Key Factors Influencing Weed Infestation of Cool-season Turfgrass *Festuca arundinacea* Schreb. Areas during Early Spring in the Tianjin Region, China

Jin-wei Zhang¹

National Engineering Research Center for Information Technology in Agriculture, Beijing, China 100193; and Tianjin Institute of Plant Protection, Tianjin, China 300384

Yi-xue Liu, Jin-ping Yu, and Wei Zhang

Tianjin Institute of Plant Protection, Tianjin, China 300384

Ya-qiong Xie

Beijing Nutrichem Company Limited, Beijing, China 102206

Ning-ning Ge

Beijing Union of Farmers' Association, Beijing, China 100062

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Abstract. In the early Spring of 2015 and 2016, weed infestation surveys were conducted in areas of cool-season turfgrass *Festuca arundinacea* Schreb. at 23 sites within Tianjin municipality in northern China. The weed community within turfgrass areas comprised 37 weed species belonging to 14 families. Perennial weeds accounted for 45.9% of the total community of weed species, whereas annual or biennial weeds accounted for 54.1%. *Asteraceae* was the dominant family (43.2%), and the percentage of broadleaved weeds was 94.6%. Statistical analyses of the weed dominance index (integrating weed relative height and relative coverage) and relative abundance (integrating weed relative density, frequency, and uniformity) showed that the 10 most common weed species during the early spring were *Ixeris polycephala* Cass., *Taraxacum mongolicum* Hand.-Mazz., *Inula japonica* Thunb., *Hemistepta lyrata* Bge., *Trigonotis peduncularis* (Trev.) Benth., *Calystegia hederacea* Wall., *Lepidium apetalum* Willd., *Plantago asiatica* L., *Cirsium segetum* Bge., and *Ixeris sonchifolia* Hance. *Ixeris polycephala* Cass. and *T. mongolicum* Hand.-Mazz were the most dominant and harmful weed species. Partial correlation analysis (PACA) indicated that the deterioration rate (percentage of bare soil or coverage of plants other than turfgrass) of the turfgrass area was significantly and positively correlated with the total dominance index [(TDI, an index to evaluate the weed infestation severity)] and that the soil organic matter (SOM) and salinity factors were negatively correlated with the TDI. Factors such as soil nutrient conditions (the contents of N, P, and K and the total N), soil physical properties (density and clay content), soil moisture, soil temperature, and soil pH did not correlate significantly with the TDI. We conclude that the deterioration rate was the most important factor influencing weed infestation in the early spring and that SOM and soil salinity might also be important factors. The results of this study can help turfgrass researchers and managers identify the most harmful weed species and integrate management strategies in areas of cool-season turfgrass *F. arundinacea* Schreb. during early spring in the Tianjin region, China.

Accompanying the rapid promotion of urbanization in China, there is an increasing demand for recreational areas, athletic fields, and other types of functional green spaces. Lawns and turfgrasses have become ubiquitous in urban landscapes; residential, commercial, and institutional lawns; parks; athletic fields; and golf courses. They play very important roles in the daily life of people (Beard and Green, 1994), especially in economically developed regions, during the past 10 years in China (Shan et al., 2013). A

current challenge in turfgrass development involves turfgrass management—although people pay considerable attention to the establishment of turfgrass areas, they pay less to their subsequent management. This inattentiveness has led to the rapid deterioration of turfgrass areas via pest infestation, anthropogenic damage, and other factors (Hu et al., 2001). Weed infestation is the major problem affecting turfgrass areas and is often the result of low-level turfgrass daily maintenance (Uddin et al., 2010). Turfgrass weeds

include grasses, grass-like plants (rushes or sedges), and broadleaved plants and with annual, biennial, and/or perennial life cycles. Weeds compete with turfgrass plants for light, nutrients, water, and space. Some weeds are hosts for pests such as pathogens, nematodes, and insects and some are irritants to humans, causing allergic reactions through the production of pollen or chemicals (Zimdahl, 2007). Some dominant species are aggressive weeds and greatly limit turfgrass growth. Other relatively rare species increase the biodiversity in the turfgrass ecosystem. However, weeds affect the appearance, value, and health of the turfgrass landscape and contribute to its deterioration. Therefore, to maintain the health and esthetic quality of turfgrass areas, weeds must be eliminated from these areas.

The weed flora composition of a given cultured area is usually strongly dependent on the geographical region and crop species (Qiang, 2005; Streibig, 1979). *Festuca arundinacea* Schreb. is a very important cool-season turfgrass plant (Charles et al., 1991). It can be planted from the northeast to the Yangtze River region of China because of its high resistance to drought, flooding, saline–alkali stress, and low need for maintenance (Hu et al., 2001). In our survey, this turfgrass plant accounted for more than 95% of plants used for landscaping in the Tianjin region. Previous surveys have been conducted regarding weed infestation and distribution in areas of this turfgrass species in China (Bai et al., 2007; Cui et al., 2003; Qiang and Li, 2000; Wei et al., 1998; Wu et al., 1997; Zhao et al., 2003). These previous reports demonstrated weed infestation at certain places or times using inexact and descriptive approaches; thus, quantitative analyses of weed community composition and dominance during certain periods are lacking. The early spring is an important period before weed management practices are conducted in turfgrass areas in the Tianjin region, China. However, information regarding the weed community composition and distribution in these areas during the early spring has not been documented. This gap in knowledge has limited the development of predictive ecological risk assessments for weed encroachment and the development of strategies to manage weeds. Therefore, a detailed weed infestation survey to determine the occurrence and importance of weed species in *F. arundinacea* Schreb. turfgrass areas during the early spring would allow turfgrass researchers and managers to develop guidelines for weed management.

