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Soil seed bank of the waste landfills in South Korea

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Abstract

The restoration of urban landfill is a topic of growing interest in reclamation ecology as the acreage of abandoned sites near cities increases. The goals of this study were to assess the ecological status of waste landfills and to elucidate the role of seed banks in the establishment of vegetation at these sites. The study sites were located at five landfills around Seoul and Kyongki Province. On average, soils were sampled on 20 plots per landfill in 2001 to record species composition and to estimate the number of seeds in the soil. Soil seed bank vegetation and the individual number of seedlings that germinated were recorded using the seedling emergence method. Relative density per species was calculated from the number of individual seedlings. We conducted canonical correspondence analysis (CCA) using the program CANOCO to survey the relationships between 23 environmental variables and plant importance values. Environmental variables included categorical and numerical variables (landfill age, landfill size, distance from landfill edge, human disturbance level, slope, periodic management level) and soil physico-chemical variables (bulk density, soil moisture content, organic matter content, total N, available P, K, Na, Ca, Mg, Cd, Cr, Cu, Fe, Mn, Ni, Pb, and Zn). The mean seedling density per m^2 differed significantly among sites ($P < 0.05$). As landfill age increased, the mean seedling density per m^2 decreased. The mean seedling density of the Sangpaedong landfill, which was less than 1 year old, was higher than that found in 6- and 7-year-old landfills. The Sangpaedong landfill mainly contained seeds of *Chenopodium album* L. and *Digitaria ciliaris* (L.) SCOP. With regard to early vegetative colonization in landfills, our results highlighted the importance of seed banks occurring in cover soils. Cover soils, derived from various sources, will determine landfill landscapes because of different seed banks present in them. The first axis of the CCA was correlated with landfill age, Na, and human disturbance level, while the second axis was correlated with landfill size, slope, periodic management level, Zn, total N, and organic matter content. Understanding seed banks in landfill cover soils is important, therefore, for proper landfill management and restoration.

Introduction

Landfilling is a globally common waste management practice. Management and the re-use of landfills have been pertinent topics in restoration ecology dealing with re-vegetation and landscaping. In particular, the use of natural vegetation to colonize waste landfills has been hailed as an economic and effective means of restoring such sites. Landfills in South Korea are artificial and specific ecosystems, covered with foreign soils, on waste dumpsites. Thus, the soil profile is composed simply of two layers, a lower waste layer and an upper cover layer. The composition of aboveground vegetation may depend on

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what kinds of seeds occur in the soils used for the cover layer. Initial colonization of plants in waste landfills reflects the vegetation growing in the areas from which the cover soil was obtained (Kim et al., 2004). Therefore, seed and bud banks of vascular plants and spore banks of bryophytes and ferns in soils can determine the early-stage vegetation occurring in waste landfills. Soil seed banks are defined as the seeds present in the soil (Barbour et al., 1999), and they play an important role in sustaining various ecosystems. Shaw (1996) conducted a study on the use of seed bank substrates as a simple and cheap method for re-vegetating waste sites, such as areas contaminated with pulverized fuel ash and gypsum. To date, however, studies of soil seed banks in disturbed and deserted areas like waste landfills have been rare. The goals of this study were to assess the ecological status of five waste landfills, provide a general description of the soil seed banks in these landfills, and to elucidate the role of seed banks in the establishment of early vegetation at these sites

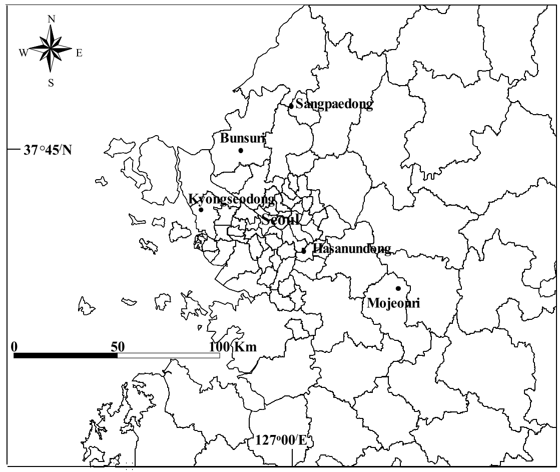

Figure 1. Location of study sites (•) in relation to Seoul, the capital of South Korea. The lines within the Korean peninsula denote the administrative territories of cities.

Materials and methods

Site description

We selected five sites among the 127 waste landfills within the Seoul metropolitan area and adjacent Kyongki Province; all five were located in the western parts of central Korea (Figure 1). The selection criteria included a high degree of natural colonization, low human disturbance, and various increments of time since closure. The study sites were the Bunsuri, Hasanundong, Kyongseodong, Mojeonri, and Sangpaedong waste landfills, with a chronosequence of time since closure ranging from 0.25 to 7.25 years, and sizes ranging from 6 to 220 ha. Details of the sites are given in Table 1. All sites are located at mid-latitudes of the Northern Hemisphere (37°18′–54′ N and 126°39′–127°29′ E) in the temperate zone, which is characterized by four distinct seasons. During the winter, from December to January, this area is cold and dry, as it is under the dominant influence of the Siberian air mass. In contrast, summers, i.e., June to August, are hot and humid with frequent heavy rainfalls associated with the East-Asian Monsoon, locally called the 'Changma'. The study area is mild during the spring and fall, with periodic passages of transient high and low pressure systems. The annual mean temperature ranges from 12 to 24 °C, except in the high mountain areas, and annual precipitation averages approximately 1400 mm (Korea Meteorological Administration, 1995–2000). More than half of the annual precipitation in this region falls during the Changma season, whereas winter precipitation constitutes less than 10% of the total. Humidity is highest in July, around 70–80%; in contrast, the lowest mean monthly humidity is around 30–40% in January and April. The Bunsuri, Hasanundong, Mojeonri, and Sangpaedong landfills are located adjacent to forested areas, whereas the Kyongseodong waste landfill is surrounded by reclaimed lands. All sites underwent natural succession after closure because they were left neglected and unmanaged, and the cover soils in all five sites were derived from construction site subsoils (pers. comm. with landfill managers). The landfills were dominated by grasses with patches of shrubs, such as *Amorpha fruticosa*, *Lespedeza cyrtobotrya*, *L. maximowiczii*, and *L. bicolor*, and trees, including *Robinia pseudoacacia*, *Salix koreensis*, *Populus sieboldii*, *Morus alba*, *Ailanthus altissima*, *Paulownia coreana*, *Populus deltoides*, *Diospyros kaki*, and *Albizzia julibrissin*.

