RESTORATION ECOLOGY
The Journal of the Society for Ecological Restoration

RESEARCH ARTICLE

Identification of restoration species for early roadcut slope regeneration using functional group approach

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Current restoration protocols for roadside cut slopes in South Korea involve hydroseeding with exotic species to achieve early greening and soil stabilization. However, exotic species can negatively affect adjacent native ecosystems. This study investigated the functional traits of early colonizers in slope restoration and surrounding environments to inform restoration methods that generate similar communities as those of native ecosystems. Slope vegetation (species density, species cover, upperstory species, canopy cover) and environment (aspect, angle, soil properties) were surveyed from the road edge to the forest boundary, and were classified as three distinct zones: a hydroseeded slope, a transition zone, and the forest edge. Naturally occurring species were classified into functional groups to examine dominant traits during early colonization. Hemicryptophyte or geophyte forest species and forest interior woody species were well established and dominant in transition zones and cut slopes. Potential native species for slope restoration can be identified by examining functional group species in the adjacent forest. These native species can achieve restoration goals and block invasive species in the same functional group. *Festuca arundinacea* (tall fescue), which is reported as an invasive alien species, rapidly spread after introduction for restoration. Thus, continuous monitoring for impact on native communities is required after sowing invasive alien species. Future slope restoration should consider native woody species and perennial forest sedge species that develop rhizomes, and reconsider the use of tall fescue. This study indicates that cut slopes can be appropriately managed to enhance the quality of habitats for native species.

Key words: forest fragmentation, functional group, hydroseeding, revegetation, secondary succession, slope greening

Implications for Practice

- Species with proper functional traits for roadcut slope restoration can be identified by studying the transition zone between cut slope and remnant forest.
- Woody species and hemicryptophyte or geophyte perennial forest sedge species that develop rhizomes and are resistant to physical disturbances are suitable for ecological restoration of roadcut slopes.
- The functional group approach achieves niche preemption that blocks the establishment of invasive species in the same functional group as native species.
- The use of *Festuca arundinacea* in restoration should be reconsidered because it is an invasive alien species in South Korea that rapidly invades adjacent forests.
- Our recommendations were derived from small sample sizes and limited study areas, but are applicable for most South Korean roadcut restorations and ecoregions with temperate broadleaf and mixed forests.

Introduction

Road construction projects involve large-scale earthworks that destroy and modify topographical features in the landscape, such as blasting, excavating, earth-moving, and material handling (Forman & Alexander 1998). Cutting slopes to build a road through a hill or a mountain requires extensive loss of soil, woody vegetation, and habitats (Forman et al. 2003; Gelbard & Belnap 2003; Hansen & Clevenger 2005). The increasing demand for road construction creates roadside slopes as byproducts, and revegetation of these disturbed areas is necessary to prevent soil erosion.

Current methods for revegetating cut slopes include the seeding of exotic vegetation for convenience and low cost, which may limit ecological value and habitat function. For decades, revegetation has been conducted by hydroseeding, which involves spraying a mixture of seeds, water, fertilizers, and fixing materials onto the area being restored (Sheldon & Bradshaw 1977; Bochet & García-Fayos 2004; Matesanz et al. 2006). The hydroseeding methodology was developed because cut slopes generally had vast exposed bedrock or limited soil substrates to support plant growth (Albaladejo Montoro et al. 2000; Bochet et al. 2009). Although hydroseeding is not a panacea for all situations (Matesanz et al. 2006), it has been used

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Author contributions: SP conceived and designed the research and wrote the manuscript draft; SP, JHK performed the surveys and analyzed the data; SP, JHK, CB, SYH edited the manuscript; EJL supervised the research.

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doi: 10.1111/rec.13424
Supporting information at:
http://onlinelibrary.wiley.com/doi/10.1111/rec.13424/suppinfo

globally because it is applicable to many demanding slope environments.

Most of the exposed bedrock on cut slopes in Korea consists of weathered granite, which lacks topsoil and water retention capacity (Cho 1984; Claassen & Zasoski 1998; Lee et al. 2013). Therefore, hydroseeding has been widely used for revegetating cut slopes (Kim 2005). Exotic grass and legume species that are commonly used for slope revegetation in Europe and America have been introduced into Korea without considering species origin (Kim et al. 1998; Kim 2005). These species are not native to the area and have generated a discontinuous landscape with the existing native vegetation.

Roadside ecosystems are often excluded from vegetation surveys because of high disturbance and instability (Rentch et al. 2005). However, the impact of a road on the surrounding ecosystem extends far beyond the road size (Forman & Deblinger 2000). Further studies on restored roadside ecosystems are required to understand their roles and impacts on surrounding ecosystems. If we do not examine these factors, the current roadside slope restoration protocol will continue to contaminate surrounding forests and degrade their ecosystem functions and services. This knowledge gap calls for research on current roadside slope vegetation and broader environment to develop best-practice ecological restoration methods for these disturbed systems.

To investigate the ecological aspects of roadcut slope restoration methods, we surveyed the road slope along three zones: hydroseeded slope, transition zone, and forest edge. Cut slope environments are usually steep and soil substrates, nutrients, and seeds are easily lost, which makes it difficult for plants to become established and results in a barren landscape (Bochet & Garcia-Fayos 2004; Feng et al. 2016). The transition zone is a strip of land between the cut slope and forest that is not hydroseeded, although it has similar conditions to the cut slope. The forest edge was previously the forest interior, but becomes a new fringe of a remnant forest after slope regeneration.

These three zones have distinct environmental conditions, which facilitates investigations of vegetation establishment and invasion. Vegetation development in these three zones can be analyzed to identify native species with a high colonization potential to stabilize the soil and prevent the spread of invasive species, and to monitor invasion from hydroseeded slopes into native surrounding ecosystems. It is important to study the transition zone as it presents an ideal opportunity to investigate colonization processes in competition-free microsites that are not hydroseeded, but few studies have assessed the transition zone (Bochet et al. 2007).

