THE PLANT COMMUNITY OF NANJIDO, A REPRESENTATIVE NONSANITARY LANDFILL IN SOUTH KOREA: IMPLICATIONS FOR RESTORATION ALTERNATIVES

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Abstract. Vegetation and soil analyses of the slopes of the Nanjido, a nonsanitary landfill in South Korea, were conducted to investigate the colonization status of plant communities, and to suggest restoration alternatives by comparing the vegetation of the landfill and the nearby forests. The vegetation of the Nanjido landfill and the control sites was surveyed by using 10×10 m quadrats. The soils were analyzed for pH, electrical conductivity, organic matter content, Total-N, P, K, Ca, Mg, sand, silt, and clay. Canonical correspondence analysis (CCA) was performed by using the extent of cover for all the recorded species, and the physical and chemical variables of soil. *Salix babylonica*, *Platanus orientalis*, *Rosa multiflora*, *Prunus persica*, *Albizzia julibrissin*, *Indigofera pseudo-tinctoria*, *Robinia pseudoacacia*, *Amorpha fruticosa*, *Ailanthus altissima*, *Forsythia koreana*, and *Paulownia tomentosa* were the commonly found tree species. *Quercus mongolica*, considered to be the natural late successional species of temperate South Korea, was recorded at the Nanjido landfill. Levels of pH, the electrical conductivity and concentrations of P, Ca, and Mg in landfill soils were significantly higher than the forest control site soils ($P < 0.05$). In CCA ordination space, landfill quadrats clustered in less acidic soils, rich in Ca and Mg, while forest control site quadrats clustered in acidic, low P soils. This study found several indications that it is possible for a nonsanitary landfill to support succession to typical and natural forests. In addition, the landfill slope vegetation could function as a biological source for the restoration of the other landfill areas that remain barren, if planned efforts are made for conservation and rehabilitation.

Keywords: landfill restoration, multivariate analysis, Nanjido, nonsanitary landfill, slope vegetation, South Korea

1. Introduction

Sanitary landfills are presently one of the most feasible methods for disposing solid wastes (Ahel *et al.*, 1998; Manna *et al.*, 1999), when constructed to meet the standards that include a liner, cap, leachate and gas-collection systems, and erosion controls. Nonsanitary landfills do not incorporate landfill gas and leachate treatment systems, thus, they include a final soil covering of low depth and quality. As a result, they produce landfill gas and leachate that impact the plant germination and growth, and they generally have soils with low N and P (Wong and Yu, 1989).

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Nonsanitary landfills, such as the Nanjido landfill in South Korea, are common in developing countries because of their relatively low management cost (Weng and Chang, 2001). Nanjido is a representative of nonsanitary landfill and is the first waste landfill to be restored in South Korea. Approximately 890 nonsanitary landfills have been constructed in South Korea since 1980 (KORECO, 1995). Because of transportation costs, waste landfills are located in close proximity to urban centers. These sites are therefore the focus of land recycling attempts, and there is currently considerable interest in the restoration of these degraded biological habitats.

The summit and plateau areas of the Nanjido landfill have stabilized. The slopes of the landfill have been left unattended, but they are currently being colonized by natural vegetation. These slopes are focal points for restoration, either anthropogenically modified or left to revegetate naturally. Study of recruitment of desirable species on these slopes is relevant to the structure and function of the disturbed, urban ecosystems, such as landfills. The aim of this study is to investigate the vegetation colonization and the plant community development of the Nanjido landfill slopes, and to suggest restoration alternatives by comparing the vegetation of the Nanjido landfill with that of the control sites.

2. Materials and Methods

2.1. Site Description

This study was conducted at the Nanjido landfill and at two control sites, Mt. Sangam and Mt. Maebong. The Nanjido landfill is located in the northwestern outskirts of Seoul, South Korea. Mt. Sangam and Mt. Maebong adjoin it to the northeast (Figure 1). The mean annual temperature and rainfall (data from 1990 to 1999) are 12.7 °C and 1546.5 mm, respectively. The climate is temperate, with four distinct seasons. July and August, corresponding to the summer season, account for 25% of the total annual rainfall.

The Nanjido landfill operated from 1978 to 1993 and is one of the largest municipal solid-waste landfills in the world (Lee *et al*., 1997). It is a huge, uncontrolled, flat-topped mound of waste. It occupies 272 ha, with a maximum waste depth of 104 m, containing 177 million tons of refuse. This waste dump is located on an isolated alluvial deposit enclosed by the main channel of the Han River. Nanjido contains municipal waste from Seoul. The refuse is composed of domestic waste, construction material, sludge, sewage, and industrial wastes. The landfill has two mounds with four manifest aspects. The left mound is referred to as the first landfill and the right mound as the second landfill. The Nanjido landfill has been disturbed by landfill gas, leachate, and soil subsidence. It has also been artificially disturbed by land restructuring, covering activities, and road construction. Plateaus of the landfill, rising to an average height of 96 m, were flattened by stabilization activities, and have been constructed into a park, sports complex, and golf courses. The

