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Improving the remediation capacity of a landfill leachate channel by selecting suitable macrophytes

Uhram Song[a], Bruce Waldman[b], Jeong Soo Park[c], Kyoo Lee[c], Soo-Je Park[a], Eun Ju Lee[b,*]

[a] Department of Biology, Jeju National University, Jeju 690-756, Republic of Korea
[b] School of Biological Sciences, Seoul National University, Seoul 151-747, Republic of Korea
[c] National Institute of Ecology, Seocheon 325-813, Republic of Korea

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ABSTRACT

To assess the remediation capacity of a leachate channel, we monitored basic environmental parameters such as bathymetry, leachate, and soil characteristics and vegetation coverage. Based on our results, we designed a series of experiments to determine the most suitable remediating plant species for sustainable wastewater treatment. We found that adaptability to water depth may be a prime driver of reduced remediation capacity. Large portions of the leachate channel were deeper than the maximum tolerance range of many candidate emergent macrophytes, resulting in only 16% total vegetation coverage. Among tested species, *Typha angustifolia* showed the most promising potential for remediation, reaching the highest aboveground biomass (3300 g/m^2) and demonstrating maximum concentrations in tissues (34,600 mg/kg of Na, 4013 mg/kg of Mg, 904 mg/kg of P, 639 mg/kg of Mn, 191 mg/kg of Fe and 62 mg/kg of Zn) when grown in leachate filled tank for six months. *Typha angustifolia* also showed greater tolerance of water depth than *Phragmites australis*, which previously was planted in leachate channels. Thus, *T. angustifolia* should be more suitable for the actual water depth of the channel. Additional planting of *T. angustifolia* will improve the vegetation coverage, the total remediation capacity and sustainability of the leachate channel. Considering water depths of target wetlands when selecting remediation plant will improve remediation ability and sustainability of remediation wetlands.

1. Introduction

Sanitary landfilling is one of the most common strategies to manage solid waste (Song and Lee, 2010). But landfills can present environmental problems, especially the containment of leachate, which forms as organic waste decomposes (Jones et al., 2006). With rainfall, leachate percolates through waste, and eventually migrates into the surrounding environment (Foo and Hameed 2009), potentially contaminating the underlying substratum (Lee and Jones-Lee, 1994). Leachate contains hazardous heavy metals and other potentially toxic materials (Jokela et al., 2002). Effective leachate processing thus is a key component of any landfill management strategy. The most widely used and effective leachate purification processes are physicochemical treatments (Deng, 2007) combined with biological treatment by microorganisms (Kargi and Pamukoglu, 2003).

The Sudokwon landfill, in Incheon, South, Korea, is one of the largest leachate processing facilities in the world. Leachate is processed by anaerobic digestion, denitrification/nitrification, coagulation, chemical consolidation, precipitation and discharge (Sudokwon Landfill Site Management Corporation, 2013). During the biological processing, denitrification, odor emission, and release temperature are controlled. The chemical processing entails oxidation and coagulation of waste. However, as in other such facilities, the physicochemical and biological treatment processes used are ineffective at removing heavy metals (Sudokwon Landfill Site Management Corporation, 2013).

Heavy metal and other pollutants can be removed from leachates using absorbents but the methodology is technically challenging and consequently expensive. Thus, other lower cost technologies have attracted interest (Mohan and Gandhimathi, 2009). Constructed wetlands that use plants for purification (i.e., phytoremediation) have emerged as a promising alternative because of their demonstrated capabilities to remove pollutants, their cost effectiveness, and environmental friendliness (Rahman et al., 2016)).

Phytoremediation systems utilize the potential of soil–plant system to degrade and inactivate potentially toxic elements in the leachate (Jones et al., 2006). The Sudokwon Landfill has a leachate channel and connected constructed wetlands for leachate treatment and phytoaccumulation. Reeds (*Phragmites australis*) are planted in the channel and methods for the enhancement of uptake have been developed (Song, 2010). However, phytoremediation only is effective if

* Corresponding author.
E-mail address: ejlee@snu.ac.kr (E.J. Lee).

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contaminants are drawn toward plant biomass, the extent to which may depend on water depth, availability of nutrients, as well as various physical, chemical, and atmospheric factors (Cunningham and Ow, 1996).

Processes of phytoremediation and phytoaccumulation of landfill leachate are still poorly understood (Kim and Owens, 2010), with studies so far focusing on the establishment of vegetation and remediation capacities. Some researches shows very effective remediation (Guittonny-Philippe et al., 2015) that can be applied for actual leachate or waste water purification. However, as the effectiveness of phytoremediation depends on how plants uptake contaminants in the leachate channel, more ecological research on how candidate plants adapt to varied environments is needed. Problems such as low vegetation cover can develop over time, as is apparent in the leachate channel of the Sudokwon Landfill. We investigated the ecological status and operating condition of this leachate channel by monitoring its topography, leachate condition, soil condition and vegetation coverage. Then we conducted leachate tank experiments to evaluate the phytoremediation capacities of candidate plant species.