Environmental and anthropogenic factors such as climate change, soil conditions, and cropping system management contribute to variability in weed infestation in cropland (Nkoa et al., 2015; Qiang, 2005). Dieleman et al. (2000a, 2000b) identified associations among site properties and weed species abundance and Andersson and Milberg (1998) determined the relationships between weed flora composition and the relative importance of crop, crop rotation, and

nitrogen. In addition, Hume (1982) and Hume et al. (1991) determined the impacts of agronomic practices on weed community composition in wheat. There have been few studies of the factors that influence weed infestation in cool-season *F. arundinacea* Schreb. turfgrass areas. Investigating weed infestation in such areas under different environmental conditions and the influencing factors can help improve weed management strategies in turfgrass areas.

The goals of this article were to a) identify the most common and dominant weed species and b) determine the factors that influence weed infestation in *F. arundinacea* Schreb. turfgrass areas during early spring in the Tianjin region by performing field surveys and quantitative analyses. The results of this study can help turfgrass researchers and managers identify the most common and harmful weed species and integrate management strategies in areas of cool-season turfgrass during early spring in this region.

Materials and Methods

Sites surveyed. Two surveys of weed infestation were conducted in mid-April of 2015 and 2016 in 23 turfgrass areas in 10 districts or counties of Tianjin, a municipality in the North China Plain. The coordinates of the 23 surveyed sites and the functions of the turfgrass areas are presented in Supplemental Table 1. *Festuca arundinacea* Schreb. was the turfgrass plant at most sites; at two sites, it was the dominant turfgrass plant but occurred along with *Poa pratensis* L. The size of the area surveyed at each site was at least 1000 m². No fertilizer, mowing, or weed management programs had been carried out at the sites, and only some sites had been irrigated before the survey.

Data collection. The plots were selected by walking across the central areas of the turfgrass sites and throwing a sample quadrat (0.25 m²) in a random direction. This resulted in a total of 15 sampling locations at each site. Our methods followed those of Andreasen et al. (1996). The weed species at each sampling location were identified and recorded for further analysis. To quantify and analyze the data, weed density, uniformity, frequency, relative density, relative uniformity, and relative frequency were calculated according to the following Eqs. [1]–

[4] in reference to the methods of Thomas (1985, 1991):

$$\text{Uniformity } (U_k) : U_k = \left(\frac{\sum_1^n \sum_1^5 X_{ij}}{5n} \right) \times 100, \quad [1]$$

where U_k is the field uniformity value for species k , X_{ij} is the presence (1) or absence (0) of species k in quadrat j (a quadrat is 0.25 m²) in field i , and n is the number of fields surveyed.

$$\text{Density } (D_k) : D_k = 4 \sum_1^n \sum_1^{15} D_{ij} / 15n, \quad [2]$$

where D_k is the density of species k (plants/m²), D_{ij} is the number of plants in quadrat j in field i , and n is the number of fields surveyed.

$$\text{Frequency } (F_k) : F_k = \left(\frac{\sum_1^n Y_i}{n} \right) \times 100, \quad [3]$$

where F_k is the frequency value for species k and Y_i is the presence (1) or absence (0) of species k in field i .

$$\text{RF}_k = \left(\frac{\text{frequency value of species } k}{\text{sum of frequency values for all species}} \right) \times 100$$

$$\text{RU}_k = \left(\frac{\text{uniformity value of species } k}{\text{sum of uniformity values for all species}} \right) \times 100$$

$$\text{RD}_k = \left(\frac{\text{mean density value of species } k}{\text{sum of mean density values for all species}} \right) \times 100$$

$$\text{RA}_k = \text{RF}_k + \text{RU}_k + \text{RD}_k, \quad [4]$$

where RF_k , RU_k , and RD_k are the relative frequency, uniformity, and density of species k , respectively, and RA_k is the relative abundance of species k .

The severity of weed infestation in cropland depends not only on the abundance of the weeds but also on the weed coverage and height. To determine the dominance of different weed species in the weed community, two indexes, the dominance index (the product of the relative height of a weed to the turfgrass plant, scaling 0 to 1, and the relative coverage of that weed in a quadrat, scaling 0% to 100%, DI) and the percentage of dominance index (PDI) were used according to Eqs. [5] and [6] following the methods of Wu et al. (1997) and Zhou et al. (2004):

$$\text{DI}_k = \text{RH}_k \times \text{RC}_k \times 100, \quad [5]$$

where DI_k is the dominance index of species k , RH_k is the relative height to the turfgrass plant of species k , and RC_k is the relative coverage in the quadrat of species k .

$$\text{PDI}_k = \left(\frac{\text{DI value of species } k}{\text{sum of DI values of all species}} \right) \times 100, \quad [6]$$

where PDI_k is the PDI value of species k . A weed species was defined as a dominant weed when $\text{PDI} \geq 10\%$, as an important weed when $1\% \leq \text{PDI} < 10\%$, and as a subdominant weed when $\text{PDI} < 1\%$.