Table 1. Characteristics of the study sites in South Korea

Waste landfill sites	Closure time (years after closure)	Size (ha)	Present landuse status	Neighboring habitats
Bunsuri	1993 Dec. (6.25)	9	Idle land	Forest
Hasanundong	1994 Jun. (5.75)	65	Idle land	Forest
Kyongseodong	1992 Dec. (7.25)	220	Idle land	Reclaimed land
Mojeonri	1994 Dec. (5.25)	15	Idle land	Forest
Sangpaedong	1999 Dec. (0.25)	6	Idle land	Forest

Closure time represents when the landfills were completed. Years after closure indicate the time elapsed between closure and 2001, when this study started. The Kyongseodong landfill was operated on coastal lands reclaimed since the 1980s.

Aboveground vegetation

The total inventory of plant species was recorded for all landfills between 1999 and 2002, and identification and nomenclature followed Lee (1985) and Park (1995). Exotic plants were classified according to Park (1995, 2001), and species that could not be identified in the field were brought to the laboratory for complete identification. A quadrat survey was conducted for herbaceous species in the landfills using the line intercept method (Bauer, 1943; Canfield, 1941). We established 0.25-m^2 square quadrats at 5-m intervals along each line transect, perpendicular to landfill edges, in September 2001 (Jose et al., 1996). The quadrat survey was repeated four times at the center of the 5-m interval of the line transect at the same sites. If the area of the landfill was >65 ha, two line transects were setup in parallel at a certain distance along the shorter axis of the landfill, and if the area was <65 ha, two line transects were laid out perpendicular to each other. In total, 90 quadrats were established for all sites. All vegetation, including tree seedlings that appeared in the quadrats, was recorded and the percent coverage by each species was estimated visually using the Braun–Blanquet scale (Fuller and Conard, 1932).

Seed bank sampling

Soil seed banks were sampled in March 2001, following stratification in winter, and prior to the onset of a natural seed rain and germination in the field. The seedling emergence method was performed with soils sampled on 10–30 plots per site at the five sites in 2001 to identify species and to conduct a quantitative analysis of the soil seed banks (Bigwood and Inouye, 1988; Roberts, 1981). Soils were sampled using a cylindrical soil core with a volume of 110.3 cm^3 (22.06 cm^2 surface area $\times$ 5 cm depth) at ten random points within the same quadrats (1×1 m) where aboveground vegetation was studied, and these ten soil cores were pooled to produce one sample per quadrat (ter Heerdt et al., 1996). Soil samples were taken at a depth of 5 cm because most seeds in grassland soil seed banks occur in the first 2 or 3 cm of soil, and numbers of seeds decline rapidly below this depth (Johnson and Anderson, 1985). Soil samples were stored in plastic bags at 4 °C prior to seed-bank analysis. The samples were not sieved, so as to include seeds on the surface of coarse materials and vegetative propagules. Individuals grown from vegetative propagules like stems and roots were categorized as bud banks and were counted separately from the seed banks. Bud banks were identified visually because they grew faster and in a more clustered fashion than did seeds. To initiate germination, soil samples were spread thinly on top of a 2-cm layer of heat-sterilized (121 °C for 15 min) vermiculite on plastic trays (length 44 cm, width 31 cm, depth 5 cm). We used ten trays with only vermiculite as controls for contamination by alien seeds. All trays were randomly arranged in an unheated greenhouse under natural light conditions. The temperature of the greenhouse was kept at a mean of 25 °C, with humidity ranging from 72 to 80%, and soil in the trays was watered daily for 6 months. Trays were rotated once a week to limit differences in light and water conditions. In the 6 month, the samples were treated with a gibberellic acid solution (1 g L^{-1} of GA_3) to stimulate, the germination of dormant seeds (Bekker et al., 1997). The trays were checked for new seedlings every day for the first 4 weeks, and once a week thereafter. Upon identification, seedlings were removed to promote the emergence of other seedlings. Some seedlings were transplanted and grown to maturity for identification. The individual number of seedlings that germinated and the species that appeared were recorded, and identification and nomenclature followed Lee (1985) and Park (1995, 2001).

Soil chemical analysis

Surface soils were removed from randomly selected locations within each quadrat by scraping the surface to a depth of 10 cm with a sterile hand shovel. Large organic debris was removed from the samples before they were placed in vinyl bags and transported to the laboratory. The samples were air-dried at room temperature in the shade. Soil moisture content and bulk density were measured according to Allen (1974) and Page et al. (1982), and sand, silt, and clay contents were analyzed by the hydrometer method (Sheldrick and Wang, 1993). Soil pH and conductivity measurements were made by shaking 5 g of dried material in 25 mL of distilled water for 1 h. The resulting solutions were then measured using a pH meter (Fisher 230A) and a conductivity meter (Philips PW9509/20). Organic matter content was quantified following the Wakley-Black method (Page et al., 1982), and total N and available P were measured with the Kjeldahl method and the Bray No. 1 method, respectively (Page et al., 1982). Exchangeable cations of Ca, K, Mg, and Na were extracted with 1 N ammonium acetate solution for atomic absorption spectrophotometer analyses (Page et al., 1982). Soils were acidified with 0.1 N hydrogen chloride prior to analysis by a Model ICP-1000 IV ICP emission spectrometer for Cd, Cr, Cu, Fe, Mn, Ni, Pb, and Zn.

