity implies an unimpaired condition or the quality or state of being complete or undivided. Biological integrity is defined as "the ability to support and maintain a balanced, integrated, adaptive biological system having the full range of elements and processes expected in the natural habitat of a region" [9,20,67]. To evaluate a restored ecosystem, the ecological attributes of the ecosystem are compared with those from an "undisturbed" reference [110–113]. In the present study, we compared the species composition of the restored sites with the natural reference vegetation, *P. densiflora* forest (lowland) and *Q. mongolica* forest (upland), and a plantation afforested by introducing several plant species such as *Alnus incana* subsp. *hirsuta*, *Betula platyphylla* var. *japonica*, *Lespedeza cyrtobotrya*, and *Robinia pseudoacacia*. In a restoration site located in a lowland area, the species composition of the restored site ecologically resembled the natural reference vegetation more closely than the non-restored sites as well as the sites afforested by introducing *Robinia pseudoacacia* (Figure 6). Even in a restoration site located in an upland area, the restored sites showed a higher similarity in species composition to the reference sites than the afforested or the non-restored sites (Figure 7). Therefore, the restorative treatment served to increase biological integrity and approached the restoration goal in both sites.

4.4. Effects of the Restorative Treatment on Species Diversity

The importance of biodiversity is based on diverse values that include various ecological functions that lead to environmental stability [114]. Biodiversity is reflective of the heterogeneity of a habitat or ecodiversity [115–120]. High biodiversity also is indicative of the integrity of an environment; a highly biodiverse ecosystem is healthy and well equipped with all of its necessary components [121,122].

The restoration effect in terms of biodiversity was not significant not only in comparison with the natural reference site, but also the afforested sites in both restoration sites located in lowland and upland areas (Figures 8 and 9). The sites (*R. pseudoacacia* and *A. incana* subsp. *hirsuta* stands in lowland and upland areas, respectively) afforested many years ago showed higher biodiversity than the ecologically restored sites, although ecological considerations were not supported during the project. Considering that the afforestation site had a stand age of more than 30 years, whereas the ecologically restored sites has stand age of just 8 years, the difference may have been due to the time elapsed after restoration rather than the restoration method. In this respect, the restoration effect in terms of biodiversity needs to be monitored further in the future. In reality, species diversity in urban rivers and forests around industrial complexes tends to increase over time after restoration [1,20].

4.5. Evaluation Based on Exotic Species

Exotic plants can cause a variety of problems in native plant communities: excluding native species; altering the habitat, hydrology, and nutrient cycling; and greatly impacting plant and animal diversity [123–127]. Exotic species can transform the structure and species composition of ecosystems by repressing or excluding native species, either directly by out-competing them for resources or indirectly by changing the way nutrients are cycled through the ecosystem [124,126,128,129]. The increasing global prevalence of relatively few invasive species threatens to create a relatively homogenous planet rather than one characterized by its rich biological diversity and local distinctiveness [124,125,130–132]. Therefore, the invasion of alien organisms, a potentially lasting and pervasive imposition, is considered to be one of the main threats to biodiversity in the modern world [133–137]. Furthermore, the prevention and control of new invasions is a clear priority in emerging policies [124,128,138–141]. Disturbed lands are favorable microsites for exotic species equipped with opportunistic or ruderal life history strategies [13–15,17,124,125,142]. Sites disturbed severely or frequently, such as coal mine spoils, support many exotic species [143,144]. Successful, sustainable restoration practices are recommended to inhibit the invasion of exotic species [15,18,101]. Exotic species prefer open places that are not highly competitive. However, the restored sites of coal mine spoils take a long time for dense vegetation to be restored due to the poor ecological characteristics. In fact, this study has shown that both restored and afforested sites did not effectively exclude exotic plants; thus, the ratio of exotic plants was rather higher than that of the non-restored site in the upland area (Figure 10). In this regard, dense planting during restoration projects and protective planting to mitigate external effects are recommended [98,145].

5. Conclusions

Vegetation is difficult to establish in very barren and toxic places such as coal mine spoils. In order to ecologically restore these sites, the substrate must be improved to a level similar to normal soil. In addition, plants that are tolerant to such degraded environments should be selected and introduced. Furthermore, ecological restoration should be carried out reflecting the reference information obtained from intact natural vegetation of the corresponding area. In this study, restoration using a soil ameliorator not only improved the chemical properties of soil, but also significantly promoted the growth of planted species. In addition, ecological restoration brought about changes in the species composition of vegetation, but did not significantly increase species diversity or exclude the occurrence of exotic plants. As a whole, the restoration effort has brought some improvement, but more active interventions are still needed to increase the diversity of the restored forests and control of the spread of exotic species.

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Appendix A

Table A1. Chemical properties of organic fertilizer chosen as a soil ameliorator in this study.

Environmental Factors	Content
Water content (%)	48.34
Organic matter (%)	33.76
Total Nitrogen (%)	1.24
Available Phosphorus (%)	1.04
Exchangeable Potassium (%)	0.26
C.E.C(cmol$^+$/kg)	35.0
Sodium (%)	0.57

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