This study utilized the functional group approach to investigate species- and community-level responses to restoration treatments (Laughlin 2014). A functional group refers to a group of plants with ecological similarities that are classified based on morpho-physio-phenological plant traits (Lavorel & Garnier 2002; Violle et al. 2007). Functional trait similarities between species lead to overlapping resource requirements and competition. This approach groups species with functionally similar characteristics into functional categories and identifies the dominant functional group in the cut slope. Consequently, it is possible to select the most appropriate species for specific sites from the functional traits of plants adapted to slope environments.

This study aims to determine the functional characteristics of species that promote natural restoration by identifying species that naturally colonize the transition zone and regenerated slope. Three objectives will achieve this aim: (1) Conduct functional group analysis to examine the characteristics of species that are likely to establish during early stages of slope regeneration; (2) Verify whether abiotic properties of restoration slopes, transition zones, and forest interiors are differentiated during early stages of slope revegetation; (3) Investigate whether species introduced via hydroseeding the cut slope invade the surrounding ecosystem.

Methods

Study Sites

We selected two study areas that represent typical and common roadcut slope sites in the Gyeonggi-do Province, which is part of the metropolitan Seoul area. The study areas were named after the construction site districts at the start and endpoints of each roadway, Jeongok-Yeongjung (JY) and Samga-Daechon (SD) (Fig. 1, Table 1). JY and SD are 100 km distance in Gyeonggi-do. The two regions share similar biota, climatic, and geological features. JY has two sites (JY1, JY2) and SD has five sites (SD1–SD5) (Table 2).

The Republic of Korea is located in the middle latitude temperate climate zone and has four distinct seasons. It is hot and humid in summer, cold and dry in winter, and sunny and dry in spring and autumn. The mean annual temperature of Gyeonggi-do Province is 12–12.5°C, with average maximum temperatures of 29.7°C in August and 2.2°C in January. The mean annual precipitation is 1,200–1,500 mm, with 50–60% of annual precipitation occurring during the summer (Korea Meteorological Administration).

Data Collection

Vegetation surveys were conducted on cut slopes along three environmental gradients: hydroseeded zone, transition zone, and forest interior (Fig. 2). The hydroseeded zone is the area adjacent to the road that was restored by hydroseeding after blasting the granite mountain. The forest edge includes the forested area outside the blasting zone. The transition zone is the area between the hydroseeded zone and the forest boundary, which is characterized by narrow width (less than 30 m), unstable environment, and mix of forest interior and cut slope. The uppermost part of the cut slope was bare in most cases due to frequent erosion and steep grade, which prevented plants from becoming established. Although this area was not hydroseeded, it enabled examination of early-stage interactions among introduced and native plant species and the spread of introduced species.

The study sites were generally surrounded by oak-pine forests and typical woods in the temperate ecosystem. The typical site

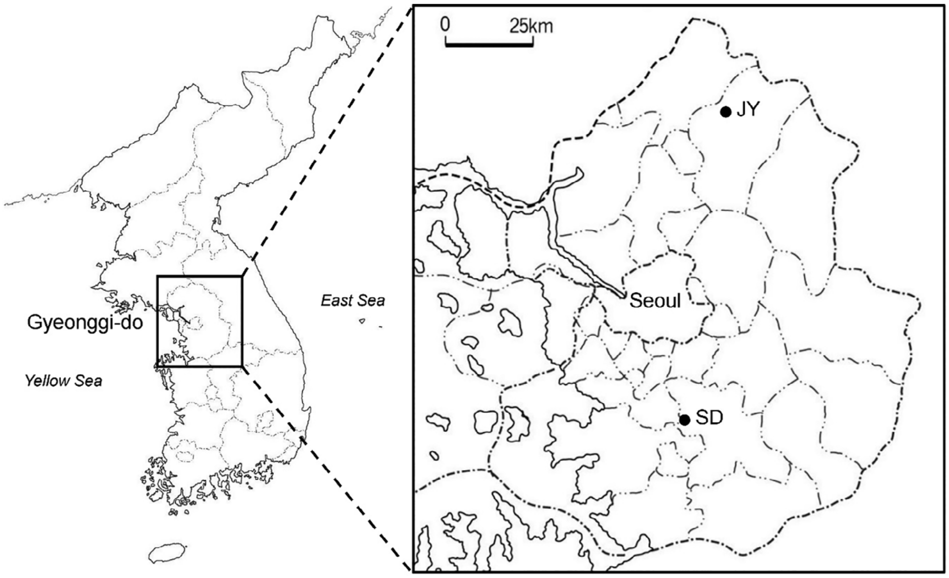

Figure 1. Map of the study sites in Gyeonggi-do Province in the central Korean Peninsula: Jeongok-Yeongjung (JY) road construction site and Samga-Daechon (SD) road construction site.

Table 1. Seven site locations were surveyed in two project areas within Gyeonggi-do Province. Two sites were surveyed with two and five slopes, respectively.

Project	*Date of Slope Construction*	*Sowing Time*	*Slope Name*	*GPS*
Jeongok-Yeongjung (JY)	Dec 2015	Oct 2016	JY 1	38°1′ 5.10″ N 127°12′ 9.76″E
	Dec 2015	Oct 2016	JY 2	38°1′8.31″ N 127°12′ 15.69″E
Samga-Daechon (SD)	May 2013	Jun 2016	SD 1	37°15′ 2.81″ N 127°8′ 31.85″E
	May 2013	Jun 2016	SD 2	37°15′3.56″ N 127°8′ 34.82″E
	May 2013	Jun 2016	SD 3	37°14′59.88″ N 127° 8′ 38.41″E
	Nov 2010	Jun 2016	SD 4	37°14′ 52.00″ N 127° 8′ 56.00″E
	May 2013	Jun 2016	SD 5	37°12′58.00″ N 127°12′ 12.00″E

Table 2. Slope information.

