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Effects of Bare-Ground Revegetation Techniques Using *Imperata cylindrica* on Changes in the Plant Cover and Species Richness during Early Succession

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Abstract

Riverdikes are habitats that must be revegetated quickly in order to prevent soil erosion. With increasing pressure to improve the cost efficiency of management, new revegetation techniques suitable under reduced mowing frequencies are required. *Imperata cylindrica* (L.) P. Beauv. is an important component of grasslands in several Asian countries. Its vigorous rhizome elongation should be useful for quickly covering bare ground. We tested the effects of sowing (at two densities), transplanting, and sodding of *I. cylindrica* on plant cover and species richness of established vegetation over 3 years. The sodding and high-density sowing treatments achieved the most rapid increase in cover, followed by low-density sowing, transplanting, and the control. By year 2, however, the cover in the low- and high-density sowing treatments was similar. The sodding treatment had significantly fewer species than the other treatments in year 1. Between years 1 and 2 and years 2 and 3, the total number of species increased in the transplanting treatment, whereas it decreased in the sodding and two sowing treatments. Accordingly, if stabilization and erosion control are the priority, introduction of *I. cylindrica* using sod and high-density sowing is the most suitable method. If immediate green-up is not imperative, low-density sowing is likely to provide available resources for new seedlings of diverse species to become established, allowing the introduction of representative species in semi-natural grasslands. More research will be needed on the effects of introducing diverse species (e.g., sowing seed mixtures) that include *I. cylindrica* on the resulting floristic composition.

Keywords

Restoration, Riverdike, Sod, Sowing, Transplanting

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1. Introduction

Across the world, large areas of native vegetation have been removed for urban, industrial, and agricultural land uses. Destruction of vegetation may increase soil erosion and undermine stability, and revegetation is essential for stabilizing such disturbed areas. Artificially revegetated sites were traditionally fertilized, mulched, and seeded with non-native grasses and legumes selected for rapid growth and effectiveness in erosion control [1]-[4]. In recent years, however, native species have been preferred for revegetation measures in order to prevent the spread of ecologically harmful invasive species and to improve ecological functions [5]-[8].

Riverdikes must be quickly revegetated to prevent soil erosion, as the collapse of dikes is directly associated with severe flooding. In Japan and South Korea, riverdikes were traditionally revegetated with grass species that were managed by mowing [9] [10]. Some means of improving the cost efficiency of managing riverdikes include reducing the frequency of mowing and replacing short-grass monocultures with taller species [11]. The taller species generally have lower ability to prevent soil erosion [12]. To date, revegetation methods that are suitable to reduce soil erosion under reduced mowing frequencies have rarely been developed.

Grasslands dominated by *Imperata cylindrica* (L.) P. Beauv. are important components of native ecosystems that support endangered species in some regions, such as Nepal [13], Australia [14], and Japan [15]. At the same time, *I. cylindrica* is one of the most cosmopolitan grass species: it grows throughout the warm temperate and tropical regions of the world [16]. It is a highly invasive perennial grass that threatens agriculture, forestry, and native plant species assemblages in many regions of the world [16]. Rhizomes can comprise over 60% of the total plant biomass of *I. cylindrica* [17]; this low ratio of shoots and roots to rhizomes contributes to its rapid regrowth after cutting, especially in disturbed habitats. Studies have indicated that its adaption to poor soils, its drought tolerance, and its prolific production of wind-dispersed seed are associated with the dominance and spread of this species [18]-[20].

Because of its vigorous lateral spread via rhizome elongation and its adaptability to a wide range of environments, researchers have proposed that *I. cylindrica* should be useful for quickly covering bare ground [9] [21]. Based on this proposal, artificial sod consisting of *I. cylindrica* has been developed. This sod was reported to cover bare ground successfully and at high density even in the first year of introduction [22]. Other revegetation techniques using *I. cylindrica* seeds and planted soil plugs (*i.e.*, both the grass and some soil) have also been developed [21]. In order to revegetate bare ground as rapidly as possible, revegetation techniques that can protect the soil should be developed; however, no scientific study has yet compared the speed of coverage by *I. cylindrica* among the various available methods. Chigaya-Sougen-Soushutu-Kenkyukai [23] reported revegetation techniques using *I. cylindrica*, yet little empirical data with enough replications was shown.

Regeneration of introduced species tends to be hampered by competition from undesirable species that often invade revegetated areas, rather than by poor germination [24]. If undesirable species increase beyond a threshold, they could shade out *I. cylindrica*, thereby preventing *I. cylindrica* from becoming dominant [25] [26]. Competitiveness is thus a particularly important trait for the survival of species in revegetation measures [27] [28]. Therefore, it is necessary to perform monitoring of how the techniques used affect the rest of the plant community, especially with regard to increases of cover by undesirable species; however, to our knowledge, no such study has been carried out.