2. Materials and methods

2.1. Study site

The Sudokwon Landfill, located in Incheon, Korea (37° 34′ 52″ N, 126° 37′ 29″ E) is one of the largest sanitary landfills in the world, with gross area of approximately 20,000,000 m^2. The landfill produces 6700 tons of leachate per day (Sudokwon Landfill Site Management Corporation, 2013), making it one of the largest leachate processing facilities in the world. The landfill has more than 5 km of leachate channel feeding into buffering wetlands to minimize the impact of the leachate on the sea after emission (Song, 2010). The elevation of the channel at the leachate release point was 6 m above sea level and the elevation of the channel at the end (buffering wetland) was 3 m. The velocity of the channel when measured at 30 cm below surface was under detection limit of the propeller type velocity meter (Kenek, Japan). The average annual temperature and precipitation in this area during the research years (2006–2009) were 12.8 °C and 1234 mm (Korean Meteorological Administration, 2010).

2.2. Experimental design

2.2.1. Leachate channel monitoring

In July of 2006, the 5 km long leachate channel was divided into four areas by vegetation coverage and natural (geographical) features (Fig. S1 in Supplementary materials). Site 1 (from the beginning to 900 m of the channel) had the highest vegetation coverage. Site 2 (from 950 to 1700 m of the channel) was separated from site 1 by a bridge, and had less vegetation coverage. Site 3 (from 1700 to 3000 m of the channel) began where the water depth rapidly deepened at 1700 m point. Site 4 (from 3000 m to the end of the channel) was largely devoid of vegetation.

We set up 12 × 12 m quadrats, with 11 replicates in each site, to examine standing vegetation and vegetation coverage. The quadrat size matched the width of the leachate channel (~12 m). We measured how water depth increased with distance (1, 2, 3 and 4 m) from the channel bank to make Sectional schematic view of the channel. In addition, we measured the maximum water depth at which a major plant species, *Phragmites australis*, could be found in the leachate channel and buffering wetlands. Soil were sampled at the bottom of the leachate channel, excluding litters (debris) on the bottom.

Organic matter (OM), pH, total nitrogen (TN), Na, Fe and Mn contents of soil were recorded, together with the temperature, electro conductivity (EC), pH, Na, Fe, Zn, Mn, Mg, TP, TN and chloride contents of leachate in the channel.

2.2.2. Leachate tank experiment

To test remediation ability and water depth tolerance, on May 14th, 2006, rhizomes (subterranean stem that sends out roots and shoots from its nodes) of several species of macrophytes were collected and planted in pots (36 cm diameter, 40 cm height) that we placed into a water tank (2x5 m) in the landfill. *Phragmites australis* Trin. (referred to as *Phragmites* below), *Typha angustifolia* Bory et Chaub (as *Typha* below), *Phacelurus latifolius* (Steud.) Ohwi (as *Phacelurus* below), *Scirpus tabernaemontani* Gmel. (as *Scirpus* below) and *Zizania latifolia* Turcz. (as *Zizania* below) were selected as test plants. These species were selected because most are common Korean macrophytes and most species were able to collect rhizomes from wetlands within 10 km from the landfill (surveyed in 2005, except *Phacelurus*). *Phacelurus latifolius* is a rather rare species that has not been previously studied for but may be effective for remediation, and rhizomes of this species were collected from wetland in Ansan, Gyeonggi province, where was about 70 km from the landfill.

Before planting, we analyzed the biomass of rhizomes in fields (except for *Phacelurus latifolius*) as a basis for comparison for subsequent measurements. *Typha* had an average of 4500 g (fresh weight) of rhizomes per m^2, and the other species had about 3000 g of rhizomes per m^2. However, considering the effects of stress to rhizomes caused by transplantation, we planted *Typha* at 6000 g per m^2 and other species at 4000 g per $m^{2.}$ Based on the pot surface area, 600 g of rhizomes per pot ware planted for *Typha* and 400 g for the other species (10 replications). Rhizomes were planted 1–2 cm deep in sand within the pots, and the water level of the tank was maintained at −10 cm depth from the surface of the soil (sand) for 2 weeks to allow the rhizomes to adapt. After 2 weeks, the piped water in the tank was drained and leachate, taken just before emission into the leachate channel, was added to 10 cm depth for the first month to facilitate shoot growth and to 30 cm afterward. Leachate in the tank was drained and replaced with fresh leachate every month. The leachate tank was covered with a transparent roof to prevent dilution by precipitation. Plant height, biomass, nutrient contents and possible pollutants including some heavy metal contents were measured after six months.

After the first year of study, *Typha* and *Phragmites* were selected for detailed analyses of effects of water depth. Rhizomes of *Typha* and *Phragmites* were collected in wetlands of the Sudokwon Landfill in early April. Four hundred g of rhizomes were planted in each pot and were placed into tanks filled with leachate immediately after planting. The water level was maintained at 10 cm for 3 weeks to give plants time to emerge and stabilize. Then, one tank was kept at a depth of 10 cm and the other one increased to 40 cm (30 replicates each). Plants were harvested later in October.

