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The return and loss of litter phosphorus in different types of sand dunes in Horqin Sandy Land, northeastern China

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Abstract: Litter phosphorus (P) return is important to maintain the P cycle and balance in the sandy land of arid areas. In this study, we determined the loss and return of litter P in sand dune areas and elucidated their relationship. We investigated litter production and litter P amount, and simulated leaf litter moving dynamics to understand the relationships between the loss of litter P and the total litter P, and between the return of litter P and the total litter P in active (AD), semi-stabilized (SSD) and stabilized (SD) dunes in Inner Mongolia, northeastern China. The vegetation litter P was 12.6, 94.5, and 201.6 mg P/m² in AD, SSD, and SD, respectively. A significant movement and loss of leaf litter P with time occurred on the three types of sand dunes. As a result, the loss of P was 7.4, 46.9, and 69.8 mg P/m² and the return of P was 5.5, 47.6, and 131.8 mg P/m² in AD, SSD, and SD, respectively. The relationship between both loss and return of P and total litter P in AD, SSD, and SD was revealed by linear regression. The slope of the regression line indicated the rate of loss or return of litter P. From AD to SD, the loss rate showed a declining slope (0.52, 0.32, and 0.17 for AD, SSD, and SD, respectively), and the return rate showed a rising slope (0.48, 0.67, and 0.83 for AD, SSD, and SD, respectively). The loss of litter P should be regarded in the local management of vegetation and land in sand dune areas. Improved vegetation restoration measures are necessary to decrease litter P loss to maintain the stability of ecosystems in sand dune areas.

Keywords: leaf litter; litter loss; litter production; sand dune areas; vegetation restoration

Phosphorus (P) is an important plant nutrient in terrestrial ecosystem productivity because the soil P reservoir derived from soil parent materials and atmospheric sources is limited (Cole *et al.*, 1977; Okin *et al.*, 2004; Filippelli, 2008). Thus, a balance between the return and loss of soil P is a key to preserving the soil P reservoir (Filippelli, 2008). However, the soil P reservoir exists at low levels in sandy soils in arid areas (Chen *et al.*, 2003; Zhao *et al.*, 2008). The mobility and availability of P are also largely restrained in such areas because phosphate ions in soils are sensitive to soil moisture, thus limiting vegetation productivity in the sandy soils (He *et al.*, 2002; Smith, 2002). A continuous P cycle and P balance in arid areas is necessary to maintain the soil P reservoir and ecosystem productivity.

Vegetation litter is important for the material cycle of terrestrial ecosystems (Berg and McLaugherty, 1989). The process of litter decomposition, nutrient release, and soil organic matter formation is important in the P cycle of an ecosystem (Berg, 2000; Osono and Takeda, 2004). With litter decomposition, soil nutrition reserves are renewed and reused by vegetation (Berg and McLaugherty, 1989; Moretto *et al.*, 2001; Martinez-Yrizar *et al.*, 2007). Therefore, the return of litter is an important factor in sustaining P cycle and soil P balance in the ecosystem.

Many researchers have studied the litter nutrient return of trees in forestry (Costa *et al.*, 2004; Meier *et al.*, 2005), plantation (Njoukam *et al.*, 1999; Yang *et*

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al., 2004), agroforestry (Silveira *et al.*, 2007; Jaramillo-Botero *et al.*, 2008), and desert (Kemp *et al.*, 2003) systems. These studies mainly focused on nutrient reuse and turnover rate. However, severe land degradation has decreased the biomass of vegetation on the surface of sandy land systems (Zuo *et al.*, 2008; Li *et al.*, 2009) and vegetation cannot effectively reduce wind speed on the soil surface, leading to leaf litter loss (Hu *et al.*, 2009). Little information is available on the litter loss and litter P return in sandy land.

The Horqin Sandy Land has a continental semi-arid monsoon climate. The landscape is characterized by a mosaic of stabilized (SD), semi-stabilized (SSD), and active (AD) dunes, including dune slacks (Liu *et al.*, 2008). According to data from the Wulanaodu meteorological station, the annual average wind speed in the area is 4.4 m/s with frequent gales during the windy season from March to May (Yan *et al.*, 2005). The daily maximum wind speed at 0.25-m elevation in Naiman county in the south-central part of the Horqin Sandy Land is 13.1, 10.1, and 7.2 m/s in AD, SSD, and SD, respectively (Li *et al.*, 2005). The vegetation cover is significantly different across different sand dune types, being <5%, 5% to 50%, and >50% in AD, SSD, and SD, respectively. As variations in vegetation cover result in different wind-breaking abilities (Hu *et al.*, 2009), varied vegetation cover and strong aeolian activities bring about different litter loss rates among the three types of sand dunes.