Similarity analysis

The similarity between the aboveground vegetation and the seed bank composition was calculated by Sorensen's similarity index (IS_s; Greig-Smith, 1983):

$$IS_s = (2C/A + B) \times 100,$$

where C is the number of species common to both quadrats, and A and B are the number of species in quadrats A and B, respectively.

Multivariate analysis

The relative density (RD_i) of species based on seedling numbers recorded in the seed bank analysis was calculated (Brower et al., 1998) and was used to represent the importance value:

$$RD_i = n_i / \sum n,$$

where n_i is the total number of individuals of species i that germinated and $\sum n$ is the total number of individuals counted for all species.

To determine the relationships between 23 environmental variables and plant importance values, the relative density values (RD_i) were ordinated by two categorical variables, four numerical variables, and 17 soil chemical variables through canonical correspondence analysis (CCA) using the CANOCO program (ter Braak and Smilauer, 1998). Canonical correspondence analysis identified relationships between environmental factors surveyed in the quadrats. Two categorical variables, human disturbance level and periodic management level, represented the presence or absence of human disturbance and periodic management. The level of human disturbance was evaluated from field inspections based on the presence or absence of fences, agricultural lands, and car tracks within the study sites. A survey of, and personal communications with, landfill managers were conducted to determine the levels of periodic management, e.g., mowing (Ministry of Environment, 1997). These two variables were coded as 1 or 0, depending on whether each factor was present. Four numerical variables represented distance from landfill edge, landfill age, landfill size, and slope. The 17 measured soil chemical variables were available P, bulk density, Ca, Cd, Cu, Cr, Fe, K, Mg, Mn, Na, Ni, organic matter content, Pb, soil moisture content, total N, and Zn.

Data analysis

All species were classified as r-selected or K-selected, according to their life history. Annuals and biennials were considered to be r-selected, and perennials were K-selected plants (Pianka, 1970). Species richness was defined as the total number of species found in the aboveground vegetation, as well as in the seed banks. The mean species richness of aboveground vegetation and in the seed banks was calculated, based on the quadrats (1 m^2), and a given soil volume (110.3 cm^3), respectively. The ratio of the number of annual, biennial, and perennial species to the total number of species in aboveground vegetation plots (1 m^2), and in the soil seed banks (110.3 cm^3), was calculated as follows:

Ratio of annual, biennial, or perennial species number to total species number
= species number of annual, biennial, or perennial/total species number.

Because the quadrat numbers were unequal among the landfill sites, we used the GT2 method to test all differences between pairs of means (Sokal and Rohlf, 1995). The following parameters were compared by the GT2 method to test multiple comparisons between sites: mean species richness, ratio of the number of annual, biennial, and perennial species to total number of species of aboveground vegetation and of the soil seed bank, and mean seedling density of the soil seed bank. The differences in soil chemical properties were also determined by the GT2 method.

Results and discussion

Aboveground and belowground vegetation

Some mosses that appeared both aboveground and in the soil seed banks were not recorded. The seed banks contained seeds from a broad range of plants: 46 annuals, 12 biennials, 15 perennials, and four woody species. Plants of 55 native and 22 exotic species germinated from the soil seed banks. *Robinia pseudoacacia* and *Salix koreensis*, two woody species, germinated in pots, but their individual numbers were small. *Rubus crataegifolius* and *Lespedeza cyrtobotrya*, two shrubs, also germinated in pots. *Setaria viridis*, *Panicum bisulcatum*, *Erigeron annuus*, *Ambrosia artemisiifolia* var. *elatior*, *Erigeron canadensis*, *P. dichotomiflorum*, *Digitaria ciliaris*, *Artemisia princeps* var. *orientalis*, *Ixeris dentata*, and *Chenopodium album* appeared frequently in the seed banks. The following eight species observed in the seed banks were not found in the quadrats surveyed for aboveground vegetation at each landfill, although they were recorded in the total inventory survey: *Capsella bursa-pastoris*, *Portulaca oleracea*, *Euphorbia supine*, *Mazus pumilus*, *Galinsoga ciliata*, *Chenopodium album*, *Galium spurium*, and *Ixeris dentata.*

Zoysia japonica, *Persicaria vulgaris*, *Stellaria aquatica*, *Cereatium holosteoides* var. *hallaisanense*, *Cardamine flexuosa*, *Capsella bursa-pastoris*, *Raphanus stivus* var. *hortensis* for. *Acandthiformis*, *Draba nemorosa* var. *hebecarpa*, *Trifolium repens*, *Erigeron annuus*, *Erigeron canadensis*, *Artemisia princeps* var. *orientalis*, *Ixeris dentata*, and *Hypericum erectum* appeared as bud banks, which contained on average 19–211 individuals per unit soil volume (110.3 cm^3). The mean species richness of aboveground vegetation varied by site (Table 2), i.e., it tended to be low in the early years after closure of a landfill, increased from 5.25 to 6.25 years post-closure, and then decreased after 6.25 years (Table 2). The mean species richness of soil seed banks was low in the early years, moderate at 5.25 to 6.25 years, and then increased at 7.25 years post-closure (Table 2).

