IOP Conference Series: Earth and Environmental Science

PAPER • **OPEN ACCESS**

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To cite this article: Shou-gang Yan and Xiao-dong Li 2017 *IOP Conf. Ser.: Earth Environ. Sci.* **81** 012057

Effects of Soil Moisture on Vegetation Invasion into Transition Zones between Windword Slopes of Active Dunes and Interdune Lowlands

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Abstract: During the vegetation natural regenerations in semi-arid sand areas, seed germination and seedling emergence are critical phases of maintaining plant population and realizing natural regeneration. It is generally accepted that soil moisture and soil seed bank are primary dependent factors in the phases. But the binary correlation analysis between seedling density and soil seed bank density as well soil moisture in transition zones between windword slopes of active dunes and interdune lowlands indicated that the correlation between seedling density and soil seed bank density was not significant ($P > 0.05$) in the plant growing season; but the one between seedling density and soil moisture was significant and positive ($P < 0.05$); moreover, seedling density increased logarithmically with the increasing of soil moisture. The conclusions reveal that soil moisture is a primary dependent factor during seedling emergence and establishment in the transition zones between the windword slopes of active dunes and interdune lowlands, but soil seed bank is not; and plant natural regeneration depends more on those propagating seeds from plant communities in neighbouring sand dunes.

1. Introduction

Soil seed bank is all survival seeds in the soil and the litterfall of soil upper layer[1]. As an important seed reserve pool, soil seed bank directly participates in plant natural regeneration through seed germination and seedling emergence, and influences composition and structure of aboveground plant communities[2]. Although, mature plant seed could propagate from one place to another with the help of various kinds propagation mediums and then forms soil seed bank, they could germinate only under the condition of an suitable soil moisture in the growing season.

During the vegetation natural regenerations in semi-arid sand areas, seed germination and seedling emergence are critical phases of maintaining plant population and realizing natural regeneration[3], in which there are a lot of dependent factors; but only soil seed bank and soil moisture are critical ones in the growing season. The relationship between soil seed bank and seedling in plant community[4-8], and the one between soil moisture and seedling[9-11] have been already studied, respectively. However, at present, the combined effects of soil seed bank and soil moisture on seedling emergence and establishment in semi-arid sand areas have not been studyed yet.

Horqin Sandy Land is a serious and deteriorating desertification area in farming -pastoral ecotone of Northern China, and is also a critical focus area of vegetation regenerations in sandy land areas[12]. Wulanaodu area is located in the western of Horqin Sandy Land, whose landscape is characterized by alternate distribution of active sand dune with low vegetation coverage and interdune lowland with high vegetation coverage. Because of violent wind erosion, a wind erosion district of good soil moisture is formed in the bottom of the windword slope in the active dune, and is also a transition zone from interdune lowland to active dune. To a large extent, vegetation natural regenerations of active dune areas depend on vegetation process of the wind erosion district[5, 13]. The research of the relationship between soil moisture and soil seed bank and emergence seedling in the transition zone between the windword slope of active dunes and interdune lowlands could to a certain extent reveal the principle of vegetation dynamic change in semi-arid sand dune areas and provide significant guidelines for vegetation restoration and management in sand dune fields that interfered by human activity.

Pre-experiment observations showed that large numbers of seedlings of *Phragmites communis* (Gramineae) (hereafter referred to as *P. communis*) and *Salix. Gordejevii* (hereafter referred to as *S. Gordejevii*) existed in transition zones between the windword slopes of active dunes and interdune lowlands in Horqin Sandy Land, however, their seeds, which are light[14] and are easily blown away by a strong wind, or germinate rapidly in moist soil surface[13], could be scarcely found in soil seed bank. Therefore, we suggest the hypothesis in this paper that the correlation between seedling density and soil seed bank density in transition zones between the windword slopes of active dunes and interdune lowlands was not significant in the plant growing season; but the one between seedling density and soil moisture was significant and positive. To test this, emergence seedling, establishment plant, soil moisture and soil seed bank were examined in field investigations, and the correlations between seedling density and soil seed bank density as well soil moisture in transition zones between the windword slopes of active dunes and interdune lowlands were analysed.

