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Road effects on vegetation composition in a saline environment

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Abstract

Aims

Road effects from maintenance and traffic have the potential to alter plant communities, but the exact relationships between these effects and changes in plant community composition have not often been studied in diverse environments. To determine the direction and level of community composition changes in saline environment due to road effects, we conducted a study along roads of different ages and in nearby non-road (i.e. natural) areas in the Yellow River Delta, China. Additionally, to potentially elucidate the mechanisms underlying the changes in the richness and composition of plant communities along roads, we evaluated physiochemical changes in soil of roadside and non-road areas.

Methods

Floristic and environmental data were collected along roadside of different ages and nearby non-road areas. To evaluate plant communities at each site, six 2 m × 2 m quadrats were placed at 3-m intervals along roads and six quadrats were arranged randomly in non-road areas. To determine the difference in plant community composition between roadside and non-road areas, we measured species richness and the abundance of each species, examined species turnover and floristic dissimilarity between the two areas and positioned plant species and sites in an abstract multivariate space. Plant community (species richness, percentage of halophytes) and soil physicochemical properties (pH, salinity, moisture content, bulk density, nitrate and ammonium nitrogen concentration) were compared between roadside and non-road areas (young roadside vs. corresponding non-road areas, old roadside vs. corresponding non-road areas) by using *t*-tests. Classification and ordination techniques were used to examine the relationship between vegetation and related environmental variables in both roadside and non-road areas.

Important Findings

For both the young and old roadside areas, species richness in roadside areas was significantly higher than in non-road areas and high floristic dissimilarity values indicated that roadside and non-road areas differed greatly in community composition. In both the young and old roadside areas, the plant communities in roadside areas had lower percentages of halophytes than non-road communities. Correspondence analysis and two-way indicator species analysis showed that halophytes dominated in the non-road areas, while a number of typical non-salt-tolerant species dominated in the roadside areas. Compared to non-road areas, activities associated with roads significantly decreased soil moisture, bulk density and salinity and increased soil pH and nitrate content. Forward selection for the environmental variables in canonical correspondence analysis showed that soil salinity was the most important factor related to the variation of species composition between roadside and non-road areas. Our study demonstrates that road effects have a significant impact on the associated vegetation and soil, and these changes are consistent across roads of different ages in our system.

Keywords: road effect • salinization • species composition • vegetation–environment relationships

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INTRODUCTION

Human activities often cause habitat fragmentation and loss, which may influence persistence of plant populations, community composition and biodiversity (Damschen *et al.* 2006; Saunders *et al.* 2002). To effectively conserve natural habitats and manage seminatural habitats, it is crucial to understand the relationship between human activities and natural communities (Vandvik *et al.* 2005).

Road construction, maintenance and traffic are major and increasing human activities worldwide (Bennett 1991; Lugo and Gucinski 2000; Trombulak and Frissell 2000). One impact of roads on plant communities is changes in species composition, e.g. transforming native vegetation into vegetation dominated by nonnative plants (Auerbach *et al.* 1997; Forman *et al.* 2002; Greenberg *et al.* 1997). Another effect of roads is changes in physical properties of soil, e.g. soil compaction in roadside areas (Trombulak and Frissell 2000). Roads can also indirectly influence biological and chemical properties of soil, including organic content, soil biota, chemical conditions and soil microclimatic conditions (Johnston FM and Johnston SW 2004; Trombulak and Frissell 2000). These changes in soil can also affect plant growth, species diversity and composition (Forman and Alexander 1998; Spellerberg 1998). Greenberg *et al.* (1997) found that the addition of clay and lime rock substrates in road construction increased soil pH and nutrient levels (aluminum, calcium, phosphorus and potassium), which enhanced the growth of uncharacteristic and nonindigenous plants and decreased the cover and number of characteristic plant species along roads. Angold (1997) found that the oxides of nitrogen from traffic exhausts promoted the growth of vascular plants, notably heather and grass species, and decreased the abundance and health of lichens near roads compared to remote survey lines. Rutter and Thompson (1986) found that the use of de-icing salt in the winter in European countries led to higher salinity and created an environment conducive to colonization by salt marsh species along roads. Johnston FM and Johnston SW (2004) demonstrated that disturbances from road construction and maintenance caused a high concentration of alien species along roads, with higher soil pH and exchangeable levels of calcium and potassium, while native species dominated the area 10 m away from the road verge, which had higher humus levels and electrical conductivity than road verges. There is no denying that road effects have the potential to alter soil properties and plant communities, but the exact relationship between these effects and changes in community composition may vary across different environments.

Researchers have emphasized spatial scale when evaluating road effects upon plant communities because road effects are most prevalent near roadsides and decline along a gradient from the road verge to the more distant natural area (Watkins *et al.* 2003). Accordingly, previous studies have often compared species composition at different distances from the road verge. However, the cumulative effects of roads on a temporal scale are often neglected (Lugo and Gucinski 2000). It is important to consider road effects across temporal scales for at least two reasons. First, different impacts of roads upon communities occur in different phases, with destructive effects being observed during the road construction phase and gradual effects occurring during the operational phase (Spellerberg 1998). Second, it is believed that the size of road effects accumulates over time (Lugo and Gucinski 2000) and that old roads are typically subject to higher cumulative levels of traffic and maintenance than young roads (Cameron and Bayne 2009).

Road age is an appropriate variable to quantify the time since road construction and the accumulation of road effects (Cameron and Bayne 2009), but determining road age is challenging. If there is a lack of local road annals or other detailed records of road construction or rebuilding, researchers usually quantify road age in terms of cadastral maps and aerial photos that document the location of roads. Although this method is simple, in almost all cases, the date that a road was built cannot be narrowed down to a single year due to gaps in coverage ranging from one to several years in length (Cameron and Bayne 2009). Instead, the date of construction is assumed to be during some broad time span within an uncertain range (Cameron and Bayne 2009; Spooner and Smallbone 2009). Additionally, other factors, including road attributes (pavement features, width, traffic volume and maintenance activities), the biodiversity and community succession of roadside biota (Flory and Clay 2009) and various anthropogenic activities may determine the road effects (Lugo and Gucinski 2000). An ideal method of minimizing these factors is identifying a road system that has clear historical records and similar attributes in an area in which anthropogenic activities are monotonous and measurable.

Our study area, the Yellow River Delta (YRD) of China, provides an ideal road ecosystem for examining the temporal change of species composition during the road operational phase. The YRD has undergone severe soil salinization, and much of the land is dominated by halophytes. As a result, plant communities consist of herbaceous plants and species composition is relatively homogeneous. The YRD is a protogenous ecosystem with predominantly primary vegetation succession and is susceptible to anthropogenic activities. Additionally, the large-scale anthropogenic activities that have occurred in this area are relatively simple and definite, consisting primarily of oil exploitation and associated transportation construction. In contrast to other areas, road construction here is mostly driven by expansion of oil field development; therefore, historical records of oil field and road construction are detailed and available from local administrations. Finally, before the road system was created, the area was not exploited for other purposes.