In this study, we investigated litter production in the three types of sand dunes, determined litter P concentration, and simulated the dynamics of litter loss. The objectives of the experiment are to clarify (1) the amount of litter P in different types of sand dunes, (2) the amount of P returned and lost in different types of sand dunes, and (3) the relationships between both return and loss of P and total litter P.

1 Materials and methods

1.1 Study area

The study area is located at the west of the Horqin Sandy Land in Wulanaodu village (43°03'N, 119°39'E; 480 m asl), Wengniute county, Inner Mongolia, China (Fig. 1). The Wulanaodu region has windy and dry winters and springs and warm and rather rain-rich

summers followed by a short and cool fall. The annual mean temperature is 6.2°C, and the mean annual precipitation is 340 mm, about 70% of which occurs between June and September. The annual potential evaporation is 2,300 mm, about six times the annual precipitation. The growing season lasts 140 d from April to September.

We conducted the experiment on AD, SSD, and SD. The AD site (43°00'N, 119°37'E) was situated at an elevation of 15 m to 20 m and showed the strongest wind erosion on the windward slope and sand burial on the leeward slope from March to May. Sand erosion and accumulation on the top of AD was significant because of sand movement. The mean advancing rate of sand dunes was 1.5 to 3.0 m/a. Large chains of sand dunes were formed by prevailing winds. The vegetation, distributed on the top and the leeward slope of the sand dunes, was highly fragmented with large bare areas covering 1% to 2% of the land. Some pioneering plants, including *Salix gordejewii*, *Artemisa wudanica*, *Agriophyllum arenarium*, and *Corispermum thelegium*, were observed in the area. The SSD site (43°02'N, 119°40'E) was located at an elevation of 3 m to 5 m with a gradual slope and had a weak wind erosion and sand accumulation during the windy season. Large soil particles characterized the surface because fine soil was eroded away by wind. The dominant species was *Caragana microphylla*, which grew sparsely in the area (mean distance 4.5 to 5.0 m, height 70 to 150 cm). Other species included the semi-shrub *Artemisia ordosica* (more sparsely distributed, 50 to 80 cm in height) and herbs *Bassia dasyphylla*, *C. thelegium*, *Cynanchum thesioides*, and *Tribulus terrestris* (<50 cm in height). The vegetation cover was about 30%. The SD site (43°03'N, 119°39'E), which was previously SSD and had been fenced off since 2004, had a vegetation cover of over 50%. The dominant species here were *C. microphylla* and *A. ordosica*. Plant distribution pattern and height of the two species were similar to those in SSD. Other species included *Chenopodium acuminatum*, *Setaria viridis*, *Digitaria sanguinalis*, *Diarthron linifolium*, and *Aristida adscensionis* (20 to 80 cm in height).

Herbs in the study sites were mainly annual plants. Stems of dead plants but few dried leaves were found

on the surfaces of all three sand dune types. The dead stems were mainly plant residuals of *B. dasyphylla*, *D. linifolium*, *A. arenarium*, *C. thelegium*, *C. acuminatum*, and so on. AD and SSD showed weak wind-breaking effects because of the sparse distribution of herb stems,

whereas SD showed greater effectiveness because of larger vegetation cover. Soils were sandy, loose in structure, and prone to wind erosion in all three sand dune types. Some soil chemical properties are shown in Table 1.