2.3. Soil, leachate and plant analyses

2.3.1. Soil characteristics

The soil was dried at 105 °C for 48 h to measure its water content. Its organic matter content was determined by loss on ignition (combustion at 550 °C for 4 h). The pH and electrical conductivity of the soil and compost were determined by using a suspension of the soil sample in water (20 g/30 ml) with conductivity meter (model 33, YSI, OH, USA) and pH meter (model 60, YSI, OH, USA). The soil respiration rate was measured with an infrared gas analyzer (EGM-4, PP-Systems, Hitchin, UK).

2.3.2. Heavy metals and other elements

For plant analysis, we harvested a whole shoot (both stem and leaves) and then grounded with a blender. Then few grams of samples were milled again to get fine powder. One gram of dried and milled soil or plants was pretreated with 60% HNO_3 for 24 h and heated to 80 °C for 2 h. Then, 10 ml of 70% perchloric acid was added and the solution was heated to 200 °C until it became clear. The samples then were filtered with Whatman 44 filter paper and their element contents were analyzed by using an inductively coupled plasma atomic emission (ICP) spectrometer (ICPS-1000IV, Shimadzu, Kyoto, Japan).

2.3.3. C and N analyses

Samples were analyzed with an elemental analyzer (Flash EA 1112; Thermo Electron, San Jose, CA, USA) for C and N. NH_4^+–N and NO_3–N analyses were performed using a Kjeldahl protein/nitrogen analyzer (Kjeltec Auto 1035 System, Tecator, Denmark).

2.3.4. Leachate analysis

The temperature of solution (leachate) was measured using a portable electrical conductivity (EC) meter (YSI 30/10 FT, YSI, Yellow Springs, OH, USA) at around 2 p.m. EC of leachate was measured using the same portable EC meter. The pH of leachate was measured using a portable pH meter (YSI 60/10 FT, YSI, Yellow Springs, Ohio, USA). Chloride (Cl) was measured using silver nitrate (Sanderson, 1952). The leachate samples were filtered with Whatman 44 filter paper and TP and TN contents analyzed by using an ICP emission spectrometer (ICPS-1000IV, Shimadzu, Japan).

2.4. Statistical analyses

One-way analysis of variance was performed to identify significant differences among treatments and when a significant difference was detected, a post hoc Duncan's Multiple Range Test was assessed using the ANOVA procedure in SAS 9.1 (SAS Institute, Cary, NC, USA). Differences were considered significant when $p < 0.05$.

3. Results and discussion

3.1. Leachate channel monitoring

Though the leachate channel was constructed and *Phragmites australis* were planted for remediation purpose 14 years ago before monitoring, even the highest vegetation coverage area (site 1) showed less than 50% coverage. The average vegetation coverage throughout the channel, considering the proportions occupied by each site, was 16.2% (see Table 1). Sites with the highest vegetation coverage had significantly more soil organic matter with higher nitrogen contents (Table 2). Site 1, which included the leachate emission point, had higher EC and Na contents. However, except for manganese (Mn) contents in the soil, which were higher than USEPA-prescribed ecological soil screening level (220 mg/kg of Mn for plants) (United States Environmental Protection Agency, 2010), values were not excessive. For example, sodium (Na) contents were less than 60% of those found in sea-reclaimed wetland areas (Ihm et al., 1998). However, as there was no management activities for remediation plants maintenance, the channel seems to have lost vegetation in many parts indicating degraded remediation ability.

Near the discharge point into the channel, the leachate (about 40 °C) raised the ambient water temperature (Fig. 1). Even in November, the water temperature remained around 20 °C. As July is in the rainy season, temperature, pH and EC decreased, resulting from dilution by precipitation. The chloride (Cl) content became very low at 3500 m, indicating that the channel served as a buffer zone. However, as the channel is very low velocity that was below detection value of velocity meter, the reason that end zone of the channel has low values could be just because they are far from releasing point with less diffused leachate, not because of remediation activity of the channel. However, the Cl concentration of all areas were lower than those reported in other studies of landfill leachate (Chiang et al., 1995; Lyngkilde and Christensen, 1992), though no Cl purifying process is performed in the Sudokwon Landfill (Sudokwon Landfill Site Management Corporation, 2013). Temperature, EC, pH and Cl values fell within usual ranges that should not limit plant growth.

Table 1
Vegetation coverage (%) of the leachate channel.

Plant species	Site 1	Site 2	Site 3	Site 4
Phragmites	42.3 ± 9.1	18.6 ± 4.1	3.2 ± 1.2	NF
Typha	2.9 ± 1.0	3.2 ± 1.0	0.9 ± 0.6	NF
Scirpus	0.1 ± 0.1	NF	NF	NF

The data are presented as the mean ± SE of eleven replicates.
※NF: Not Found.
※ Site 1: From beginning to 900 m of the channel; Site 2: From 950 m to 1700 m of the channel; Site 3: From 1700 to 3000 m of the channel; Site 4: From 3000 m to the end of the channel.