This study describes the effects of roads on species composition in a saline environment. We wanted to determine the direction and level of community composition changes, analyze the mechanisms that drive these changes and determine if these changes were affected by road age. Inspired by the previous studies, we hypothesized that road effects have induced plant species composition changes via alteration of soil characteristics adjacent to the road. To examine this hypothesis, the occurrence of different plant species and soil characteristics were compared between roadside areas of different ages and their corresponding non-road areas. In addition, we determined which soil characteristics were most closely related to the species richness and composition changes in both roadside and non-road areas.

MATERIALS AND METHODS

Study area

This study was conducted in the northern area of the YRD of China (118°05′–119°15′E, 37°25′–38°10′N), which is composed of several superlobes resulting from shifts of the lower river channel. The tail channel of the Yellow River has changed 10 times since 1885, successively forming the contemporary delta (composed of 3 sub-deltas) and the modern delta (composed of 4 sub-deltas; Fig. 1). The YRD is the youngest fluvial plain in China, and it still expands with land forming at a rate of 31.3 km^2/year (Zhang and Duan 2009).

The YRD has undergone severe soil salinization over the past decades. High marine erosion and lateral seepage from the Yellow River provide soluble salt resources for salinization. Meanwhile, the flat terrain, a large imbalance between precipitation and evaporation, and increased human activities accelerate the process of salinization in the topsoil. As a result, >70% of the total YRD area is covered by saline land, and the salinity of the soil surface (0–15 cm) ranges from 0.4% to 1.5% (Shi and Zhang 2003). Vegetation succession in this area is primarily driven by soil salinity (Table 1), and the succession sequence begins from bare land and usually experiences three stages to climax community (Hou *et al.* 2007; Wu *et al.* 1994). The species richness of the non-halophytic community in low-saline areas is higher than that of the halophytic community dominated in high-saline areas (Wang and Zhou 2000)

Petroleum exploitation is the primary anthropogenic activity in the study area. In the 1960s and 1980s, large-scale oil exploitation was conducted in Shengtuo and Gudong, which are located in the sub-deltas formed from 1855 to 1929 and from 1953 to 1963, respectively (Fig. 1). At that time, road systems were built during different periods to facilitate the construction and operation of the oil field. For example, the roads across Shengtuo oil field were constructed between 1965 and 1967, while roads across Gudong oil field were constructed from the late 1990s to the early 2000s. Because of the unique purpose and the similar maintenance activity, the roads have similar pavements, widths, traffic volumes and main vehicles. Roads in the oil fields are narrow (6 or 7 m), asphalt based (occasionally resurfaced with oil and rock chip treatments) and

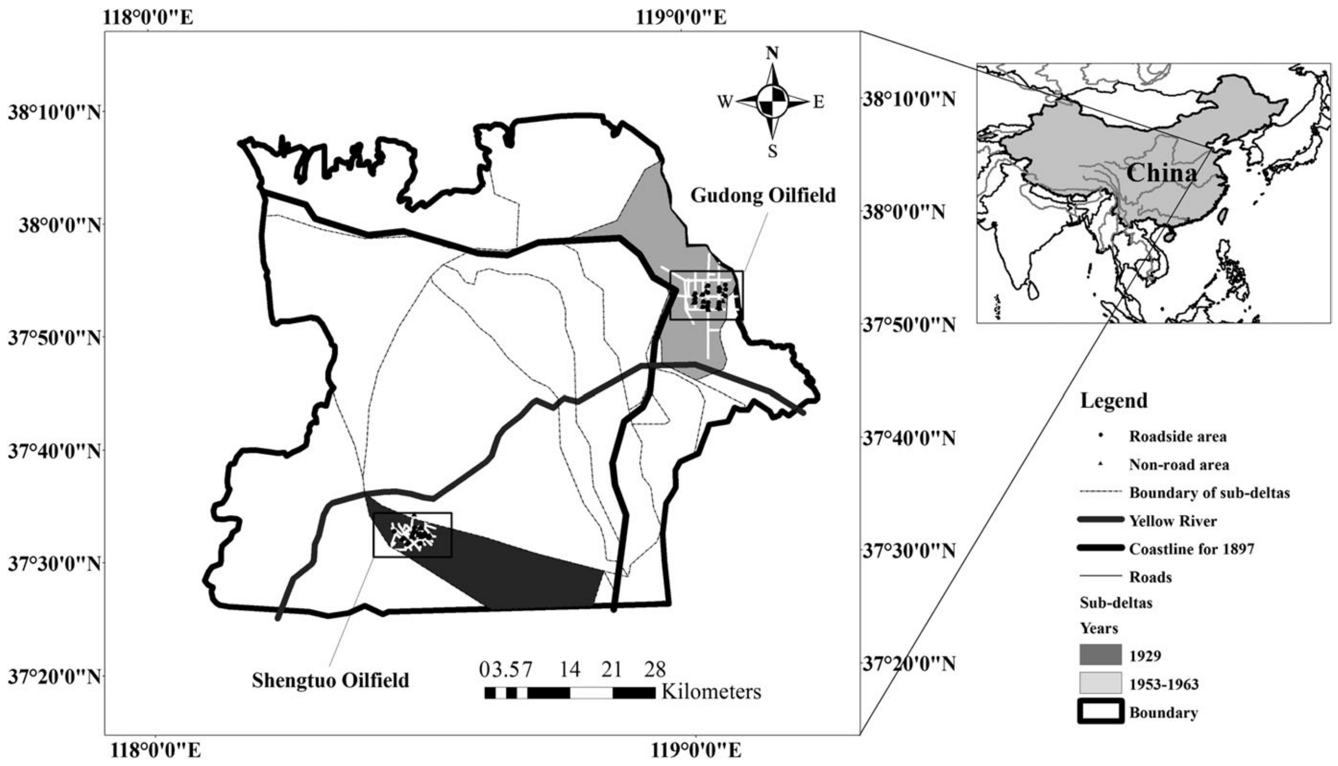

Figure 1: location of study area in northern area of the YRD, Shandong Province of China. The polygons filled with different shades represent sub-deltas that were formed in different periods. The circle symbol represents sites along roads, and the triangle symbol represents the sites in non-road areas (>200 m away from any roads in all directions). In total, 34 sites along roads and 37 sites in non-road areas were present in the Shengtuo and Gudong oil fields.

Table 1: the vegetation succession sequence in the YRD, which is primarily driven by soil salinity (Wang and Zhou 2000)

Succession stage	Sub-stage	Constructive species	Classification	Salinity (%)
i		—	Bare land	1.82
ii		*Suaeda salsa* (L.) Pall.	Halophyte	1.43
iii	1	*Tamarix chinensis* Lour.	Halophyte	1.25
	2	*Suaeda glauca* (Bge.) Bge.	Halophyte	1.00–3.00
	3	*Aeluropus sinensis* (Debeaux) Tzvel.	Halophyte	0.76–0.93
	4	*Phragmites australis* (Cav.) Trin. ex Steud. and *Artemisia capillaris* Thunb.	Halophyte/non-halophyte	0.80
	5	*Imperata cylindrica* (L.) Beauv. and *P. australis* (Cav.) Trin. ex Steud.	Halophyte/non-halophyte	0.30–0.50
	6	*I. cylindrica* (L.) Beauv. and *Glycine soja* Sieb. et Zucc.	Non-halophyte	<0.30

have traffic volume from 25 to 33 cars per hour. Most of the roads in the oil field are not bordered by drainage ditches and have unimproved shoulders. The roadbed and shoulder are elevated in construction, so the road surface is slightly higher than the surrounding natural areas. There is a downward slope (<5°) from the road verge to more distant natural areas. Roadside shoulders are usually mowed once or twice each year, and the use of de-icing salt is restricted in the winter.

