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Research article

Mowing: A cause of invasion, but also a potential solution for management of the invasive, alien plant species *Erigeron annuus* (L.) Pers

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ABSTRACT

Erigeron annuus is one of the major invasive, alien plants in Korea, and therefore research to manage (control) this invasive plant is essential. In this research, studies were conducted to determine the mechanisms by which *E. annuus* became the dominant plant at a landfill site and to develop management strategies for this alien plant. Because the seeds and seedling stage did not have superior adaptations to disturbed soil, demonstrate allelopathy, outcompete other species, or show rapid growth, the disturbance from mowing was likely the primary reason for the dominance of *E. annuus*. The areas without mowing showed a significant decrease in the coverage of *E. annuus*, whereas the mowed (managed) areas showed a significant increase. Additionally, mowing once increased the weight of reproductive organs by 50% and suppressed the growth of native species. Thus, the primary factor in the invasion of the alien species *E. annuus* was mowing, and, to control such an invasion, areas should be protected from mowing. Additionally, with selective mowing that targeted only *E. annuus*, mowing three times produced only approximately 10% of the reproductive organ biomass compared with that of the control. Because the flower stalk of *E. annuus* was relatively tall compared with that of native species in early summer, selective mowing might also provide a solution to control invasions of *E. annuus*. Therefore, with improved ecological understanding of the site and species, mowing of the right target during the optimal season and at an appropriate frequency is an environmental friendly solution to the management of *E. annuus*.

1. Introduction

The threat of alien species invasions to native species and biodiversity has become a major focus of ecological research. Many human activities, including agriculture, recreation, and transportation, promote both the intentional and accidental spread of species across their natural dispersal barriers (Kolar and Lodge, 2001). Invasive alien plants reduce species richness, and loss of diversity is not only a primary concern in ecology (Knops et al., 1999) but also closely related to global environmental and economic concerns (Lodge, 1993), which makes research on alien plant invasion an important issue. Moreover, research on invasive alien plants is essential to understand the dynamics of ecological communities and to predict ecological and economic impacts in guiding restoration. Predicting the species that are most likely to be alien invaders is a long-standing goal of ecologists (Kolar and Lodge, 2001); however, recently, with the effects of invasions becoming more extensive, research on mitigation and management strategies has become a priority. Therefore, research is actively being conducted to identify the interactions that affect invasive alien plant dispersal and the general causes of dispersal (Esler and Milton, 2007; Harris et al., 2009). Additionally, to avoid damage caused by alien plant invasion, a lot of previous research focused on preventing introduction in the belief that "the best offense is a good defense" (Mehta et al., 2007). However, with invasions now inevitable through numerous pathways, the management of invasive species has assumed greater importance. Management of invasive plants begins with an optimal detection strategy (Mehta et al., 2007) followed by control methods. Management protocols based on education (Mehta et al., 2007), competition with native species (Hoffmann et al., 2002), and simple removal (Erskine Ogden and Rejmánek, 2005) have been studied as methods to control the invasions of alien species. The management of invasive plants was recently extended to modeling (Lee et al., 2009), using decision-making models or those for predictions of future distributions of vegetation. *Erigeron annuus* (L.) Pers. is originally from northern America, is

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frequently observed in cities, in enclosed fields, and along county roadsides (Lee, 1980), and is one of the major invasive plants in Korea (Lee and Kim, 1991). *Erigeron annuus* is a biannual plant and a successional winter annual (Regehr and Bazzaz, 1979). The anti-germination constituents (5-butyl-3-oxo-2,3-dihydrofuran-2-yl)-acetic acid, 3-hydroxy-pyran-4-one, and two cinnamic acid derivatives have been isolated from *E. annuus* (Oh et al., 2002), together with other phenolic constituents (Lee and Seo, 2006), showing the potential for allelopathy. *Erigeron annuus* is now one of the dominant plants at the research site, the Sudokwon Landfill in Korea, which is one of the oldest sites dominated by *E. annuus*, (Song, 2010). The indications are that *E. annuus* will continue to dominate future vegetation at the landfill. Therefore, research on methods to manage (control) this invasive plant is essential. Additionally, *E. annuus* naturalized rapidly to become one of the dominant plant species in Korea (Kang and Shim, 2002), and is now found nationwide (Lee et al., 1992) where it competes with native species. *E. annuus* is now one of the major weeds in crop fields (Kim et al., 2008), and it reduces biodiversity by dominating fields (Lim et al., 2009). However, how it became a successful invader is still unclear. *E. annuus* likely has a competitive edge, possibly because of the increased survival of its seeds, rapid seedling and rosette stages, and/or allelopathic activity. It is important to determine the reason for its successful invasion to prevent and control further invasion. Therefore, the objectives of this research were to determine the reasons for the dominance of *E. annuus* at the research site and to identify management and control strategies for this plant. First, vegetation at the research site was monitored to confirm whether the site was under invasion or had already been invaded by *E. annuus*. Then, a series of experiments designed to study competition with native species, allelopathy effects, photosynthesis, and resistance to management activities were implemented to find what could be the major reason of invasion. Then, the effects of mowing, which is suspected to be one of the main reasons for dominance, were verified by monitoring vegetation changes with and without mowing. Finally, using mowing as a controlling method, we identified environmental friendly and efficient management strategies.