Slope	*Length (m)*	*Height (m)*	*Inclination (°)*	*Aspect*	*Topsoil Type*	*Parent Material*
JY1	118.5	58.51	20–50	N	Gravelly loam	Residuum on granite gneiss
JY2	93.43	30.63	30–50	S	Gravelly loam	Residuum on granite gneiss
SD1	148.75	46.35	20–50	NE	Gravelly sandy loam	Residuum on granite
SD2	106.75	25.92	20–50	SW	Gravelly sandy loam	Residuum on granite
SD3	101.65	47.8	20–40	NE	Gravelly sandy loam	Residuum on granite
SD4	103.02	51.63	20–60	SW	Gravelly sandy loam	Residuum on granite gneiss
SD5	95.53	33.84	10–50	NE	Gravelly loam	Residuum on granite gneiss

pedon was gravelly loam on granite (National Institute of Agricultural Sciences, https://soil.rda.go.kr, accessed 1 Nov 2020). We considered safety when selecting locations for investigating forest interior vegetation on the cut slopes. Hydroseeding on SD and JY sites was conducted in June 2016 and October 2016, respectively (Table 1). The seed mixtures for hydroseeding include woody/non-woody species and native/exotic species (Table 3), with 62.5% of sown species as non-native species that can spread extensively out of the hydroseeded site in Korea. Seed mixtures were similar across the seven sites and are commonly used in South Korea (Ministry of Land, Transport and Maritime Affairs 2009). The field surveys were conducted during September–October 2017.

The slope length was 109.66 ± 19.08 m (mean ± SE), and slope height was 42.10 ± 12.1 m (Table 2). We set three to five line transects depending on the slope length, and each transect was 45–50 m long and perpendicular to the roadway. Each area was explored using 1 m × 1 m quadrats at an interval of 7 m to survey understory vegetation along the line transects and identify the species composition along the environmental gradient

(Fig. 2). The total length of forest edge and hydroseeded slope was 24 m, whereas the transition zone length was 5–10 m. Due to the narrow transition zone width, the total of 193 quadrats studied consisted of 55 quadrats in the transition zone and 69 quadrats in each of the forest edge and hydroseeded slope. For each 1 m × 1 m quadrat, we recorded species identity, number of plants, upperstory species, and percent tree canopy coverage, and collected a soil sample. The percent tree canopy coverage was estimated by one investigator. Slope aspect and slope angle were recorded for each quadrat (Table 2). The presence of sown and self-sown (naturally occurring) species was recorded for each transect. The records of observed species and lists of planted species were checked with the Environmental Impact Assessment (EIA) statement for each road construction project (Environmental Impact Statement of JY Road Construction 2003, 2007; Table 2). The species introduction status was ascertained from Korean Plant Names Index (2018). The nomenclature is based on that of Lee (2014).

Figure 2. Three zones of the surveyed slopes: forest edge, transition zone, and hydroseeded slope. Eachslope was evaluated using 1 m × 1 m quadrats at an interval of 7 m to survey understory vegetation along the line transects and identify the species composition along the environmental gradient. The interval between each quadratis 7 m, but quadrats in transition zones had 3–7 m intervals depending on the transition zone size.

Functional Classification

We analyzed functional traits to explore the characteristics of plant communities at the study sites (McGill et al. 2006). Data on seed mass, height at maturity, woodiness, longevity, photosynthetic pathway, and cotyledon form were compiled from the Korean Plant Names Index (2018), TRY Plant Trait Database (Kattge et al. 2011), United States Department of Agriculture (USDA) Plants Database (2020), and Lee (2014), whereas data on disseminules, dormancy, and growth forms were compiled from Raunkiær's life form classification (Raunkiær 1934; Lee 2014). These functional traits are relevant for the leaf-height-seed plant ecology strategy scheme (Westoby 1998), as the common core list of plant traits related to dispersal, establishment, and persistence (Weiher et al. 1999), and functional traits related to competitive ability and growth (Funk et al. 2008). It is important to classify species into functional groups based on these relevant traits to discriminate among plant identities and characteristics (Byun et al. 2013).

Table 3. Plant species sown for roadcut slope revegetation at two road construction sites in Korea [Jeongok-Yeongjung (JY) and Samga-Daechon (SD)]. Non-native species spread widely out of the hydroseeded slope zone and are regarded as invasive species in Korea. EIA listed denotes species that were recorded on the environmental impact assessment statement, which was completed before the road construction project started.

Plant Species	*Status*	*Growth Form*	*Sites*	*EIA Listed*
Indigofera amblyantha	Non-native	Shrub	JY, SD	–
Lespedeza cyrtobotrya	Native	Shrub	JY, SD	JY, SD
Rhus javanica	Native	Tree	JY, SD	JY, SD
Albizia julibrissin	Native	Tree	JY, SD	JY
Dendranthema boreale	Native	Forb/herb	JY, SD	JY
Coreopsis lanceolata	Non-native	Forb/herb	JY, SD	–
Silene armeria	Non-native	Forb/herb	JY, SD	–
Dianthus chinensis	Native	Forb/herb	JY, SD	JY
Leucanthemum x superbum	Non-native	Forb/herb	JY, SD	–
Lotus corniculatus	Non-native	Forb/herb	JY, SD	–
Lespedeza cuneata	Native	Subshrub,Forb/herb	JY, SD	–
Medicago sativa	Non-native	Forb/herb	JY, SD	–
Coreopsis tinctoria	Non-native	Forb/herb	JY, SD	–
Centaurea cyanus	Non-native	Forb/herb	JY, SD	–
Artemisia princeps	Native	Forb/herb	JY, SD	JY, SD
Poa pratensis	Non-native	Graminoid	JY, SD	–
Lolium perenne	Non-native	Graminoid	JY, SD	–
Festuca arundinacea	Non-native	Graminoid	JY, SD	–
Rudbeckia bicolor	Non-native	Forb/herb	SD	–
Cosmos sulphureus	Non-native	Forb/herb	SD	–
Arundinella hirta	Native	Graminoid	SD	JY, SD
Aster yomena	Native	Forb/herb	SD	SD
Taraxacum officinale	Non-native	Forb/herb	SD	JY, SD