Selection of study sites

The classical method commonly used in community ecology studies known as chronosequencing (Kenkel *et al.* 1997) was employed in this study by using the technique of space-for-time substitution. To examine plant communities in roadside and non-road areas, we selected 34 sites along roads (Table 2) and 37 sites in non-road areas in the Gudong (young) and Shengtuo (old) oil fields (Fig. 1). To avoid the effect of the drainage ditches, sites were located along ditch-free roads. Roadside areas were located directly alongside the road (0–2 m from road itself). To determine if the direction and level of plant composition changes were affected by road age, we selected roads from two age groups (young vs. old). According to the local road annals and detailed records from Bureau of Public Roads of Dongying city, roads in Gudong and Shengtuo oil fields were selected to represent age groups of 0–10 and 30–40 years, respectively (Fig. 1). The corresponding non-road areas (control group) were also selected in Gudong and Shengtuo oil fields, respectively. Because areas completely free of roads could not be found in the oil field, the non-road areas here refer to areas with little road effect (>200 m away from any roads in all directions). According to the formation history of the sub-deltas, the non-road areas in the Gudong and Shengtuo oil fields represent areas that have undergone natural succession for 40–50 and >80 years, respectively.

Vegetation sampling procedures

Quantitative surveys of vegetation were conducted from July to August in 2008 and 2009. Specifically, the quadrat sampling method was used to quantify the plant community in both roadside and non-road areas. We conducted preliminary experiments to determine the minimum number and size of quadrats needed to detect most of the plant species present. We randomized the occurrence of species, species–area and running mean curves demonstrated that six 2 m × 2 m quadrats were adequate to detect at least 95% of the species present (Fig. 2). Thus, at each roadside site, six 2 m × 2 m quadrats at 3-m intervals were placed in a line alongside the road (0–2 m from the road), and in non-road sites, the six quadrats were placed randomly. Within each quadrat, we identified and counted all vascular plants.

Soil sample collection and analysis

Six topsoil samples (upper 5 cm) were collected at each site using a core cutter (100 cm^3) and pooled together, after which they were mixed as thoroughly as possible to form one composite sample. Composite samples were air-dried and passed through a 2-mm sieve to remove gravel and debris. Next, the portion finer than 2 mm was preserved for further physicochemical analysis according to the national agricultural industry standards of China (Lu 1999) and Jackson (1967). Soil pH was measured *in situ* using an electrode pH meter (HI8424; Hanna). Total soluble salt (salinity) in topsoil was measured in a soil–water extract composed of 1:5 soil:distilled water using an electric conductivity meter (SevenEasy S30; Mettler Toledo). Soil moisture content was determined using the oven drying method, with the sample drying to constant weight at 105°C for 3–5 days, and the soil bulk density was calculated using the core cutter method. The remaining soil was crushed and sieved through a 100-mesh sieve screen, after which Smart Chem 200 (Alliance) was used to measure the inorganic nitrogen concentration (NO_3^--N, NH_4^+-N) according to US EPA 350 (Environmental Protection Agency). The brief procedures and computational formulas of soil analysis are provided in online supplementary Appendix 1.

Data analysis

To determine the difference in community composition between roadside areas of different age and corresponding non-road areas,

Table 2: list of roads surveyed in the YRD, China

No.	Grade	Pavement material	Width (m)	Location	Construction (year)	Length (m)	Number of sites sampled
1	4	Macadamize	7	ST	1965	3 573	5
2	4	Macadamize	6	ST	1965	4 463	3
3	4	Macadamize	6	ST	1965	4 563	2
4	4	Macadamize	4	ST	1967	1 334	1
5	4	Macadamize	6	ST	1967	4 538	3
6	4	Macadamize	7	ST	1967	1 497	1
7	4	Macadamize	7	GD	1998	6 271	3
8	4	Macadamize	9	GD	1998	2 670	3
9	4	Macadamize	7	GD	2000	17 204	5
10	4	Asphalt	9	GD	1996	4 835	5
11	4	Soil stabilization	5	GD	2005		3

ST = Shengtuo oil field, GD = Gudong oil field.

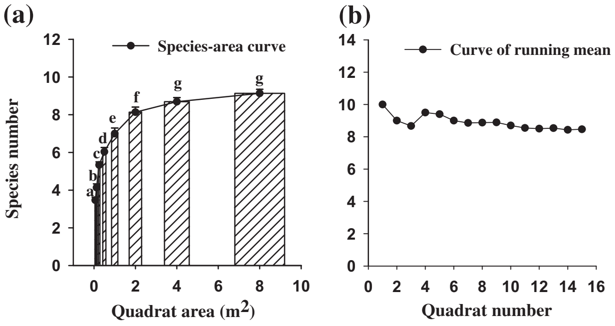

Figure 2: vegetation sampling protocol. (**a**) Species–area curve; (**b**) curve of running mean showed that six 2 m × 2 m quadrats were adequate to detect most species present.

we measured species richness and the abundance of each species, examined species turnover and floristic dissimilarity between the two areas and positioned plant species and sites in an abstract multivariate space (Cook *et al.* 2005). To examine species turnover, we first used a modified version of Sorensen's community correspondence index (CCI; Mueller-Dombois and Ellenberg 1974): CCI = $2C/(A + B)$, where A, B and C are the species numbers in area groups A and B and their combination, respectively. Next, the quantity $D = 1 - \text{CCI}$ (Cook *et al.* 2005), which is an index illustrating how much a species list changes from area group A to group B, was calculated. Low D values indicate little change in species composition, while high values indicate large changes (Cook *et al.* 2005).

Species richness was defined as the number of species present. Due to severe salinization in this area, halophytes were the focal species that we tracked. To evaluate changes in abundance of focal species, we determined the percentage of halophytes in each community. First, to examine site effects on plant communities and environmental conditions, we used t-tests ($\alpha = 0.05$) to evaluate the difference in species richness, percentage of halophytes and soil physicochemical properties between the corresponding non-road areas in Shengtuo and Gudong oil field. Then, within each oil field, the difference in species richness and percentage of halophytes between roadside and non-road areas was compared using t-tests ($\alpha = 0.05$). Similar t-tests were used to determine the difference in the six soil physicochemical properties (pH, salinity, moisture content, bulk density, nitrate and ammonium nitrogen concentration) between roadside and non-road areas. The mean, standard error, T value, P ratio and level of significance ($\alpha = 0.05$) were calculated for all soil properties. All statistical analyses were conducted using the STATISTICA® 7 software package.