As neither soil nor leachate conditions seemed to be limiting the survival of the plant species in the channel, the low vegetation coverage in sites 2, 3 and 4 is difficult to explain but corresponds to topographical features of the channel. The depth of the leachate channel rapidly deepens (Fig. S2 in Supplementary materials) so that, except in the first 500 m of the channel, water depth exceeds 70 cm within 2 m of the channel's edge. However, as the maximum water depth of the most abundantly planted *Phragmites* species was only 58 cm (Table S1 in Supplementary materials), most of the areas in the channel were not suitable for *Phragmites*. Forty cm is the normal maximal water depth for *Phragmites* (Vretare et al., 2001) although *Phragmites* can live at deeper water depths (Coops et al., 1994). However, leachate constitutes a harsh environment, which together with greater depth, may seriously impair plant survival. Overall, most areas of the leachate channel were deeper than the tolerance depth for *Phragmites* (underlined areas in Table S2 in Supplementary materials). Owing to this condition, the vegetation coverage of the leachate channel, dominated by reeds, was very low. Such low vegetation coverage should seriously compromise the remediation capacity of the leachate channel and also low biodiversity (single dominant plant species) could make the channel ecosystem more vulnerable to disturbance. Clearly, management to increase the vegetation coverage and biomass would be desirable to improve the remediation function of the wetlands.

3.2. Leachate tank experiment

For leachate analysis, P (phosphorus), Mg (manganese) and N (nitrogen) were analyzed for nutrient contents. Zn (zinc), Na (sodium) and Fe (iron), were examined as they are known to be major elements of leachate (Song, 2010). Mn (manganese) had been omitted from previous studies of Sudokwon Landfill, but is known to be an important component of leachate in other landfills, so was analyzed as well. Most of the monthly values were similar, except that Na and Mn differed substantially among months (Table S3 in Supplementary materials), perhaps due to variation in precipitation and temperature (Lee et al., 2000).

We did not expect to find high metal content in the leachate, as the landfill is well managed to minimize environmental contamination. However, the leachate was characterized by high Na content, comparable to the highest measures reported by the United States Environmental Protection Agency (2004). Elevated Na measures may be attributable to food waste (Lee et al., 2000). Fe, Zn and Mn contents of the leachate, however, were much lower than average measures reported by the USEPA (Fe: average 34 mg/L; Zn: average 12 mg/L and 13 mg/L for Mn) of USEPA. TN, TP and EC values were unremarkable, falling within accepted USEPA limits (0–3320 mg/L, TP between 0 and 234 mg/L and pH between 3.7 and 8.9) (USEPA, 2001).

Zizania did not survive leachate treatment (Fig. 2). *Typha* and *Scirpus* grew taller and attained more biomass than the other species. Even so, total biomass did not reach 400 g per pot, the original rhizome mass. As the area of a pot is about 0.1 m^2, the expected biomass of plants per square meter are 3300 g for *Typha*, 3000 g for *Scirpus*, 990 g for *Phragmites* and 960 g for *Phacelurus*. Furthermore, plants grew on average to less than 120 cm for each species, less than their growth in

Table 2
Soil characteristics of the leachate channel.

	OM (%)	TN (%)	EC (dS/m)	pH	Na (mg/kg)	Fe (mg/kg)	Mn (mg/kg)
Site 1	7.3 ± 0.2[a]	0.22 ± 0.00[a]	3.49 ± 0.01[a]	7.8 ± 0.1	2089.4 ± 25.9[a]	1052.1 ± 41.2[ab]	340.5 ± 3.0[b]
Site 2	4.8 ± 0.1[b]	0.14 ± 0.00[b]	2.38 ± 0.01[b]	7.4 ± 0.2	1335.4 ± 6.3[b]	936.1 ± 10.4[b]	355.4 ± 4.2[b]
Site 3	2.9 ± 0.1[c]	0.14 ± 0.00[b]	3.23 ± 0.05[a]	7.8 ± 0.1	1273.8 ± 12.4[b]	1323.2 ± 11.2[a]	297.2 ± 2.6[c]
Site 4	2.8 ± 0.1[c]	0.14 ± 0.00[b]	3.47 ± 0.03[a]	7.7 ± 0.2	1984.8 ± 12.4[a]	1252.3 ± 138.8[a]	412.1 ± 13.9[a]

The data are presented as the mean ± SE of three replicates.
The means within a column followed by the same letter are not significantly different at $p < 0.05$.
※ Soil samples were collected at points where water depth was 30 cm.
※ OM, TN and pH were measured in 2006. Other items were measured in 2007.
※ OM: Organic matter, TN: Total nitrogen, EC: Electrical Conductivity.

natural conditions. For comparison, when originally harvested, *Phragmites was* 235 ± 23 cm, *Typha* 199 ± 18 cm, *Scirpus* 156 ± 17 cm, and *Phacelurus* 187 ± 21 cm (mean ± SE, n = 20, investigated in 2006).