2. Experimental methods

Study site

The investigation site was at Wulanaodu area (119°39′–120°02′ E, 42°29′–43°06′ N; 480 m a.s.l.) of Horqin Sandy Land in the northeastern Inner Mongolia, China. The region has semi-arid, continental monsoon climate of temperate zone. The annual average air temperature is only 6.3 °C, the coldest and hottest months are January and July, respectively. The annual mean precipitation is 340 mm, 70 per cent of which falls during June–September. The annual mean wind velocity is 4.4 m s^{-1}. The dominant wind direction of March–May is northwestern. The days of strong wind (>16m s^{-1}) are 21–80.

2.1 Methods for field observations

The study sample plots are located in the centres of active dune areas, the high of active dune is 15-25m, moving 5~7m every year. The study area is the typical active dunes, whose vegetation cover is less than 5 percent. The dune pioneer plants widely distribute the study area, such as *Agriophyllum squarrosum* and *Artemisia wudanica*, and those community structures are simple, the plants often form the mono-dominant community. The interdune lowlands, surrounded by the crescent-shaped sand dunes, have the typical characters with good moisture conditions, and with a variety of community types, and with abundant species, and with a large number of non-psammophytes, such as *Typha minima* and *Calamagrostis epigeios*.

In two selected active dune areas, seven typical interdune lowlands were selected. The interdune lowland areas, soil and vegetation types were surveyed, and the transition zone positions between windward slopes of active dunes and interdune lowlands were determined and numbered according to the azimuth sequences (Site 1~7).

Four transects were set up in every transition zone between the windward slope of active dune and interdune lowland, and 1m×1m quadrats were set up for every 1-meter distance in every transect. With the change of the transition zone width (from the interdunes lowland edge to the windward slope bottom of active dune), each transect has about 5~7 quadrats. Soil seed bank, soil moisture and emergence seedling were surveyed in every quadrat.

2.2 Investigation methods

2.2.1 The survey of soil seed bank. Soil seed banks near the quadrats were investigated in the second day of every month in the plant growth season (from May to September), in 2012. There were 5 investigations of soil seed banks. The soil near each quadrat (1m x 1m) was divided into 3 layers (0~5cm, and 5~15cm and 15~30cm), the soil in each layer was sampled by the cylindrical soil sampler with the diameter of 7cm and the high of 10cm. Then the soil samples were taken back the laboratory and air-dried naturally, and sieved through the 0.5mm sieves. The seeds in soil samples were picked out the seeds, and the seed types were recorded, and the seed activity was tested.

2.2.2 Investigation of soil moisture. Using the drying and weighing method, soil moisture of 0~30cm depth near every quadrat was measured one time every 10d from May 8 to September 18, 2012. The soil near each quadrat (1m x 1m) was divided into 3 layers (0~5cm, and 5~15cm and 15~30cm), the soil in each layer was sampled by the cylindrical soil sampler with the diameter of 3cm. Soil samples were put into small aluminum boxes with the diameter of 4cm and the high of 2cm and take back the laboratory immediately, and weighed. In the thermostat of 105°c, soil samples had been dried for 8h, and then weighed again.

*2.2.3 Investigation of emergence seedlings and establishment plants.*The types, the numbers and heights of emergence seedlings in every quadrat were investigated one time every 10d from May 10 (when seedlings began to emerge) to September 20 (when seedlings did not emerge), 2012. These seedlings were recorded and then removed; the experiment had lasted for 130d. Outside of every quadrate of monitoring emergence seedlings, a new quadrat (1m x 1m) was built to investigate the richness, abundance and height of establishment plants in September 22, 2012.