Classification and ordination techniques were used to analyze the relationships between vegetation and environmental variables (Abd El-Ghani and El-Sawaf 2005). To classify the floristic presence/absence data matrix of 71 sites and 62 species, we employed the two-way indicator species analysis (TWINSPAN) method, which is performed using the software package PC-ORD 4. Additionally, the software package CANOCO 4 was used for all ordinations. Prior to ordination analysis, a preliminary analysis was conducted to determine the optimal ordination technique, and the analysis was then made by applying detrended correspondence analysis (DCA) to check the magnitude of change in species composition along the first ordination axis [i.e. gradient length in standard deviation (SD) units]. We found that the compositional gradient in the vegetation data was >3 (i.e. 3.516), indicating that the use of unimodal ordination methods [corresponding analysis (CA), DCA and canonical correspondence analysis (CCA)] was appropriate. Specifically, CA ordination was first used to group the selected sites on the basis of plant species presence/absence. The DCA, which was calculated with detrending by segments and Hill's scaling, was then used to determine how much of the variation in species data could be accounted for by the environmental variables. Finally, CCA followed by forward selection was applied to inspect the marginal effects of all environmental variables (Braak 1986), which helps to select the environmental variables most related to changes in community composition.

RESULTS

Comparison of plant communities between roadside and non-road areas

A total of 62 plant species were recorded, and most of the plants (64.5%) belonged to three families, Gramineae, Asteraceae and Chenopodiaceae (see online supplementary Appendix 2). Overall, 98.4% of the species were found in roadside areas, while 33.9% were found in non-road areas, indicating that up to 66% of the plant species only occurred in areas along roads. In both oil fields (young and old), species richness in roadside areas was significantly higher than in corresponding non-road areas (Fig. 3a and b). Species richness in old roadside areas was higher than in young roadside areas (Fig. 3), while no significant difference was observed between the two non-road areas ($t_{(35)} = -1.37$, $P = 0.18$).

The high value of the floristic dissimilarities ($D = 0.71$) indicated that the roadside and non-road areas differed significantly in community composition. The species turnover (as measured by $D = 1 - \mathrm{CCI}$) was low between the two non-road areas, suggesting that the community composition in these two areas was similar (Table 3). Conversely, species turnover was found to be high both between the young roadside and corresponding non-road areas (0.43) and between old roadside and corresponding non-road areas (0.59). These results were in agreement with CA ordination. Roadside areas were clearly separated from non-road areas based on the presence or absence of plant species (Fig. 4a). These findings confirmed that species composition in the roadside and non-road areas differed significantly (Fig. 4b). Only three sites in old non-road areas had a species composition comparable to that along young roads. This separation of biotypes could be explained by species ordination (Fig. 4b). Specifically, halophytes such as *Suaeda glauca* (Bge.) Bge., *Aeluropus sinensis* (Debeaux) Tzvel., *Tamarix chinensis* Lour. and *Limonium sinense* (Girard) Kuntze were situated in the right portion of the ordination diagram, where the non-road areas clustered (Fig. 4b). Conversely, a number of typical species in low-salinity areas [e.g. *Imperata cylindrica* (L.) Beauv., *Setaria viridis* (L.) Beauv. and *Artemisia mongolica* (Fisch. ex Bess.) Nakai] were located on the left of the ordination diagram, where roadside areas occurred (Fig. 4b). These results also corresponded with the comparison of percentage of halophytes between roadside and non-road areas. In both oil fields, the percentage of halophytes in roadside areas was significantly lower than in non-road areas (Fig. 3c and d). The percentage of halophytes in old roadside areas was lower than in young roadside areas (Fig. 3), while no significant difference was observed between the two non-road areas ($t_{(35)} = -0.75$, $P = 0.46$).

Vegetation classification

Classification of the presence/absence data set of 62 species recorded at 71 sites using TWINSPAN analysis yielded 22 subtypes at level six of the hierarchy (Table 4; see online supplementary Appendix 3). These subtypes could be categorized at level three of the classification into four major types (labeled I–IV; see online supplementary Appendix 3). Table 4 showed that communities iii_4, iii_5 and iii_6 of the succession sequence (Table 1) were abundant in the two roadside areas, while community ii of the succession sequence was prosperous in the two non-road areas. The 62 species could also be categorized into four major vegetation groups at level three of the hierarchy (labeled A–D, see online supplementary Appendix 4 and Table 5). Group A was composed mainly of typical plants in succession stage iii (Table 1), while Group D was composed primarily of halophytes, the main constructive species in succession stage ii. Overall, 66% of the species had a frequency <5%, and only *S. glauca* (Bge.) Bge. and *Phragmites australis* (Cav.) Trin. ex Steud. had a frequency >50%.

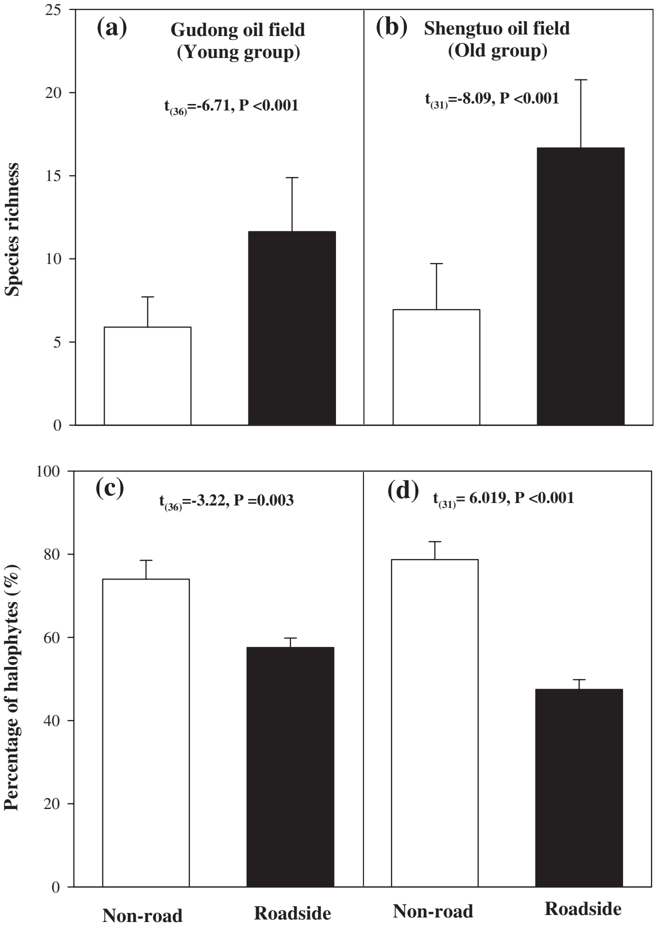

Figure 3: changes of species richness and percentage of halophytes between roadside and corresponding non-road areas in Shengtuo and Gudong oil fields. Error bars represent 1 SE. Significant differences ($\alpha = 0.05$) between roadside and non-road areas were determined by using *t*-tests.

Comparison of physiochemical soil properties between roadside and non-road areas

In both oil fields, the soils in the non-road areas were more acidic than in roadside areas (Table 6), but no significant difference in soil pH was found between the two non-road areas

Table 3: species turnover across four area groups

		Shengtuo oil field (old group)		Gudong oil field (young group)		
Habitats	Areas	Non-road	Roadside	Non-road	Roadside	Non-road areas
Shengtuo oil field (old group)	Non-road					
	Roadside	0.59				
Gudong oil field (young group)	Non-road	0.28	0.65			
	Roadside	0.34	0.41	0.43		
Roadside areas						0.71
Total number of species		21	57	12	30	

The species turnover was measured by $D = 1 - \text{CCI}$.