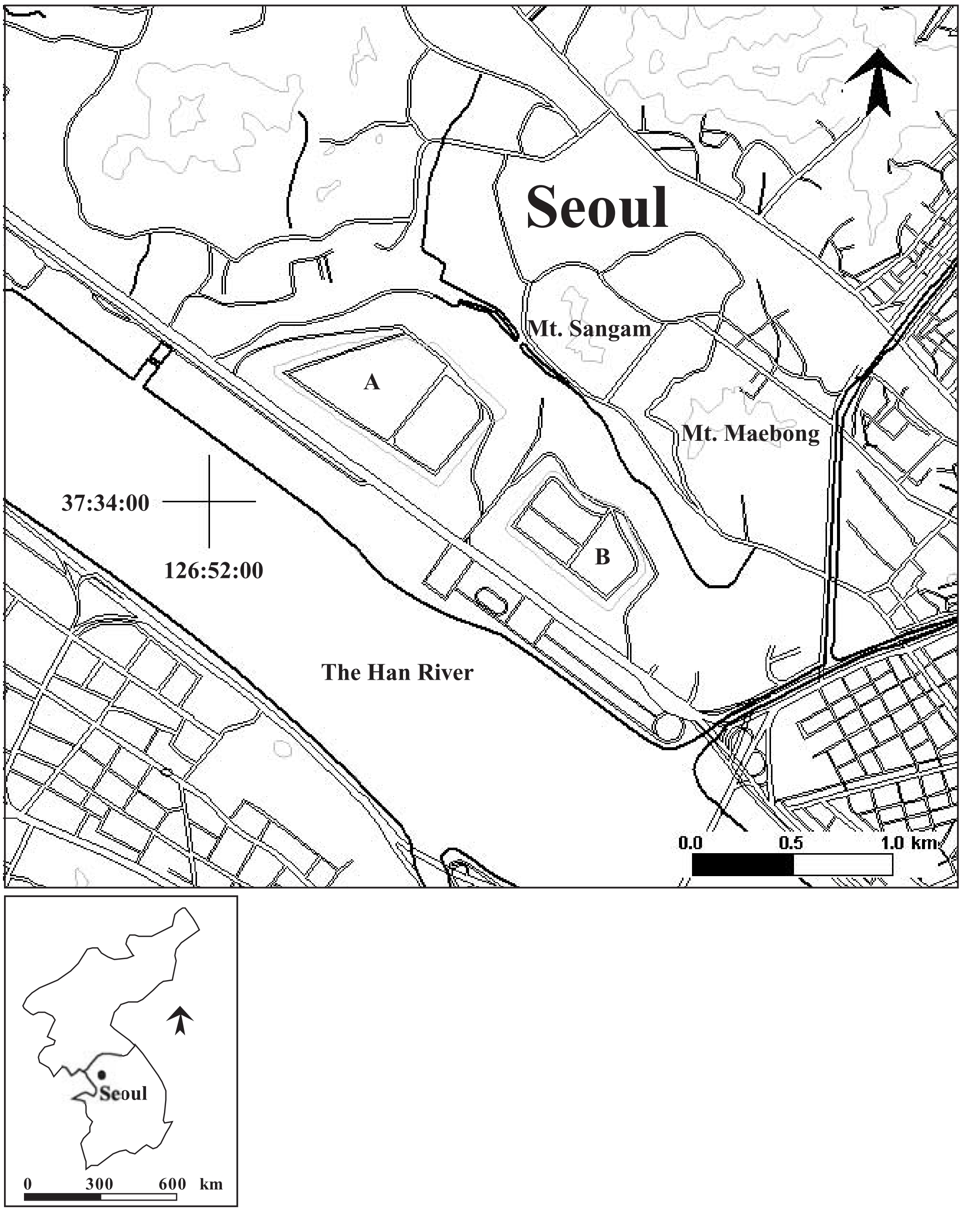

Figure 1. Study sites. The Nanjido landfill includes the first (A) and the second (B) landfills and is surrounded by Mt. Sangam and Mt. Maebong.

landfill slopes have been neglected and vegetated naturally. There is a small planted area at the eastern end of the landfill.

2.2. Methods

2.2.1. *Vegetation Analysis*

Complete inventories of the vegetation of the landfill and the two forest control sites (Mt. Sangam and Mt. Maebong) were recorded seasonally in 2000 and 2001. The vegetation of the Nanjido landfill was also surveyed by quadrats (10 $\times$ 10 m) located in physiognomically representative sites on the four slopes (north, northeast, southeast, and southwest). A total of 29 quadrats were sampled: 26 on the Nanjido landfill, 2 on Mt. Sangam, and 1 on Mt. Maebong. Three control quadrats were sufficient for comparison with the landfill quadrats because the controls had very homogeneous vegetation. All landfill quadrats were located mid-slope along the landfill access road. Plant species cover, including trees, shrubs, and grasses, per quadrat was recorded using the Braun-Blanquet scale (Fuller and Conard, 1932). Cover was estimated as the area within the quadrat shaded by all the members of a species. The Braun-Blanquet scale was converted to a mean cover degree (Mueller-Dombois and Ellenberg, 1974). For species identification and nomenclature, we followed Lee and Park (Lee, 1999; Park, 1995). All species were classified as either native or exotic. Exotic species were defined as species not indigenous to Korea that have been introduced intentionally or unintentionally. Plant communities were named after dominant species, followed by subdominant species, in quadrats. The domination degree of species was estimated from the extent of their cover in the quadrats.

2.2.2. *Diversity Analysis*

To compare biodiversity status among study sites, we calculated species richness, species evenness, Simpson's index, and the Shannon-Wiener's index in the quadrats (Barbour *et al*., 1999).

2.2.3. *Soil Analysis*

Soils were sampled between 0-10 cm for chemical analysis, using a hand shovel. Samples from 10 points within each 10 $\times$10 m quadrat were collected and pooled. The soil samples were analyzed using the following methods: pH (1:2 = W/V; Jackson, 1967); electrical conductivity (1:5 = W/V; Page *et al*., 1982); organic matter (Walkley-Black method; Page *et al*., 1982); total-N (Kjeldahl method; Page *et al*., 1982); P (Bray No. 1 method; Page *et al*., 1982); K, Ca, and Mg (ammonium acetate extraction method; Page *et al.*, 1982); sand, silt and clay (hydrometer method; Carter, 1993).

2.2.4. *Ordination Analysis*
Multivariate analyses, including detrended correspondence analysis (DCA) and canonical correspondence analysis (CCA), were performed.

Cover per species was transformed into a relative cover value (RC). The RC values were used with DCA to elucidate variation in floristic composition across the sites. In CCA, the RC values were ordinated with soil chemical variables to relate species data to soil chemistry. These analyses were performed using CANOCO 4.02 (ter Braak and Smilauer, 1998). A Monte Carlo permutation test was applied to determine the significance of eigenvalues corresponding to the CCA canonical axes (ter Braak, 1988). The results are presented in a biplot diagram of the sites and environmental variables. All soil chemical contents and other factors were statistically analyzed using SAS (SAS Institute, 1985).