2.3 Data processing methods
The density of the soil seed bank was represented by the active seed numbers in a soil unit area (1 m^2); the emergence seedling density was represented by the seedling number in a quadrat (1m x 1m); the soil moisture was represented by the percentage of moisture weight and soil dry weight.
The whole Application of SPSS 11.5 and Excel software were used for statistical analysis of the data. The significance of difference of soil seed bank, the emergence seedling, and soil moisture in different months in every sample plot were tested by the T-test method of paired samples. Using the binary variable correlation analysis method, the correlations between emergence seedling and soil seed bank, soil moisture were analysed. Using the linear regression analysis method, the relationship between emergence seedling and soil moisture was determined.

3. Results and analysis

3.1 Seedling density in the transition zone
Nine plants were found in the transition zones between windward slopes of active dune and the interdune lowland, including four Psammophytes, i.e. *Phragmites. Communis*, *Salix. Gordejevii*, *A. squarrosum* and *A. Wudanica*; four limnocryptophyte-meadow plants, i.e. *Setaria. viridis*, *Populus spp*., *T. Minima* and *Inulae. Britannica*; and a grassland plant, i.e. *Sonchus. Brachyotus*.

In the transition zones, the seedling densities of different plant types showed significant difference (Table 1). In Site 6 and Site 3, the seedling density of *Salix. gordejevii* was maximum, i.e. 114.7±22.7 and 136.8±25.1 m^{-2}, respectively. The sexual reproduction seedlings of *Phragmites. communis* only appeared in Site 6 and Site 3, the densities of which were 23.7±5.6 and 40.7±6.3m^{-2}, respectively. In any one transition zone, the seedling density difference of *A. squarrosum* and *A. wudanica* were significant. Compared with *A. squarrosum*, the seedling density of *A. wudanica* was small in any one site. The seedling of *Populus spp.* only appeared in Site 6 and Site 3, the densities of which were 9.0±2.6 and 11.2±2.9m^{-2}, respectively; Other plant type seedlings only appeared sporadically in the transition zones, the densities of which were smaller than 2m^{-2}.

3.2 The relationships between seedlings and soil seed bank, soil moisture

The bilateral correlation analysis between seedling densities and soil seed bank, and soil moisture in seven transition zones showed that the correlation between the seedling densities and soil seed bank from different depths (0~5cm, 5~15cm, 15~30cm) was not significant ($P > 0.05$); but the one between the seedling densities and soil moisture from different depths (0~5cm, 5~15cm, 15~30cm) was significantly positive in the plant growing season ($P < 0.05$) (Table 2).

The Linear Regression Analysis between seedling densities and soil moisture in the plant growing season showed that seedling densities increased logarithmically with the increasing of soil moisture of the 0~5cm depth; the seedling density variations of 82%, 86%, 96%, 97% and 63% were attributed to the variation of soil moisture of May, June, July, August and September, respectively (Figure 1). The seedling densities also increased logarithmically with the increasing of soil moisture of the 5~15cm and 15~30cm depths in the plant growing season. The relation figures were similar to Figure 1, and were omitted.

Table 1 Seedling densities in transition zones between windward slopes of active dunes and interdune lowlands in the growing season (m^{-2})

Plant type	Site 7	Site 6	Site 5	Site 4	Site 3	Site 2	Site 1
P. communis	0	23.7±5.6	0	0	40.7±6.3	0	0
S. gordejevii	0.4±0.12	114.7±22.7	0.1±0.05	0.4±0.14	136.8±25.1	0	6.4±1.7
A. squarrosum	12.2±2.1	3.2±1.4	3.9±0.8	13.0±1.5	1.2±0.5	23.4±6.7	27.3±8.3
A. wudanica	5.7±1.4	0.1±0.05	2.6±0.6	0.2±0.08	0.7±0.2	0.1±0.05	4.1±1.1
S.viridis	0.4±0.01	0.5±0.2	0	0.2±0.08	0.6±0.2	0	0.1±0.05
Populus spp.	0	9.0±2.6	0	0	11.2±2.9	0	0
T.minima	0	1.6±0.4	0	0	1.5±0.4	0	0
S.brachyotus	0	0.4±0.1	0	0	0.5±0.1	0	0
I.britannica	0	0.7±0.2	0	0	0.8±0.3	0	0