To identify an appropriate method to revegetate riverdikes, we set out to answer two questions: What is the fastest method (sowing, planting, or sodding) to revegetate riverdikes with *I. cylindrica* in terms of the effects on plant cover and species richness of the established vegetation? In each method, do natural colonizers become established over time?

2. Materials and Methods

2.1 Study Site

The study site is located in the high-water channel of the Tone River, 30 km northeast of Tokyo, Japan (35˚54'54"N, 140˚0'59"E, **Figure 1**). Mean annual precipitation at the nearby Ryugasaki Meteorological Station is 1344 mm. The mean annual temperature is 14.1˚C, with a mean minimum of 3.1˚C (January) and mean maximum of 25.6˚C (August). The site was surrounded by tall herbaceous vegetation dominated by *Miscanthus sacchariflorus* (Maxim.) Benth., and no vegetation management was carried out. The neighboring riverbank, which is located approximately 20 m from the study site, was dominated by *Solidago altissima* L., *Schedonorus*

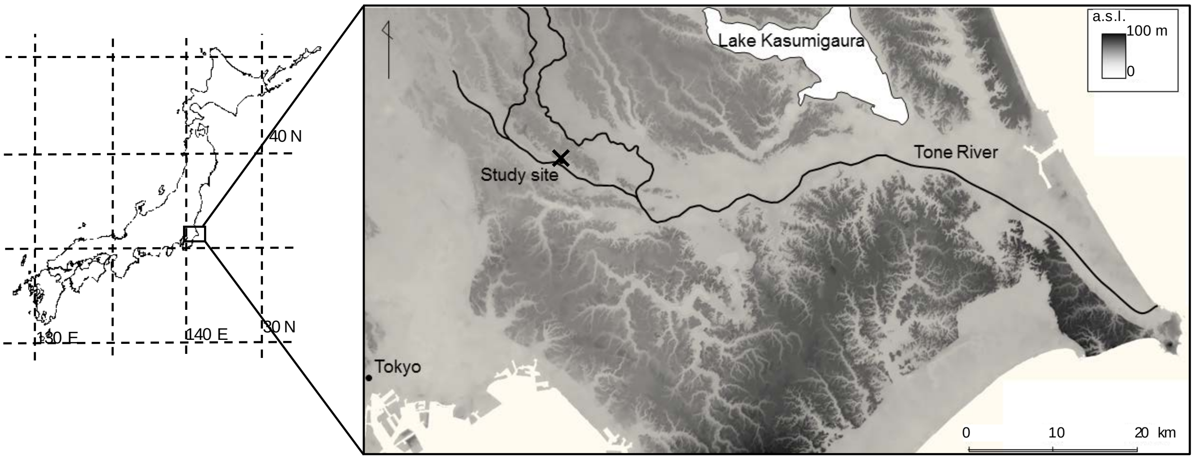

Figure 1. Location of the study site.

phoenix (Scop.) Holub, *Lolium multiflorum* Lam., and *I. cylindrica*.

2.2. Experimental Design

The study site is within an area where soil is prepared for the construction of riverdikes. Soil hardness measured with a Yamanaka-type soil penetrometer (Fujiwara Factory Co. Ltd., Tokyo, Japan) was 19 - 28 mm (median 24 mm), which is similar to that in established riverdikes (personal communication with H. Sasaki, Foundation of River and Watershed Environment Management, Japan). Available nitrogen content in the surface soil was 0.1 mg N/g, indicating relatively nutrient-poor soil conditions.

Topsoil in a 10 m × 10 m area was removed to a depth of 30 cm in July 2010. Within this area, we set up five treatments: sodding, sowing at two seed densities, transplanting, and control. Treatments were carried out in 1.5 m × 1.5 m (2.25 m^2) plots arranged in a randomized block design, with three replications of each. Each block was separated by 20 cm deep ditches to avoid rhizome contamination between plots. Each plot was placed 70 cm away from an adjoining plot.

For the sodding treatment, *I. cylindrica* sod composed of 12-month-old plug-plants that was commercially developed for riverbank revegetation was raised for 3 months and then applied to the plots in 1.1 m × 1.1 m squares. For the two sowing treatments, either 10,000 seeds m^{-2} (hereafter high-density sowing) or 1000 seeds m^{-2} (low-density sowing) were sown. The *I. cylindrica* seeds were obtained from the nearby riverbank in late May 2010. For the transplanting treatment, 12-month-old plug-plants raised in 1 cm × 1 cm cell pots were established at a density of 25 individuals m^{-2}. In the sowing treatments, seeds were integrated with stabilizer (2 cm^3 per 2.25 m^2 of acrylic acid resin and polyvinyl acetate resin) and short-fiber wood mulch (405 g per 2.25 m^2) before being broadcast in order to add weight and achieve better adherence to the soil. Plug-plants and sod were produced by ESPEC MIC Inc. (Nagoya, Aichi, Japan). In the control treatment, the ground was left bare.