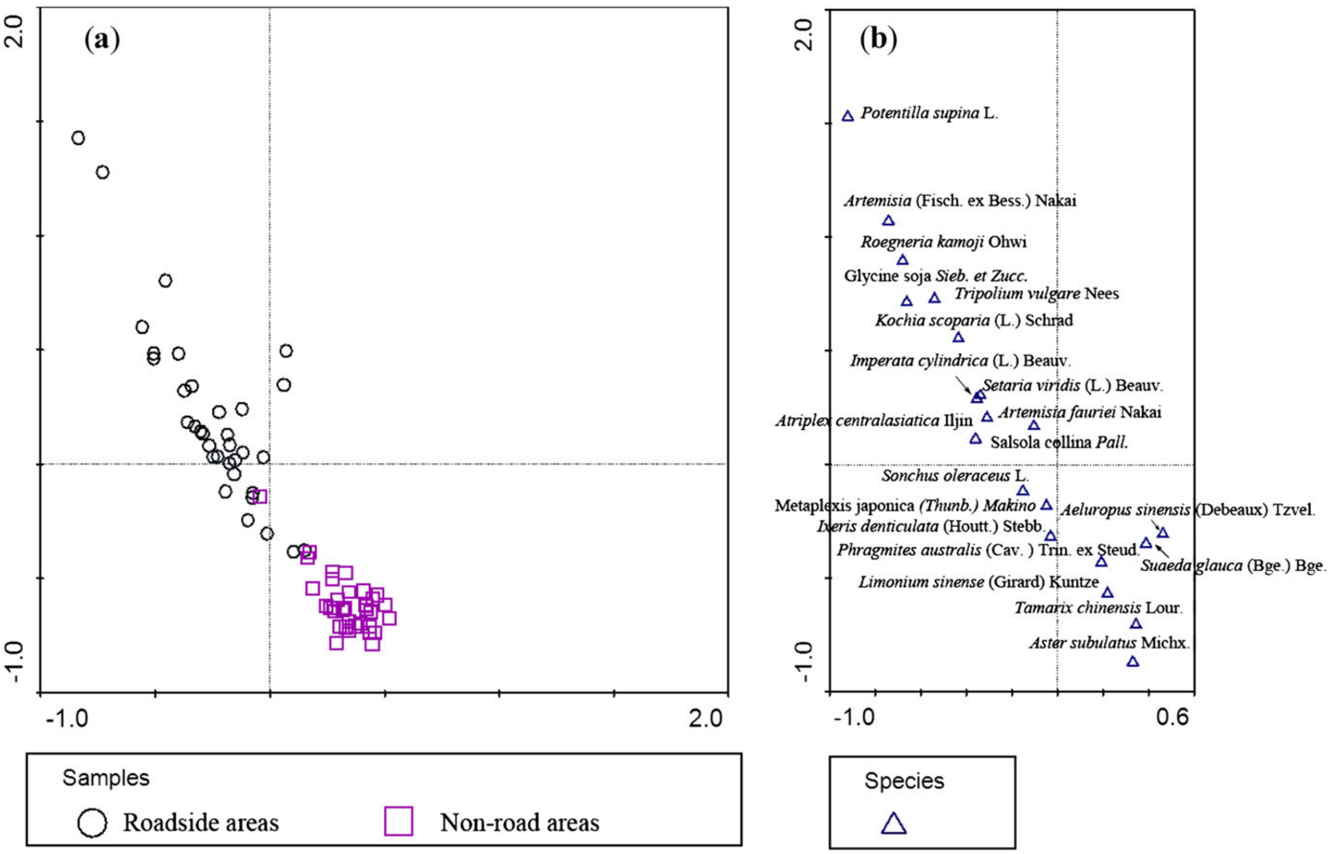

Figure 4: the CA ordination of (**a**) all sites based on the presence/absence of plant species and (**b**) the species carrying the largest weights in the analysis. The circle symbol represents roadside areas and the square symbol non-road areas.

($t_{(35)} = -1.15$, $P = 0.14$). The soils in non-road areas also had significantly higher soil moisture content and bulk density than in roadside areas (Table 6). The soil moisture content in old roadside areas was found to be significantly higher than in young roadside areas ($t_{(32)} = -3.8873$, $P < 0.001$). There were statistically significant differences in salinity across the soils. In both oil fields, the soils of non-road areas had significantly higher salinity than that of roadside areas (Table 6), but there was no significant difference in soil salinity between the two non-road areas (Table 6; $t_{(33)} = 0.92$; $P = 0.37$).

For the macronutrients, the nitrate nitrogen concentration differed significantly between roadside and non-road areas in Shengtuo oil field, but there was no significant different in Gudong oil field (Table 6). Additionally, no significant difference was found in the concentration of nitrate nitrogen between the two non-road areas (Table 6; $t_{(29)} = 0.49$, $P = 0.62$). Similarly, no significant difference in the ammonium nitrogen concentration was observed between roadside and corresponding non-road areas (Table 6).

Table 4: characteristics of the 3 vegetation types and 22 subtypes in 4 area groups derived from TWINSPAN at level three and six of the hierarchy, respectively

			Area groups						
Vegetation type	Subtype	No. of recorded sites	OR	YR	ON	YN	Characteristic species	Frequency (%)	Species richness
I	1	2			2		*Suaeda salsa* (L.) Pall.	92	4.5
	2	4			4		*Aeluropus sinensis* (Debeaux) Tzvel.	92	7.0
							Suaeda glauca (Bge.) Bge.	83	
	3	3			2	1	*S. glauca* (Bge.) Bge.	72	6.7
							A. sinensis (Debeaux) Tzvel.	67	
							Phragmites australis (Cav.) Trin. ex Steud.	67	
	4	4			4		*S. glauca* (Bge.) Bge.	96	4.5
							A. sinensis (Debeaux) Tzvel.	92	
	5	4			1	3	*S. glauca* (Bge.) Bge.	100	3.5
							P. australis (Cav.) Trin. ex Steud.	79	
II	6	1			1		*P. australis* (Cav.) Trin. ex Steud.	100	9.0
							Echinochloa crusgali (L.) Beauv. var. mitis (Pursh) Peterm.Fl.	100	
	7	4		1	2	1	*S. glauca* (Bge.) Bge.	75	11.0
							A. sinensis (Debeaux) Tzvel.	71	
	8	13				13	*P. australis* (Cav.) Trin. ex Steud.	92	6.2
							S. glauca (Bge.) Bge.	90	
	9	2				2	*P. australis* (Cav.) Trin. ex Steud.	100	5.0
							Metaplexis japonica (Thunb.) Makino	100	
	10	1			1		*P. australis* (Cav.) Trin. ex Steud.	100	12.0
							A. sinensis (Debeaux) Tzvel.	83	
							Limonium sinense (Girard) Kuntze	83	
III	11	2		2			*Setaria viridis* (L.) Beauv.	100	9.5
							S. glauca (Bge.) Bge.	100	
							Salsola collina Pall.	100	
	12	3		3			*Se. viridis* (L.) Beauv.	94	11.0
							M. japonica (Thunb.) Makino	94	
	13	3		3			*M. japonica* (Thunb.) Makino	83	8.3
							S. glauca (Bge.) Bge.	83	
	14	4	1	2	1		*S. glauca* (Bge.) Bge.	83	
							P. australis (Cav.) Trin. ex Steud.	67	
	15	4		4			*Imperata cylindrica* (L.) Beauv.	75	15.0
							M. japonica (Thunb.) Makino	70	
	16	1		1			*I. cylindrica* (L.) Beauv.	83	15.0
							Se. viridis (L.) Beauv.	83	
							M. japonica (Thunb.) Makino	83	
							Melilotus officinalis (L.) Desr.	83	
	17	2		2			*Sa. collina* Pall.	100	15.0
							M. japonica (Thunb.) Makino	100	