Table 2 The correlation coefficients between seedling densities and soil seed bank as well soil moisture in different monthes

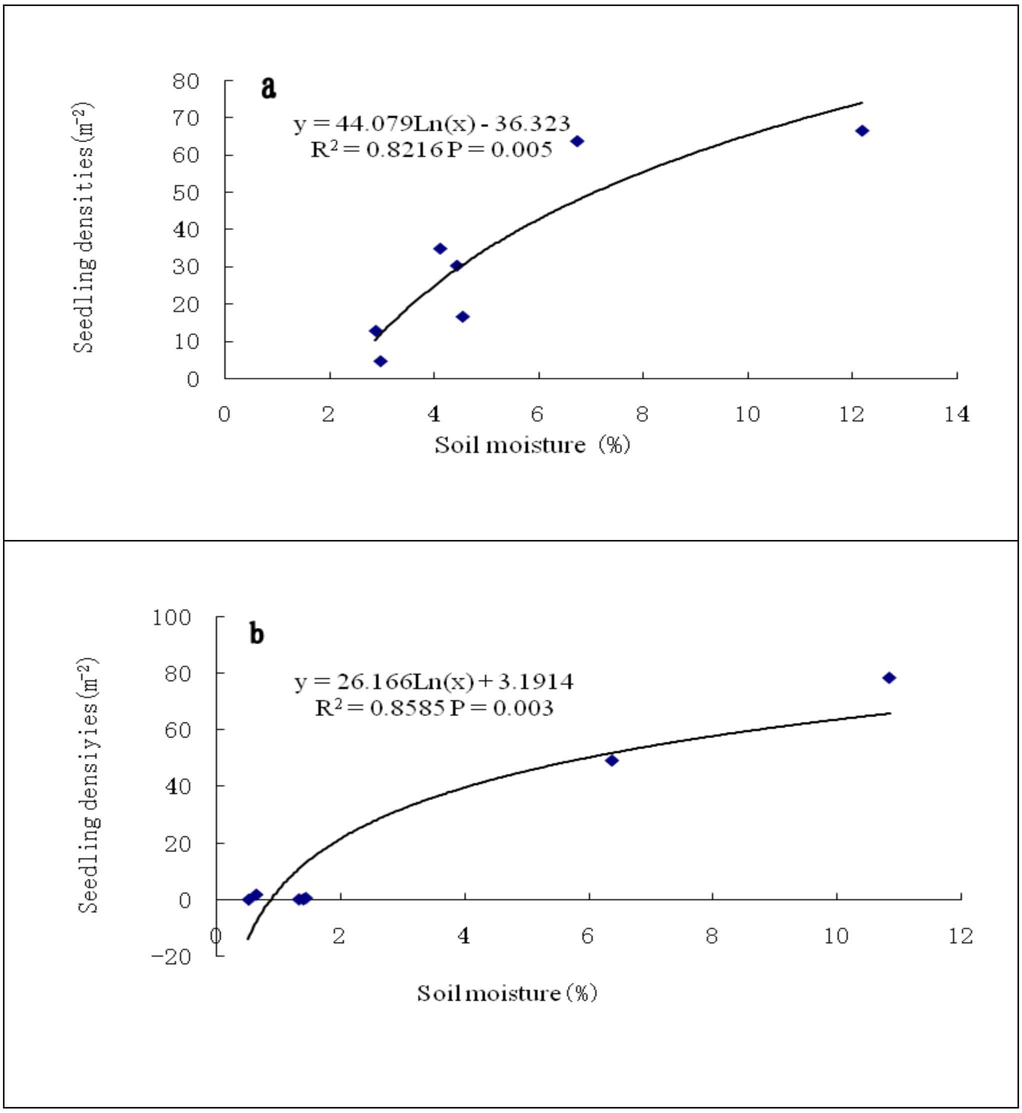
Correlation coefficients (r)		Investigation time (Month)				
		May	June	July	Oct.	Sep.
Seed bank	0-5cm	0.239	-0.672	0.232	-0.175	-0.332
	5-15cm	0.162	-0.335	-0.124	-0.333	-0.055
	15-30cm	-0.471	-0.595	-0.407	0.226	-0.371
Soil moisture	0-5cm	0.847*	0.992**	0.997**	0.998**	0.712*
	5-15cm	0.878*	0.994**	0.996**	0.998**	0.724*
	15-30cm	0.891*	0.998**	0.995**	0.998**	0.739*