Most seed banks are characterized by high spatial variability, poor correspondence with the standing vegetation, and a relatively low representation by perennials (Rice, 1989). The seed banks of the landfills in this study also possessed such characteristics. For example, the landfill seed banks were not dominated by one or two species of annuals. Seedling density of all species was of consecutive magnitude, based on landfill age. It is possible that 7.25 years post-closure was too short a time interval to show clear patterns of succession. A general feature of seed banks is the disparity between the species contained in them, as compared to the vegetation growing on them (Moore, 1980). The density of seed banks generally decreases with successional age (Roberts and Vankat, 1991); in this study, we also found that seedling density of the waste landfills showed a clear decreasing trend with landfill age (Table 2). The ratio of the number of annual species (RA) to the total number of species in the aboveground vegetation plots and in the soil seed bank decreased with landfill age, although this ratio did not differ significantly among the five sites (Table 2). The ratio of perennial species to total species (RP) on plots of aboveground vegetation was significantly higher in the Mojeonri landfill than in the Sangpaedong landfill

Table 2. Species richness, mean species richness, and ratio of the number of annual, biennial, and perennial species to the total number of species (± standard error) in the aboveground vegetation and the soil seed banks, and seedling density in the soil seed banks, at five different landfill sites in South Korea

Parameter	Sites (years after closure)				
	Sangpaedong (0.25)	Mojeonri (5.25)	Hasanundong (5.75)	Bunsuri (6.25)	Kyongseodong (7.25)
Aboveground Vegetation					
Species richness[a]	41	78	93	53	141
Species richness[b] (/m^2)	21	20	45	25	23
Mean species richness[c] (/m^2)	$6.4^{a} \pm 1.3$	$4.6^{b} \pm 0.9$	$5.5^{c} \pm 0.8$	$7.1^{d} \pm 0.6$	$5.4^{e} \pm 0.4$
RA[d]	$0.95^{a} \pm 0.02$	$0.70^{b} \pm 0.06$	$0.69^{b} \pm 0.03$	$0.68^{b} \pm 0.04$	$0.79^{c} \pm 0.03$
RB[e]	$0.01^{a} \pm 0.01$	$0.03^{a} \pm 0.02$	$0.06^{a} \pm 0.01$	$0.06^{a} \pm 0.02$	$0.02^{a} \pm 0.01$
RP[f]	$0.03^{a} \pm 0.01$	$0.26^{b} \pm 0.05$	$0.24^{b} \pm 0.03$	$0.24^{b} \pm 0.03$	$0.18^{b} \pm 0.02$
Seed bank					
Species richness[g] (/110.3 cm^3)	39	22	55	28	54
Mean seedling density[h] (seedlings/m^2)	$26484^{a} \pm 6384$	$10312^{b} \pm 2643$	$8741^{c} \pm 1625$	$9885^{d} \pm 2032$	$15223^{e} \pm 2346$
Mean species richness[i] (/110.3 cm^3)	$13.6^{a} \pm 1.5$	$8.5^{b} \pm 1.0$	$10.5^{c} \pm 0.7$	$10.6^{b} \pm 1.0$	$12.1^{d} \pm 0.8$
RA[d]	$0.83^{a} \pm 0.04$	$0.75^{a} \pm 0.03$	$0.65^{b} \pm 0.20$	$0.61^{a} \pm 0.02$	$0.64^{b} \pm 0.03$
RB[e]	$0.14^{a} \pm 0.04$	$0.15^{a} \pm 0.02$	$0.20^{a} \pm 0.02$	$0.24^{a} \pm 0.02$	$0.21^{a} \pm 0.02$
RP[f]	$0.01^{a} \pm 0.01$	$0.09^{a,b} \pm 0.02$	$0.14^{b} \pm 0.01$	$0.13^{b} \pm 0.02$	$0.14^{b} \pm 0.01$
Contribution Percentage[j]	95	28	59	53	38

Woody species were excluded. Years after closure indicate the time elapsed between closure and 2001, when this study started. Different superscripts indicate significant differences among the landfills assessed by the GT2 method ($P < 0.05$).
[a]Total number of species within the landfill.
[b]Total number of species on plots.
[c]Mean number of species on plots.
[d]The ratio of the number of annual species to total number of species.
[e]The ratio of the number of biennial species to total number of species.
[f]The ratio of the number of perennial species to total number of species.
[g]Total number of species per soil unit volume.
[h]Mean seedling number per m^2.
[i]Mean number of species per soil unit volume.
[j](Species richness of seed bank)/(species richness of aboveground vegetation)×100.

($P < 0.05$; Table 2). In the soil seed banks, RP increased and reached a plateau with increased landfill age (Table 2). In terms of seedling density, the three perennial species *Artemisia princeps* var. *orientalis*, *Ixeris dentata*, and *Aster pilosus* contributed greatly to the number of seedlings, despite their lower counts, as compared to annuals (Table 4). This study showed that annual species declined and that perennial species increased with landfill age, although perennials were relatively scarce in the soil seed banks. It is possible that different factors related to plant invasion from surrounding areas and different soil origins could have affected the soil seed bank composition, although these waste landfills had similar disturbance histories because of the landfilling process.

Succession of belowground vegetation

The mean total seedling density was 12,789 ± 1268 seedlings m^{-2} (average ± S.E.), with a range of 407–72,308 seedlings m^{-2}. Samples from the 0.25-year old Sangpaedong waste landfill produced 26,484 germinable seeds m^{-2} (Table 4). Mean species richness of the soil seed bank per unit soil volume (110.3 cm^3) was highest at that site, as compared to the other waste landfills, with 13.6 species (Table 2). The mean seedling density of the soil seed bank per unit soil volume (110.3 cm^3) differed significantly among landfill sites, based on the GT2 method ($P < 0.05$, Table 2). The seedling density of the Sangpaedong landfill was highest among the landfills, whereas the Hasanundong landfill had the lowest seedling density

Table 3. Sorensen's similarity indices between the aboveground vegetation and the soil seed banks at five different landfill sites in South Korea

Sites (years after closure)				
Sangpaedong (0.25)	Mojeonri (5.25)	Hasanundong (5.75)	Bunsuri (6.25)	Kyongseodong (7.25)
$18.2^{a} \pm 2.4$	$17.6^{a} \pm 2.2$	$17.5^{a} \pm 1.5$	$20.4^{a} \pm 2.2$	$16.7^{a} \pm 1.7$

Years after closure indicate the time elapsed between closure and 2001, when this study started. Different superscripts indicate significant differences among the landfills assessed by the GT2 method ($P < 0.05$).