Soil nutrient conditions (the contents of total nitrogen, hydrolyzable nitrogen, rapidly available phosphorus, rapidly available potassium, and organic matter) and soil physical properties (clay content and soil density) for the 0- to 25-cm soil layer were analyzed by the Tianjin Institute of Resource and Environmental Science. At sampling, the soil temperature of the 0- to 18-cm layer was measured with a digital probe thermometer (Kat. Nr. 30.1021; TFA Dostmann GmbH & Co. KG, Wertheim-Reicholzheim, Germany). The soil salinity of the 0- to 18-cm layer and the soil pH at the 0- to 11-cm layer were measured with PNT3000 and pH3000 m, respectively (STEP Systems GmbH, Nürnberg, Germany). The soil moisture of the 0- to 18-cm layer was measured with a Field Scout TDR 100 system (Item# 6440FS, Spectrum® Technologies, Inc., Aurora, IL). The soil moisture data consisted of mass water content in 2015 and volumetric water content in 2016. Except for soil temperature and soil moisture (measured and analyzed separately in 2 years as two repetitions), the soil variables were measured in 2015 alone because they were not expected to change drastically in two successive years (Supplemental Table 1). Visual estimation of turfgrass deterioration was conducted during the survey. Deterioration ratings were based on a scale from 0% to 100% (where 0% = no turfgrass deterioration and complete coverage of the ground by turfgrass plants and 100% = severe turfgrass deterioration and either completely barren ground or ground-covered by other plants).

Statistical analysis. Total weed density (TWD) and TDI (the sum of DI value that is the product of relative height and the relative coverage of each weed species) of all weed species in a 0.25-m² quadrat of each survey sites were calculated. To determine the correlations between the factors that might influence weed infestation and TDI in the turfgrass sites, PACA was performed using the software SPSS 19.0 (SPSS, Inc., Chicago, IL). Correlations between TDI and each of the 12 potential influencing factors (the abovementioned soil nutrient conditions, soil physical properties, temperature, moisture, salinity, pH, and turfgrass deterioration) for each survey site were calculated. PACA was used to determine the correlation between TDI and each of the 12 factors holding the effects of the remaining factors constant. Pearson correlation analysis was used to evaluate the correlation between two variables and two-tailed P values were calculated to indicate the significance at $\alpha = 0.05$. Factors that were significantly correlated with TDI have influence on weed infestation. The data from 2015 and 2016 were analyzed separately because significant interactions of year with TDI, soil moisture, and other variables were found.

Results

Weed community composition. Across all turfgrass sites surveyed during early spring in both years, 37 weed species belonging to 14

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¹Corresponding author. E-mail: zhangjinweibeyond@aliyun.com.

different families were identified; these species are presented in alphabetic order in Supplemental Table 2. When classifying each weed according to life cycle, there were 17 perennial weeds, accounting for 45.9% of all of the weed species, and 20 annual or biennial weeds, accounting for 54.1% of the weed species. *Asteraceae* (16 species) and *Brassicaceae* (five species) were the dominant weed families, representing 43.2% and 13.5% of the weed species, respectively. When classified from the point of weed management, there were 35 broadleaved weed species and two grass weed species, accounting for 94.6% and 5.4% of the weed species, respectively.

Weed dominance analysis. To quantify the dominance of each weed species surveyed across all sites over 2 years, the relative abundance value of each weed species (incorporating weed density, distribution uniformity, and frequency parameters) was calculated. The results from both years indicated that *I. polycephala* Cass., *T. mongolicum* Hand.-Mazz., *I. japonica* Thunb., *H. lyrata* Bge., *T. peduncularis* (Trev.) Benth., *C. hederacea* Wall., *L. apetalum* Willd., *P. asiatica* L., *Cirsium segetum* Bge., and *I. sonchifolia* Hance. were the 10 most abundant weed species during the early spring, although their rank order slightly differed between the 2 years. All 10 weed species were broadleaved weeds and they belonged to five families: *Asteraceae* (six species), *Boraginaceae*, *Brassicaceae*, *Plantaginaceae*, and *Convolvulaceae* (one species each) (Tables 1 and 2).

In addition to relative abundance, the PDI of each weed (integrating weed coverage and height) was calculated to reflect the dominance of each weed in the community. The results indicated that *I. polycephala* Cass.

and *T. mongolicum* Hand.-Mazz. were the two dominant weed species, with PDI values above 10% in both years.

Weed infestation variability and key influencing factors. For each site, the TWD and TDI were calculated, and the dominant weed species were identified and summarized to identify the weed community and the differences in infestation severity among sites. The severity of weed infestation varied widely in both years. Both TWD and TDI were low at some survey sites (e.g., Chaoyang Avenue and Jingjin New City) and high at others (e.g., Jixian County and Xiaodian Park). The dominant weed species differed among the 23 survey sites and some were not among the 10 most common weed species at each site (Table 3).

Correlations between TDI and each of the 12 factors (including the soil nutrient conditions, soil properties, temperature, moisture, salinity, pH, and turfgrass deterioration) potentially related to weed infestation of turfgrass at each site were analyzed by PACA. The results indicated that the deterioration rate (D) of a turfgrass area was significantly and positively correlated with TDI ($P = 0.001$ in 2015 and $P = 0.004$ in 2016, with a partial correlation coefficient of 0.8238 in 2015 and 0.7648 in 2016) in both years. Soil organic matter and soil salinity (S) were negatively correlated with TDI, and the correlations were significant in 2015 ($P < 0.05$). However, no significant correlation between TDI and the remaining nine factors was observed in either year (Table 4).