*significant at $P < 0.05$; **significant at $P < 0.01$

3.3 The temporal dynamics of emergence seedlings, soil seed bank and soil moisture

The maximum values of the soil seed bank densities of 0~5cm depth in different transition zones appeared in different months of the plant growing season (from May to Nine), which did not show obvious regularities (Figure 2a). The characteristic figures of soil seed bank densities of the 5~15cm and 15~30cm depths in the growing season were similar to Figure 2a, and were omitted.

The maximum values of seedling densities and soil moisture of 0~5cm depth all appeared in the same month, which was in May (except for Site 6 and 3) (Fig. 2b & 2c). More than 87% of the seedlings were emerged in May (the seedling emergence peak in Site 3 was in June). In the whole growing season, the seedling densities in Site 6 and 3 were greatly more than the ones in other sites (i.e. Site 7, 5, 4, 2, 1); the difference of which was extremely significant (P < 0.01) (Fig. 2b).



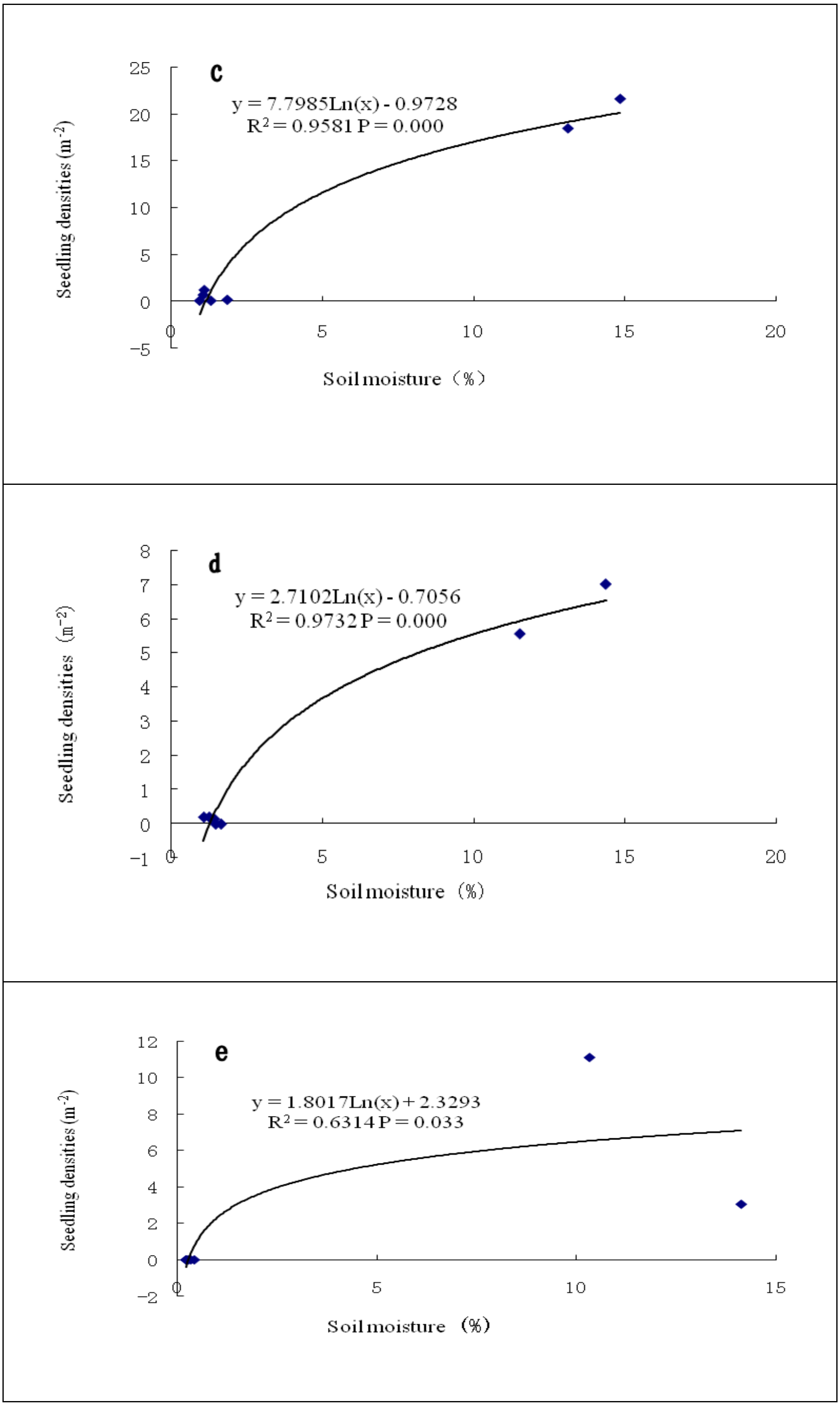


Fig. 1 The logarithmic relationship between seedling densities and soil moisture of 0~5cm depth in

different monthes (a, May; b, Jun.; c, Jul.; d, Oct.; e, Sep.); seedling densities increased logarithmically with the increasing in soil moisture.

Similarly, the soil moisture of 0~5cm depth in Site 6 and 3 were greatly more than the ones in other sites (i.e. Site 7, 5, 4, 2, 1); the difference of which was extremely significant ($P < 0.01$) (Fig. 2c). The characteristic figures of soil moisture of the 5~15cm and 15~30cm depths in the growing season were similar to Figure 2c, and were omitted.