3. Results

3.1. General descriptions of the vegetation at the Nanjido landfill and the forest control sites

The tree species frequently recorded in the inventories at all aspects of the Nanjido landfill were *Salix babylinica*, *Platanus orientalis*, *Rosa multiflora*, *Prunus persica*, *Albizzia julibrissin*, *Indigofera pseudo-tinctoria*, *Robinia pseudoacacia*, *Amorpha fruticosa*, *Ailanthus altissima*, *Forsythia koreana*, and *Paulownia tomentosa.* The primary tree communities at the landfill were *Robinia pseudoacacia*, *Salix babylinica*, and *Robinia pseudoacacia – Salix babylinica*. Grassy open area communities were *Humulus japonica*, *Pueraria thunbergiana – Brassica juncea* var. *integrifolia*, and *Ambrosia trifida* (Table I). Details of communities follow:

- *Robinia pseudoacacia* community: This community was located on the southeast side of the first and the second Nanjido landfills. Canopy cover was over 70%, with an average tree layer height of 12 m. *Robinia pseudoacacia* and *Ailanthus altissima* dominated the shrub layer. The herb layer consisted of *Ageratina altissima*, an exotic species that is rapidly invading forested areas in South Korea (Chun *et al*., 2001), with an average height of 1 m.
- *Salix babylonica* community: This community was distributed on the northeast side of the first landfill and on the southeast side of the second landfill. The canopy cover was around 50–70%, with an average height of 7 m. The shrub layer included *Robinia pseudoacacia*,*Ailanthus altissima*, *Paulownia tomentosa,* and *Rosa multiflora*. In the herb layer, *Chrysanthemum boreale*, *Humulus japonica*, *Ipomoea hederacea*, and *Brassica juncea* var. *integrifolia* were evenly distributed.
- *Robinia pseudoacacia – Salix babylonica* community: This community was distributed on the north and southeast sides of the first landfill, and on the northwest and northeast sides of the second landfill. *Robinia pseudoacacia* and

Salix babylonica were mixed in the tree layer. The shrub layer consisted only of *Robinia pseudoacacia*. In the herb layer, *Brassica juncea* var. *integrifolia*, *Ageratina altissima*, and *Erigeron annuus* dominated.

- *Humulus japonica* community: This community, the simplest of all the communities, is found in disturbed areas such as clearcuts or overturned soils in South Korea. *Humulus japonica* covered 100% of the area; there was no tree or shrub layer. *Lactuca indica* var.*laciniata* and *Setaria viridis* were present.
- *Pueraria thunbergiana – Brassica juncea* var. *integrifolia* community: *Pueraria thunbergiana* overlaid *Brassica juncea* var. *integrifolia* with an average height of 1 m. *Lactuca indica* var. *laciniata*, *Sonchus brachyotus*, and seedlings of *Robinia pseudoacacia* were present.
- *Ambrosia trifida* community: This community was located on the north side of the first landfill. *Ambrosia trifida* covered 100% of the area, with an average height of 3 m.

The *Robinia pseudoacacia* community appeared mainly in the south of the Nanjido landfill, at sites that were drier than any of the landfill slopes. The *Salix babylonica* community appeared primarily in the north of the landfill that was wetter than any of the landfill slopes. The mean coverage of tree communities on the landfill was 53.6%. A small *Quercus mongolica* community was located in the southeast of the Nanjido landfill. *Populus tomentiglandulosa*, *Salix babylonica*, *Platanus orientalis*, *Robinia pseudoacacia*, and *Albizzia julibrissin* were mixed in the tree layer of the *Quercus mongolica* community. *Humulus japonica*, *Pueraria thunbergiana – Brassica juncea* var. *integrifolia*, and *Ambrosia trifida* communities were grass communities found in the areas disturbed by soil erosion from subsidence. In addition to these communities, the *Ailanthus altissima* tree community was located, on a small scale, in the southeast of the Nanjido landfill. *Robinia pseudoacacia*, *Pueraria thunbergiana – Brassica juncea* var. *integrifolia*, and *Ambrosia trifida* covered more than 50% of the vegetation area.

The representative communities of the forest control sites were *Robinia pseudoacacia* and *Quercus aliena*. In the *Robinia pseudoacacia* community, the canopy cover was more than 70%. *Robinia pseudoacacia*, *Rhus trichocarpa*, and *Symplocos chinensis* for. *pilosa* were distributed in the shrub layer. The herb layer was composed of exotic species of *Ageratina altissima* and *Phytolacca americana* and native species of *Oplismenus undulatifolius*, *Spodiopogon sibiricus* and *Parthenocissus tricuspidata*. In the *Quercus aliena* community, the canopy cover of *Quercus aliena* was 50-70%, with an average height of 12 m. *Quercus aliena* was mixed with *Pinus densiflora*, *Alnus hirsute*, and *Prunus serrulata var. spontanea*. *Rhus chinensis* dominated the shrub layer that was mixed with *Rubus crataegifolius*, *Spodiopogon cotulifer*, *Oplismenus undulatifolius*, *Artemisia japonica* and *Quercus aliena* seedlings present. The mean coverage of tree communities on the control sites was 70.8%.