Discussion

Weed community composition. When weeds appear in a crop production system,

identification of the weed community composition is required before economical and effective management practices can be undertaken (Frick and Thomas, 1992; McCully et al., 1991; Thomas, 1985, 1991). The results of our survey indicated that perennial and biennial broadleaved weed species belonging to the families *Asteraceae* and *Brassicaceae* are the weeds to target during early spring in the Tianjin region, China. Severely harmful annual weed species, e.g., large crabgrass [*Digitaria sanguinalis* (L.) Scop.] and small crabgrass (*Digitaria ischaemum* Schreb. ex Muhl.) had not infested by mid-April in this region. The absence of these species might be due to unsuitable environmental conditions for weed infestation (e.g., the combination of soil temperature and moisture) during this period (Masin et al., 2005).

Festuca arundinacea Schreb., as a popular cool-season turfgrass plant, is planted extensively in large areas of China. The present findings of weed community composition in turfgrass areas during the early spring in Tianjin, a typical region of the North China Plain, are of broad interest to turfgrass researchers and managers from other regions where *F. arundinacea* Schreb. is planted.

Common and dominant weed species. Weed density, frequency, uniformity, and their relative values to the whole community are commonly used parameters to analyze weed composition in crop production systems. However, each parameter has limitations when used independently because it might not accurately reflect the ecological importance of a species within a community (Andreasen and Stryhn, 2008; Nkoa et al., 2015; Thomas, 1985; Uddin et al., 2010). Hence, we integrated weed density, field frequency, and field uniformity into relative

Table 1. The 10 most common weed species in areas of *Festuca arundinacea* Schreb. turfgrass during the early Spring of 2015.

Weed species	Uniformity (%)	Density (plant/m ²)	Frequency (%)	Relative uniformity (%)	Relative density (%)	Relative frequency (%)	Relative abundance (%)	PDI (%)
<i>Trigonotis peduncularis</i> (Trev.) Benth.	19.42	20.74	60.87	11.70	45.89	8.43	66.02	8.06
<i>Ixeris polycephala</i> Cass.	44.93	8.61	100.00	27.06	19.06	13.85	59.97	24.70
<i>Taraxacum mongolicum</i> Hand.-Mazz.	16.52	1.17	69.57	9.95	2.59	9.64	22.18	13.06
<i>Inula japonica</i> Thunb.	11.59	4.48	34.78	6.98	9.90	4.82	21.70	5.89
<i>Hemistepta lyrata</i> Bge.	9.86	0.56	60.87	5.94	1.23	8.43	15.60	6.36
<i>Lepidium apetalum</i> Willd.	10.14	1.98	34.78	6.11	4.39	4.82	15.32	7.71
<i>Plantago asiatica</i> L.	10.14	0.72	47.83	6.11	1.59	6.62	14.33	4.42
<i>Calystegia hederacea</i> Wall.	6.09	0.53	34.78	3.67	1.18	4.82	9.66	2.40
<i>Cirsium segetum</i> Bge.	3.48	0.35	21.74	3.10	0.77	4.01	7.88	3.31
<i>Ixeris sonchifolia</i> Hance.	2.61	0.14	21.74	1.57	1.31	4.01	6.89	3.77

PDI = percentage of dominance value of the weed species.

Table 2. The 10 most common weed species in areas of *Festuca arundinacea* Schreb. turfgrass during the early Spring of 2016.

Weed species	Uniformity (%)	Density (plant/m ²)	Frequency (%)	Relative uniformity (%)	Relative density (%)	Relative frequency (%)	Relative abundance (%)	PDI (%)
<i>Ixeris polycephala</i> Cass.	39.86	4.36	91.30	23.75	16.78	11.80	52.33	19.07
<i>Trigonotis peduncularis</i> (Trev.) Benth.	15.58	6.99	52.17	9.28	26.87	6.74	42.89	6.18
<i>Taraxacum mongolicum</i> Hand.-Mazz.	21.74	1.57	73.91	12.96	6.02	9.55	28.52	18.13
<i>Inula japonica</i> Thunb.	10.14	3.48	43.48	6.05	13.38	5.62	25.04	3.17
<i>Hemistepta lyrata</i> Bge.	10.87	0.64	60.87	6.48	2.45	7.86	16.79	5.16
<i>Calystegia hederacea</i> Wall.	10.14	1.17	43.48	6.05	4.52	5.62	16.18	3.41
<i>Plantago asiatica</i> L.	8.33	0.65	52.17	4.97	2.51	6.74	14.22	2.85
<i>Lepidium apetalum</i> Willd.	6.52	1.10	30.43	3.89	4.24	3.93	12.06	8.16
<i>Ixeris sonchifolia</i> Hance.	6.16	0.64	21.74	4.67	2.45	4.61	11.73	6.13
<i>Cirsium segetum</i> Bge.	5.43	0.64	26.09	3.24	2.45	3.37	9.06	2.95

PDI = percentage of dominance value of the weed species.

Table 3. Weed infestation and dominant weed species in 23 survey sites in the Tianjin region during the early Spring of 2015 and 2016.