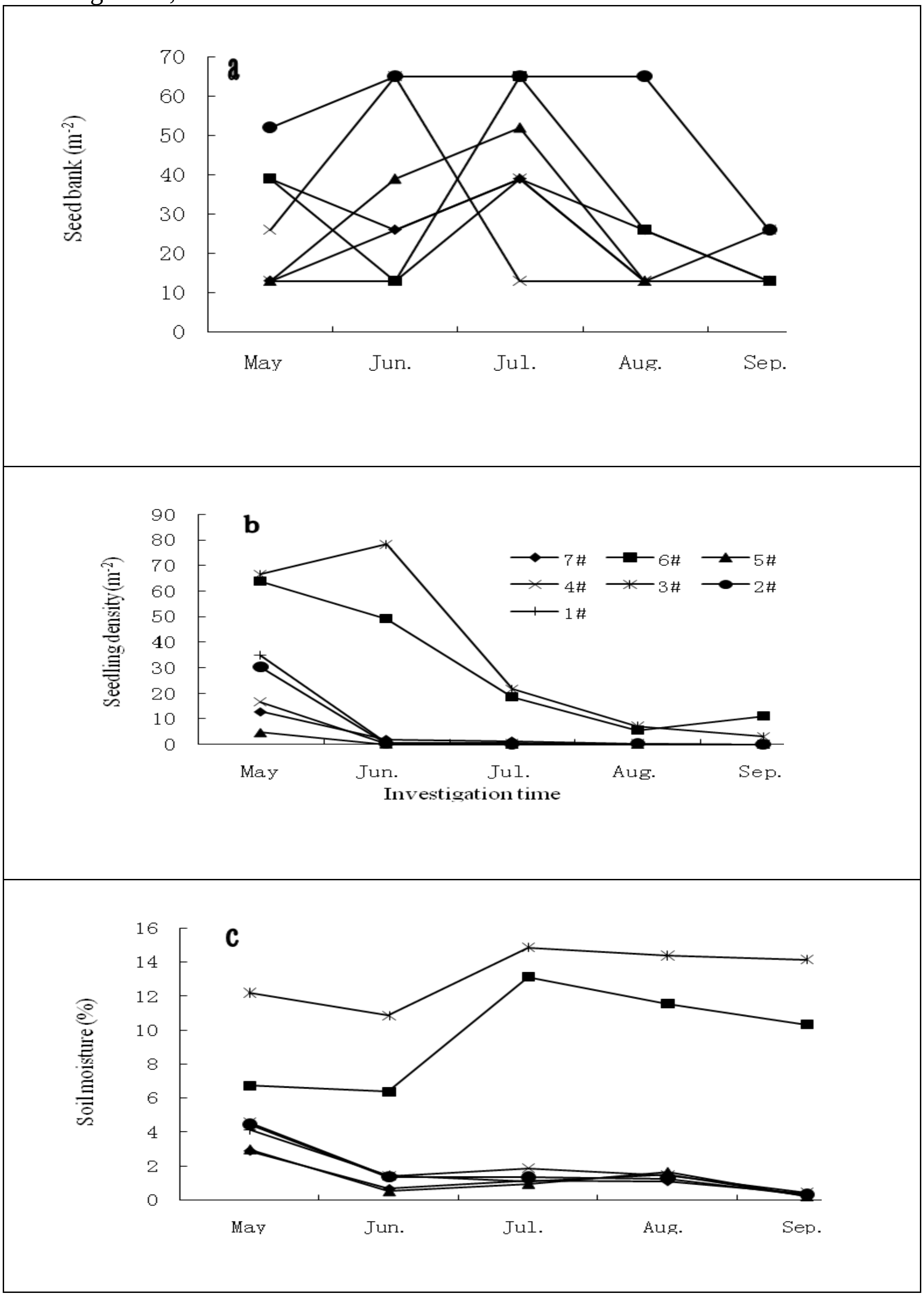


Fig. 2 Temporal dynamics of soil seed bank densities of 0~5cm depth (a), seedling densities (b) and soil moisture of 0~5cm depth (c) in the growing season in sample sites

3.4 The correlation between emergence seedling densities and establishment plant densities

In general, establishment plant densities in the end of the growing season accounted for 47.9 percent of total seedling densities in the growing season. The correlation between emergence seedling densities in May and establishment plant densities was significantly positive in seven sample sites ($P < 0.05$). In addition, the one between emergence seedling densities in June and establishment plant densities was significantly positive in Site 6, 4, 3, 2 ($P < 0.05$); the one between emergence seedling densities in July and establishment plant densities was significantly positive in Site 6, and 3 ($P < 0.05$) (Table 3).

Table 3 Correlation coefficients of densities between emergence seedling in each month and establishment plant in the end of the growing season

Site	May	June	July	Oct.	Sep.
7	0.528*	0.111	0.085	-0.065	----
6	0.957**	0.798**	0.516*	0.111	0.189
5	0.520*	0.046	-0.051	----	----
4	0.780**	0.637**	0.130	0.106	----
3	0.976**	0.988**	0.579*	0.150	0.096
2	0.924**	0.775**	-0.069	-0.082	----
1	0.582*	-0.134	-0.135	----	----

** significant at $P < 0.01$; * significant at $P < 0.05$; ---- No seedling emergence

4 Discussion

The relations between seed dispersal and germination, seedling emergence and establishment and dynamic change of plant population and community are considerably close[17]. How is the correlation between plant population density and soil seed bank density is at present controversial, probably on account of the difference coenotype and environmental factor. O’Connor and Pickett (1992)[18] found that the correlation between plant population density and soil seed bank density in the African savanna was significant and positive, however, Harper (1977)[19], Thompson and Grime (1979)[20], Coffin and Lauenroth (1989)[21] thought that the one between plant population density and soil seed bank density in the pasture of perennial herb was not significant. Our study conclusions in transition zone between the windword slope of active sand dune and interdune lowland were not consistent with the ones of O’Connor and Pickett, but were consistent with the ones of Harper, Thompson and Grime, Coffin and Lauenroth.