Table 4:
Continued

Vegetation type	Subtype	No. of recorded sites	Area groups OR	YR	ON	YN	Characteristic species	Frequency (%)	Species richness
IV	18	2	2				*Se. viridis* (L.) Beauv.	67	17.0
							S. glauca (Bge.) Bge.	67	
							Sa. collina Pall.	67	
	19	1	1				*Se. viridis* (L.) Beauv.	100	9.0
							M. japonica (Thunb.) Makino	100	
							S. glauca (Bge.) Bge.	100	
	20	3	3				*S. glauca* (Bge.) Bge.	89	10.0
							Sa. collina Pall.	83	
	21	4	4				*S. glauca* (Bge.) Bge.	75	17.0
							Sa. collina Pall.	70	
	22	3	3				*Sa. collina* Pall.	72	23.0
							Se. viridis (L.) Beauv.	61	

YN = young non-road areas, ON = old non-road areas, YR = young roadside areas, OR = old roadside areas.

Variable plant communities across four area groups with respect to the environmental variables

The surrounding environments provided a remarkable explanation of the variation in species composition. The entire data set was divided into two parts based on the six soil properties. The DCA ordination plot of the 71 sites and the soil properties on axes 1 and 2 were shown in Fig. 5b, with the four TWINSPAN area types superimposed (Fig. 5a). The sites were spread out >3 SD units (i.e. 3.516) of the first axis (eigenvalue = 0.443), expressing the high floristic variation among the sites and indicating that considerable turnover in species composition took place. Vegetation Group A and sample sites of III and IV were separated toward the negative end of the DCA axis, while Group D and sample sites I and II were separated along the other end of the axis. High species–environment correlation coefficients (0.67 and 0.45 for DCA axes 1 and 2, respectively) demonstrated that the species compositions were strongly related to the measured environmental variables. DCA axis 1 and 2 reflected the variation of species composition along the soil salinity and moisture gradient, respectively.

Forward selection for the environmental variable in CCA ordination showed that soil salinity was the most important factor related to the variation of species composition across the four area groups (Table 7). The species–environment correlations were higher for the first three canonical axes upon CCA analysis, explaining 76% of the cumulative variance. These results suggest a strong association between vegetation and the measured environmental parameters present in roadside and non-road areas. The sum of all canonical eigenvalues (0.641) was also significant (Monte Carlo test, $F = 2.159$, $P = 0.002$). The unrestricted Monte Carlo permutation test revealed that the F ratio for the eigenvalue of CCA axis 1 and the trace statistics were significant ($P = 0.002$), indicating that the observed patterns did not arise by chance.

DISCUSSION

Soil salinization has been very severe in our study area (Wu *et al.* 1994) due to low and flat terrain, high groundwater table (frequently at 1–3 m depth) and high mineralization rate (5–30 g/l). As a result, plant communities consist of halophytic herbaceous plants and overall lower species richness in most areas. Our results show that road effects from maintenance and traffic can dramatically alter plant communities and adjacent environmental conditions in this distinctly saline environment.

In many systems, roadside vegetation is characterized by banded areas parallel to roads, comprising a narrow strip of strongly altered vegetation at the road verge compared to surrounding vegetation (Forman *et al.* 2002). This zoning highlights the differences between vegetation growing along the road and that vegetation in the zone at the interface of the road with natural vegetation (Johnston FM and Johnston SW 2004). The widely accepted view is that road effects reduce the species number and diversity of natural vegetation while promoting exotic species (Auerbach *et al.* 1997; Greenberg *et al.* 1997). Johnston FM and Johnston SW (2004) illustrated that natural soil, with its complete undisturbed profile, supported a wide range of plant life forms. In contrast to these florally rich areas, the subalpine road verge soil supported only a limited array of species (predominantly exotic). In our study, we found that roadsides supported a wide range of vegetation (predominantly non-halophyte) with high levels of species richness, while non-road areas supported mostly halophytes. This predominance of non-halophyte in roadside areas reflects the adaptation of non-halophytes to the environmental conditions in roadside areas, especially decreased soil salinity. Previous research conducted in European countries indicated that the use of de-icing salt in winter led to higher salinity and created an environment along roads conducive to colonization by salt marsh species (Rutter and Thompson 1986). This suggests

Table 5: list of plant species in four TWINSPAN vegetation groups

Group	Species names
A	*Imperata cylindrica* (L.) Beauv., *Glycine soja* Sieb. et Zucc., *Setaria viridis* (L.) Beauv., *Kochia scoparia* (L.) Schrad, *Chenopodium glaucum* L., *Atriplex centralasiatica* Iljin, *Potentilla supina* L., *Tripolium vulgare* Nees, *Artemisia mongolica* (Fisch. ex Bess.) Nakai, *Cynodon dactylon* (L.) Pers., *Artemisia capillaris* Thunb., *Datura stramonium* L., *Abutilon theophrasti* Medicus, *Chenopodium album* L., *Eclipta prostrata* (L.) L. Mant., *Eleusine indica* (L.) Gaertn., *Hibiscus trionum* L., *Plantago depressa* Willd., *Portulaca oleracea* L., *Taraxacum mongolicum* Hand.-Mazz., *Humulus scandens* (Lour.) Merr., *Convolvulus arvensis* L., *Polygonum aviculare* L., *Chenopodium serotinum* L., *Polygonum orientale* L., *Hippochaete ramosissima* (Desf.) Boerner, *Helianthus annuus* L., *Hemistepta lyrata* (Bge.) Bge., *Amaranthus lividus* L., *Pharbitis nil* (L.) Choisy, *Cucurbita moschata* (Duch. ex Lam.) Duch. ex Poiret, *Roegneria kamoji* Ohwi, *Conyza canadensis* (L.) Cronq., *Kummerowia striata* (Thunb.) Schindl., *Artemisia rubripes* Nakai, *Melilotus officinalis* (L.) Desr., *Chloris virgata* Swartz, *Salsola collina* Pall., unknown #1, unknown #2, unknown #3, unknown #4, unknown #5, unknown #6
B	*Messerschmidia sibirica* L., *Echinochloa crusgali* (L.) Beauv. var. mitis (Pursh) Peterm.Fl., *Artemisia fauriei* Nakai, *Sonchus oleraceus* L., *Eragrostis minor* Host
C	*Metaplexis japonica* (Thunb.) Makino, *Ixeris denticulata* (Houtt.) Stebb.
D	*Suaeda glauca* (Bge.) Bge, *Tamarix chinensis* Lour., *Aeluropus sinensis* (Debeaux) Tzvel., *Phragmites australis* (Cav.) Trin. ex Steud., *Limonium sinense* (Girard) Kuntze, *Aster subulatus* Michx., *Apocynum venetum* L., *Inula japonica* Thunb., *Suaeda salsa* (L.) Pall., *Cyperus rotundus* L.