As collecting and re-planting rhizomes damages root structure (Twilley et al., 1977), some reduction in plant growth after rhizome transplantation would be expected. Survival of shoots varied considerably, some having few surviving shoots or small biomass. Excluding pots with less than 200 g of biomass (5 pots), the mean biomass of *Typha* was 430 g. *Phragmites* in the leachate channel grew to 186 ± 17 cm and *Typha* to 184 ± 23 cm. This suggests that plants in the leachate channel were under more stress than those in natural wetlands.

Typha species showed significantly higher accumulation values than other species that have been studied (Table 3). The remediation capacities of *Phragmites* and *Scirpus* appeared similar, both greater than *Phacelurus* (Table 3). However, comparisons among studies are difficult to make because the composition of leachate can vary widely. In addition, the efficacy of aquatic macrophytes for leachate phytoremediation has not been well studied.

The concentrations of metals that we found in our study are similar to or higher than those found in comparable studies (Bernard and Lauve, 1995; Peverly et al., 1995). The heavy metal concentration of the Sudokwon Landill leachate was much lower than that found in other studies, with Fe, Zn and Mn contents less than 10% of previous findings and the Mn contents of the leachates similar to concentrations found before. However, accumulation by macrophytes in this study significantly exceeded that found in those same previous studies. Overall, the element concentration of plants in Table 3 is shows much more high values (*Typha* species for example, 15 times higher Na concentration, 30 times higher Mg concentration, 1500 times higher P concentration, 575 times higher Mn concentration, 5590 times higher Fe concentration and 62 times higher Zn concentration) compared to leachate concentration (Table S3 in Supplementary materials) of same

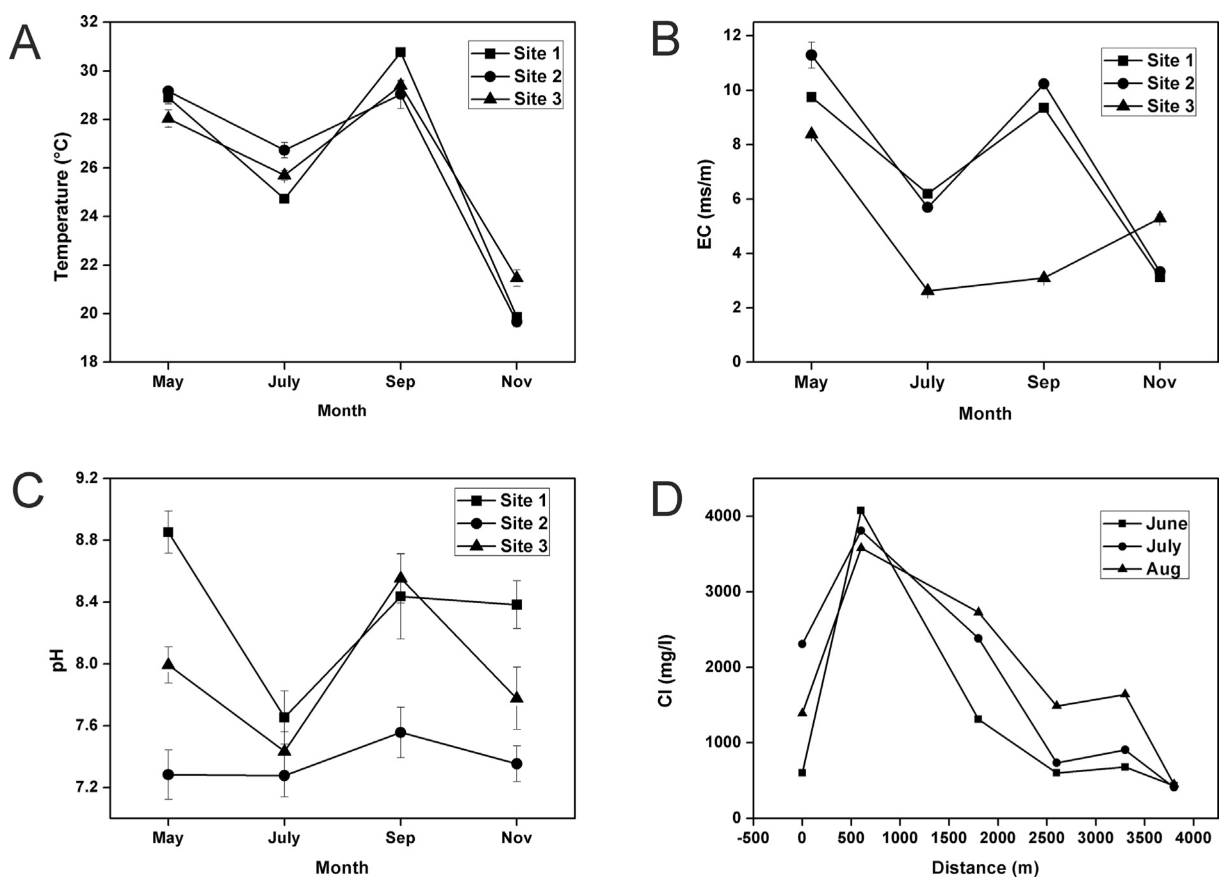

Fig. 1. Characteristics of leachate channel in 2007. A: Temperature; B: Electro-conductivity; C: pH; D: Chloride. The data are presented as the mean ± SE of three replicates.