Because germination of *I. cylindrica* requires a relatively high temperature [29], the experiment was started at the beginning of July 2010. Although the experiment was started during the rainy season, manual irrigation was applied daily for the first 2 weeks after planting, and then twice weekly until 30 September 2010. Mowing management was carried out twice a year, in May and October (with the first mowing occurring in May 2011).

2.3. Monitoring

Seedling establishment success was assessed by counting germinated plants in 0.1 m × 0.1 m quadrats randomly located at five non-overlapping points within each sowing plot. For the transplanting treatment, the number of surviving plants was recorded in the whole 2.25-m^2 plot. Monitoring was carried out on 9 September 2010. For monitoring species diversity, we measured the maximum height and visually estimated the percent cover of each species on 28 October 2010, 23 August 2011, and 3 September 2012. Total vegetative cover was also estimated on these dates. The survey in 2010 was delayed because vegetation was mostly composed of small seedlings, making species identification difficult for many individuals. The vegetation survey preceded mowing in each autumn. Species identification was made in the study site, supplemented by subsequent room identification using Flora of Chiba Prefecture [30].

To assess belowground biomass, soil was sampled to a depth of 30 cm using an auger with a 4-cm diameter on11 April 2013. In each plot, the center and four points equidistant from the center and each edge were sampled. Each soil sample was separated into 0 - 10, 10 - 20, and 20 - 30 cm portions, and the upper, middle, and lower portions from the five sampling points within each plot were each combined. Live plant parts were removed from each soil sample, dried for 3 days at 80˚C, and weighed.

2.4. Analysis

The recorded species were classified as annuals (including biennials), perennials, and woody species. The description of species attributes followed Numata and Yoshizawa [31] and Chibaken-shiryou-kenkyuzaidan [30]. Species diversity was calculated using the Shannon-Weaver diversity index (H_0) [32].

Cover data were normalized by square-root transformation. We performed one-way ANOVA and Tukey's *post hoc* tests to determine the significance of differences in the number of species, plant cover, and belowground biomass between treatments. We also performed repeated two-way ANOVA and Tukey's *post hoc* tests to assess the differences in plant cover and number of species between years. A P value < 0.05 was considered to be significant. Statistical analyses were performed using R ver. 2.13.1 (R Development Core Team 2013).

3. Results

A total of 89 species were recorded. Fifty species were annuals, 37 were perennials, and 2 were woody species. Forty-two taxa were exotic species. *Equisetum palustre* L. was observed at frequencies of more than 0.5 (*i.e*., in more than 7 plots) in each year. *Panicum bisulcatum* Thunb., *Cyperus iria* L., and *Cayratia japonica* (Thunb.) Gagnep. were observed at frequencies of more than 0.5 in year 1, and *Erigeron canadensis* (L.) Cronquist and *Solidago altissima* were observed at frequencies of more than 0.5 in years 2 and 3.

3.1. Germination and Survival Rates

Mean seedling survival rates were similar in the two sowing treatments (high density: 24.6% ± 8.8%; low density: 30.7± 4.2%). The survival rate in the transplant treatment was 41.3% ± 31.0%.

3.2. Floristic Changes in the Various Treatments

Imperata cylindrica cover, total plant cover, and total number of species recorded in each experimental year are illustrated in **Figure 2**. Changes in species categories among years are described in **Table 1**. In year 1, the sodding and high-density sowing treatment produced significantly greater *I. cylindrica* cover, followed by low-density sowing and transplanting. In year 2, *I. cylindrica* cover was similar in the low-density sowing, high-density sowing, and sodding treatments, whereas the transplanting treatment had significantly less *I. cylindrica* cover. The relationship among treatments with regard to total plant cover was similar to that for *I. cylindrica* cover in years 1 and 2. No significant differences in total plant cover were observed among treatments in year 3, with all treatments having more than 80% cover.

In year 1, the sodding treatment exhibited a significantly smaller total number of species than all other treatments. Between years 1 and 2, the total number of species increased in the transplanting treatment, but decreased in the sodding and two sowing treatments (**Table 1**). Between years 2 and 3, the total number of species decreased in the low-density sowing and transplanting treatments and control, but increased in the sodding treatment. Consequently, by year 3 the sodding treatment had achieved a significantly greater total number of species than the other treatments, except the control.