Sites	2015			2016		
	TWD (plants/m ²)	TDI	Dominant weed species	TWD (plants/m ²)	TDI	Dominant weed species
Panshan Mountain	4.83 ± 1.10	8.63 ± 1.44	IXESO > IXEPO	7.42 ± 1.08	11.33 ± 2.26	IXESO > IXEPO
Jixian County	29.83 ± 5.69	17.06 ± 2.36	INUJA > PLAAS > VIOYE > TARMO	28.00 ± 4.02	11.83 ± 1.65	TRIVU > TARMO > VIOYE
Jinji Highway exit	34.72 ± 8.17	8.64 ± 1.80	TRIBE > TARMO > INUJA > ANDUM	8.33 ± 2.17	7.83 ± 1.24	TARMO > ANDUM > INUJA
Lingang Restaurant	18.17 ± 5.50	9.81 ± 2.58	TARMO > TRIPE	2.75 ± 0.63	7.18 ± 1.15	TARMO
Binhai District gov.	57.17 ± 22.72	10.20 ± 3.67	TRIBE > LEPAP	67.17 ± 12.72	11.20 ± 1.67	TRIBE > LEPAP > IXEPO
Beitang Town	2.28 ± 1.06	5.87 ± 1.53	HEMLY > IXEPO > TARMO	4.08 ± 0.87	6.74 ± 0.76	IXEPO > CALHE > TARMO > SONBR
DagangXuefu Plaza	5.40 ± 1.15	3.46 ± 0.77	LEPAP > IXEPO > TARMO	2.00 ± 0.39	5.33 ± 0.78	TARMO > SONBR > TRIVU
Siundian Town	7.86 ± 0.78	4.62 ± 0.99	IXEPO > TARMO > HEMLY	4.75 ± 1.07	7.61 ± 0.74	IXEPO > TARMO > HEMLY
Wuqing Swan Lake	39.81 ± 10.29	5.31 ± 1.27	TRIBE	11.25 ± 3.54	6.48 ± 0.69	TARMO > INUJA > HEMLY > TRIPE
Meichang Market	9.54 ± 4.92	2.48 ± 0.71	LEPAP > CHEAL > IXEPO > CALHE > TARMO	10.33 ± 5.27	3.10 ± 0.67	PLAAS > CHEAL > IXEPO > CALHE > HEMLY
Jingjin New City	2.20 ± 0.78	2.10 ± 0.56	LACIN > INUJA > IXEPO	2.20 ± 0.76	2.15 ± 0.56	LACIN > SONBR > INUJA > IXEPO
Chaoyang Avenue	1.83 ± 0.82	1.48 ± 0.69	CALHE > HEMLY	1.83 ± 0.82	1.57 ± 0.69	CALHE > HEMLY
Qilithai Park	2.56 ± 0.60	3.43 ± 1.16	PLAAS > IXEPO > LEPAP > HEMLY	4.92 ± 0.70	6.62 ± 1.21	PHRCO > INUJA > TRIVU > CALHE
Jiulong Company	11.50 ± 3.42	10.67 ± 1.43	IXEPO	11.42 ± 4.07	13.65 ± 2.07	IXEPO > LEPAP > TARMO > CIRAR
Jinghai County	13.86 ± 1.94	6.02 ± 1.07	IXEPO > TRIPE > LEPAP	16.08 ± 2.85	8.28 ± 2.20	TRIBE > IXEPO > VIOYE
Xishuanggang Park	5.89 ± 1.44	11.23 ± 2.00	LEPAP > HEMLY > TRIVU > THESA	7.50 ± 2.05	14.23 ± 3.35	LEPAP > HEMLY
Tuanbo Town	6.61 ± 1.33	4.77 ± 1.21	IXEPO	4.17 ± 1.01	7.47 ± 1.80	LEPAP > IXEPO > INUJA > CIRAR
Xianda School	2.59 ± 0.69	2.41 ± 0.66	IXEPO > TARMO > HEMLY > LACIN	2.83 ± 0.86	2.98 ± 0.85	IXEPO > TARMO > LACIN
Fubao Industry	4.06 ± 0.58	10.39 ± 1.62	IXEPO > LEPAP > TARMO > HEMLY	6.00 ± 1.17	18.63 ± 2.61	LEPAP > IXEPO > CAPBU > HEMLY
Beichen Mansion	5.50 ± 0.73	6.28 ± 1.11	IXEPO > IXESO	2.17 ± 0.65	4.01 ± 0.74	IXEPO > IXESO > TARMO
Xiaodian Park	18.33 ± 2.77	12.61 ± 2.08	IXEPO	14.83 ± 2.87	10.68 ± 2.91	IXEPO > LEPAP > CAPBU
Dongli Lake Park	5.61 ± 1.79	8.36 ± 2.67	LEPAP > IXEPO > LEPLA	3.67 ± 0.70	9.13 ± 1.10	TARMO > CIRAR
Huangm Town	2.07 ± 0.33	4.73 ± 0.72	IXEPO > TRIPE > TARMO	3.17 ± 0.76	6.73 ± 1.09	IXEPO > TRIPE > TARMO > LACIN