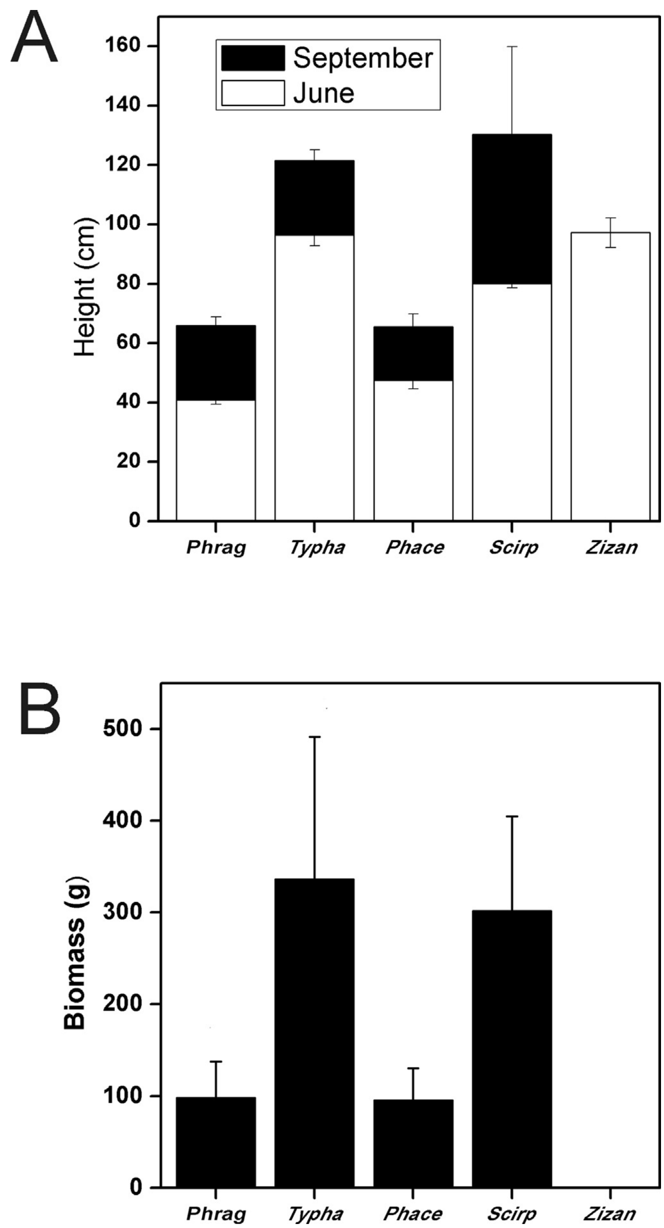

Fig. 2. Heights (A) and harvested biomasses (B) of selected macrophytes in the leachate tank. A): Every shoot was measured. The measured number of shoots in June (September) was 162 (241) for *Phrag*, 95 (148) for *Typha*, 45 (45) for *Phace*, 64 (63) for *Scirp* and 37 (0) for *Zizan*. B): Harvested biomasses are weights of harvested above ground biomass per pots. Symbols and bars represent mean ± SE of 10 replicates. ※ Phrag: *Phragmites australis*, Typha: *Typha angustifolia*, Phace: *Phacelurus latifolius*, Scrip: *Scirpus tabernaemontani* and Zizan: *Zizania latifolia*.

weight indicating uptake of plants. These results suggest that the macrophytes that we tested have excellent potential for phytoremediation.

As the Na content of the landfill leachate is high (Lee et al., 2000), the capacity of the macrophytes to accumulate Na should be useful for remediation. Previous studies of leachate remediation with *Populus* species (Zalesny et al., 2006), albeit not in a wetland system, showed less than 10% of the concentration of Na that we found in *Typha* species. Also, other studies of sewage-treating wetlands (Vymazal and Šveha, 2012) showed less than 5% of the Na concentration that we found in *Phragmites* leaves. Since the macrophytes accumulated P at high concentrations (Table 3), they would be useful for reducing side effects of P loading such as eutrophication. Plants also isolated nitrogen (Table S4 in Supplementary materials) which landfill leachate usually contains in abundance (Zalesny et al., 2006). C contents, however, did not differ substantially among the species.

Our results suggest that macrophytes in the leachate channel effectively decrease nutrient loading and reduce concentrations of potentially hazardous metals that would be released into the sea. Overall, *Typha*, *Phragmites* and *Scirpus* species showed excellent remediation capacities but, except for *Typha*, the other species were not notable in their performance. Considering that *Phragmites* and *Typha* are the most abundant species in Korea (Kim and Lee, 2003), we further studied these two species for that adaptability to water depths. *Phragmites* is already planted in the leachate channel but *Typha* showed highest potential remediation capacity.