The numbers of species and cover of annuals and perennials are shown in **Table 2** (The number of woody species was too small to include in this analysis). In years 1 and 2, the numbers of annuals in the higher-density sowing and sodding treatments were smaller than those in the transplanting treatment and control. The number of annuals decreased over time in all treatments, except for the sodding treatment in year 3 (**Table 1**). By year 3, there were almost no annual species in the plots except for the sodding treatment. There was no clear trend among years with regard to the number of perennials, but there were more perennial species than annual species in years 2 and 3 in all treatments. Likewise, the percent cover of perennials was greater than that of annuals in

Table 1. Between-year trends in each species category for the various revegetation treatments.

	Year 1 vs. Year 2			Year 1 vs. Year 3			Year 2 vs. Year 3		
	F value	*P* value	+/−	*F* value	*P* value	+/−	*F* value	*P* value	+/−
Sodding									
Number of species									
Total	4.2008	0.0012	-	2.5205	0.0510		6.7213	<0.0001	+
Annual	2.7301	0.0331	-	1.3650	0.3774		4.0951	0.0016	+
Perennial	4.9320	0.0002	-	3.2880	0.0098	+	8.2199	<0.0001	+
Exotic species	0.0000	1.0000		7.2660	0.0000	+	7.2660	0.0000	+
Cover									
Total	1.5643	0.2837		0.6795	0.7779		2.2438	0.0880	
I. cylindrica	1.7327	0.2180		2.7647	0.0307	+	1.0320	0.5659	
Annual	2.8215	0.0273	-	1.8948	0.1661		4.7163	0.0004	+
Perennial [a]	4.6470	0.0004	-	4.1726	0.0013	+	8.8196	<0.0001	+
Exotic species	0.0000	1.0000		7.4754	0.0000	+	7.4754	0.0000	+
Shannon's diversity	2.1766	0.0999		2.3380	0.0733		4.5146	0.0006	+
High-density sowing									
Number of species									
Total	5.0410	0.0002	-	5.8812	<0.0001	-	0.8402	0.6830	
Annual	8.1903	<0.0001	-	9.5553	<0.0001	-	1.3650	0.3774	
Perennial	0.8220	0.6941		1.6440	0.2510		0.8220	0.6941	
Exotic species	0.4323	0.9026		0.1644	0.9852		0.2678	0.9613	
Cover									
Total	0.9766	0.0195	+	5.0858	0.0002	+	2.1092	0.1133	
I. cylindrica	6.6533	<0.0001	+	7.1176	<0.0001	+	0.4643	0.8886	
Annual	6.1693	<0.0001	-	6.4687	<0.0001	-	0.2994	0.9519	
Perennial [a]	0.9081	0.6416		4.7276	0.0004	+	5.6356	<0.0001	+
Exotic species	1.6630	0.2437		4.2481	0.0011	+	2.5851	0.0447	+
Shannon's diversity	1.8073	0.1927		2.1965	0.0962		0.3892	0.9202	
Low-density sowing									
Number of species									
Total	3.7808	0.0032	-	7.9816	<0.0001	-	4.2008	0.0012	-
Annual	8.1903	<0.0001	-	13.6505	<0.0001	-	5.4602	0.0001	-
Perennial	1.6440	0.2510		0.0000	1.0000		1.6440	0.2510	
Exotic species	3.0135	0.0180	+	1.2491	0.4393		4.2626	0.0011	-