Whipple thought that there were four relations between plant population and soil seed bank. The first one was that seeds and plants coexisted, the second one was that seeds existed and plants did not, the third one was that plants existed and seeds did not, the fourth one was that seeds and plants all did not exist[22]. The landscape of dune areas is characterized by alternate distribution of sand dune and interdune lowland (Liu and Ma, 2008). One of the most obvious features in active sand dune is recurrent sand burial and wind erosion. In such severe environment, the relations between plant population and soil seed bank are completely different, one is that plants existed and seeds not, and the other is that seeds existed and plants not, because different psammophytes have evolved and undergone different reproductive modes to adapting to sand activities[23, 24]. For example, some seeds, such as *P. communis* and *S. Gordejevii*, have hairiness or pinniform appendants. These mature seeds spread everywhere owing to the blow of the wind. With the coming of the growing season, the weather becomes warmer and warmer, dispersal seeds rapidly germinate in moist soil surface, and then seedlings emerge and grow into plants. Therefore, the relations between *P. communis* and *S. Gordejevii* population and their soil seed bank was that plants existed and seeds did not. However, other seeds of psammophytes possess temporal and spatial dormancy, such as *S.viridis*, there are some viable seeds in soil seed bank, but the number of seeds is very little, and germination rate is also low, leading to the few number of seedlings and unestablishment or fewer of plants. Hence, the relatioans between *S.viridis* population and its soil seed bank was above the second one.

However, seedlings emergence need viable seeds, suitable soil moisture and temperature[9] . Due to the strong wind erosion, soil moistures in Site 3 and 6 were very suitable during the whole growing season, leading to continual emergence of seedlings. Nevertheless, in Site 1, 2, 4, 5 and 7, the temporal patterns of seedling emergence were completely different from the ones in two other sites. Compared to other months, soil moistures in May in these sites were relatively suitable (3~5%) (Figure 2c). In addition, average temperatures of month in the growing season in the study area were 16.3~22.2°C [15], and suit to seed germination and seedling emergence. Hence, in the sites, the number of seedling emergence in May accounted for 94.6 percent of the whole number(Figure 2 b). From June to September, the precipitation and soil evaporation increased rapidly with the climate warming, and meanwhile, water retaining capacity of sandy soil was weak, which leaded to soil moisture decrease below 2 percent after a rainfall[4]. The lack of soil moisture restrainted seed germination in the arid place and season.

The study revealed that there was a kind of dormancy of moisture control in the annual plant seeds in temperate deserts[25], i.e. a threshold value of soil moisture. Some researchers found that there was a threshold value of soil moisture in seed germination and seedling emergence of *Agropyron cristatum* (L.) Gaertn in Hunshadake Sandy Land[9]; when soil moisture was below 3 percent, seeds of *Agropyron cristatum* (L.) Gaertn could not germinate, when soil moisture was below 6 percent, seedlings could not emerge. In field natural conditions, there could also be threshold values of soil moisture in seed germination and seedling emergence in Horqin Sandy Land. How to find the threshold values of soil moisture would be finished through field investigations and controlled experiments in the future.

In semi-arid sand areas, strong wind erosion and sand burial leads to seed spatial and temporal redistributionin in the seed bank[3]. Our results revealed that the density maximum value of soil seed bank appeared in different months in different transition zones between the windword slope of active dune and interdune lowland(Figure 2 a), which could result from strong wind erosion in transition zones, ripening time and propagation time of seeds.

In brief, the vegetation natural regenerations of active sand dune in semi-arid sand areas depend largely on the vegetation process[5,13], which includes seed germination, seedling emergence and establishment and initiates a new vegetation succession stage of active sand dune, in the transition zone between the windword slope of active dune and interdune lowland. In this vegetation process, soil moisture is a primary dependent factor, and soil seed bank is not; these seeds that are needed in the vegetation natural regenerations are from the plant communities near the active sand dune.

Acknowledgements
This work was financially supported by the Scientific and Technological Research and Development Programs of Jilin Provincial Science and Technology Agency (20140101211JC) and the Thirteenth Five-year Scientific Research Projects of Jilin Provincial Education Agency (JJKH20170005KJ).

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