Table 6: physicochemical properties (mean ± stand error) of soil samples taken from four area groups

Environmental variables (soil properties)	Shengtuo oil field (old group)		Gudong oil field (young group)	
	Non-road areas (d.f. = 18)	Roadside areas (d.f. = 15)	Non-road areas (d.f. = 18)	Roadside areas (d.f. = 19)
Salinity (mg/g)	$16.97^{a} \pm 1.34$	$3.05^{b} \pm 0.38$	$19.16^{a} \pm 1.95$	$3.17^{b} \pm 0.93$
Moisture content (%)	$20^{a} \pm 0.6$	$14^{b} \pm 1.5$	$19^{a} \pm 0.4$	$7^{b} \pm 0.9$
Bulk density (g/cm^3)	$1.56^{a} \pm 0.050$	$1.34^{b} \pm 0.032$	$1.59^{a} \pm 0.080$	$1.32^{b} \pm 0.060$
pH	6.53 ± 0.15	7.12 ± 0.13	6.21 ± 0.15	6.72 ± 0.17
[NO$_3^-$-N](mg N/g)	$0.014^{a} \pm 0.002$	$0.053^{b} \pm 0.010$	0.015 ± 0.002	0.016 ± 0.003
[NH$_4^+$-N] (mg N/g)	0.005 ± 0.0005	0.004 ± 0.0005	0.004 ± 0.0003	0.003 ± 0.0003

Superscript letters (a, b) of mean values indicate significant difference at the level $\alpha = 0.05$ between roadside and corresponding non-road areas by using *t*-tests.

that the effects of roads on plant communities may depend on local environmental conditions. Therefore, understanding road effects on plant communities in different environments will require further experimental studies. Our study also demonstrates that soils found in roadside areas are physically and chemically altered due to road-induced effects, and the difference in community composition and soil properties between roadside and non-road areas has not changed with road age. In our study, activities associated with roads decreased soil moisture content, bulk density and salinity and increased soil pH and nitrate (Table 6). Foreign materials used in construction may be carried into surrounding soils, causing a significant change in pH (Angold 1997). Petroleum asphalt (pH 8–10) is used to pave road surfaces in the YRD, so the pH of the soil becomes higher than that of natural soil (Table 6). Similarly, limestone-based roads of the Roman road near Orleans, France, have created a locally alkaline soil in the naturally acidic podzol community (Detwyler 1971). The higher soil pH near the road may also be attributed to the leachate of petroleum asphalt during road use. This is supported by the finding that soil pH in old roadside areas was higher than in young roadside areas. Activities associated with roads may have reduced the soil moisture content next to the roads (Table 6) due to the hard surface of the road that increases surface temperature compared to bare soil (Trombulak and Frissell 2000). Additionally, the heat islands around roads may accelerate the loss of water vapor (Auerbach *et al.* 1997; Forman *et al.* 2002). Rutter and Thompson (1986) examined the effects of salt usage and rainfall on sodium and chloride concentrations in the soil of central reserves. They found that the soil from road verges had higher salinity due to the use of de-icing salt in the winter. These results contrast with our results that the soil of roadside areas had lower salinity compared to corresponding non-road areas. Soils along roadside had considerably higher nitrate compared to non-road areas; additionally, old roadside areas were found to have higher amounts than young roadside areas (Table 6). Previous work has shown that high levels of nitrogen alongside roads may originate from nitrogen oxides of vehicle exhaust (Greenberg *et al.* 1997). Bignal *et al.* (2007) also observed an increase in NO$_2$ concentrations to the roadside, while Cale and Hobbs (1991) verified that roadside soils contained significantly higher levels of soil phosphorus and NO than off-road soils. In general, our study supports recently published research showing that changes to the soil can significantly alter the configuration of plant species growing in a given area

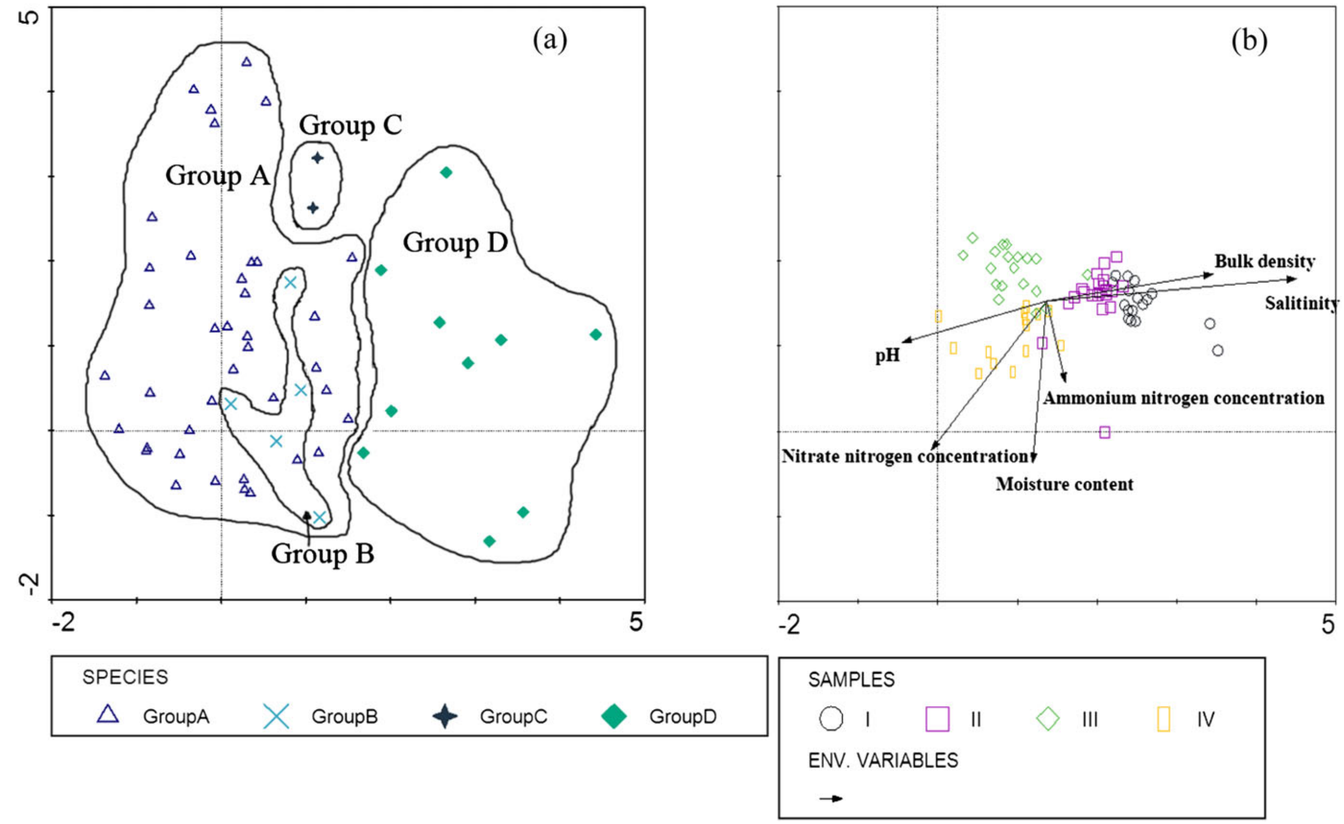

Figure 5: (**a**) ordination diagram of DCA of 62 species, with their TWINSPAN vegetation groups; and (**b**) ordination biplot yielded by DCA of 71 sample sites, with their TWINSPAN area types and environmental variables.