Continued

Cover									
Total	6.6428	<0.0001	+	7.3205	<0.0001	+	0.6777	0.7790	
I. cylindrica	17.0100	<0.0001	+	19.8905	<0.0001	+	2.8804	0.0240	+
Annual	7.9035	<0.0001	-	7.8763	<0.0001	-	0.0272	0.9996	
Perennial [a]	0.2447	0.9676		3.7961	0.0031	+	3.5514	0.0054	+
Exotic species	1.8626	0.1756		4.2161	0.0012	+	2.3536	0.0711	
Shannon's diversity	3.8876	0.0025	-	5.7071	<0.0001	-	1.8195	0.1888	
Transplanting									
Number of species									
Total	4.6209	0.0005	+	3.3607	0.0084	-	7.9816	<0.0001	-
Annual	3.4126	0.0074	-	11.6029	<0.0001	-	8.1903	<0.0001	-
Perennial	13.1519	<0.0001	+	6.5780	<0.0001	+	6.5780	<0.0001	+
Exotic species	8.5797	0.0000	+	5.7611	0.0000	+	2.8186	0.0274	-
Cover									
Total	4.2404	0.0011	-	6.4340	<0.0001	+	10.6743	<0.0001	+
I. cylindrica	15.9731	<0.0001	+	25.3143	<0.0001	+	9.3412	<0.0001	+
Annual	5.9218	<0.0001	-	8.1022	<0.0001	-	2.1803	0.0992	
Perennial [a]	0.9718	0.6026		6.8965	<0.0001	+	5.9248	<0.0001	+
Exotic species	5.7948	0.0000	+	7.3126	0.0000	+	1.5178	0.3041	
Shannon's diversity	3.7599	0.0034	+	4.0321	0.0018	-	7.7920	<0.0001	-
Control									
Number of species									
Total	1.2603	0.4331		4.2008	0.0012	-	5.4611	0.0001	-
Annual	3.4126	0.0074	-	10.9204	<0.0001	-	7.5078	<0.0001	-
Perennial	5.7540	<0.0001	+	3.2880	0.0098	+	2.4660	0.0569	
Exotic species	0.4906	0.8765		1.4135	0.3531		0.9229	0.6325	
Cover									
Total	4.3687	0.0008	+	15.8325	<0.0001	+	11.4639	<0.0001	+
I. cylindrica	10.6189	<0.0001	+	22.5079	<0.0001	+	11.8890	<0.0001	+
Annual	0.0139	0.9999		2.9315	0.0215	-	2.9454	0.0209	-
Perennial [a]	0.6529	0.7929		5.5930	0.0001	+	6.2459	<0.0001	+
Exotic species	2.8265	0.0270	+	9.6538	0.0000	+	6.8273	0.0000	+
Shannon's diversity	2.0157	0.1343		3.0557	0.0164	-	5.0714	0.0002	-

[a]Cover of perennials excludes that of *Imperata cylindrica*.