We conducted a preliminary test in 2006, planting rhizomes in 60 cm water depth with piped water and found emergence of shoots above the water surface for *Typha* but no other species. Therefore, we subsequently decreased the maximum water depth to 40 cm. In these conditions, 67 *Typha* shoots had emerged two months after rhizome planting. Additional shoots emerged between June and September and were included in our analyses (Table 4). *Phragmites* grew significantly higher in 40 cm than in 10 cm water depth, but with reduced stem diameters. The stems of *Phragmites* in deep water need to extend above the water surface, so plants grow taller but with thinner stems in these conditions. Similar tradeoffs can be seen in our results (Table 4) between height and other parameters such as shoot number and rhizome biomass (Vretare et al., 2001). By contrast, *Typha* had similar shoot numbers and aboveground biomass (Table 4), indicating tolerance of deeper depth. The biomass of rhizomes significantly decreased in 40 cm depth for both species, but *Typha* showed better adaptation to deeper water.

Phragmites grown in 40 cm water depth showed lower N content (Table S5 in the Supplementary materials), indicating less capacity for N remediation and a higher C/N ratio. These characteristics decrease the suitability of the plant for composting (Zhu, 2007). Overall, height, biomass and nutrient content results demonstrate that *Typha* is better adapted to deeper water than *Phragmites*. *Typha* demonstrated significantly greater remediation capacity than *Phragmites* at every water depth (Table 5). Except for Zn contents in 10 cm water depth, every pollutant that we analyzed was present in higher concentration in *Typha*. Moreover, both *Typha* and *Phragmites* demonstrated higher concentrations of these toxins than were found in previous studies (Bernard and Lauve, 1995; Peverly et al., 1995).

In 2007, Na and Mg were accumulated at less than half the rate as in 2006 while the Fe accumulation rate more than doubled (Tables 3, 5).

Table 3
Chemical contents of tested macrophytes in tanks (mg/kg).

Items	Na	Mg	P	Mn	Fe	Zn
Phrag	14861.4 ± 297.7[b]	1660.4 ± 88.2[b]	873.4 ± 90.3[a]	345.9 ± 127.9[b]	154.1 ± 20.2	85.0 ± 3.2[a]
Typha	34603.0 ± 2223.5[a]	4013.6 ± 398.6[a]	904.1 ± 131.6[a]	639.0 ± 92.3[a]	190.9 ± 33.9	61.8 ± 9.3[b]
Scirpus	14514.7 ± 2549.5[b]	1762.7 ± 109.2[b]	950.6 ± 132.3[a]	624.9 ± 122.2[a]	126.2 ± 23.2	59.7 ± 4.3[b]
Phacelurus	7064.8 ± 3025.5[c]	917.8 ± 4.2[c]	473.0 ± 27.0[b]	110.8 ± 4.9[c]	150.1 ± 1.8	39.9 ± 4.1[c]

The data presented are means of five replicates (mean ± SE).
Means within a column followed by the same letter are not significantly different at the 0.05 level.

Table 4
Height (cm), number of shoots and biomass of plants by species and leachate depth.

Water depth and species	Height (June)	Height (Oct.)	Total N of shoots	N of shoots per pot	Above ground biomass (g)	Underground biomass (g)
10-*Phrag*	33.1 ± 1.2[d]	95.4 ± 20.1	189	6.3 ± 0.2[a]	151.0 ± 5.0[b]	350.5 ± 10.3[b]
40-*Phrag*	46.8 ± 1.1[c]	64.2 ± 24.3	103	3.4 ± 0.1[b]	80.8 ± 4.9[c]	246.5 ± 9.1[c]
10-*Typha*	54.1 ± 1.6[b]	114.1 ± 29.4	105	3.5 ± 0.2[b]	257.7 ± 14.8[a]	499.5 ± 26.1[a]
40-*Typha*	66.6 ± 1.8[a]	104.7 ± 18.6	102	3.4 ± 0.1[b]	232.0 ± 12.0[a]	394.5 ± 16.4[ab]

The data presented are mean ± SE of sixty-seven replicates for height (June), one hundred replicates for height (Oct.), thirty replicates for N of shoots per pot and above ground biomass and ten replicates for underground biomass.
Means within a column followed by the same letter are not significantly different at the 0.05 level.
N: Number.
※The numbers before dashes indicate water depth.
※ Total number and biomass of plants were measured in October.
※ *Phrag*: *Phragmites australis* and *Typha*: *Typha angustifolia*.
※ Oct.: October.

These data suggest selective uptake of elements by *Typha* and *Phragmites* depending on environmental conditions (Dykyjová, 1979). Overall, *Typha* were better at accumulating contaminants than *Phragmites* at every water depth. *Typha* grew taller and to larger total mass, and demonstrated higher accumulation rates in deep water than *Phragmites*. Considering the water depth of the leachate channel (Table S2 and Fig. S2 in Supplementary materials), *Typha* species, which have more tolerance of water depth, would be a better choice for the leachate channel.