(Table 2). These differences were due, in the main, to the seedling densities of *Digitaria ciliaris* (Table 4). No seed contamination was evident in control trays. The most dominant species, with the highest number of seedlings in the seed banks, differed among the study sites (Table 4), but overall, *Digitaria ciliaris*, *Erigeron annuus*, *Trifolium repens*, and *Galium spurium* were the most dominant species in the seed banks (Table 4). Exotic species, including *Chenopodium album*, *Erigeron annuus*, and *Trifolium repens*, were also abundant in the seed banks (Table 4). The mean species richness of the seed banks per unit volume differed significantly among the sites, with the exception of the Mojeonri and Bunsuri waste landfills, which had a similar mean species richness ($P < 0.05$, Table 2). Seed bank analysis showed that mean seedling densities differed significantly among landfill sites and that the Sangpaedong landfill, which had been closed for less than 1 year, had a higher seed density than the other landfills. Excluding the Kyongseodong landfill, the mean seedling density decreased with landfill age. This decreasing trend in seedling density of seed banks over time was similar to trends observed during the course of old-field succession, in other countries (Pickett and McDonnell, 1989). Newer landfills like Sangpaedong and Mojeonri had more *r*-selected species that produced more seeds, whereas older sites like Hasanundong, Bunsuri, and Kyongseodong had more *K*-selected species, which tended to produce fewer seeds (Table 4). Representative *r*-selected plants that showed a higher seed productivity were *Digitaria ciliaris, Erigeron annuus, Setaria viridis, Chenopodium album, Cyperus microiria, Echinochloa crus-galli, Panicum bisulcatum, Ambrosia artemisiifolia var. elatior, and Panicum dichotomiflorum* (Table 4). *Ixeris dentata, Aster pilosus, Zoysia japonica, Potentilla paradoxa, and Rubus crataegifolius* were typical *K*-selected plants (Table 4). Thus, the contribution of aboveground vegetation to seed banks decreased with increased landfill age.

Seed bank flora represents belowground vegetation. The initial vegetation of the waste landfills depended on the origin and variability of the cover soils used. The major contributors to soil seed banks are wind, splash, adhesive dispersal, and endozoochory (Pakeman et al., 1999). However, in waste landfills, the most important contributors were the cover soil, co-transportation with waste, and waste transportation. The seed bank species not observed in the aboveground vegetation of each waste landfill (e.g., *Capsella bursa-pastoris*, *Portulaca oleracea*, *Euphorbia supine*, *Mazus pumilus*, *Galinsoga ciliata*, *Chenopodium album*, *Galium spurium*, and *Ixeris dentate*) were probably remnants from the cover soils used at these sites. In particular, the seed bank species not observed in the aboveground vegetation of the most recent landfill, Sangpaedong, must have been contained in soils used for the cover layer. The seeds could not have been transported by natural mechanisms because of the short time since closure (0.25 years). Notwithstanding the absence of seed bank vegetation, aboveground vegetation at the Sangpaedong landfill, such as *Chenopodium album, Setaria viridis, Erigeron canadensis, Humulus japonica, Cyperus iria, Ambrosia artemisiifolia* var. *elatior, Panicum dichotomiflorum, Digitaria ciliaris, Echinochloa crus-galli, Portulaca oleracea, Artemisia princeps* var. *orientalis, Persicaria nodosa, Solanum nigrum, Eleusine indica, Cyperus sanguinolentus, C. microiria, Glycine soja, and Kummerowia striata,* were presumed to have arrived concomitantly with cover soil rather than having been the result of external dispersal.

In grasslands, the upper parts of the soil show a higher seed density than the lower parts (Kalamees and Zobel, 1998), although seeds in the lower parts have a greater potential for decomposition, which causes their germination ability

Table 4. Mean seedling density (No. $m^{-2} \pm SE$) in topsoil from 0 to 5 cm in landfills in South Korea and their life history and species origin