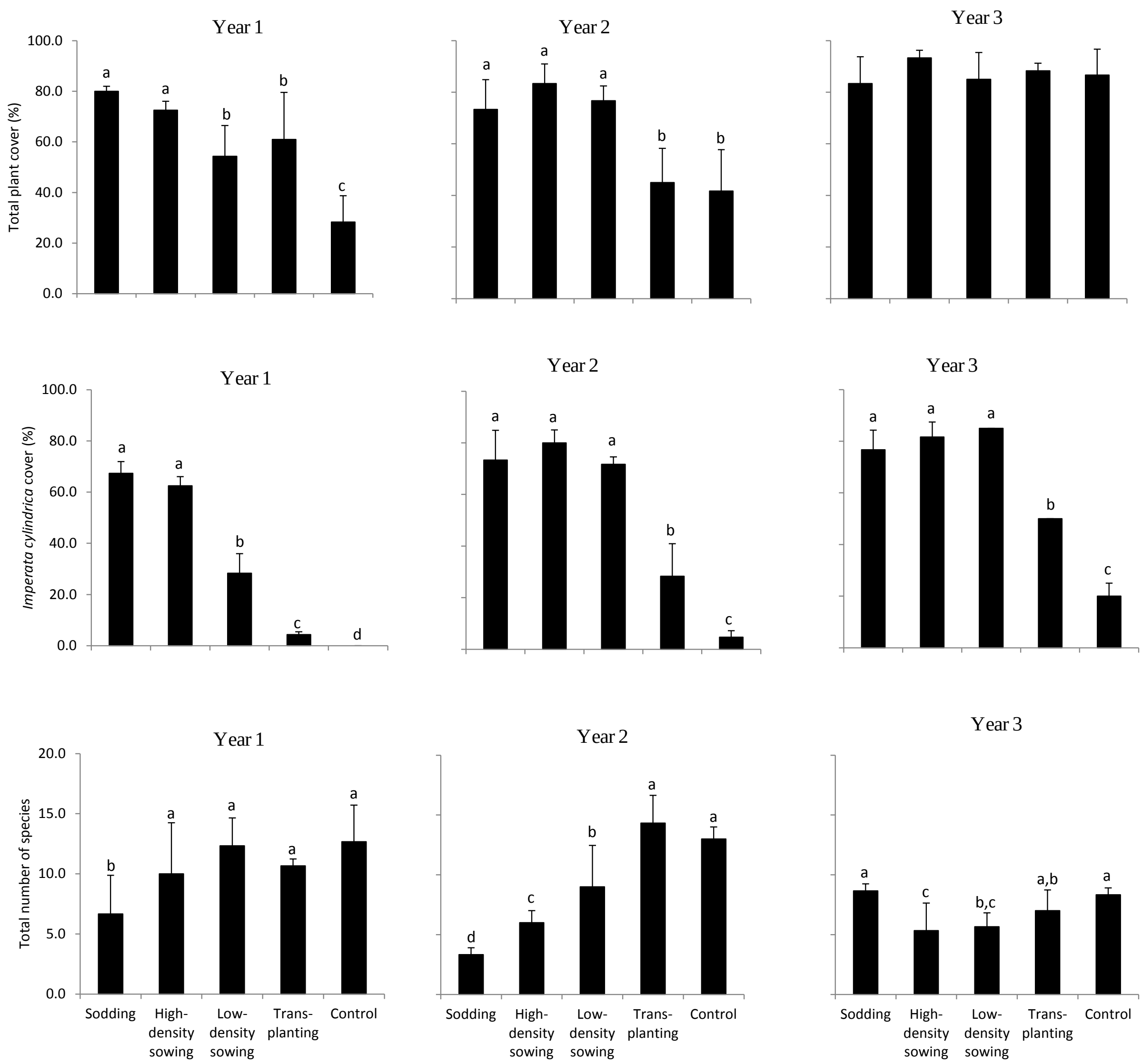

Figure 2. Total plant cover (upper), *Imperata cylindrica* cover (middle), and total number of species (lower) in each treatment from year 1 to year 3. Mean values ± SD followed by the same letter are not significantly different according to Tukey's LSD (P > 0.05).

years 2 and 3 in all treatments (**Table 1**), particularly in the transplanting treatment and control. The percent covers of exotic species in year 3 were greater than those in year 1 in all treatments (**Table 1**). In year 3, the control treatment showed significantly greatest cover of exotic species among treatments. Shannon's diversity index was greatest in the transplanting treatment and control in year 2, and in control in year 3 (**Table 2**).

3.3. Belowground Biomass

Belowground biomass is illustrated in **Figure 3**. At soil depth of 0 - 10 cm, biomass in the sodding treatment was significantly greater than those in the transplanting treatment (P = 0.034) and control (P = 0.007). There were no significant differences among treatments at depths of 10 - 20 and 20 - 30 cm.

4. Discussion

In vegetation studies with small plots, interplot seeding (*i.e.*, seed rain from adjacent plots) typically becomes a problem after the second season [33] [34]. In the present study, *I. cylindrica* occurred in control plots in year 2.

Table 2. Number of species and cover of annuals and perennials.

		Sodding				High-density sowing				Low-density sowing				Transplanting				Control			
Year 1	Number of species																				
	Annual	2.0	±	1.7	c	4.5	±	3.5	b	7.7	±	2.5	a	7.3	±	1.5	a	7.0	±	1.0	a
	Perennial	4.0	±	1.0	a	5.5	±	0.7	a	4.3	±	1.2	a	3.3	±	1.2	a	5.7	±	2.1	a
	Exotic species	0.7	±	0.6	c	2.3	±	2.3	b	2.3	±	1.5	a,b	0.7	±	0.6	c	4.3	±	0.6	a
	Cover																				
	Annual	3.4	±	3.1	b	8.1	±	0.1	a,b	18.2	±	12.2	a	30.1	±	8.2	a	21.2	±	11.2	a
	Perennial [a]	6.8	±	0.5		5.8	±	0.8		5.5	±	4.0		16.4	±	24.0		9.5	±	2.6	
	Exotic species	0.1	±	0.1	b	1.5	±	2.4	b	0.9	±	1.2	b	1.3	±	1.5	b	6.5	±	1.5	a
	Shannon's diversity	1.3	±	0.5	b	2.1	±	0.6	b	3.0	±	0.7	a	3.0	±	0.3	a	3.1	±	0.9	a
Year 2	Number of species																				
	Annual	1.3	±	0.6	c	1.0	±	1.0	c	3.7	±	1.2	b	5.7	±	2.1	a	5.3	±	1.2	a,b
	Perennial	2.0	±	0.0	c	5.0	±	1.7	b	5.3	±	2.3	b	8.3	±	0.6	a	7.3	±	0.6	a
	Exotic species	0.7	±	0.6	c	2.0	±	1.7	b	4.3	±	2.5	a	5.0	±	1.0	a	4.0	±	1..0	a
	Cover																				
	Annual	0.1	±	0.1	b	0.4	±	0.6	b	1.7	±	2.1	b	9.3	±	2.3	a	22.5	±	14.5	a
	Perennial [a]	0.1	±	0.0	c	3.3	±	2.3	b,c	3.6	±	2.4	a,b	13.3	±	7.1	a	7.6	±	2.3	a,b
	Exotic species	0.1	±	0.1	c	2.0	±	1.0	b	2.4	±	3.3	b	6.9	±	1.4	a	12.1	±	7.5	a
	Shannon's diversity	0.7	±	0.1	c	1.5	±	0.3	b,c	2.3	±	1.1	b	3.9	±	0.6	a	3.6	±	0.2	a
Year 3	Number of species																				
	Annual	3.3	±	0.6	a	0.3	±	0.6	b	1.0	±	1.0	b	1.7	±	0.6	a,b	1.7	±	0.6	a,b
	Perennial	5.3	±	1.2	a,b	5.0	±	2.6	b	4.7	±	0.6	b	5.0	±	1.0	a,b	6.3	±	0.6	a
	Exotic species	4.0	±	1.0	a	2.0	±	1.0	a,b	1.7	±	1.2	b	3.0	±	1.0	a,b	3.3	±	0.6	a,b
	Cover																				
	Annual	5.2	±	0.8	a,b	0.3	±	0.6	c	1.4	±	1.6	b,c	5.3	±	4.9	a,b	14.0	±	16.5	a
	Perennial [a]	22.2	±	7.3	b,c	21.0	±	9.2	b,c	17.7	±	9.0	c	44.7	±	25.5	a	34.0	±	3.0	a,b
	Exotic species	5.9	±	1.2	b	5.3	±	3.8	b	5.3	±	6.7	b	10.0	±	6.1	b	29.7	±	10.5	a
	Shannon's diversity	1.9	±	0.5	a,b	1.4	±	0.7	b	1.6	±	0.5	a,b	2.0	±	0.8	a,b	2.4	±	0.1	a