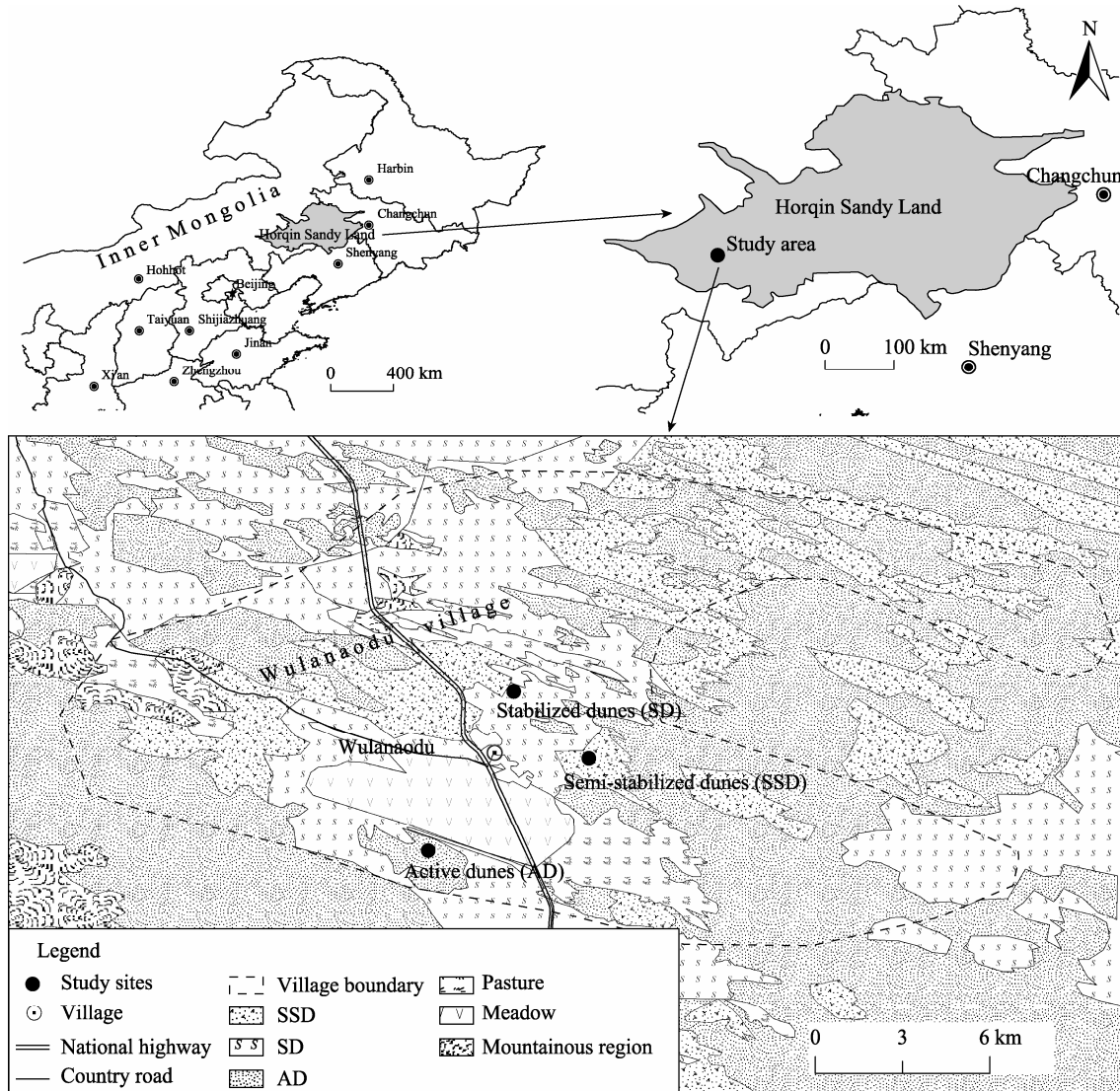


Fig. 1 Location of the study area in Horqin Sandy Land and the study sites for three sand dune types, i.e. AD, SSD, and SD