All classification procedures were performed using R ver. 3.5.3 (R Core Team 2019). The number of ideal clusters was determined before classification using the "NbClust" function of the *NbClust* package (Charrad et al. 2014). Plant species were sorted by cluster analysis with the ward option using the "hclust" function. Only naturally occurring species have been investigated using the functional group approach. Clustering according to functional traits was targeted to species in the transition zone and the hydroseeded slope. Differences between each functional group were confirmed by analysis of similarities (ANOSIM, Clarke 1993) and similarity percentage (SIMPER, Clarke 1993). The clustering result was visualized using a non-metric multidimensional scaling (NMDS) plot (Kruskal 1964), and the set of traits was tested using maximum correlation with community dissimilarities ($p < 0.05$).

Soil Analysis

Soil samples were collected from three points at 3 cm below the organic matter layer in each quadrat. Samples were dried, sieved through 2 mm mesh, and analyzed for soil characteristics by laboratory experiments. Electrical conductivity (Slavich & Petterson 1993) and pH (ISO 10390:2005) were determined by measuring a solution of air-dried soil:distilled water (1:5 v/v) using a glass electrode (PC 2700, Eutech Instruments, Singapore). Soil moisture content was quantified by drying samples in the oven at 105°C for 24 h. Soil organic matter was measured after heating the sample in an electric furnace at 550°C for 4 h (Boyle 2004). NO_3–N and NH_4–N were extracted from the soil with 2 M KCl (Kim et al. 2004), and their quantities were measured using the hydrazine-copper reduction and indophenol methods, respectively (Kamphake et al. 1967; Scheiner 1976). PO_4–P was extracted from soil using Bray's method and then quantitated using the ascorbic acid reduction method (Bray & Kurtz 1945).

Statistical Analysis

Soil abiotic factors, including soil properties and slope inclination, were analyzed using the Kruskal–Wallis test to determine any differences among slopes. Self-sown species were divided into functional groups to determine the species belonging to each zone. Then, the coverage of each functional group was analyzed using a Kruskal–Wallis non-parametric approach. When statistically significant differences were found between functional groups, a post hoc test was conducted by pairwise comparisons using the Conover test (Conover & Iman 1979). Differences in environmental variables for the slope landscape positions were examined using the Kruskal–Wallis test and the Conover pairwise test. Species were arrayed by coverage within each slope zone to explore species dominance in the forest edge, transition zone, and hydroseeded slope. ANOSIM and SIMPER analyses were conducted based on the Bray–Curtis distance of the total plant species observed in each region. A bootstrap randomization of 999 replicates was performed with ANOSIM. NMDS plots were generated to ascertain the species distribution. The relationship between species occurrence and environmental variables (e.g. soil properties) was investigated by performing canonical correspondence analysis (CCA, Cajo 1986). The Monte Carlo permutation test was used to verify the level of significance for each species to explain species composition gradients. The spread of hydroseeded (sown) species was determined by analyzing the continuous distribution of sown species coverage in the transition zone and the forest interior. All statistical analyses were performed using R ver. 3.5.3 (R Core Team 2019).

Results

Plant Species in the Forest Edge, Hydroseed Slope, and Transition Zone Environments

A total of 126 vascular plant species were identified in the 193 sample quadrats, with 69 plots and 55 species in the forest edge, 69 plots and 84 species in the hydroseeded slope, and 55 plots and 73 species in the transition zone.

Emblematic forest plants of the central Korean Peninsula were dominant in the forest edge. Understory shrub coverage was high, including *Rhododendron mucronulatum*, *Styrax japonicus*, and *Smilax sieboldii*. Tree species commonly found in the central Korean Peninsula were dominant (Table S1), such as *Castanea crenata*, *Lindera obtusiloba*, and *Quercus mongolica*. Among forbs, *Oplismenus undulatifolius* was dominant.

Hydroseeded slopes were dominated by sown exotic and native species. Self-sown species also were abundant, which originated as seeds in the soil used during road construction or in rain runoff from adjacent forests. Dominant sown species included *Coreopsis lanceolata*, *Festuca arundinacea*, and *Lespedeza cyrtobotrya*. Dominant self-sown species included *Digitaria ciliaris* and *Erechtites hieracifolia* (Table S2).

Forest edge species often occurred in the transition zone, including *Lespedeza bicolor*, *Spodiopogon sibiricus*, and *Robinia pseudoacacia*. Sown species such as *C. lanceolata*, *F. arundinacea*, *L. bicolor*, *Rhus javanica*, and *Artemisia princeps* were frequently observed as native forest edge species (Table S3).

Functional Properties of Self-Sown Species in the Hydroseeded Slope and Transition Zone

We recorded 64 self-sown species on the hydroseeded slope (Tables 4 and S2, Figs. S1and S2). Several species (S-FG) naturally became established on the cut slopes; among these species, there was a significant difference between the abundances of S-FG1, S-FG2, S-FG3, S-FG4, and S-FG7 in the hydroseeded slopes ($p < 0.05$, Fig. 3). S-FG3 was the most dominant naturally established species during early stages of slope restoration.