TWD = total weed density of all weed species; TDI = total dominance index value of all weeds in a 0.25 m² quadrat. Dominant weed species denotes those species with a percentage of DI ≥ 10% (percentage of dominance index value ≥ 10%); IXESO = *Ixeris sonchifolia* Hance; IXEPO = *Ixeris polyccephala* Cass.; TRIPE = *Trigonotis peduncularis* (Trev.) Benth.; TARMO = *Taraxacum mongolicum* Hand.-Mazz.; INUJA = *Inula japonica* Thunb.; ANDUM = *Androsace umbellata* (Lour.) Merr.; PLAAS = *Plantago asiatica* L.; VIOYE = *Viola yedoensis* Makino; LEPAP = *Lepidium apetalum* Willd.; HEMLY = *Hemistepia lyrata* Bge.; CHEAL = *Chenopodium album* L.; CALHE = *Calystegia hederacea* Wall.; LACIN = *Lactuca indica* L.; TRIVU = *Tripolium vulgare* Nees.; THESA = *Thellungiella salsuginea* (Pall.) O. E. Schulz; LEPLA = *Lepidium latifolium* L. Var. affine C. A. Mey.; CAPBU = *Capsella bursa-pastoris* (Linn.) Medic.; SONBR = *Sonchus brachyotus* DC.; CIRAR = *Cirsium arvense* (L.) Scop.; PHRCO = *Phragmites communis* Trin.

Table 4. Partial correlation analysis results of weed infestation and 12 related factors in the Tianjin region during the early Spring of 2015 and 2016.

Factor	2015		2016	
	Partial correlation coefficient	P value	Partial correlation coefficient	P value
CP	0.2964	0.350	0.1330	0.680
SD	-0.0679	0.834	-0.0518	0.873
TN	0.5188	0.084	0.3718	0.234
N	-0.1653	0.608	-0.3583	0.253
P	-0.1328	0.681	0.3404	0.279
K	-0.0846	0.794	-0.1778	0.580
SOM	-0.6269	0.039 ²	-0.4279	0.165
S	-0.5919	0.043 ²	-0.4071	0.189
pH	0.1388	0.667	0.3376	0.283
D	0.8238	0.001 ²	0.7648	0.004 ²
SM	-0.3461	0.270	0.2225	0.487
ST	0.0086	0.979	0.2088	0.515

²Denotes that the correlation was significant at $\alpha = 0.05$.

DI = product of the relative height and the relative coverage value of a weed in a quadrat; CP = clay content percentage of the soil; SD = soil density; TN = total nitrogen content of the soil; N = hydrolyzable nitrogen; P = rapidly available phosphorus; K = rapidly available potassium; SOM = soil organic matter; S = salinity content of the soil; D = deterioration rate of the turfgrass (on a scale from 0% to 100%); SM = soil moisture; ST = soil temperature at a depth of 0–18 cm.

abundance, and we integrated relative height and coverage into PDI for each weed species. The top 10 weed species ranked according to PDI value were the same as those ranked according to relative abundance value (Tables 1 and 2). This demonstrated that these two parameters are appropriate for determining the severely infesting weed species, and our ranking of the 10 most common weed species we identified during this period in this region is highly credible.

Based on the analyses of PDI for the 2 years, *I. polycephala* Cass. and *T. mongolicum* Hand-Mazz. were identified as the two dominant weed species. Esmaili and Salehi (2009) and Ferguson et al. (2016) reported that *Taraxacum officinale* is problematic for turfgrass managers each year, and this plant strongly competes with turfgrass plants for resources (Franssen and Kells, 2007). Although *T. mongolicum* Hand-Mazz. is a different species from the congeneric *T. officinale* and although there are few reports on *I. polycephala* Cass infestation of turfgrass areas, infestation by the two weed species identified here warrants attention.

Key factors influencing weed infestation. Weed populations in turfgrass areas are governed by both ecological and human activities, and the interactions that invariably occur between weed species and environmental or management variables are very complex (Nkoa et al., 2015). According to the PACA in our study, the deterioration rate of turfgrass was significantly and positively correlated with TDI in both years. Most of the turfgrass areas with high deterioration rates were severely infested by weeds and located in residential areas (e.g., Xishuangtang Park and Xiaodian Park). This observation is consistent with the results of Uddin et al. (2010), who demonstrated that residential lawns had more weeds than did golf course putting greens, athletic fields, and sod farms. High daily foot traffic, low daily maintenance, and aged turfgrass plants are likely reasons for this phenomenon. Soil organic matter typically influences weed abundance

in the field (Dieleman et al., 2000a, 2000b; Medlin et al., 2001). The negative correlation observed between SOM and TDI in our study might be due to the positive effects of high SOM on turfgrass growth. It precludes severe weed invasion and establishment. Similar to SOM, soil salinity showed a negative correlation with TDI (e.g., the soil salinity at the Chaoyang Avenue site was high, but the weed infestation severity was low). This result might be due to inhibitory effects of high soil salinity on the growth of most of the weed species and the subsequent reduction of the weed infestation of turfgrass. No significant correlation between TDI and any of the remaining nine parameters was observed; it is possible that the differences in these parameters among the different turfgrass areas were too small to be detected statistically.