2. Materials and methods

2.1. Site description

The Sudokwon Landfill in Incheon, South Korea, is one of the largest sanitary landfills in the world, with an approximate area of 20,000,000 m^2. The landfill has four sites for reclamation, and, now, the second reclamation site is accepting wastes (Sudokwon Landfill Site Management Corporation, 2013). Reclamation site 1, which was closed in 2001, has eight levels; each level accepted wastes and then was covered with soil, and a new level was formed for new reclamation. The geographic coordinates of the center point of the landfill are 37°34′52″ N, 126°37′29″ E. The average annual temperature and precipitation for this area during the years of research (2005–2009) were 12.5 °C and 1284 mm, respectively (Korean Meteorological Administration, 2010).

2.2. Vegetation monitoring and soil analysis

To determine whether *E. annuus* was invading the research site, quadrat sampling was used to monitor seasonal vegetation at the landfill. Detailed methods are described in Appendix 1 in Supplementary Materials. Vegetation at nine sites in the landfill was monitored to determine whether *E. annuus* was invading the landfill. Plants were identified based on ‘Illustrated Flora of Korea’ by Lee (1993). The importance of herbaceous vegetation was calculated according to Cottam and Curtis (1956). Methods for soil analysis are presented in Appendix 2 in Supplementary Materials.

2.3. Competition and allelopathy experiments

The survival rates and growth of seeds, seedlings and rossettes of *E. annuus* and the other dominant (*Glycine soja*) or artificially planted (*Aster koraiensis* and *Lotus corniculatus*) native species in the landfill were compared to uncover why *E. annuus* had a competitive edge over other species. Detailed methods are described in Appendix 3 in Supplementary Materials.

For the test of allelopathy, aqueous extracts from 200 g leaves and (or) roots of *Erigeron annuus* (L.) Pers, stirred with one liter of distilled water for 24 h, were used (Kil and Yun, 1992). The germination test was conducted in Petri dishes with filter paper wetted with the extracts (Patterson Iii and Olson, 1983). Twenty seeds were evenly dispersed in each dish. The Petri dishes were maintained in a growth chamber (HB-301L; Hanbaek Scientific Co., Korea) at 20 °C with 12 h of daylight. The germination rate was examined for 5 weeks (six replicates). Two native species, *Aster koraiensis* and *Lotus corniculatus* var. *japonicus*, were used in the germination test. To measure effects on seedling growth, ten seedlings of *Aster koraiensis* that germinated within two days were placed in Petri dishes (ten replicates), and 5 ml of extracts was added daily for a week. These dishes were maintained in the growth chamber under the same conditions as in the germination experiment. To prevent disturbance of shoot growth, the covers of the Petri dishes were not used; instead, extracts were used for the first week, and, after the first week, distilled water was added daily to prevent drying.

2.4. Effects of traditional management activities and photosynthetic rates

The landfill was under continuous management using traditional methods such as mowing, pulling out of weeds by hand, and planting native species. To determine whether these management practices were effective or could be effective in managing *E. annuus* invasion, 1 × 1 m quadrats were established in early March 2006, with approximately 10 cm buffer zone on each side. Eight treatments were employed: 1) control; 2) removal of above ground *E. annuus* using mowing); 3) removal of *E. annuus* and planting of *Aster koraiensis* Nakai (Re-Aster-P); 4) removal of *E. annuus* and planting of *Lotus corniculatus* var. *japonicus* Regel planted (Re-Lotus-P); 5) planting of *A. koraiensis* (Aster-P); 6) planting of *L. corniculatus* planted (Lotus-P); 7) spraying of *A. koraiensis* seeds (Aster-S); and 8) spraying of *L. corniculatus* seeds (Lotus-S). For ‘planted’ treatments, 20 individuals were planted in each quadrat. For ‘seed sprayed’ treatments, 30 ml of seeds was mixed with 100 ml of soil and then sprayed onto quadrats. Each treatment had five replicates. In May and September, the coverage of *E. annuus* and the other two species (*A. koraiensis* and *L. corniculatus*) in each quadrat was determined. Additionally, in March 2006 and 2007, the numbers of *E. annuus* in each quadrat were counted. In 2007, the photosynthetic rates of *E. annuus* and a native species, *Aster koraiensis* Nakai, continuously transplanted to landfill slopes, were determined to find out whether *E. annuus* had a high photosynthetic rate that would explain its invasion success. Detailed methods are described in Appendix 4.