TABLE I

Coverage of tree and herbaceous species present in at least 5 of the 29 10 ×10 m quadrats. Quadrats 1–15 belonged to the first Nanjido landfill, quadrats 16–26 belonged to the second Nanjido landfill, and quadrats 27–29 belonged to the control sites

Family	Species	Quadrat number																												
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29
	Tree																													
Salicaceae	*Salix babylonica* L.		15			62.5	37.5							15		62.5	37.5	15		15	2.5	2.5		37.5						
Simaroubaceae	*Ailanthus** *altissima* Swingle		2.5	37.5		2.5										2.5			2.5				0.1			37.5				
Leguminosae	*Robinia** *pseudo-acacia* L.	85	62.5	37.5	0.1	2.5	15		62.5		37.5			62.5		15	62.5	85	15	85	85	2.5	62.5	62.5		37.5		62.5	85	
	Herbaceous																													
Commelinaceae	*Commelina communis* L.		2.5			15	15		2.5		2.5		2.5	0.1	2.5	15	2.5				2.5	0.1	2.5		2.5	0.1	15		0.1	0.1
Cannabinaceae	*Humulus japonica* S. et .Z.			2.5				37.5		15	15	87.5	62.5			37.5	2.5	0.1	0.1			2.5				2.5	87.5			
Polygonaceae	*Persicaria perfoliata* Gross					37.5		2.5			0.1		0.1			15									15					
Chenopodiaceae	*Chenopodium* **album* L.		2.5	0.1	0.1			2.5					0.1						0.1		0.1									
Papaveraceae	*Chelidonium majus* var. *asiaticum* (Hara) Ohwi	0.1											0.1		2.5		2.5	0.1			2.5		2.5							
Cruciferae	*Brassica** *juncea* var. *integrifolia* Sinsk	87.5	15	37.5	62.5	37.5	37.5							62.5	62.5	37.5	62.5		87.5	15	37.5				62.5	62.5				
Leguminosae	*Pueraria thunbergiana* Bentham		2.5	15	62.5	37.5	37.5											0.1	87.5						62.5					
Asclepiadaceae	*Metaplexis japonica* (Thunb.) Makino			0.1							2.5					2.5	0.1					15				0.1				
Convolvulaceae	*Quamoclit* **angulata* Bojer			0.1		0.1							0.1			15			15		2.5									
	Ipomoea **purpurea* Roth			2.5			2.5									15	2.5		2.5		2.5									
	*Ipomoea***hederacea* Jacq.				0.1	2.5							37.5		2.5	37.5	2.5		2.5		15	2.5								
Compositae	*Ambrosia* **artemisiifolia* var. *elatior* Descourtils			0.1				15			2.5		15		2.5		2.5	0.1	15		0.1	15					15			
	*Ageratina***altissima* (L.) R. King & H. Robinson		0.1	37.5		37.5	62.5		0.1		0.1			37.5	37.5	2.5	37.5	2.5		62.5	62.5	2.5	37.5	62.5		37.5		62.5	2.5	
	*Erigeron***annuus* (L..) Pers	2.5	2.5	2.5					2.5	0.1	0.1		15	2.5	2.5	2.5	37.5	2.5	2.5	2.5		2.5				0.1			2.5	
	Chrysanthemum boreale Makino	15		15			2.5		15					0.1		62.5		37.5					15	0.1						
	Artemisia princeps var. *orientalis* (Pamp.) Hara	15	15	15		15	15	2.5	2.5	0.1	37.5		2.5	2.5	37.5	15	37.5	0.1	2.5		0.1	2.5			0.1	2.5				
	Lactuca indica var. *laciniata* Hara				2.5						0.1	2.5	37.5		2.5	2.5	0.1		2.5						2.5					

The superscript* above generic name means exotic plants.

TABLE II

Total number of native and exotic species on the Nanjido landfill and at the control forest sites

Sites	Native	Exotic	Total (Native +Exotic)
The First Landfill	155 (71%)	64 (29%)	219 (100%)
The Second Landfill	133 (70%)	57 (30%)	190 (100%)
The Nanjido landfill	185 (63%)	70 (27%)	255 (100%)
Mt. Sangam	98 (80%)	25 (20%)	123 (100%)
Mt. Maebong	124 (84%)	24 (16%)	148 (100%)
Control sites	157 (83%)	32 (17%)	189 (100%)

3.2. Diversity analysis of the vegetation

The total number of species at the first landfill, the second landfill, and the entire Nanjido landfill was 219, 190, and 255, respectively (Table II), and the total number of species at the control sites was 189. Species richness per 100 m^2 of the first landfill was 11 $\pm$ 1.5 (number $\pm$ SE), and 11 $\pm$ 1.4 in the second landfill. Species richness per 100 m^2 at the control sites was 17 $\pm$ 0.3. Species richness per unit area of the control sites was higher that that of landfill sites. The difference of species evenness between the Nanjido landfill and the control sites was significant (Wilcoxon rank sum test; $P < 0.05$); the evenness at the Nanjido landfill (0.64 $\pm$ 0.03) was higher than that at the control sites (0.49 $\pm$ 0.05). Simpson's and Shannon-Wiener's diversity indices for the landfill and control sites did not show a significant difference (Wilcoxon rank sum test; $P > 0.05$). The ratio of the number of exotic plant species to the total number of plant species did not vary significantly among landfill aspect. However, the exotic species ratios of the Nanjido landfill sites were significantly higher than those of the control sites (Wilcoxon rank sum test; $P < 0.05$).

3.3. Soil properties

There was considerable variation in the depth of soil cover on the Nanjido landfill. The soils were significantly less acidic than those of the control sites (Table III; $P < 0.05$). The organic matter content of the Nanjido landfill and the control site soils were not significantly different (Table III). The electrical conductivity of soils on the Nanjido landfill was 2.6 times greater than that of soils at the control sites (Table III; $P < 0.05$). The total nitrogen content of soils on the Nanjido landfill and at the control sites was not significantly different (Table III). The P content of soils on the Nanjido landfill was 21.4 times greater than at the control sites (Table III;

TABLE III

Comparison of physico-chemical properties of the soils on the Nanjido landfill and the control sites, Mt. Sangam and Mt. Maebong. Different superscripts indicate a significant difference between sites at the 0.05 level, using the Willcoxon rank sum test. Values are mean ± SE