Our 2-year survey identified the 10 most common and the two most harmful weed species in *F. arundinacea* Schreb. turfgrass areas and the three key factors (turfgrass deterioration rate, SOM and salinity) influencing weed infestation of these areas during early spring in the Tianjin region, China. These findings allow turfgrass researchers and managers to target specific harmful weed species. In addition, they can improve the development of preventive and curative weed management programs and promote precise and efficient weed control. By understanding the key factors that influence weed infestation, nonchemical strategies to control harmful weeds can be adopted, such as optimizing daily turfgrass maintenance (e.g., mowing, irrigation, fertilization, and other practices), restoring areas of turfgrass deterioration and controlling weeds by using saline water (see Uddin et al., 2014).

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Supplemental Table 1. Survey sites and values of 12 factors measured in *Festuca arundinacea* Schreb. turfgrass areas in the Tianjin region during the early Spring of 2015 and 2016.

Location	Turfgrass function	Coordinates	CP (%)	SD (g·cm ⁻³)	TN (g·kg ⁻¹)	N (mg·kg ⁻¹)	P (mg·kg ⁻¹)	K (mg·kg ⁻¹)	SOM (%)	S (g·L ⁻¹)	pH	D (2015/2016)		SM (%)		ST (°C)	
Panshan Mountain	Roadside greening belt	40°4.216'N, 117°16.326'E	68	1.23	0.927	58.49	7.88	239.5	1.859	0.39	8.64	6/7	6/7	12.60	51.8	8.1	12.8
Jixian County	Roadside greening belt	40°3.306'N, 117°28.357'E	50	1.38	1.04	67.84	7.37	303	2.1	0.46	8.32	65/65	65/65	16.29	29.3	7.6	12
Jinji Highway exit	Roadside greening belt	40°2.015'N, 117°21.479'E	40	1.39	0.66	51.08	7.12	113.5	1.185	0.38	8.32	8/9	8/9	19.47	36.5	10	11
Lingang Restaurant	Building landscape lawn	38°56.504'N, 117°42.532'E	38	1.45	0.634	44.06	7.8	139.5	1.142	0.30	8.47	3/3	3/3	20.05	45.1	9.5	11.5
Binhai District gov.	Building landscape lawn	39°1.108'N, 117°41.243'E	38	1.40	0.936	62.38	20.85	184	1.533	0.42	8.41	15/18	15/18	14.41	39.3	11.9	11.3
Betang Town	Building landscape lawn	39°6.274'N, 117°43.091'E	38	1.52	1.191	131.4	35.17	218	1.692	0.30	7.79	55/57	55/57	14.82	40.1	10.8	12
DagangXuefu Plaza	Building landscape lawn	38°51.331'N, 117°25.946'E	24	1.69	0.845	62.77	13.56	107.5	1.538	0.13	8.27	60/55	60/55	7.89	26.5	10.9	14.2
Sicundian Town	Building landscape lawn	39°28.758'N, 116°56.977'E	44	1.48	0.392	24.95	6.61	156.5	0.717	0.46	8.69	3/4	3/4	18.94	32.3	9	10.3
Wuqing Swan Lake	Building landscape lawn	39°24.913'N, 117°3.532'E	34	1.21	1.186	93.19	62.88	128	2.052	0.36	8.26	4/5	4/5	17.95	35.1	9.2	11.6
Meichang Market	Roadside greening belt	39°21.789'N, 117°11.377'E	40	1.43	0.648	47.18	5.42	160.5	1.087	0.39	8.72	12/13	12/13	8.80	44.8	8.5	12.4
Jinjin New City	Roadside greening belt	39°32.683'N, 117°21.248'E	44	1.38	0.744	42.23	4.32	168.5	1.337	0.78	9.07	25/28	25/28	14.88	26.8	11.1	11.8
Chaoyang Avenue	Roadside greening belt	39°41.320'N, 117°18.052'E	46	1.42	0.812	49.91	13.9	227.5	1.236	0.83	8.34	30/33	30/33	10.99	92.3	11.5	13.2
Qilihai Park	Natural park landscape	39°16.738'N, 117°23.575'E	44	1.46	0.756	52.25	16.77	187.5	1.26	0.29	8.29	11/12	11/12	17.60	28.7	11.9	13
Jiulong Company	Roadside greening belt	39°18.797'N, 117°44.870'E	48	1.40	0.634	35.48	4.97	231	1.121	0.42	8.58	12/13	12/13	14.99	39.8	13	14.2
Jinghai County	Roadside greening belt	38°56.378'N, 116°57.342'E	50	1.42	1.338	88.9	25.97	515	2.485	0.70	9.07	3/5	3/5	17.64	60.1	11.5	13.5
Xishuanggang Park	Residential landscape	38°52.174'N, 116°54.046'E	34	1.52	0.659	43.67	11.65	209	1.154	0.56	8.5	45/55	45/55	9.96	71.2	14.4	14.5
Tuanbo Town	Roadside greening belt	38°54.554'N, 117°9.804'E	56	1.34	1.102	58.49	11.13	607	1.812	0.48	8.77	5/8	5/8	18.25	59.8	8.2	12.9
Xianda School	Roadside greening belt	39°3.569'N, 116°55.187'E	54	1.53	1.118	63.94	46.55	940.5	2.186	0.96	8.63	5/7	5/7	12.88	74	8.5	11.9
Fubao Industry	Roadside greening belt	39°4.900'N, 117°2.163'E	60	1.43	0.98	57.32	28.75	649	1.707	0.31	8.9	8/9	8/9	17.50	37.9	8.7	11.6
Beichen Mansion	Roadside greening belt	39°13.747'N, 117°8.421'E	46	1.48	0.723	48.35	6.53	243	1.418	0.36	8.79	25/28	25/28	16.03	27.6	9	11.2
Xiaodian Park	Residential landscape	39°14.804'N, 117°13.139'E	54	1.44	0.795	44.84	23.45	548	1.348	0.66	8.86	5/7	5/7	19.82	61.8	8.5	12.5
Dongli Lake Park	Roadside greening belt	39°10.844'N, 117°28.407'E	56	1.68	1.025	59.26	21.55	557	1.833	0.41	8.91	9/11	9/11	17.20	33.7	12	13
Huaming Town	Roadside greening belt	39°9.589'N, 117°20.919'E	56	1.59	0.611	41.33	5.31	347	1.044	0.38	8.73	12/13	12/13	14.06	47.9	10.9	13.2