2.5. Mowing experiments and reproductive organ weight differences after mowing

Ten quadrats (1 × 1 m) were established in level one, a level in which *E. annuus* was the most dominant species. By protecting 100 m^2 (5 × 20 m) in large quadrats (5 m is the width of the flattened area of level one), *E. annuus* in the ten quadrats was protected from mowing and was monitored from 2006 to spring 2009. Twenty other quadrats were established that were not protected from mowing. Two mowing treatments were examined, 1 and 2. Mowing 2 treatments were under the control of the landfill managers, and the area was mowed once in September 2006 and August 2007, twice in May and October 2008, and once in August 2009 by managers. The mowing 1 treatment was also not protected from the mowing activity of the landfill managers and was additionally mowed in late June 2007 and again in 2008 when *E. annuus* (L.) Pers. was blooming. Vegetation coverage was monitored each summer (in 2009, the vegetation was monitored before mowing activity).

In spring 2008, eight 1 × 2 m quadrats were established in the landfill. Two quadrats were used as controls, two quadrats were mowed on July 15, two quadrats were mowed on July 15 and 31, and the final two quadrats were mowed on July 15 and 31 and August 21. The timing of the mowing was based on when individuals in the treatments were blooming. The mowing activity was conducted approximately 40 cm above the ground. The mowing treatments, 0, 1, 2, and 3 times, were controlled by the mowing frequency. Five random individuals in each quadrat were harvested before release of the seeds. Control treatments were harvested on July 29, and the second and third pairs of quadrats were harvested in late August. The final quadrats were harvested in early September, 15 days after the second harvest.

2.6. Post-landscaping and management (mowing) and monitoring of invasion

Sites with the following properties were identified: (1) Recently reclaimed sites with properties similar to those of the landfill slope after closing; (2) Sites with and without management/mowing; and (3) Sites big enough to minimize edge effects and seed dispersal from nearby areas.

In spring 2011, a park was constructed in a deserted area of Gyeonggi Province, Korea. The geographic coordinates of the center point of the landfill are 37°38′36″ N, 126°45′03″ E. The park and the surrounding areas were newly reclaimed. Then, the surrounding area near the park was divided into two sites by a newly constructed road, and the new site near the park was managed with complete mowing and transplanting in the areas near the edge of the road. The size of the landscaped and managed area was approximately 100 × 100 m, and the size of the adjacent, undisturbed (unmanaged) area was approximately 200 × 100 m. The landscaped area was mowed once in 2011 between July and August, once in August 2012, and once during summer 2013 (the first author was abroad during the summer but found mowed plants in November, 2011). No mowing activity occurred in 2014. The undisturbed site was not mowed during the research period. In June 2015, the vegetation of edge areas of the two sites was monitored using 1 × 1 m quadrats (20 replicates each). The vegetation and soil characteristics were compared between the sites.

2.7. Statistical analyses

For simple comparisons, a one-way ANOVA was performed to identify the significant differences among treatments, and, when significant differences were detected, a post-hoc Duncan's multiple range test was performed using the SAS 9.1 statistical software package (SAS Institute Inc., USA). Differences between two groups or treatments were analyzed using a *t*-test (SAS 9.1). The differences were considered significant when $p < 0.05$.

For testing 'Management activities', we employed linear mixed models (LMMs) using 'lme4' package (Bates et al., 2015) of R ver. 3.1.1. (R Development Core Team, 2015). Treatment and the timing of surveys (i.e., before or after treatment) as well as their interactions were used as explanatory variables, and each quadrat plot was used as a random factor.

For analysis of 'Post-landscaping and management and monitoring of invasion', detrended correspondence analysis (DCA) was performed to describe the plant community composition using the vegan package of the R statistical software package (Oksanen et al., 2013). The species coverage data were log-transformed ($\log(x + 1)$) to approximate a normal distribution (Alday et al., 2011). Permutational multivariate analysis of variance (PERMANOVA, "adonis" function) using Euclidean distance matrices was also performed to examine the differences in vegetation composition between management treatments (Ghorbani et al., 2015). Changes in species importance values were calculated, and t-tests were used to assess the difference in vegetation composition between management treatments.