Cover of perennials excludes that by *Imperata cylindrica*. Within each row, mean values ± SD followed by the same letter are not significantly different according to Tukey's LSD ($P > 0.05$).

These individuals were likely recruited from seeds produced in adjacent plots and surrounding habitats via the prolific wind-disseminated seed. Nevertheless, cover of *I. cylindrica* was significantly lower (<10%) in the control compared with other treatments, suggesting that the influence of interplot seeding was marginal.

4.1. Behavior of *Imperata cylindrica*

In all treatments, *I. cylindrica* cover reached more than 70% or increased throughout the experimental period. The sodding and higher-density sowing treatments achieved the most rapid increase in the cover. Sodding of turf grasses has been shown to cover the ground more rapidly than broadcast seeding [30] [35]. One reason for the better performance in terms of the abundance of *I. cylindrica* in the high-density sowing treatment would be the

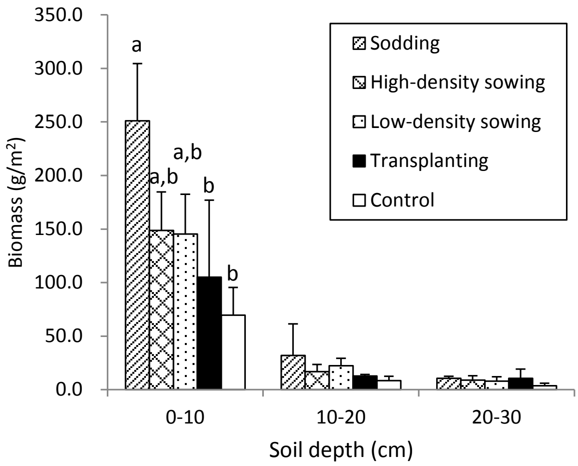

Figure 3. Belowground biomass in each treatment in 2013. Mean values ± SD followed by the same letter are not significantly different according to Tukey's LSD ($P > 0.05$).

much greater seed density than that used in previous research [36]. If we compare sodding with the low- density sowing treatment, then our findings correspond to these previous results. In another study of *I. cylindrica*, Tominaga [37] reported that each new plant borne from a rhizome piece (ramet) produced 31 rhizomes totaling 8 m in length in a single season. In this study, the number of plug-plants originally introduced into a sod roll was small (*i.e.*, 25 individuals m^{-2}), but the 12-month maturation period before the introduction of sod would have enhanced the rapid expansion of rhizomes and thus contributed to the increase in the cover.

It was only in the first year that cover in the low-density sowing treatment was less than that in the high-density treatment. A similar trend was observed by Stevenson *et al.* [36] and Burton *et al.* [38]. In high-density sowing, individual seedlings experience intense competition, resulting in some mortality and self-thinning [38]. Another explanation for this result is that, although plant cover of natural colonizers was greater in the low-density sowing treatment in year 1, the majority of the cover was by annuals, thus more space was available for *I. cylindrica* in the low-density plots in the following spring.

The transplanting treatment had the lowest *I. cylindrica* cover in all treatments, except the control. One reason is clearly that the transplant survival rate in year 1 was lower than expected (41.3% ± 31.0%). Tominaga [37] reported that *I. cylindrica* ramets (new plants from rhizome pieces) produced fewer rhizomes than genets (seedlings). Ezaki *et al.* [39] demonstrated that when planted at 16 individuals m^{-2}, *I. cylindrica* plant density was saturated by the fourth year. Therefore, it may be the case that it takes longer for *I. cylindrica* to become dominant when established by plug-plants rather than by seeds and sod. *Imperata cylindrica* favors high-light environments, and Patterson [17] reported a markedly higher mortality rate in shaded environments. We observed a higher percent cover of perennials in the transplanting treatment than in the sowing treatments. Under such conditions, *I. cylindrica* cover would not likely increase to form a monospecific stand over the short experimental period.