A total of 73 self-sown species classified into seven functional groups (T-FG) appeared in the transition zone (Tables 4 and S3, Figs. S2 and S3). Functional group analysis of the transition zone showed a statistically significant difference between T-FG1, T-FG3, and T-FG5 ($p < 0.05$, Fig. 4). T-FG1 and T-FG3 were the most dominant naturally established species in the transition zone.

Table 4. Functional groups (FG) defined for slope and transition zones.

	Hydroseeded Slope (S-FG)		*Transition Zone (T-FG)*	
	Functional traits	*No. of species*	*Functional traits*	*No. of species*
FG1	Dicotyledonous herbaceous plants	24	Shrubs	8
FG2	Annual monocotyledonous plants (C4 plants)	9	Grass and sedge, no special mode of dissemination	17
FG3	Perennial monocotyledonous plants (C3 plants), some dicotyledonous plants, dormancy type with hemicryptophyte or geophyte	8	Canopy trees	12
FG4	Canopy trees	5	Understory trees	6
FG5	Understory trees or shrubs	9	Forbs and herbs	21
FG6	Herbaceous vines	4	Herbaceous vines	6
FG7	Dicotyledonous with growth type of pseudo-rosette form or procumbent form	5	Dicotyledonous with growth type of rosette or partial rosette form	3

Relationship Between Plant Community Populations and Environmental Conditions

The community of plant species in the three zones differed according to the ANOSIM results ($R = 0.33$, $p < 0.001$). SIMPER indicated that forest edge and transition zone were 7.56% similar, transition zone and hydroseeded slope were 9.52% similar, and forest edge and hydroseeded slope were 1.88% similar (Tables S4 and S5, Fig. S4). Species in forest interior and revegetated slope were dissimilar, whereas transition zone harbored a mix of species from forest edge and hydroseeded slope. The number of plants, plant coverage (%), tree canopy coverage (%), and canopy trees did not significantly differ between the slopes.

Next, we analyzed several environmental variables to determine the relationship between plant communities and the environment. Although no significant differences were detected between the seven sites (Kruskal–Wallis test, $p > 0.05$), the environmental characteristics of each zone were distinct (Table 5). Soil nutrients (NO_3–N, NH_4–N, and PO_4–P) differed between slope zones (Conover's test, $p < 0.05$). Moisture content and organic matter content differed between forest edge and transition zone/restored slope (Conover's test, $p < 0.05$). The CCA plot was generated using species coverage and abiotic factors, and revealed that the three zones had different species and different physical environments (Fig. 5). The first axis explained 38.6% of the variation, and the second axis explained 20.5% of the variation. The Monte Carlo permutation test indicated that species abundance and environmental variables were significantly correlated with the first and second axes ($p < 0.05$). Environmental variables that were most correlated with the first axis were pH, moisture content, slope, and organic matter.

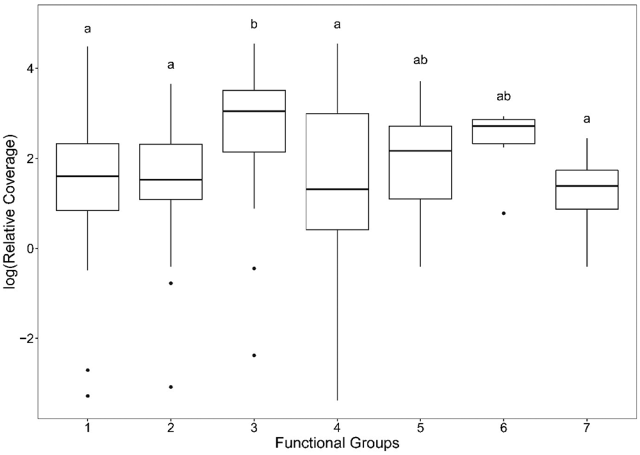

Figure 3. Relative coverage of species by functional group in hydroseeded slopes. Letters represent significant differences between treatments (Conover test, $p < 0.05$). S-FG1, dicotyledonous herbaceous plants; S-FG2, annual monocotyledonous C4 plants; S-FG3, primarily perennial monocotyledonous C3 plants with some dicotyledonous plants. The dominant life forms of S-FG3 were hemicryptophyte or geophyte. S-FG4, canopy trees; S-FG5, understory trees or shrubs; S-FG6, herbaceous vines; S-FG7, dicotyledonous plants with pseudo-rosetteor procumbent growth types.

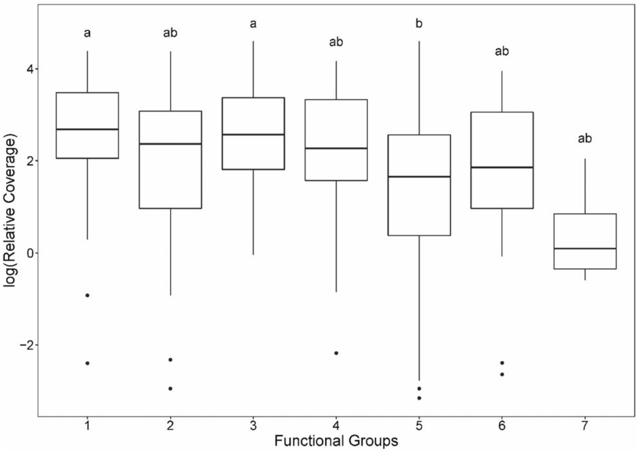

Figure 4. Relative species coverage by functional group in transition zones. Letters represent significant differences between treatments (Conover test, $p < 0.05$). T-FG1, shrubs; T-FG2, primarily grass and sedge; T-FG3, canopy trees; T-FG4, understory trees; T-FG6, herbaceous vines.T-FG7 species were dicotyledonous with growth types classified as rosette or partial rosette growth forms; T-FG5 species were herbaceous plants that did not belong to other groups.