3. Results and discussion

3.1. Vegetation monitoring and soil analysis

As shown in Tables S1–S3 in Supplementary Materials, *E. annuus* was one of the dominant herbaceous species at the landfill. The condition of the landfill soil was not that poor (Table S4 in Supplementary Materials) considering it was a reclaimed area, and the soils were not polluted because it was a sanitary landfill (Song et al., 2013); therefore, the composition of the vegetation of the landfill should be the result of plant introduction and secondary succession (Song, 2010), not the result of the micro-condition of the soil. Therefore, old levels (level with low numbers) should show the results of succession. The result of this vegetation research is one of the good examples of vegetation pattern of an ecosystem after restoration that could be used for future restoration activities (You and Lee, 2003). However, when vegetation was monitored in the oldest sites, levels one and two on the landfill slopes, *E. annuus* was overwhelmingly dominant with an importance value of 22% (Table 1), and, in the quadrat research, the vegetation coverage of *E. annuus* exceeded 60%. Thus, the oldest levels of the landfill, which were dominated by the alien species, *E. annuus*, revealed the future of landfill vegetation. According to Table 1, the future vegetation of the landfill will likely be dominated by alien species, and therefore proper management will be required. Additionally, Table 1 shows that, among the top ten species, most were species with a rosette or subterranean stem, except for *Glycine soja* and *Humulus japonicas*, which are vine species. Because disturbances such as mowing and construction activities were often observed on the landfill (Song, 2010), it was notable that annual species were not dominant on the site, because such sites with frequent disturbance are usually dominated by annual, herbaceous plants (Grime, 1977). With these results we became to wonder effects of mowing activity on *E. annuus* invasion.

3.2. Competition and allelopathy experiments

The survival rates and growth of seeds, seedlings, and rosettes (rhizomes) of *E. annuus* and other dominant or planted native species on the landfill were compared. The tests began in the spring, which represented the beginning of the growing season, and also in late fall to test whether rosettes and seeds were superior for cold season endurance and early spring occupation. The survival rate of seedlings of *E. annuus* was relatively low compared with that of native species (Table S5 in Supplementary Materials). However, the survival of seeds was not significantly different compared with that of native species (Table S6 in Supplementary Materials); therefore, although the number of *E. annuus* seeds on same volume was much higher than that of other species (i.e.,

Table 1
Species with top ten importance values (I.V.) in quadrats in low and old levels (levels one and two) of the landfill in June.

Scientific name	Native/Alien	I.V. (%)
Erigeron annuus (L.) Pers.	Alien	21.82
Artemisia princeps var. *orientalis* (Pamp.) Hara	Native	14.25
Equisetum arvense L.	Native	6.80
Sonchus brachyotus A.P. DC.	Native	4.54
Trifolium repens L.	Alien	4.34
Erigeron canadensis L.	Alien	4.26
Glycine soja S. et Z.	Native	4.07
Lactuca indica var. *laciniata* Hara	Native	4.00
Humulus japonicus S. et Z.	Alien	3.35
Phragmites australis Trin.	Native	3.18

Table 2
Germination rates of two native species with various treatments.

Treatment	*Lotus corniculatus*	*Aster koraiensis*
Control	79.0 ± 2.7	34.0 ± 7.8^{b}
Hyponex	79.0 ± 1.7	57.0 ± 3.7^{a}
Leaf	72.0 ± 2.3	53.0 ± 5.9^{a}
Root	72.0 ± 3.4	53.0 ± 1.1^{a}
H + L	81.0 ± 3.0	43.0 ± 2.7^{ab}
H + R	78.0 ± 4.2	48.0 ± 6.1^{ab}

Data are presented as the mean ± SE of six replicates.
Means within a column followed by the same letter are not significantly different at $p < 0.05$. H: Hyponex; L: Leaf; R: Root.

Glycine soja, *Aster koraiensis*, and *Lotus corniculatus*) in the identical volume of soil, the survival rate was much lower. For the experiment that started in fall, the coverage of *E. annuus* was not higher after winter or after one and a half years compared with that of native species (Fig. S1, Supplementary Materials). Collectively, these results indicated that *E. annuus* was not dominant because of superior survival ability in recently disturbed areas. Although *E. annuus* has rosettes that might provide an advantage during winter and in early spring (Sachs et al., 1959), the native species also has rhizomes to endure a cold winter and to ensure rapid growth in spring with the energy stored in roots.