Most other non-remediation wetlands in the landfill consist of a mixture of *Phragmites* and *Typha* species, segregated by depth with *Phragmites* occupying shallow zones and *Typha* deeper zones (Song, 2010). Additional planting of *Typha* species in the channel should increase the vegetation coverage, remediation capacity, biodiversity and landscape of the leachate channel. The present remediation channel was planted only with *Phragmites* species), but our results suggest that when planning new landfills, *Typha* species should be preferentially planted to promote better functioning of the leachate channel.

Until now, *Phragmites* species have been preferred as remediation plants (Choi, 2005), but our results demonstrate that *Typha* species have superior depth tolerance, accumulation ability capacity and biomass. Additional planting of *Typha angustifolia* should increase the vegetation coverage, biodiversity and eventually the total remediation ability capacity of the leachate channel. To make the environment more favorable for remediation plants, modifications to channel design to decrease overall water depth also should be considered. Also species witch prefers water depth of target wetlands should be considered for planting.

4. Conclusions

The low vegetation coverage of the Sudokwon Landfill leachate channel clearly indicates its degraded remediation capacity. Furthermore, plants remaining after remediation re-release accumulated pollutants and nutrients into the channel. To solve the low vegetation coverage problem, the water depth of the channel should be reduced. Also, by planting macrophyte species with greater water depth tolerance, the channel will gain both increased vegetation coverage and increased sustainability. Among the species we tested, *Typha angustifolia* showed the best remediation capacity, resulting in high biomass (3300 g/m^2) and accumulation (34,600 mg/kg of Na, 4013 mg/kg of Mg, 904 mg/kg of P, 639 mg/kg of Mn, 191 mg/kg of Fe and 62 mg/kg of Zn). *Typha angustifolia* also was more tolerant of water depth (83 cm) than a previously selected remediation plant, *Phragmites australis* (54 cm). Thus, *T. angustifolia* should be preferentially used in the landfill.

These results implies that when planning a remediation wetland, environmental factors such as water depth should be considered as important factors for designing and remediation plants with suitable water depth tolerance should be selected, not only considering their remediation abilities. Usually these ecological factors are not applied for planning and management of remediation wetlands and related researches are difficult to find. However, our results suggest whether considering environmental factors such as water depth or not could determine success of remediation wetland. Also other factors such as soil texture, water velocity and water qualities would affect remediation success that further researches are required. With careful planning and proper management, the remediation function and sustainability of the landfill leachate channel can be improved.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.jher.2018.04.005.

Table 5
Chemical contents (mg/kg) of *Typha angustifolia* and *Phragmites australis* with different leachate depth tanks.

	Na	Mg	P	Mn	Fe	Zn
10-*Phrag*	5647.6 ± 612.9[c]	990.3 ± 129.6[b]	455.6 ± 90.9	339.7 ± 41.9[b]	432.7 ± 124.3	377.9 ± 49.5[a]
40-*Phrag*	6803.4 ± 399.4[c]	979.8 ± 178.1[b]	528.7 ± 82.0	639.9 ± 88.5[ab]	554.9 ± 289.5	86.8 ± 33.8[c]
10-*Typha*	15324.3 ± 1470.5[b]	2726.3 ± 141.5[a]	828.0 ± 254.6	1041.0 ± 107.5[a]	928.0 ± 386.4	249.8 ± 60.4[ab]
40-*Typha*	21970.4 ± 3102.0[a]	2464.4 ± 568.2[a]	819.0 ± 196.4	1044.0 ± 252.5[a]	1106.6 ± 368.9	117.6 ± 36.2[bc]

The data presented are means of five replicates (mean ± SE).
Means within a column followed by the same letter are not significantly different at the 0.05 level.
※The numbers before dashes indicate water depth.
※ *Phrag*: *Phragmites australis* and *Typha*: *Typha angustifolia*.

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Uhram Song is an assistant professor of Jeju National University of Korea, department of Biology. His work focuses on applied ecology including bioremediation, environmental toxicity and invasion control. Song earned his Ph.D in biology from Seoul National University, Korea.

Bruce Waldman is a professor of Seoul National University of Korea, department of Biological Science. His work focuses on conservation biology and balancing selection for MHC variation. Bruce earned his Ph.D from Cornell University, USA.

Jeong Soo Park is a researcher of National institute of Ecology of Korea, division of ecological assessment research. His work focuses on riparian ecosystem assessment. Park earned his Ph.D. from Seoul National University, Korea.

Kyoo Lee is a researcher of National Institute of Ecology (NIE). His work focuses on plant ecology.

Soo Jae Park is an assistant professor of Jeju National University of Korea, department of Biology. His work focuses on ecology including bioremediation, microbial community analysis and environmental management. Park earned his Ph.D in biology from Chungbuk National University, Korea.

Eun Ju Lee is a professor of Seoul National University of Korea, department of Biological Science. His work focuses on Plant ecology and environmental management. Lee earned his Ph.D from University of Manitoba, Canada.