Species	Biological traits[a]	Sites (years after closure)				
Tree		Sangpaedong (0.25)	Mojeonri (5.25)	Hasanundong (5.75)	Bunsuri (6.25)	Kyongseodong (7.25)
Robinia pseudo-acacia L.[b]				136		
Grass						
Digitaria ciliaris (RETZ.) KOEL.	A	9557 ± 4295	2376 ± 1081	640 ± 327	158 ± 62	2702 ± 771
Chenopodium album L.[b]	A	3198 ± 1311	754 ± 361	496 ± 182		498 ± 256
Echinochloa crus-galli (L.) BEAUV.	A	2109 ± 648	181 ± 94	578 ± 251		308 ± 81
Cyperus microiria STEUD.	A	1278 ± 407	525 ± 317	870 ± 538		1186 ± 661
Portulaca oleracea L.	A	1222 ± 573	136	121 ± 54		
Panicum dichotomiflorum MICHX.[b]	A	869 ± 329		185 ± 47	191 ± 56	204 ± 83
Oenothera biennis L.[b]	B	769 ± 136		136 ± 34	121 ± 36	
Setaria viridis (L.) BEAUV.[b]	A	517 ± 259	2161 ± 1469	1069 ± 356	417 ± 189	1483 ± 651
Cyperus difformis L.	A	437 ± 370				
Erigeron annuus (L.) PERS.[b]	B	317 ± 159	339 ± 294	743 ± 209	5868 ± 2243	294 ± 96
Cyperus amuricus MAX.	A	226 ± 81				
Alopecurus aequalis var. *amurensis* (KOM.) OHWI	A	181 ± 91		226 ± 181		
Artemisia princeps var. *orientalis* (PAMPAN.) HARA	P	181		375 ± 71	1633 ± 515	397 ± 127
Mazus pumilus (BURM. f.) VAN STEENIS	A	151 ± 54				106 ± 40
Kyllinga brevifolia var. *leiolepis* HARA	A	113 ± 68				
Ambrosia artemisiifolia var. *elatior* DSCOURTILS[b]	A	106 ± 36	136	264 ± 75	540 ± 126	539 ± 174
Chenopodium ficifolium SMITH[b]	A		1358 ± 688			
Persicaria blumei GROSS	A		1312	226 ± 181	215 ± 47	
Persicaria perfoliata H.	A		517 ± 181			
Erigeron canadensis L.[b]	B		385 ± 133	113 ± 25	121 ± 30	
Persicaria vulgaris WEBB et MOQ.	A		226	379 ± 130		191 ± 62
Euphorbia supine RAFIN.[b]	A		204 ± 39			226
Panicum bisulcatum THUNB.	A		181 ± 45	251 ± 167	1161 ± 1080	119 ± 23
Ixeris dentata (THUNB.) NAKAI	P		158 ± 113			238 ± 101
Persicaria nodosa OPIZ	A		136			
Cardamine flexuosa WITH.	B				215 ± 117	416 ± 170
Cassia mimosoides var. *nomame* MAKINO	A			249 ± 68	166 ± 54	
Aster pilosus WILLD.[b]	P			226 ± 72	151 ± 66	
Glycine soja S. et Z.	A			131 ± 33	146 ± 20	
Rubus crataegifolius BUNGE	P				136	
Lepidium virginicum L.[b]	B				113 ± 68	
Trifolium repens L.[b]	P			5977 ± 3671		
Kummerowia striata (THUNB.) SCHINDL.	A			1067 ± 314		
Stellaria aquatica SCOP.	B			899 ± 465		387 ± 160
Lespedeza cuneata G. DON	P			815		
Galium spurium L.	B			634 ± 312		3961 ± 1695
Bidens frondosa L.[b]	A			317 ± 163		
Aster subulatus MICHX. var. *sandwicensis* A. G. JONES[b]	A			287 ± 153		121 ± 42

Table 4. Continued

Species	Biological traits[a]	Sites (years after closure)				
		Sangpaedong (0.25)	Mojeonri (5.25)	Hasanundong (5.75)	Bunsuri (6.25)	Kyongseodong (7.25)
Avena fatua L.[b]	B			256 ± 189		
Mosla dianthera MAX.	A			249 ± 204		
Cyperus iria L.	A			226		
Galinsoga ciliata (RAF.) BLAKE[b]	A			113 ± 68		
Zoysia japonica STEUD.	P					272
Potentilla paradoxa NUTT.	P					206 ± 56
Artemisia annua L.	A					181 ± 65
Amphicarpaea edgeworthii var. *trisperma* OHWI	A					136
Commelina communis L.	A					113 ± 26
Total		21231	11085	18118	11352	14284
r-selected percentage[c]		99.1	98.5	59.1	83.0	92.2
K-selected percentage[d]		0.8	1.4	40.8	16.9	7.7

Years after closure indicate the time elapsed between closure and 2001, when this study started. Only species with seed bank densities greater than 100 m^{-2} are shown.
[a] A-annual; B-biennial; P-perennial.
[b] Exotic plants.
[c] *r*-Selected percentage: (annual seedling density + biennial seedling density)/(total seedling density)×100.
[d] *K*-Selected percentage: (perennial seedling density)/(total seedling density)×100.

to decrease over time. A soil seed bank analysis at a depth of 5 cm was suitable to ascertain the potential of waste landfill vegetation. However, this type of analysis has a weakness in that it cannot differentiate between transient and persistent seed banks (Thompson, 1992). The soil seed banks contained in the cover soils determined the initial vegetation of waste landfills. Therefore, the soils used for covering waste landfills have important implications for the restoration and management of waste landfills.

The variable patchiness of grasses growing in waste landfills arose from differences in microhabitat. Many microhabitats in waste landfills are the result of topological variations formed by artificial landfilling. Waste emerging from a covered landfill will create various habitats around landfills. These local differences may impact the germination and distribution of species. Environmental pollution sources of landfills, such as biogas and leachate, will have no beneficial effects on seed viability and germination. No significant seasonal differences were evident in the numbers of grass seeds found in a disturbed road bank that had been landfilled (Odgers, 1999). As germination patterns are very sensitive to light, fluctuating temperatures, oxygen availability, soil texture, and other factors, seedling emergence techniques may underestimate the abundance of viable buried seeds (Simpson et al., 1989); however, seedling emergence is desirable for community level studies on waste landfill re-mediation.

The first axis of the CCA explained 5.9% of the species variation and 15.7% of the species-environment variation, and the second axis explained 11.1% of the species variation and 29.7% of the species-environment variation (Figure 2). A Monte Carlo permutation test confirmed that these relationships were significant ($F = 1.85$, $P < 0.01$). The CCA indicated that the first axis was highly correlated with landfill age ($R = -0.3904$), Na content ($R = 0.3445$), and human disturbance level ($R = 0.3188$). Therefore, of the environmental factors, landfill age had a significant influence on the variation in landfill vegetation. The second axis was highly correlated with landfill area ($R = 0.5150$), slope ($R = 0.4496$), periodic management level ($R = 0.4483$), Zn content ($R = 0.4384$), total N content ($R = 0.3673$), and organic matter content ($R = 0.3510$; figure 2). These results, indicating significant relationships between variations in seed bank species composition and environmental factors such as landfill age and human disturbance levels, suggest a trend of artificial impacts on seed bank vegetation (Figure 2). The result of the CCA showed a segregation of quadrats conforming to landfill sites. Excluding categorical variables, the first axis was highly correlated with Na content and the second axis was highly correlated with Zn content.