Table 7: marginal and conditional effects obtained from the summary of forward selection in CCA

Marginal effects			Conditional effects				
Environmental variable (soil properties)	Variable number	Lambda1	Environmental variable (soil properties)	Variable number	LambdaA	*P*	*F*
Salinity (mg/g)	6	0.21	Salinity (mg/g)	6	0.21	0.002	3.92
Bulk density (g/cm^3)	5	0.16	Moisture content (%)	4	0.14	0.002	2.82
Moisture content (%)	4	0.14	[NO_3^--N] (mg N/kg)	1	0.09	0.038	1.81
[NO_3^--N] (mg N/kg)	1	0.12	Bulk density (g/cm^3)	5	0.08	0.146	1.55
pH	3	0.11	pH	3	0.07	0.092	1.41
[NH_4^+-N] (mg N/kg)	2	0.07	[NH_4^+-N] (mg N/kg)	2	0.06	0.288	1.10

(Angold 1997; Auerbach *et al.* 1997; Trombulak and Frissell 2000).

Chapin *et al.* (2002) suggested that population persistence is strongly influenced by plant spread and colonization, which in turn depend on site and seed limitation. As a corridor, it has been confirmed that roads provide dispersal conduits for plant species (Flory and Clay 2006; Forman and Alexander 1998; Hansen and Clevenger 2005; Johnston FM and Johnston SW 2004). In roadside areas, the majority of non-halophyte species belong to Gramineae, which usually produces a large quantity of tiny seeds that spread by wind, (e.g. *I. cylindrica* (L.) Beauv. and *Se. viridis* (L.) Beauv.). Increased exposure, storm water runoff and vehicle traffic along roads facilitate the easy movement of wind, water and animals that transport seeds, thus roads may promote the dispersal of anemogame plants (Forman and Alexander 1998; Trombulak and Frissell 2000). The distribution of such species can expand along with the road networks (Hodkinson and Thompson 1997; Lonsdale and Lane 1994; Trombulak and Frissell 2000; Von der Lippe and Kowarik 2007). Conversely, there is less human disturbance in non-road areas, which is dominated by halophytes, e.g. *S. glauca* (Bge.) Bge. has two types of propagules, brown and black seed. Wang *et al.* (2010) showed that the brown seed could be dispersed by wind for long distances, thus sporadic *S. glauca* (Bge.) Bge. can be found along roads. In contrast, the black seeds disperse with wind within a short distance or stay within maternal plants (Wang *et al.* 2010); as a result, *S. glauca* (Bge.) Bge. usually forms a large pure community in natural areas. The dispersal function of roads is not the only option; alternatively, seeds of most species could be everywhere and favorable germination determines distribution and abundance. Indeed, some studies have suggested that the role of roads as suitable habitats are superior to their function as potential conduits because the availability of suitable habitats for colonization and establishment of plant species are necessary before populations begin to spread (Sykora *et al.* 2002).

Most of the land in the YRD has undergone severe soil salinization, so the soil salinity is the factor limiting the occurrence of plant communities (Hou *et al.* 2007). For example, *I. cylindrica* (L.) Beauv. can only survive in the environment where soil salinity is below 0.3%, while *S. glauca* (Bge.) Bge. community can grow well even if the soil salinity is above 1% (Wang and Zhou 2000). High marine erosion and lateral seepage from the Yellow River provide abundant salt for salinization. Meanwhile, the flat terrain, a large imbalance between precipitation and evaporation and increased human activities accelerate the process of salinization in the topsoil. The government applies the method 'elevating ground and developing fishery in the low-lying land' to mitigate salinization and plant non-halophyte species with high value, such as cotton, in most areas. The purpose of elevating the ground is to decrease the relative water level of underground water and suppress the vertical migration of soluble salt. The low-lying land next to the elevated ground (soil is used to elevate the ground) is used to develop fisheries; in this case, the abundant water resource may facilitate desalination by leaching. Our results show that roads help to decrease soil salinity alongside roads (Table 6), similar to the agricultural method of the government. The roadbed is elevated in construction, and the terrain of the road and shoulder are slightly higher than the natural areas. Additionally, road effects may mitigate salinization by directly or indirectly changing water availability along roads. The abundant runoff from road surfaces forms gullies that go from roadside to natural habitats (Forman *et al.* 2002). During these processes, sediment and nutrient-rich water from road surface and upper slopes are transported down the slope and deposited on existing soil and vegetation, which directly changes the soil moisture along roads (Forman and Alexander 1998) and decreases soil salinity by leaching. Activities associated with roads may increase the availability of water by disrupting surface flow and groundwater or creating new routes for water flow (Forman *et al.* 2002). Soil salinity and water availability are closely linked (Guan 2001). In our study, the soil moisture content of old roadside areas was found to be higher than that of young roadside areas (Table 6). Our other unpublished work on roadside ditches shows that soil salinity in road systems with ditches is significantly lower than in road systems without ditches. Furthermore, there was a low level of soil bulk density in roadside areas (Table 6), indicating that there might be more pores that would facilitate leaching. Conversely, the compacted soil layer may block the vertical movement of runoff and maintain water in the surface layer. As a result, the soluble salt quickly dissolves out of the topsoil with evaporation. Finally, the field survey revealed that the use of de-icing salt is forbidden in winter; therefore, road maintenance in this area was unlikely to bring about additional soluble salt. Thus, increased runoff from the compacted road surface over time as well as the decreased level of underground water creates an area with a low level of soil salinity alongside roads.

CONCLUSIONS

Our study demonstrates that roads have a significant impact on associated vegetation and soil. During their operational phase, road effects increase plant diversity, accelerate species turnover and change species composition by providing favorable habitats for plant species, including increased water availability and rich nutrients, and most importantly decreased salinity stress. As a result, more non-halophytic plants survive in the roadside area, while halophytic plants dominate in non-road areas. Compared to the published successional sequence, the roadside communities are more similar to later successional stages (predominantly various non-halophytes), while the non-road communities are more related to earlier stages (dominated by halophyte). Additionally, we conclude that in our system, the differences in plant communities and soil properties between roadside and non-road areas are consistent across roads of different ages.

SUPPLEMENTARY MATERIAL

Supplementary Appendices 1–5 are available at *Journal of Plant Ecology* online.

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