Belowground biomass in the transplanting treatment and control were smaller than that in the other treatments. This pattern more closely resembled that of *I. cylindrica* cover than total cover. Although we did not distinguish among species when assessing belowground biomass, the roots and rhizomes of *I. cylindrica* likely accounted for much of the belowground biomass. The belowground biomass recorded in this study was markedly smaller than that reported in mature plant communities dominated by *I. cylindrica*on riverdikes [9], reflecting that belowground biomass in our study site was still increasing in year 3.

4.2. Effect on Natural Colonizers

Compared with the control, the cover of annuals was suppressed in the sodding and sowing treatments, particularly in years 2 and 3. The number of annual species also decreased to less than 2.0 in the high-density sowing treatment by year 2 and in the low-density treatment in year 3. The presence of annuals was strongly linked to the presence of bare ground in plots, as reported previously [36]. Closed and productive vegetation dominated by perennial generalists also hampers the chances for the establishment of migrated species [40] [41]. Previous studies found that the suppression of migrated species was high only when grass species were made up at least 70% cover [33] [42] [43], and it was low when the proportion of grasses was 50% [36]. Plant cover in the treatment plots was >70% in years 2 and 3, suggesting that competitive exclusion was occurring within a few years of initiating the treatments. For the transplanting treatment, Shannon's diversity index and the total number of species were similar to those in the control over the course of the experiment, indicating that there was no clear competitive exclusion due to *I. cylindrica* in the transplanting treatment.

In year 3, the covers of exotic species in treated plots were significantly larger than those in control plots, suggesting that introduction of *I. cylindrica* regardless to the treatments contributed to inhibiting the increase in the cover of exotic species. The low percent cover of undesirable exotic species (e.g., *Solidago altissima*) after 3 years suggests that establishment of such species is unlikely to become a major problem in a short time. Nevertheless, the cover of exotic species increased gradually, indicating that it is unclear whether exotic species suppress *I. cylindrica* in the long term, as Mitchell *et al*. [28] reported. Further work is required to identify method(s) to control these perennial species.

The number of species in the sodding treatment was significantly smaller than other treatments in years 1 and 2, whereas the sodding treatment had the greatest number of species in year 3. Plant cover was similar in the sodding and high-density sowing treatments. By covering the existing seed banks with sod, weed germination and establishment would be eliminated [34]. However, the artificial materials contained in the sod deteriorate by year 3, the deterioration opens gaps in the sod that let light hit the underlying soil and thus enhance germination

4.3. Implications for the Revegetation of Riverdikes Using *Imperata cylindrica*

Sodding and sowing with *I. cylindrica* suppressed both the total cover and the number of naturally colonizing species. If stabilization and erosion control are the priority, introduction of *I. cylindrica* using sod and sowing at high density were shown to be the most effective techniques. Sod produced greater belowground biomass than the other treatments, indicating that sodding is particularly well-suited to bare-ground revegetation of riverdikes. However, our findings indicated that transplanting is inappropriate because *I. cylindrica* cover would not likely increase to form a monospecific stand within a short period.

Land managers often attempt not only to achieve rapid coverage by vegetation, but also to increase the functionality of the target communities [44] [45]. Thus, ideally, revegetation using *I. cylindrica* should also enhance the establishment of other desirable species. Nevertheless, except for *I. cylindrica*, only *Rumex acetosa*, *C. japonica*, and *Plantago asiatica* were common to existing semi-natural grassland (Nemoto *et al*., unpublished data), possibly due to seed limitation of the target species, as noted in previous studies (e.g., [46]).

The most widely applicable method for actively restoring a diverse plant community is sowing seeds of numerous species [47]. When considering such goals, sod is less useful due to the severe limitation on the colonization of migrating species. However, Abe *et al*. [48] reported successful introduction of several grassland species on reclaimed riverdikes by sowing seeds. Therefore, using a seed mixture of *I. cylindrica* and diverse desirable species would likely provide available resources for new seedlings. If immediate green-up is not imperative, sowing with a lower seed density will provide equivalent levels of cover over time. When revegetation is performed on the side of a riverdike opposite to the stream, there is not an extreme demand to prevent soil erosion. In such locations, sowing with lower seed density (1000 individuals m^{-2}) should be suitable, as it will achieve equivalent levels of cover by the end of two growing seasons and save some of the expense of gathering regional seeds of *I. sylindrica*.

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