Table 1 Chemical properties of soils in the three types of sand dunes

| Depth (cm) | Soil type | Total N (g/kg) | Total P (g/kg) | Total K (%) | Available P (mg/kg) | pH | Organic C (g/kg) |
|------------|-----------|------------------------|-------------------------|-------------------------|-------------------------|------------------------|------------------------|
| 0–10 | AD | 0.04±0.01 ^c | 0.12±0.02 ^b | 2.81±0.14 ^a | 2.19±0.48 ^b | 7.83±0.16 ^a | 0.06±0.01 ^c |
| | SSD | 0.17±0.06 ^b | 0.14±0.03 ^{ab} | 2.51±0.23 ^b | 2.95±0.43 ^b | 6.89±0.27 ^b | 0.65±0.12 ^b |
| | SD | 0.30±0.06 ^a | 0.19±0.04 ^a | 2.85±0.21 ^a | 5.47±2.53 ^a | 6.88±0.09 ^b | 1.28±0.11 ^a |
| 10–20 | AD | 0.03±0.00 ^b | 0.12±0.01 ^b | 2.77±0.05 ^{ab} | 2.56±0.60 ^a | 7.74±0.17 ^a | 0.05±0.01 ^c |
| | SSD | 0.15±0.05 ^a | 0.14±0.02 ^{ab} | 2.60±0.24 ^b | 1.01±0.62 ^b | 6.72±0.21 ^b | 0.49±0.02 ^b |
| | SD | 0.16±0.06 ^a | 0.15±0.02 ^a | 2.96±0.13 ^a | 1.83±0.73 ^{ab} | 6.89±0.10 ^b | 1.05±0.08 ^a |

Note: Means with different letters indicate significant differences at $P < 0.05$; Mean±SD.

We selected three sand dunes for each sand dune type and one plot (50 m×50 m) on the top of each sand dune. That is, in total, three plots, as replicates, were set up for each sand dune type.

1.2 Litter production of shrubs and semi-shrubs

Shrub and semi-shrub litter including wilted flowers, fruits and leaves was collected from each study plot using 5 square litter traps (0.5 m×0.5 m×0.1 m, made of 1 mm nylon net) from April to October 2008. We emptied the traps once a month. We investigated shrub and semi-shrub cover in quadrats (4 m×4 m) by drawing projected areas on graphing paper to evaluate cover accurately. According to the coverage and litter biomass in the traps, the average litter production of shrubs and semi-shrubs in a quadrat could be calculated as follows:

$$P=S \times C. \quad (1)$$

Where P is the litter production under shrub or semi-shrub canopy (g/m^2); S is the shrub or semi-shrub litter biomass in the trap (g/m^2); and C is the shrub and semi-shrub cover (%).

Litter samples from each trap were oven dried at 80°C for 24 h, milled (<0.15 mm), mixed, and stored for analysis.

1.3 Litter production of herbs

Herb leaves and stems were treated as litter, because they decompose after the growing season and, thus, enter the material cycle. Winds blow away the leaves and herb stems remain during the windy season. Therefore, we investigated the biomass of leaves and stems of herbs separately.

Twenty random quadrats (1 m×1 m) were investigated in each spot, a total of 60 quadrats for each sand dune type. The leaves and stems of each species in every quadrat were gathered respectively, oven dried (at 80°C for 24 h) and weighted. Five replicates of the stem and leaf samples of each species were taken, dried, and milled (<0.15 mm) respectively, and stored for analysis.

All samples were analyzed for total P (TP) concentration by colorimetric analysis following the Kjeldahl digestion method (Bremner, 1996). The amount of P in leaves and stems was calculated according to the P concentration and biomass in the study sites.

1.4 Leaf litter movement simulation

We conducted a simulation experiment on litter movement by wind power in three plots to determine the leaf loss amount. We placed 200 pieces of small, circular paper (8 mm in diameter) to simulate leaves in a little circle (50 cm in radius) in the middle of each spot on 1st October 2008. The origin was set at the centre of the circle. The direction of the prevailing wind was regarded as the positive Y-axis, and the line perpendicular to the Y-axis through the origin was the X-axis (Fig. 2). The coordinates of the repositioned pieces of paper were measured along the x and y axes using a meter stick. We surveyed the locations of the paper pieces and recorded the coordinates $P(x_i, y_i)$ every 2 months until 1st April 2009.