Table 5. Abiotic factors in different landscape positions (average ± SE). Subscript letters represent significant differences among slope environments.

	NO_3–N (mg kg^{-1})	NH_4–N (mg kg^{-1})	PO_4–P (mg kg^{-1})	Moisture Content (%)	Organic Matter (%)	pH	Electrical Conductivity (μS cm^{-1})	Slope (°)
Forest edge	6.08 ± 0.8^{a}	16.95 ± 1.5	2.44 ± 0.4^{b}	15.60 ± 0.5^{a}	8.53 ± 0.5^{a}	4.52 ± 0.0^{a}	158.1 ± 108.7^{ab}	16.28 ± 1.1^{b}
Transition zone	2.67 ± 0.6^{b}	14.82 ± 1.6	5.72 ± 1.4^{b}	12.74 ± 0.7^{b}	6.28 ± 0.6^{b}	4.85 ± 0.1^{b}	36.58 ± 2.6^{b}	19.33 ± 1.3^{b}
Hydroseeded slope	7.07 ± 2.3^{ab}	12.87 ± 1.0	25.10 ± 4.3^{a}	10.70 ± 0.7^{b}	5.49 ± 0.2^{b}	6.18 ± 0.1^{c}	142.60 ± 23.8^{a}	34.14 ± 1.3^{a}

Distribution of Sown Species Beyond the Hydroseeded Slope

We analyzed the distribution of sown species throughout the restored slope, transition zone, and forest edge (Fig. 6). Of the 20 hydroseeded species, 11 occurred in the transition zone. Among them, three species with high coverage in the transition zone also were confirmed in the forest edge: *R. javanica*, *L. bicolor*, and *F. arundinacea*.

Discussion

Functional Traits of Plant Species in the Early Successional Stage of Roadcut Slopes

The functional properties of recorded species were synthesized to identify effective species for the ecological restoration of road slopes. The S-FG3 perennial sedges (e.g. *Carex* spp.) were commonly distributed in Korean forests and had the most suitable traits for slopes. Sedge species propagate via barochory (gravity-mediated dispersal), and they were likely introduced to the slopes via animal activity. These plants utilize vegetative propagation, which appears to be the most prevalent type of plant propagation during early slope revegetation when there are frequent disturbances from fixing and managing slopes. Thus, the potential of rapid expansion by vegetative propagation would allow these species to prosper in the slope environment. Their geophyte and hemicryptophyte life forms with growth zones at ground level or below confer a high probability of survival despite the disturbances caused by slope work (Dale et al. 2002).

Plants that naturally grow in the transition zone can be evaluated to identify candidates for revegetating the cut slopes. Shrubs and trees have a high potential of inhabiting the transition zone during the early stages of revegetation. Species with these traits are abundant in forests, suggesting that the young woody plants in transition zones are likely to have originated from the forest. The seeds drop from trees and get mixed with the soil, eventually populating the transition zone.

S-FG3 perennial sedge species were repeatedly observed in T-FG2, which also achieved high species coverage following T-FG1 and T-FG3. Similarly, T-FG1 shrubs also were observed in S-FG5, which was the dominant group following S-FG3. The abundance of woody species seemed to be affected by proximity to mother trees and seed sources; thus, transition zone species are consistent with forest species populations. The abundances of T-FGs and similarities between T-FGs and S-FGs indicate that S-FG3, T-FG1, and T-FG3 species are valid candidates for the natural recovery and revegetation of roadcut slopes.

Abiotic Properties of the Slope Environment During Early Roadcut Restoration

Analyses of abiotic properties indicated that forest, slope, and transition zone differed after slope generation, with transition zone properties that were between forest and slope conditions. This was reflected in the transition zone vegetation, which was a mosaic of that in forest and slope zones. The primary differences between transition zone and revegetated slope (e.g. PO_4–P and pH) appeared to originate in the hydroseeding

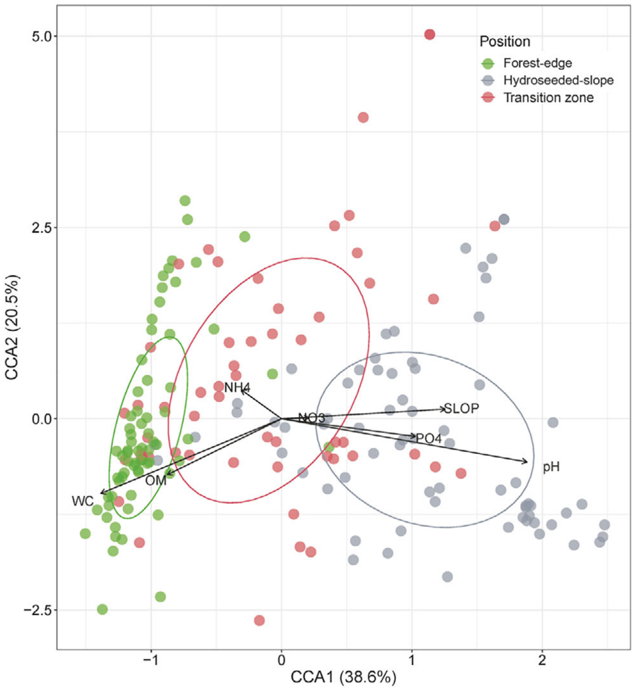

Figure 5. Canonical correspondence analysis (CCA) ordination plot shows the relationships between193 quadrats based on species composition and environmental variables. Thethree zones display distinct abiotic properties. WC, soil water content; OM,soil organic matter; SLOP, slope inclination.

treatment and manure spraying. This treatment was necessary to grow vegetation as a topsoil layer cannot act as a nursery bed on cut slopes. Thus, naturally growing species did not differ due to natural abiotic differences. These combined results suggested that species occurring in the transition zone were suitable candidates for slope revegetation. Supplementing the topsoil layer will help woody plants take root and facilitate ecological restoration.