Property	Nanjido landfill (n=16)	Control sites (n=3)
pH[1]	$7.6^a \pm 0.1$	$4.3^b \pm 0.1$
Electrical conductivity[2] (μS/cm)	$161^a \pm 15$	$63^b \pm 13$
Organic matter (%)	$2.9^a \pm 0.3$	$3.6^a \pm 0.2$
Total-N (mg/g)	$18.9^a \pm 3.6$	$17.3^a \pm 1.1$
P (μg/g)	$10.7^a \pm 1.3$	$0.5^b \pm 0.1$
K (mg/g)	$0.09^a \pm 0.01$	$0.04^a \pm 0.01$
Ca (mg/g)	$3.77^a \pm 0.30$	$0.34^b \pm 0.05$
Mg (mg/g)	$0.10^a \pm 0.01$	$0.03^b \pm 0.00$
Sand (%)	$59.2^a \pm 1.8$	$57.5^a \pm 5.2$
Silt (%)	$34.1^a \pm 1.7$	$32.5^a \pm 4.9$
Clay (%)	$6.7^a \pm 0.5$	$10.0^b \pm 0.5$

[1] Soil : water = 1 : 2 (W/V); [2]Soil : water = 1 : 5 (W/V).

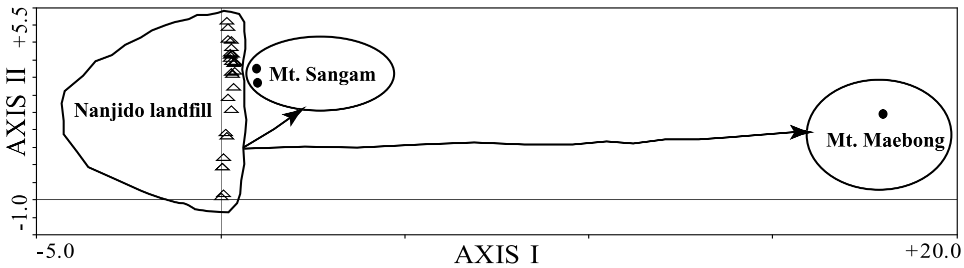

Figure 2. Ordination diagram based on detrended correspondence analysis, showing positions of Nanjido landfill quadrats (∆) and control site quadrats (•) along the first two axes. The proximity of Nanjido landfill and Mt. Sangam quadrats indicates a similarity in species composition, whereas the greater distance between Nanjido landfill and Mt. Maebong quadrats indicates substantial differences in species composition. The circled regions are the different sites. Arrows indicate the natural direction of vegetation change at the Nanjido landfill. The first two floristic axes accounted for 30.6% of the variation, with axis I explaining 17.1% of the variation.

$P < 0.05$). The extractable cation contents, such as K, Ca, and Mg, of landfill soils were greater than those of control site soils. Ca and Mg contents of landfill soils were significantly different from those of control site soils (Table III; $P < 0.05$). The soil texture at both the Nanjido landfill and the control sites was sandy loam (Table III). Clay content of the landfill soils was significantly lower than in control site soils.

3.4. Ordination analysis

Site ordination (DCA) showed a separation of quadrats along the first floristic axis (Figure 2). The quadrats of the Nanjido landfill and Mt. Sangam were segregated in the left-hand side of axis I, indicating that these sites had similar floristic compositions. The distribution of these sites was compressed in ordination space, and individual sites could barely be distinguished, whereas the Mt. Maebong sites were positioned to the right end of the axis, owing to their well-conserved state and the presence of more rare species. This DCA showed, therefore, that the vegetation of Mt. Maebong differed from the vegetation of the other sites, the Nanjido landfill and Mt. Sangam (Figure 2).

The Nanjido landfill quadrats were clustered separately away from the control site quadrats in the CCA diagram (Figure 3). Unlike the vegetation composition pattern, the soil chemical environment of the Nanjido landfill was different from that of control sites. Specifically, the Mg content of soils was strongly correlated with the first axis ($R^2 = 0.87$), and the second axis correlated with soil P content. Mg and P content were the most important environmental factors for the Nanjido landfill and control site quadrats.

4. Discussion

4.1. Vegetation characteristics and species diversity

The commonly found tree species in urban areas, *Albizzia julibrissin, Indigofera pseudo-tinctoria*, and *Paulownia tomentosa*, were found only on the Nanjido landfill, but not at the control sites. *Quercus mongolica*, known as a natural late succession species in temperate Northeast Asia, were also recorded on the Nanjido landfill (Nakagoshi, 1985; Jang *et al*., 1997). Consequently, succession apparently is occurring on the slopes of the Nanjido landfill.

Many mixed communities, ecotones linking various tree and grass communities, covering small areas, were found at the Nanjido landfill. *Quercus aliena* communities at the control sites were thought to be natural to the area. The vegetation structure of the Nanjido landfill was monolayer, with only trees or grasses, or bilayer, with trees and grasses, but without shrubs. The structure of the control sites was multilayer, with tree, shrub, and grass layers.

The desirable restoration method for the landfill slopes is therefore to create stable, multilayered forests with many saplings and seedlings. The colonization of the Nanjido landfill is from the seed bank and bud bank. Therefore, the initial status of the vegetation depends upon the origin of the cover soils. This situation differs from some cases in other countries, where plants have been allowed to recruit naturally from off site, and artificial soils have been used for covering (Robinson *et al*., 1992).