Relationships between aboveground and belowground vegetation

The mean species richness per m^2 of aboveground vegetation and per 110 cm^3 of seed bank varied by site (Table 2). Sorensen's similarity index for the comparison of aboveground and belowground vegetation ranged from 16.7 to 20.4% (Bunsuri landfill; Table 3). The means for the similarity index were not significantly different among sites, based on the GT2 method ($P > 0.05$). This discrepancy between above- and belowground composition was similar to the divergence of these values in grasslands of other countries (Rice, 1989). The dissimilarity between aboveground and seed bank vegetation reflects changes in the input of seeds from within and from outside of the quadrats, the partial dormancy of the seeds, and the decay of initial seed banks. It is noteworthy that the Sangpaedong landfill had the highest value (95%) in terms of the contribution of aboveground vegetation to seed bank vegetation (Table 2) because the source of most standing vegetation probably came from the soil seed bank, due to the short establishment time after closure.

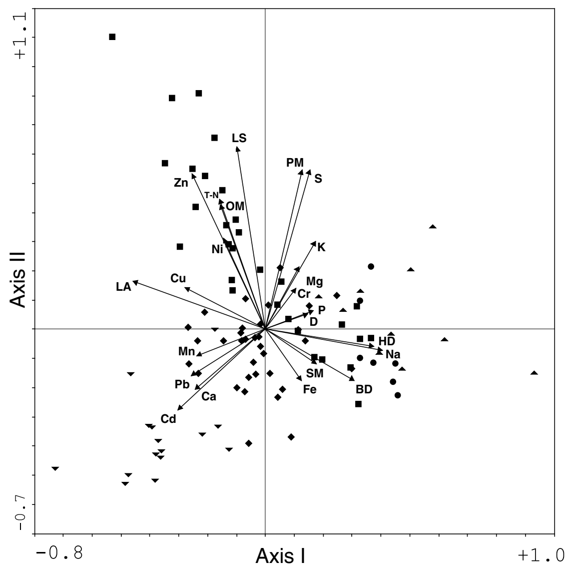

Figure 2. Site-environmental variable biplots using canonical correspondence analysis, showing quadrat scores of seed bank vegetation at five landfill sites in South Korea with environmental-factor arrows. Environmental variables with long arrows are more strongly correlated with the ordination axes than those with short arrows. Quadrat names have been omitted. (Environmental variable abbreviations: BD – bulk density of soils; Ca – calcium content of soils; Cd – cadmium content of soils; Cu – copper content of soils; Cr – chromium content of soils; D – distance from landfill edge; Fe – iron content of soils; HD – human disturbance level; K – potassium content of soils; LA – landfill age; LS – landfill size; Mg – magnesium content of soils; Mn – manganese content of soils Na – sodium content of soils; Ni – nickel content of soils; OM – organic matter content of soils; P – available phosphate content of soils; PM – periodic management level; Pb – lead content of soils; S – slope; SM – soil moisture content of soils; T-N – total nitrogen content of soils; Zn – zinc content of soils, Site symbols: ▼ – Bunsuri; ◆ – Hasanundong; ■ – Kyongseodong; ▲ – Mojeonri; ● – Sangpaedong).

Soil characteristics

Soil texture of most of the waste landfills was mainly sandy loam, although the Hasanundong landfill was loamy sand (Table 5). The landfills had no O layer, but they included shallow litter in some parts. The soil moisture content of Sangpaedong, Mojeonri, Hasanundong, and Bunsuri was greater than that of Kyongseodong, due to direct light interference by the peripheral forests (Table 1). The bulk density of the landfills ranged from 0.60 to 1.53, and the bulk densities of Mojeonri and Hasanundong were significantly higher that those of the other sites ($P < 0.05$; Table 5). The pH values of the landfills were basic, except at Mojeonri (5.67). The conductivity and total N content of the soils in the landfills did not differ significantly among sites (Table 5), whereas available P content declined with increased age (Table 5). Ca, K, Mg, Na, Fe, Mn, and Zn content differed significantly among sites ($P < 0.05$; Table 5).

Roles and implications of soil seed banks in waste landfills

The major priority in waste landfill restoration is to increase botanical diversity. Species present in the soil seed bank may be promoted by soil or

Table 5. Soil physical and chemical characteristics (means ± SE) in relation to landfill age in Sangpaedong, Mojeonri, Hasanundong, Bunsuri, and Kyongseodong, South Korea (pooled quadrats; n = 22).