As shown in Table 2, *E. annuus* did not have significant allelopathic effects on the germination of native plant species. Although the germination rate of *Aster koraiensis* decreased with the nutrient supply [because extracts also supplied nutrients, 1:1000 diluted Hyponex (Hyponex Corporation, OH, USA) treatments were also prepared] and the extracts (i.e., H + L and H + R) compared with the Hyponex treatment alone, the values remained higher than those of the control. Additionally, the root and shoot growth of *Aster koraiensis* did not decrease and even showed better growth than that of the control (Table 3). The results showed that allelopathic effects of *E. annuus* were not significant, and therefore *E. annuus* did not become the dominant species through the mechanism of allelopathy. Although allelopathic constituents from *E. annuus* were identified in previous research (Oh et al., 2002), *E. annuus* apparently does not affect germination and early growth of other plants in the field, and, even in a controlled environment with limited precipitation (watering) and little soil, no differences are observed.

3.3. Effects of traditional management activities and photosynthetic rates

Removal, seed spraying, and transplanting of native species were the methods used to control and reduce the dominant levels of *E. annuus* in the landfill. We found significant effects of treatment (Table 4; $\chi^2 = 15.01$, d.f. = 7, $p = 0.036$), timing of the survey ($\chi^2 = 21.61$, d.f. = 1, $p < 0.001$), and their interaction ($\chi^2 = 28.86$, d.f. = 7, $p < 0.001$). Post-hoc paired t-tests showed that the number of *E. annuus* decreased significantly (or marginally significantly) only when *E. annuus* was removed (Table 4: Removal, $t_4 = 3.00$, $p = 0.04$; Re-Aster-P, $t_4 = 2.53$, $p = 0.06$; Re-Lotus-P, $t_4 = 3.54$, $p = 0.02$) and not in the other treatments (all $p > 0.2$). Additionally, after removal, the numbers of *E. annuus* recovered by 30% in the following year (Table 4). Even after removal in March, seedlings of *E. annuus* emerged and coverage reached 11% in May. Because the site was dominated by *E. annuus*, these results were somewhat expected and were an indication that *E. annuus* had a large soil seed bank. Therefore, seed spraying and transplanting treatments were examined. However, the treatments with *E. annuus* removal and native plants transplanted (Re-Aster-P and Re-Lotus-P) did not show reduced coverage of *E. annuus*, which indicated that only removal was effective. Based on these results, we did not identify any advantages that ensured the dominance of *E. annuus* in the landfill nor any effective management strategy except for removal. Removing roots (rosettes) resulted in reduced vegetation coverage of *E. annuus*, but because the removal of roots requires a lot of labor, it was difficult to apply to the landfill slope. Also, even after removal, *E. annuus* recovered via the soil seedbank and seed dispersal; thus, this strategy was not cost-effective. Additionally, managers of the landfill do not selectively remove *E. annuus* but also remove weeds (including native species) with the exception of grass; thus, this type of removal does not seem to be a solution for the control of *E. annuus*.

Therefore, we tested whether physiological superiority was a factor by measuring photosynthetic rates. However, as shown in Fig. S2 in Supplementary Materials, the photosynthetic rates of *E. annuus* were not different from those of the massively transplanted native plant *A. koraiensis*. Although the photosynthetic rate is only one parameter, it is a comprehensive measure of water uptake, nutrient use efficiency, and growth (Kang and Zhang, 2004; Small, 1972); thus the dominance of *E. annuus* was not the result of physiological factors related to growth.

Table 3
Seedling growth of *Aster koraiensis* with various treatments.

Treatment	Root (cm)	Shoot (cm)
Control	0.54 ± 0.04	1.25 ± 0.10^{c}
Hyponex	0.56 ± 0.06	2.32 ± 0.27^{b}
Leaf	0.58 ± 0.06	2.21 ± 0.18^{b}
Root	0.53 ± 0.07	2.27 ± 0.21^{b}
H + L	0.62 ± 0.04	2.32 ± 0.24^{b}
H + R	0.58 ± 0.07	2.67 ± 0.31^{a}

Data are presented as the mean ± SE of six replicates.
Means within a column followed by the same letter are not significantly different at $p < 0.05$.
H: Hyponex; L: Leaf; R: Root.