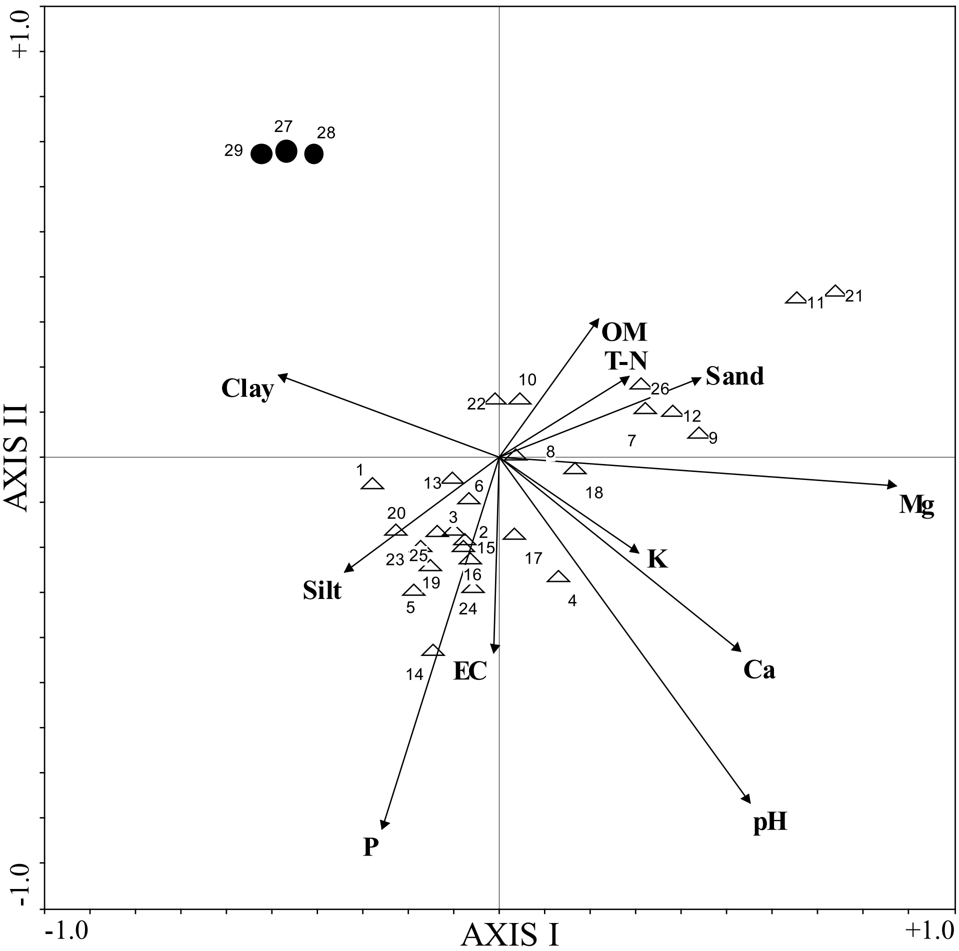

Figure 3. Ordination diagram of canonical correspondence analysis of 29 quadrats from the Nanjido landfill (Δ) and control sites (•) relative to 11 environmental variables. Each number refers to number of quadrats. The characters at arrow ends indicate soil environmental variables: pH, EC (electrical conductivity), OM (organic matter), T-N (total nitrogen), P (phosphate), K, Ca, Mg, sand, silt, and clay. A Monte-Carlo permutation test indicated that the first canonical axis was significantly different ($F = 1.401$; $P = 0.001$).

Quantitative analyses of quadrat survey data showed that the flora of the Nanjido landfill and the control sites did not overlap (Table I). Succession is believed to occur on a small scale. Species evenness analysis showed that the species were more evenly distributed on the Nanjido landfill than at the control sites, as dominant species have not yet been established. The Simpson and Shannon-Wiener diversity indices did not differ between the Nanjido landfill and the control sites, indicating that the plant diversity of the Nanjido landfill has developed as much as it did in the nearby forests. Consequently, succession on the Nanjido landfill appeared to be proceeding, in stages, to the vegetation of the control sites. Exotic species, however, seemed to be disturbing the colonization of native species. The landfill sites had higher exotic plant species ratios than did the control sites. Management is therefore essential in areas that are dominated by exotics.

4.2. Comparison of Vegetation at the Nanjido Landfill with Landfills in Other Countries

The Nanjido landfill is a representative of nonsanitary landfill with no pollution controls, such as top-capping, gas vents, bottom liners, or leachate collecting systems. It is an open refuse and waste dump site, exposed with no cap in parts of the landfill. The waste is covered by residue soils of variable thickness, generally thought to be about 1 m deep. Residue soils of various origins and qualities, from multiple adjacent sites, make up the cover layer of the Nanjido landfill. These soils may be a mixture of topsoil and subsoil. In other countries, artificial soils, such as permanent clay or mineral soil, have been used instead (Chan *et al.*, 1996; Robinson *et al.*, 1992).

The quality of soil cover material has been shown to influence the number of plant species and the plant cover (Ettala *et al.*, 1988). Woodland establishment was possible, and natural succession occurred at a faster pace at some sanitary, capped, landfill sites in Hong Kong (Chan *et al.*, 1997). Woodland establishment is known to be difficult if the landfill cap has not been properly laid, or if leachate collection and gas venting systems have not been installed properly (Leone *et al.*, 1982; Wong, 1988; Wong and Yu, 1989). Although the Nanjido landfill has many of these deterrents, this study showed that woodlands have become established and succession has proceeded at the rates that are representative for the area.

The mean coverage of the tree layer at the landfill reached 53.6%, higher than the values for sanitary landfills in Finland (Ettala *et al.*, 1988). Tree species such as *Ailanthus altissima, Platanus orientalis, Prunus persica, Rhus chinensis, Robinia pseudoacacia*, and *Salix babylonica*, recorded at the nearby control sites, formed stable woodlands all over the Nanjido landfill. The presence of forest tree species, such as *Rhus chinensis* and *Robinia pseudoacacia*, on the landfill indicated that urban forest woodlands has been created at the Nanjido landfill. The emergence of *Quercus mongolica* on the southeast slopes of the second landfill indicated that some small regions of the landfill has proceeded to the late successional stages of temperate forests.