Soil characteristics	Sites (landfill age; years)				
	Sangpaedong (0.25)	Mojeonri (5.25)	Hasanundong (5.75)	Bunsuri (6.25)	Kyongseodong (7.25)
Soil moisture content (%)	$7.59^{a} \pm 1.08$	$17.87^{b} \pm 0.90$	$13.03^{b} \pm 0.55$	$8.59^{a} \pm 2.30$	$4.63^{a} \pm 0.32$
Bulk density (g/cm^3)	$1.04^{a} \pm 0.09$	$1.30^{b} \pm 0.02$	$1.48^{b} \pm 0.01$	$0.90^{a} \pm 0.06$	$1.21^{a} \pm 0.01$
Sand[a] (%)	64.2	72.6	83.9	80.0	70.4
Silt[a] (%)	18.7	12.8	6.4	10.1	14.5
Clay[a] (%)	17.1	14.6	9.7	9.9	15.1
pH	$7.83^{a} \pm 0.14$	$5.67^{a} \pm 0.75$	$6.14^{a} \pm 0.66$	$7.91^{a} \pm 0.04$	$7.83^{a} \pm 0.14$
Conductivity (μS/cm)	$167.5^{a} \pm 15.1$	$65.3^{a} \pm 7.4$	$89.0^{a} \pm 7.5$	$147.3^{a} \pm 20.3$	$435.9^{a} \pm 134.7$
Organic matter content (%)	$2.49^{a} \pm 0.22$	$0.75^{a,b} \pm 0.27$	$3.25^{a} \pm 0.30$	$0.45^{b} \pm 0.08$	$0.58^{b} \pm 0.09$
Total N (%)	$0.117^{a} \pm 0.023$	$0.054^{a} \pm 0.009$	$0.118^{a} \pm 0.019$	$0.059^{a} \pm 0.014$	$0.143^{a} \pm 0.015$
Available P (mg/kg)	$19.64^{a} \pm 3.17$	$8.13^{b} \pm 1.72$	$7.85^{c} \pm 1.07$	$8.00^{c} \pm 2.13$	$7.57^{d} \pm 0.56$
Ca (mg/kg)	$2351.2^{a} \pm 561.0$	$380.7^{b} \pm 64.7$	$1537.2^{c} \pm 117.2$	$1955.3^{d} \pm 231.8$	$1711.8^{e} \pm 112.3$
K (mg/kg)	$177.2^{a} \pm 26.9$	$152.6^{b} \pm 25.1$	$123.0^{c} \pm 10.0$	$111.0^{d} \pm 23.7$	$138.9^{e} \pm 12.3$
Mg (mg/kg)	$52.5^{a} \pm 5.6$	$85.6^{b} \pm 7.4$	$123.9^{c} \pm 8.4$	$59.7^{d} \pm 9.7$	$194.3^{e} \pm 13.8$
Na (mg/kg)	$15.11^{a} \pm 3.79$	$9.99^{b} \pm 3.77$	$6.05^{c} \pm 0.52$	$6.31^{d} \pm 0.53$	$33.43^{e} \pm 4.84$
Cd (mg/kg)	$0.158^{a} \pm 0.041$	$0.004^{b} \pm 0.003$	$0.073^{b} \pm 0.006$	$2.219^{c} \pm 0.532$	$0.177^{a} \pm 0.013$
Cr (mg/kg)	$0.535^{a} \pm 0.232$	$0.027^{b} \pm 0.006$	$0.157^{c} \pm 0.015$	$0.118^{c} \pm 0.018$	$0.225^{d} \pm 0.031$
Cu (mg/kg)	$6.62^{a} \pm 2.72$	$3.57^{b} \pm 1.33$	$3.10^{c} \pm 0.43$	$6.32^{a} \pm 1.75$	$5.99^{d} \pm 0.59$
Fe (mg/kg)	$115.6^{a} \pm 35.0$	$27.7^{b} \pm 9.2$	$170.9^{c} \pm 16.9$	$60.3^{d} \pm 14.3$	$126.7^{e} \pm 14.5$
Mn (mg/kg)	$57.0^{a} \pm 9.0$	$34.2^{b} \pm 2.5$	$97.7^{c} \pm 6.3$	$152.5^{d} \pm 19.8$	$178.3^{e} \pm 17.5$
Ni (mg/kg)	$0.452^{a} \pm 0.085$	$0.095^{b} \pm 0.029$	$1.060^{c} \pm 0.137$	$0.170^{b} \pm 0.053$	$0.754^{d} \pm 0.096$
Pb (mg/kg)	$7.36^{a} \pm 2.24$	$9.34^{b} \pm 4.84$	$2.54^{c} \pm 0.15$	$53.41^{d} \pm 15.93$	$7.42^{a} \pm 0.91$
Zn (mg/kg)	$25.3^{a} \pm 11.2$	$23.3^{b} \pm 17.4$	$3.7^{c} \pm 0.4$	$57.1^{d} \pm 11.2$	$149.6^{e} \pm 39.3$

Different superscripts within rows indicate values that are significantly different among the landfills (P < 0.05; GT2 Method).
[a] It was measured one times after soil samples at the same site pooled.

vegetation disturbances such ploughing or burning (Roberts, 1981). Many geomorphic disturbances, such as soil subsistence and erosion generated from gaps caused by waste decomposition in landfills, could provide opportunities for germination. Soil seed banks thus provide potential for vegetative changes in disturbed regions of waste landfills, and they could determine successional patterns. We speculated that seed banks of landfills contained long-term persistent species that remained in the soil for at least 5 years. In particular, *Digitaria ciliaris* and *Chenopodium album* were dominant species in the Sangpaedong landfill, representing long-term persistent species (Table 4) that will determine the vegetation of the post-disturbance stages. The seed bank vegetation of the Sangpaedong landfill contributed to aboveground vegetation and was composed almost exclusively of annuals except for three species, *Oenothera biennis, Erigeron annuus*, and *Artemisia princeps* var. *orientalis*. Annuals such as *Commelina communis* and *Persicaria blumei* were presumed to facilitate the initial development of flora in the landfills, in a manner similar to that observed by Jang (1999), who examined burned forested areas. Soil seed banks speed up secondary succession on abandoned bare soils such as old fields and some ruderal urban sites (Prach and Pyšek, 2001). The mean seedling density of the Sangpaedong landfill, which was less than 1 year old, was higher than that found in 6- and 7-year-old landfills. This shows the importance of seed banks in cover soils for early vegetative colonization in landfills.

Although perennial grasses invade waste landfills after closure, as shown in this study, the introduction of post-successional species, including trees, is recommended to accelerate succession in landfills. Modifications of the initial vegetative cover must be performed to restore woody species (Long et al., 2002). Artificial changes to the soil seed bank to increase the contribution to aboveground vegetation are also recommended as a restoration method. In the landfills surveyed in this study, grass cover was higher than tree cover. Colonization by tree species was possibly hindered by grass tussocks, which competed for light and nutrients. Therefore, gaps are necessary between grassy areas to provide habitat for trees in order to facilitate succession. Therefore, artificial disturbances to create such gaps are necessary for accelerating succession in landfills.

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