CP = clay content percentage of the soil; SD = soil density; TN = total nitrogen content of the soil; N = hydrolyzable nitrogen; P = rapidly available phosphorus; K = rapidly available potassium; SOM = soil organic matter; S = salinity content of the soil; D = deterioration rate of the turfgrass (on a scale from 0% to 100%); SM = soil moisture; ST = soil temperature at a depth of 0–18 cm.

Supplemental Table 2. Alphabetical list of weed species found in *Festuca arundinacea* Schreb. turfgrass areas in the Tianjin region during the early Spring of 2015 and 2016.

Scientific name	Life cycle	Family	Year
<i>Androsace umbellata</i> (Lour.) Merr.	B	Primulaceae	2015, 2016
<i>Artemisia annua</i> L.	B	Asteraceae	2015, 2016
<i>Artemisia argyi</i> Levl. et Vant.	P	Asteraceae	2015, 2016
<i>Calystegia hederacea</i> Wall.	P	Convolvulaceae	2015, 2016
<i>Capsella bursa-pastoris</i> (Linn.) Medic.	B	Brassicaceae	2015, 2016
<i>Cirsium arvense</i> (L.) Scop.	P	Asteraceae	2015, 2016
<i>Cirsium setosum</i> Willd.	P	Asteraceae	2015
<i>Chenopodium album</i> L.	A	Chenopodiaceae	2015, 2016
<i>Convolvulus arvensis</i> L.	P	Convolvulaceae	2015, 2016
<i>Conyza canadensis</i> (L.) Cronq.	B	Asteraceae	2016
<i>Cynanchum chinense</i> R.Br.	P	Asclepiadaceae	2015, 2016
<i>Cynodon dactylon</i> (L.) Pers.	P	Gramineae	2016
<i>Descurainia sophia</i> (L.) Schur.	A or B	Brassicaceae	2015
<i>Gnaphalium affine</i> D. Don	B	Asteraceae	2015, 2016
<i>Hemistepta lyrata</i> Bge.	B	Asteraceae	2015, 2016
<i>Heteropappus altaicus</i> (Willd.) Novopokr.	P	Asteraceae	2016
<i>Humulus scandens</i> (Lour.) Merr.	A	Moraceae	2015, 2016
<i>Inula japonica</i> Thunb.	P	Asteraceae	2015, 2016
<i>Ixeris polycephala</i> Cass.	A or B	Asteraceae	2015, 2016
<i>Ixeris sonchifolia</i> Hance	P	Asteraceae	2015, 2016
<i>Lactuca indica</i> L.	A or B	Asteraceae	2015, 2016
<i>Lactuca tatarica</i> (L.) C.A.Mey.	P	Asteraceae	2016
<i>Lagopsis supina</i> (Stephan.) IK.-Gal. ex Knorr.	B	Labiatae	2015, 2016
<i>Lepidium apetalum</i> Willd.	A or B	Brassicaceae	2015, 2016
<i>Lepidium latifolium</i> L. Var. affine C. A. Mey.	P	Brassicaceae	2015
<i>Phragmites communis</i> Trin.	P	Gramineae	2015, 2016
<i>Plantago asiatica</i> L.	P	Plantaginaceae	2015, 2016
<i>Polygonum aviculare</i> L.	A	Polygonaceae	2015, 2016
<i>Potentilla supina</i> L.	B	Rosaceae	2015, 2016
<i>Rumex acetosa</i> L.	A	Polygonaceae	2015
<i>Salvia plebeia</i> R. Br.	A or B	Labiatae	2015
<i>Sonchus brachyotus</i> DC.	P	Asteraceae	2015, 2016
<i>Taraxacum mongolicum</i> Hand.-Mazz.	P	Asteraceae	2015, 2016
<i>Thellungiella salsuginea</i> (Pall.) O. E. Schulz	A	Brassicaceae	2015, 2016
<i>Trigonotis peduncularis</i> (Trev.) Benth.	A or B	Boraginaceae	2015, 2016
<i>Tripolium vulgare</i> Nees.	A	Asteraceae	2015, 2016
<i>Viola yedoensis</i> Makino	P	Violaceae	2015, 2016

A = annual; B = biennial; P = perennial; A or B = annual or biennial. All of the information on the weed species was obtained from the Chinese colored weed illustrated book (Institute for the Control of Agrochemicals and Ministry of Agriculture and The Japanese Association for the Study of Plant Regulator, 2000).