Quercus mongolica, a typical, deciduous, broad-leaved woody species of South Korea, has been shown to be an indicator of the late successional stages in the stands disturbed by human activities, such as clear cutting, grazing, or logging of temperate zone (Nakagoshi, 1985; Jang *et al.*, 1997). In the cool-temperate deciduous zone of the middle and southern South Korea, *Q. mongolica* communities are dominant or climax forests (Lee *et al.*, 1994). At the Nanjido landfill, however, *Q. mongolica* was distributed at small scales and was less dominant. The *Q. mongolica* sites should be well conserved and managed for *Q. mongolica* expansion into the surrounding areas. Forest trees have been shown to invade sanitary landfills (Sukopp and Starfinger, 1999). The present study shows that succession can progress, and that forest trees can also invade nonsanitary and uncontrolled waste landfills.

The developmental history of the Nanjido landfill vegetation is postulated as follows. The initial vegetation started from the seed or bud bank, and then small woodlands developed randomly on the landfill. Gradually, the small woodlands expanded until natural forests developed. The increase in plant cover occurred relatively quickly corresponding to secondary succession, from the soil seed bank present at the onset (Prach and Pyšek, 2001). In the Nanjido landfill, the seed pool (from cover soils of various sources) was sufficient to produce prosperous vegetation. The seed and bud bank were found to be the determinant variable affecting the plant colonization and distribution at this nonsanitary waste landfill (Kim, 2001).

4.3. Relationship of soil physico-chemical properites and plant distributions

The pH of the Nanjido landfill soils ranged from 7.0 to 7.8, while the pH of the control site soils ranged from 4.1 to 4.5. Woody species can better survive in landfill soils when the soil pH is optimal (Gilman *et al.*, 1976). Therefore, pH adjustments, by the addition of fertilizer or lime, would be needed to alter species compositions. The organic matter in the Nanjido landfill and the control site soils is too low to compensate for the coarse texture or to enhance water and nutrient retention capacity (Marton, 1996).

Nonsanitary landfills, such as the Nanjido landfill, can generate leachate with an alkaline pH and also fairly high NH_4, P, and K contents from raw refuse (Hasselgren, 1998). The soils of nonsanitary landfills can, therefore, have higher concentrations of these elements than other sites. Ca and Mg levels in Nanjido landfill soils were significantly higher than those in control site soils. Soil salination has been shown to be the result of evapotranspiration in semi-arid and arid regions, such as open landfills (Hernández *et al.*, 1998, 1999). Landfill gas has been presumed to raise atmospheric and soil temperatures, and to result in higher levels of evapotranspiration. The capacity of the Nanjido landfill soils to adsorb water and other chemical substances is lower than the soils of the forest control sites because of low clay content (Table III). Although bulk density was not measured in this study, satisfactory woodlands can be achieved on uncapped landfills only if adequate physical soil conditions are obtained (Dobson and Moffat, 1999).

Soil chemical analyses revealed significant differences in soil chemical characteristics, such as pH, electrical conductivity, P, Ca, and Mg, between the landfill and the control sites. The differences can be explained by the different origins of the soils. Soil characteristics have been shown to be major factors controlling species abundance and community composition (Tilman, 1988). The soil chemical environment can stimulate or limit colonization. The flourishing plant growth at the Nanjido landfill seems to indicate that all soil toxicity has been mitigated after 7 yr of landfill closure (Gilman, 1980). Soil improvement is needed, however, to produce the more stable forest structures found at the control sites.

4.4. Ordination analysis: spatial variation in stand composition

The floristic composition of the Nanjido landfill sites was similar to that of the Mt. Sangam sites, but not to that of the Mt. Maebong site, which had more natural vegetation. *Pinus densiflora* and *Quercus mongolica*, the dominant tree species at Mt. Maebong, are found in Korea in the tree stage of abandoned field succession, following shifting cultivation (Lee, 2002). Consequently, DCA showed that the vegetation of the Nanjido landfill slopes was in part similar to the nearby urban forest vegetation (Figure 2).

According to our CCA ordination results, soil salinity content, including Mg content, differs between the Nanjido landfill and the control sites. Soil improvements on the Nanjido landfill are needed for vegetation like that found at the control sites, because edaphic factors, like soil chemistry, affect vegetation composition (Tilman, 1988).

4.5. Heavy metals and landfill gases in the Nanjido landfill

Two major elements of disturbance in waste landfills that can influence plant succession are heavy metals and landfill gases. Waste landfills are known to be ecologically disturbed by water pollution, landfill gas, and soil subsidence (Leone *et al.*, 1979). Anaerobic decomposition of organic materials in the surface layers results in higher contents of CO_2 and CH_4 (Gilman *et al.*, 1976). Other gases, such as H_2S, NH_3, amines, and mercaptane, are also produced. These gases move horizontally, and seep out at the sides of waste landfills. They are obstacles to plant growth. Anaerobic conditions in waste landfills may also cause heavy metals to concentrate in the soils (Tosh *et al.*, 1994). Fe, Mn, Cu, and Zn concentrations are consistently higher in anaerobic soils than in aerobic soils (Duell *et al.*, 1986). Landfill gas and increased contents of Fe, Mn, Cu, and Zn in landfill soil systems have detrimental effects on tree growth (Gilman *et al.*, 1981). The leachate generated from domestic waste landfills contains a small amount of heavy metals (Kim *et al.*, 1997). Most heavy metals in surface soils of the Nanjido landfill may be from leachates and contaminated soils used for landfill cover. Studies show that leachates from the Nanjido landfill are highly toxic, complex mixtures of a number of toxic compounds (Kaur *et al.*, 1996). Leachates from the Nanjido landfill have formed streams and pools, which continuously seep from the sides because of the uncontrolled nature of nonsanitary waste landfills. There are no studies, however, on the impact of the leachates from the Nanjido landfill on vegetated surface soils. Other studies have shown that Pb and Zn concentrations in Nanjido landfill soils are higher than in natural site soils: 5.01 and 9.45 ppm, respectively (Koo *et al.*, 1997). The concentrations of Pb and Zn correspond to ranges acutely toxic to plant growth

(Kabata-Pendias, 2000). Furthermore, the concentrated heavy metals in a part of Nanjido landfill soils may affect plant growth and subsequently retard succession.