3.4. Mowing experiment and reproductive organ weight differences after mowing

During experiment, frequent mowing at old levels in the landfill was observed. Also, we found that at some levels, *E. annuus* became rapidly dominant after mowing (Song, 2010). Therefore, we hypothesized that mowing might be responsible for the increase in *E. annuus* and therefore the effects of mowing were tested. We made treatments with/without mowing management and, as a result, established mowed and unmowed treatments. In the original design, two unmowed treatments were established, one in areas highly dominated by *E. annuus* and one in areas with similar numbers and coverage of *E. annuus* to those of mowed treatments. However, managers unintentionally mowed the areas of the second unmowed treatment in 2006 and 2007, although they were protected with ropes and posts and managers were informed of the need for protection. Nevertheless, the results were clear; the numbers of *E. annuus* were reduced in the unmowed treatments, whereas the numbers in mowed treatments increased significantly (Table 5). Even with the additional mowing in the blooming season of *E. annuus* (mowing 1), the numbers of *E. annuus* increased significantly. With a significant decrease in the coverage of *E. annuus* in the unmowed treatments (Table 6), the coverage of other species increased. However, in the mowing 2 treatment, the coverage and even numbers decreased (Table 5), which was an indication that many individuals in mowing 2 treatments were seedlings that germinated in 2009 and that old individuals with larger rosettes decreased. Therefore, the generations changed but with more seedlings than in 2006. As continuous mowing constitutes a severe disturbance and potentially reduces the resilience of landfill sites, it can lead to invasion by alien species (Park et al., 2016).

An explanation for why mowing during blooming season did not reduce the number of *E. annuus* can be found in Table 7. Mowing only once (treatment 1) significantly increased the weight and flower/biomass ratio of plants. Even after the second mowing, the species produced 50% more flowers by weight compared with the control. Therefore, the resilience to mowing activity was very high for *E.*

Table 4
Plant coverage and number in quadrats in 2006 and 2007 with various treatments.

Season		Control	Removed	Re-*Aster*-P	Re-*Lotus*-P	*Aster*-P	*Lotus*-P	*Aster*-S	*Lotus*-S
Spring	*Erigeron*	43.3 ± 4.0	11.0 ± 1.0	10.0 ± 0.0	14.0 ± 1.9	37.0 ± 4.6	44.0 ± 8.4	51.0 ± 5.1	46.0 ± 2.4
	Other	64.4 ± 6.6	44.0 ± 5.8	82.0 ± 12.8	51.0 ± 4.8	64.0 ± 13.2	48.0 ± 4.1	61.0 ± 14.6	38.0 ± 6.2
Summer	*Erigeron*	25.0 ± 3.3	16.0 ± 4.0	16.0 ± 2.4	16.0 ± 2.4	21.0 ± 3.3	24.0 ± 5.1	34.0 ± 5.1	36.0 ± 4.0
	Other	57.8 ± 4.0	44.0 ± 4.0	82.0 ± 10.2	46.0 ± 6.2	66.0 ± 10.3	35.0 ± 3.2	50.0 ± 8.4	40.0 ± 6.3
2006	*Erigeron* N	42.7 ± 12.1	43.0 ± 9.5	27.2 ± 4.6^{a}	34.2 ± 5.5^{a}	37.2 ± 6.2	36.4 ± 8.0	50.0 ± 12.0	64.4 ± 13.8
2007	*Erigeron* N	45.0 ± 11.0	15.8 ± 2.4	15.0 ± 1.8^{b}	12.0 ± 2.2^{b}	32.4 ± 4.3	31.2 ± 8.7	49.8 ± 9.6	62.6 ± 12.3

*Vegetation coverage of planted/seed sprayed treatments (underlined treatments).
***Aster*-P**: 40.0 ± 0.0% *Aster*; ***Lotus*-P**: 20.0 ± 0.0% *Lotus*; ***Lotus*-S**: 10.0 ± 1.6% *Lotus*.
****Aster***: *Aster koraiensis*; ***Lotus***: *Lotus corniculatus*; ***Erigeron***: *Erigeron annuus*.
Data are presented as the mean ± SE of five replicates.
Means within a row followed by the same letter are not significantly different at $p < 0.05$.
***N**: Number; **RE**: Removed; **P**: Planted; **S**: Seeds sprayed; Other: Sum of coverage of other species.
All values are cover (%), except *Erigeron* N (number) in spring 2006 and 2007.
Erigeron annuus was removed in March, and vegetation coverage was monitored in May (spring) and September (summer).

Table 5
Numbers of *Erigeron annuus* (L.) Pers. rosettes in March by treatment.