An increase in forest edge habitat may promote species invasion into the forest interior. The plant community is determined by dispersal limitation and the ability to become established and persist (Pywell et al. 2003). However, abiotic factors also can limit species establishment (Thompson et al. 2001; Bullock et al. 2002; Tormo et al. 2006; Bochet & García-Fayos 2015), which is one reason why different species were dominant in different zones. Our results indicated that the forest interior soil properties included low pH due to decaying leaves (Hur & Joo 2002; Osman 2013), thick leaf litter mats (Normann et al. 2016), and high moisture levels (Craib 1929). These properties were altered along the forest edge, resulting in increased sunlight (Davies-Colley et al. 2000), reduced leaf litter, decreased humidity, increased soil temperature (Jung et al. 2017b), and altered wind dynamics (Chen et al. 1993). Thus, the forest edge was more susceptible to plants invading from the slope and the transition zone (Froud-Williams et al. 1983; Cadenasso & Pickett 2001). The slope zone had high resource availability and was vulnerable to invasion by species with rapid dissemination and growth (Davis et al. 2000). These combined factors were responsible for the successional restoration stages of the slope. A previous study investigating the stages of slope revegetation reported that hydroseeded herbaceous plants were dominant at first, but as PO_4 levels dropped in the following 2–3 years, most herbaceous plants diminished and only plants that can survive harsh conditions remained (Kim 1998).

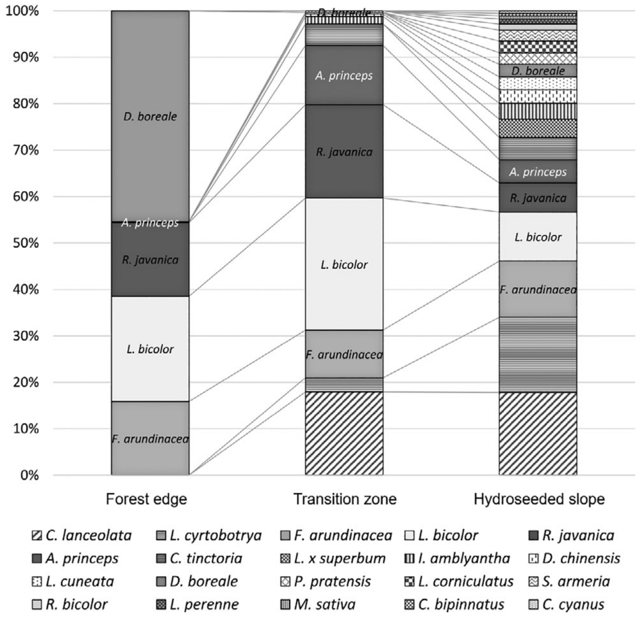

Figure 6. Relative coverage of the top 10 plant species on revegetated slopes in different landscape positions. *C. lanceolata, Coreopsis lanceolata*; *L. cyrtobotrya, Lespedeza cyrtobotrya*; *F. arundinacea, Festuca arundinacea*; *L. bicolor, Lespedeza bicolor*; *R. javanica, Rhus javanica*; *A. princeps, Artemisia princeps*; *C. tinctoria, Coreopsis tinctoria*; *L. x superbum, Leucanthemum x superbum*; *I. amblyantha, Indigofera amblyantha*; *D. chinensis, Dianthus chinensis*; *L. cuneata, Lespedeza cuneata*; *D. boreale, Dendranthema boreale*; *L. corniculatus, Lotus corniculatus*; *S. armeria, Silene armeria*; *R. bicolor, Rudbeckia bicolor*; *L. perenne, Lolium perenne*; *M. sativa, Medicago sativa*; *C. bipinnatus, Cosmos bipinnatus*; *C. cyanus, Centaurea cyanus*.

Impact of Introduced Species on the Surrounding Ecosystem

Introduced plants may disturb the native ecosystem if they invade remnant vegetation. This study captured the invasion of *Festuca arundinacea* (tall fescue) into the forest edge. Hydroseeded *R. javanica*, *L. bicolor*, and *F. arundinacea* were identified in the forest edge. *R. javanica* and *L. bicolor* were common (naturally occurring) in the forest edge and interior, but *F. arundinacea* was only introduced via hydroseeding the cut slope. Thus, we cannot assume that *R. javanica* and *L. bicolor* invaded the forest edge after hydroseeding the cut slope, but can assume that *F. arundinacea* was an invasive species because it was not recorded in the species inventory of the EIA conducted before slope generation.

F. arundinacea is native to Europe and North Africa, and is considered as a worldwide invasive species and noxious weed in native grasslands, woodlands, and other habitats, where it reduces native biodiversity through competition. This species is expanding rapidly along roadsides in other regions of Korea, indicating high invasiveness (Chung et al. 2015; Jung et al. 2017a). These observations suggest that slope regeneration may be the source of invasive tall fescue in Korea. This fescue is a bunchgrass species, has an extensive root system and robust adaptive capacity, and tolerates a wide range of abiotic conditions (Gibson & Newman 2001; Henson 2001). We observed that *F. arundinacea* rapidly penetrated the forest within 1 year after sowing, despite its reproductive methods of gravity dispersion, rhizomes, and animal dispersion (Gibson & Newman 2001). Although this study did not record a large number of individual fescue plants in the forest, there is a possibility of further dispersion assisted by animal vectors (Campbell & Gibson 2001).