The presence of landfill gases in landfill soil results in increased concentrations of Fe and Zn in the soils (Leone *et al.*, 1979). If landfill gases replace O_2, and microorganisms using O_2 are active, the pH of soils would become reductive, and then the concentrations of microelements, including Fe and Zn, would increase (Leone *et al.*, 1979). The concentrations of CH_4 and CO determined from 42 ventpipes in the Nanjido landfill were 7.31 ± 2.75 ppm and 1.40 ± 1.21 ppm, respectively (Kim *et al.*, 2002). Therefore, it is thought that the concentrations of heavy metals are high in places in the Nanjido landfill, and their impact on plant germination and growth may affect plant distribution. However, this vegetation analysis showed that trees and grasses covered most of the Nanjido landfill, probably because of the natural alleviation over time of these pernicious factors after the landfill closure.

4.6. Implications for Restoration

The ability of natural woodlands to establish on degraded sites is a very important concern of plant ecologists (Robinson *et al.*, 1992). Grasses, shrubs, and trees have occupied the barren soil of the Nanjido landfill since its closure, and succession to natural woodlands appears to be occurring. Landfill vegetation has various roles and functions as urban vegetation (Smardon, 1988). Vegetation reduces surface runoff, increases evapotranspiration, and controls erosion (Landreth *et al.*, 1991). The causes of landfill soil erosion include irregular subsidence of the landfill surface and slope steepness. The steepness of the Nanjido landfill, between 36–84%, inhibits soil stabilization and can be a stochastic factor to invoke vegetation instability. The landfill slope area is 3.5 times greater than the total cover area of the Nanjido landfill (Lee *et al.*, 1997). While the side slope vegetation blends into the surrounding landscape, enhancing public acceptance (Smith *et al.*, 1997), it also functions as a biological source for other biologically sparse areas inside landfills, increasing the local biodiversity. This study may be helpful in formulating species prescriptions for revegetation of other landfill sites. Furthermore, the plant invasion on the Nanjido landfill slopes has occurred rather rapidly, and woodlands similar to the surrounding forests have already formed. As succession occurs on the slopes of the Nanjido landfill, slope conservation and soil erosion prevention can accelerate landfill restoration. Reducing the pH and the Ca and Mg content of the landfill soils to the level of the control sites could help adjust the vegetation composition of the Nanjido landfill to that of the nearby forests. We are aware that in contrast to the abandoned disturbed sites such as mines, the systems managed with human assistance can be rehabilitated decades sooner (Wali, 1999). The Nanjido landfill is fragmented inside by access roads, and it is also fragmented outside by the connecting roads. Therefore, it is largely cut off from biological sources. The present slope vegetation arose mainly from seed and bud banks in the cover layer soil and dumped sweepings. The urban construction subsoils and the nearby forest edge topsoils were generally used for the landfill cover layer. These soils included many seeds, plant cuttings, and sprouts. These initial biological materials may have enhanced a facilitative succession in the Nanjido landfill. The spontaneous facilitative succession from the soil biological bank is a component of restoration in these areas. However, this initial, unstable, restricted, and largely exotic vegetation could depress the development of the Nanjido landfill ecosystem. Moreover, the tree cover of the landfill was low or nonexistent at some sites. Revegetation and introduction of plants that grew at the site pre-disturbance or at a similar, nearby site would help restoration of the Nanjido landfill (Cairns and Heckman, 1996). Connection of the Nanjido landfill to Mt. Sangam and Mt. Maebong as a green corridor will help the Nanjido landfill restoration via seed rain (Bergen *et al.*, 2001). In contrast to sanitary landfills, waste in sublayers of nonsanitary landfills that lack capping has detrimental impacts on plant root growth. Landfill gas and leachate, escaping through soil crevices, also have no beneficial effects on plant growth (Tosh *et al.*, 1994; Ahel *et al.*, 1998; Wong and Yu, 1989). These disturbance factors in nonsanitary landfills could result in simple, degenerate, and sterile landfill vegetation. A thick vegetative cover on waste landfills may prevent these problems, through distributive processes. Hence, conservation and management of the landfill slope vegetation that has developed spontaneously on the Nanjido landfill is urgently needed to restore this typical nonsanitary landfill, and this approach is more economical than revegetating waste landfills by using artificial planting of slopes.

5. Conclusions

This study observed the vegetation that has developed on a large nonsanitary waste landfill 7 years after its closure. The nonsanitary waste landfills of South Korea have heterogeneous soils, of various origins, unlike the unified artificial soils that are widely used in other developed countries. While the status of vegetation development on nonsanitary landfills is site-specific, it can be compared with vegetation conditions on other sanitary or nonsanitary waste landfills, and methods can be sought to restore nonsanitary and uncontrolled waste landfills. The study results presented here led us to the following conclusions:

(1) *Robinia pseudoacacia*, *Salix babylonica* and their mixed communities appeared on the Nanjido landfill with monolayer or dilayer simple structures of trees or grasses. Woodlands have become established all over the Nanjido landfill. They appear to be unstable communities, on a community structure basis, in comparison to the nearby forest control sites.

(2) On some slopes of the Nanjido landfill, small *Quercus mongolica* communities have formed, revealing that at local scales, succession has proceeded to the stage of representative oak forests that is typical in the temperate zone of South Korea.

(3) The DCA results also show that the vegetation on the Nanjido landfill has shifted towards the vegetation pattern of the nearby urban forests. The CCA ordination of the Mg and P content of soils explained the differences in the vegetation composition in the Nanjido landfill and the forest control sites well.

(4) The pH, electrical conductivity, and P, Ca, Mg, and clay contents of the soils on the Nanjido landfill were significantly higher than those of the soils at the nearby forest control sites. Soil improvement, such as fertilization, is recommended for development of vegetation on the Nanjido landfill. Conservation and management of the wooded slopes on the Nanjido landfill are needed because they are the biological sources for restoration of other nonvegetated areas of the nonsanitary landfill.

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