	Unmowed	Mowing 1	Mowing 2
2006	76.6 ± 7.6^{a}	24.4 ± 0.8^{b}	23.9 ± 0.7^{b}
2007	69.6 ± 8.2^{a}	31.0 ± 3.2^{a}	27.9 ± 1.7^{b}
2008	62.0 ± 9.1^{a}	30.8 ± 1.4^{a}	33.5 ± 2.1^{a}
2009	23.6 ± 1.7^{b}	31.9 ± 2.0^{a}	32.9 ± 1.2^{a}

Data are presented as the mean ± SE of ten replicates.
Means within a column followed by the same letter are not significantly different at $p < 0.05$.

Table 6
Coverage of *Erigeron annuus* (L.) Pers. And other species in 2006 and 2009 by treatment.

Species coverage	Year	Unmowed	Mowing 1	Mowing 2
Erigeron annuus	2006	73.0 ± 5.0	57.0 ± 4.3	74.0 ± 4.5
	2009	25.5 ± 2.4***	56.0 ± 4.0	58.0 ± 4.7***
Sum of coverage of other species	2006	62.0 ± 10.4	62.0 ± 2.9	72.0 ± 2.9
	2009	81.0 ± 6.0	63.0 ± 4.0	53.1 ± 4.4***

Data are presented as the mean ± SE of ten replicates.
***$p < 0.001$.
The #2 quadrats in mowing 2 treatment were lost in 2009, and therefore the values of the mowing 2 treatment in 2009 are means of eight replicates.

annuus. Additionally, most mowing activities on the landfill were after the rainy season (July), with mowing activity that occurred once in September 2006 and August 2007, twice in May and October 2008, and once in August 2009. Although the maximum blooming season of *E. annuus* was in late June, the other major species of the landfill (Table S2 in Supplementary Materials) bloomed after August, except *Trifolium repens* (Lee, 1993), which is an introduced species. Therefore, mowing activities after the rainy season will be advantageous to *E. annuus*, whereas most native plants will be negatively affected by mowing. As mentioned previously, the most dominant species in old levels of the landfill were species with rosettes or rhizomes, which implied that biannual or perennial plant species with more investment in roots had resistance against mowing activity, compared with annual species, which do not have resistance (Nemoto, 1979). The effects of mowing and management on the dominance of *E. annuus* were monitored in the following experiment.

3.5. Post-landscaping and management and monitoring of invasion

The managed (landscaped and mowed) and unmanaged quadrats were overlain on a biplot, and 64% of the variation in the data was explained by axes one and two (Fig. S3, in Supplementary Materials). The species composition varied between management methods according to the different regions of the ordination plot along axis one (Adonis analysis; $r^2 = 0.128$, $p = 0.001$). Unmanaged quadrats were on the right side of the plot and contained *Erigeron canadensis* (E. ca), *Setaria viridis* (S. vi), and *Artemisia lavandulaefolia* (A. la). Managed quadrats were on the left side and included *Erigeron annuus* (E. an), *Taraxacum officinale* (T. of), and *Ambrosia trifida* (A. tr). Although differences were not significant for soil chemical properties (Table S7, in Supplementary Materials), changes in values of species importance showed that the composition of vegetation was significantly different between management types (Fig. 1). The differences caused by mowing have also been frequently reported in previous research (Schlapfer et al., 1998), but the change observed in the importance of the value of *E. annuus* is specific to this study. Changes in importance values of the primary seven species (*A. lavandulaefolia*, *A. rosea*, *A. trifida*, *C. drummondii*, *E. annuus*, *R. bicolor*, and *S. viridis*) led to the differences in the composition of vegetation among management treatments. Importance values of five species, *A. rosea*, *A. trifida*, *C. drummondii*, *E. annuus*, and *R. bicolor*, increased, whereas those of two species, *A. lavandulaefolia* and *S. viridis*, decreased significantly, in managed quadrats. In particular, *E. annuus* was remarkably dominant in managed compared with unmanaged quadrats ($p < 0.001$). Therefore, based on monitoring results, mowing clearly increased the dominance of *E. annuus* in only a few years.

Table 7
Numbers, weights, and sex organ ratios of *Erigeron annuus* (L.) Pers. by treatment.

Treatment	N of flowers	W of flowers	W of flower	W of *Erigeron*	Flowers/ Biomass (%)
Control	22.70 ± 1.13^{b}	4.54 ± 0.23^{b}	0.20 ± 0.00^{a}	124.20 ± 5.55^{a}	3.68 ± 0.18^{c}
Treat 1	33.60 ± 0.81^{a}	6.61 ± 0.14^{a}	0.20 ± 0.00^{a}	76.00 ± 2.67^{b}	8.77 ± 0.29^{a}
Treat 2	14.00 ± 1.25^{c}	2.74 ± 0.20^{c}	0.20 ± 0.01^{a}	50.60 ± 3.78	5.52 ± 0.33^{b}
Treat 3	2.70 ± 0.40^{d}	0.45 ± 0.07^{d}	0.15 ± 0.02^{b}	42.20 ± 2.68^{c}	1.12 ± 0.20^{d}

Data are presented as the mean ± SE of ten replicates.
Means within a column followed by the same letter are not significantly different at $p < 0.05$.