F. arundinacea may be useful for early colonization of roadcut slopes in Europe and North Africa, where it is a native species. However, it degrades its surroundings as an alien species because it is difficult for native plants to replace *F. arundinacea* and other invasive graminoids (Kameyama 1977; Woo et al. 1996; Kim 1997). Even if native plants take root alongside these invasive graminoids, they will likely be outcompeted by the alien species. The adverse effects of invasive fescue species on regional biodiversity have been reported in other countries and regions (Walck et al. 1999; Spyreas et al. 2001; Rudgers et al. 2007; NIE 2019). Our study confirmed the invasive spread of *F. arundinacea* into the forest where other species have difficulty invading; thus, it has a high potential to disrupt the native ecosystem. We recommend that the use of *F. arundinacea* for slope restoration should be reconsidered, and that areas where it has been introduced via hydroseeding should be continuously monitored for adverse effects of this invasive species.

Functional Group Analysis to Identify Efficient Colonizers for Roadcut Slope Restoration

Although the small sample size in this study limits its applications, road construction and roadcut slope regeneration protocols in South Korea utilize standard guidelines. Our study suggests that S-FG3 species have high potential for active revegetation of cut slopes, whereas T-FG3 and T-FG1 species are good candidates for natural establishment of cut slopes. Species that belong to these functional groups (similar functional characteristics) are good candidates for active roadcut slope restoration. Native S-FG3 species in Korea include *Lysimachia clethroides*, *Polygonatum odoratum*, *Calamagrostis arundinacea*, *Oplismenus undulatifolius*, *Carex breviculmis*, *Carex humilis*, and *Carex lanceolata*. These species are effective and rapid colonizers that occupy available niches in bare slopes created by road construction.

The theory of priority effect explains the importance of “first come, first served” syndrome (Stuble & Souza 2016). Early and fast-growing species preempt a niche and inhibit slower-growing species during community assembly. S-FG3 species prevent soil erosion and landslides on slopes, and may block the establishment of invasive species such as *Phytolacca americana* (which also belongs to S-FG3). The sedge perennial functional group can serve as an efficient early colonizer in roadcut slopes, whereas later succession stages naturally lead to longer-lived tall trees (Pickett et al. 1987). The plant communities occurring in the transition zone and forest edge may reveal this succession process with time after active revegetation.

The dominance of invasive species in cut slopes due to current hydroseeding practices is a severe problem in the Republic of Korea that requires urgent action by construction planners and authorities. Although hydroseeding is intended to assist natural restoration by alleviating harsh conditions for natural succession, many plants cannot withstand the lack of nutrients and intense summer heat. Instead, robust grasses such as *F. arundinacea* (tall fescue), *Poa pratensis* (Kentucky bluegrass), *Eragrostis curvula* (weeping lovegrass), and *Dactylis glomerata* (orchard grass) remained and obstructed natural succession for decades after slope restoration (Kim et al. 1998; Kil & Kim 2014). These exotic species occur along the roadside in Korea (Kim et al. 1998; Kil & Kim 2014), and they are highly likely to survive and thrive in disturbed habitats (Prach & Pyšek, 2001). Some of these species may invade the forest, thereby changing the species composition and eventually altering the forest ecosystem.

The soil used in road construction must be addressed. Naturally, regenerated vegetation is primarily derived from seeds in rain runoff or seed banks in the soil (de la Riva et al. 2011; Mola et al. 2011). A previous study evaluated the use of buried seed banks of existing forests for ecological restoration of cut slopes (Hosogi et al. 2006). However, in practice, soil from other areas is used to cover the cut slopes, and it is highly likely to contain seeds of invasive plants.

In summary, it is imperative to recognize that current road slope restoration protocols provide an ideal environment for the propagation of invasive alien species. Natural restoration of cut slopes requires an understanding of the site-specific ecosystem. A careful study and plan should be conducted to achieve ecosystem restoration for cut slopes. This study offers novel insights into the impacts of current revegetation practices and provides guidelines for planning cut slope restoration protocols.

Acknowledgments

We thank Shin Wonhyeop and Oh Minwoo for field work assistance, and Park Euiseon and Park Jeongwook for providing field information. This work was supported by grants from the National Institute of Ecology (NIE-C-2017-04) and the National Research Foundation of Korea (NRF) funded by the Korean government (MSIT) (2018R1C1B6005351).

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Supporting Information

The following information may be found in the online version of this article:

Table S1. Top 20 understory plant species by coverage in the forest edge zone. T, species that appeared in the transition zone.

Table S2. Top 20 plant species by coverage in the hydroseeded slope. T, species that appeared in the transition zone.

Table S3. Top 20 plant species by coverage in the transition zone. F, species that appeared in the forest edge; P, species that appeared on the hydroseeded slope; Hydroseeded, species that were sown for revegetation.

Table S4. Results of SIMPER analysis of species composition dissimilarity using presence-absence data in the forest edge and transition zone.

Table S5. Results of SIMPER analysis of species composition dissimilarity using presence-absence data in the transition zone and hydroseeded slope.

Table S6. Results of SIMPER analysis of species composition dissimilarity using presence-absence data in the forest edge and hydroseeded slope.

Figure S1. Classification of self-sown plant species on hydroseeded slopes.

Figure S2. Non-metric multidimensional scaling (NMDS) ordination shows the functional distribution of plant species that occurred on hydroseeded slopes.

Figure S3. Classification of self-sown plant species in transition zones.

Figure S4. Non-metric multidimensional scaling (NMDS) ordination shows the functional distribution of plant species that occurred in transition zones.

Coordinating Editor: Sara Ashpole

Received: 12 January, 2021; First decision: 16 February, 2021; Revised: 28 April, 2021; Accepted: 28 April, 2021