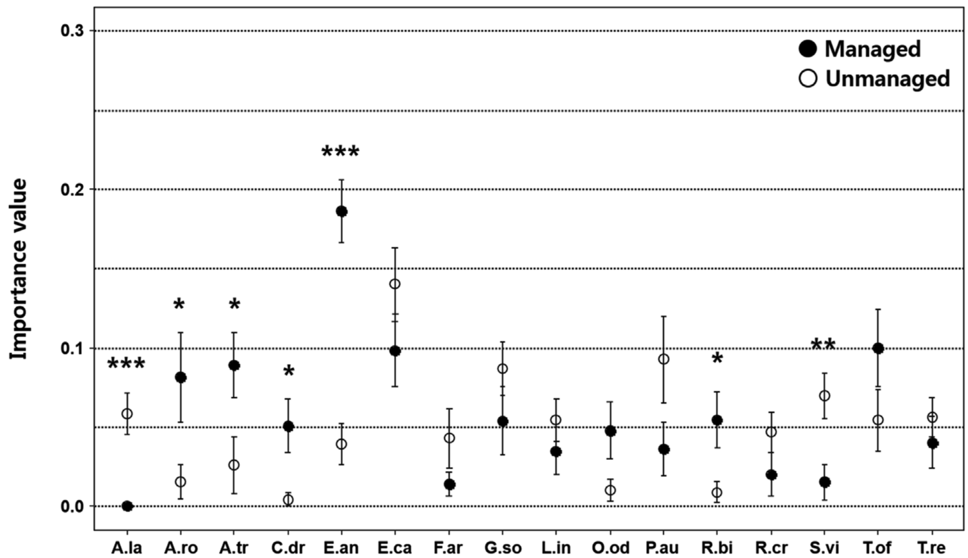

Fig. 1. Changes in the importance value for each species (n = 20) in different management treatments. The asterisks indicate significant differences ($p < 0.05$) between managed and unmanaged quadrats.

Collectively, these results indicate that *E. annuus* became dominant in recently reclaimed or disturbed areas not by adaptability to disturbed soil, allelopathy, outcompeting other species, or rapid growth, but because of continuous disturbance by mowing. Therefore, mowing was likely the primary reason for the invasion of *E. annuus*. This result was completely unexpected, because mowing activities are usually conducted to control weeds (Donald, 2000; Lee et al., 2010), despite side effects such as loss of soil (Gilley et al., 2000), loss of biodiversity (Fynn et al., 2004), and cost of labor. Moreover, the results also showed that, when sites were protected from mowing, *E. annuus* lost any advantage and was less dominant. Therefore, without an understanding of the ecological factors that regulate a dominant plant species in an area, mowing activities can result in an increase in alien and invasive species such as *E. annuus*.

4. Conclusion

Our results show that mowing is one of the main causes of *E. annuus* invasion. Other suspected factors, such as seed superiority and seedling growth, allelophathy, photosynthesis, and resistance to disturbance did not provide *E. annuus* with an advantage. Therefore, mowing, which is commonly used to control vegetation biomass, should be conducted carefully when managing landfill sites. Managers should first monitor standing vegetation and then decide whether mowing is required. Additionally, changes in the timing and frequency of mowing can help to manage *E. annuus*. Because *E. annuus* blooms earlier than the native species on the site, starting to mow earlier would help with management without damaging the flower stems of other plants. Additionally, as shown in Table 7, selective mowing of *E. annuus* three times significantly reduced the weight of flowers, which would ultimately lead to a reduction in *E. annuus*. Mowing three times might be difficult, but, because the flower stalk of *E. annuus* is taller than that of other plants in its blooming season, selective mowing would not be too difficult to implement. Because the purpose of mowing is to cut the flower stem, mowing would not damage the flower stalks of plants that were shorter than those of *E. annuus*. This type of selective mowing causes less damage to the vegetation of sites because of the cutting height and may improve the ecological health of the site by increasing biodiversity, maintaining biomass of vegetation, and decreasing soil loss after vegetation removal. Overall, although mowing was the primary factor explaining the invasion of the alien species *E. annuus*, with a comprehensive ecological understanding of the site and the species, mowing could also contribute to the management of *E. annuus*.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jenvman.2018.06.057.

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