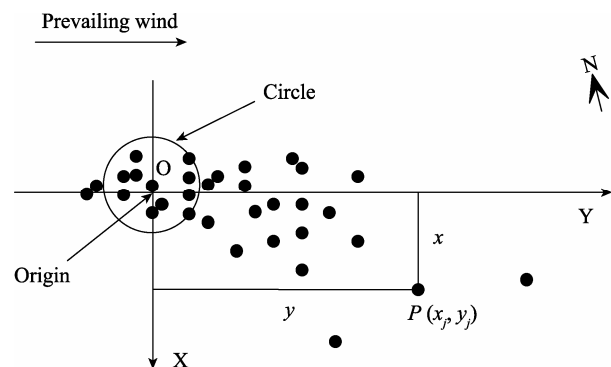


Fig. 2 Method of determining the location of paper in simulated leaf litter moving dynamics. Point O is the origin of the intersection of the X-axis and Y-axis. Point $P(x_i, y_i)$ represents the coordinates of paper. The distance x from the Y-axis to the point and y from the X-axis to the point. We determined the coordinates of the point by measuring x and y using a meter stick.

We assumed that the P in the litter not blown away was returned to soil through decomposition. The litter P balance can then be calculated as:

$$P_{\text{Return}} = P_{\text{Total}} - P_{\text{Loss}}. \quad (2)$$

Where P_{Return} is the P returned to soil from litter through decomposition; P_{Total} is the P in total plant litter on the sand dunes from different sites; and P_{Loss} is the P in the litter blown away by wind.

1.5 Data analysis

One-way ANOVA was carried out to test the significance of treatment effects on litter biomass and the amounts of P in shrub, semi-shrub, and herbaceous

leaves and stems. Means were compared using Duncan's least significant ranges (LSRs) when the treatment effects were significant. Regression analysis was used to generate the regression coefficient between the loss and return of P in the three types of sand dunes. All statistical analyses were determined using SPSS 12.0.

The distribution of the pieces of paper was drawn using the mapping software ArcGIS v. 9.0. Histograms of the number of paper pieces distributed at various distances and the graph of the regression relationship between the loss and return of P in the three types of sand dunes were plotted using SigmaPlot v. 9.0.

2 Results

2.1 Amount of P in shrubs and semi-shrubs litter from different types of sand dunes

Litter biomass and amount of P in shrubs were significantly higher than in semi-shrubs in SD and SSD ($P<0.01$, Table 2). However, no significant differences in the litter biomass and amount of P between shrubs and semi-shrubs were found in AD ($P>0.05$,

Table 2). The litter biomass and amount of P in shrubs and semi-shrubs were significantly different ($P<0.05$, Table 2) among SD, SSD, and AD. The sum of litter biomass and amount of P in shrubs and semi-shrubs were significantly different among the three study sites ($P<0.01$, Table 2). The sum of shrub litter biomass in SD was the highest (1.2 times and 25.7 times those in SSD and AD, respectively) among the three types of sand dunes. The total amount of litter P in shrubs in SD was 1.2 and 20.5 times those in SSD and AD, respectively.

2.2 Contribution of herbs to the amount of litter P

The litter biomass of herbaceous stems was 2.1 and 2.0 times those of leaves in SSD and SD, respectively ($P<0.01$, Table 3). However, the total biomasses of both stems and leaves were not significantly different in AD ($P>0.05$, Table 3). The biomasses of leaves, stems, and their sum in SD were significantly higher than those in SSD and AD ($P<0.01$, Table 3). However, individual differences in SSD and AD were not significant ($P>0.05$, Table 3). The sum of leaf and stem biomasses in SD was 3.1 and 11.7 times those in SSD and AD, respectively.

Table 2 Litter biomass and the amount of P in shrub and semi-shrub litter in the three types of sand dunes

| | Life form | AD | SSD | SD | P value |
|--|------------|----------------------|-------------------------|-------------------------|---------|
| Average litter biomass (g/m ²) | Shrub | 0.8±3.6 ^b | 26.6±13.4 ^{a*} | 28.9±16.7 ^{a*} | <0.001 |
| | Semi-shrub | 0.6±2.2 ^b | 3.2±5.4 ^b | 7.1±7.9 ^a | 0.010 |
| P value | | 0.539 | 0.000 | 0.000 | |
| Total biomass in three sites (g/m ²) | | 1.4±4.1 ^b | 29.8±16.1 ^b | 36.0±19.8 ^a | <0.001 |
| Litter P amount (mg P/m ²) | Shrub | 1.1±4.1 ^b | 35.0±17.9 ^{a*} | 38.0±22.4 ^{a*} | <0.001 |
| | Semi-shrub | 1.3±4.3 ^b | 4.2±5.1 ^{ab} | 9.3±7.3 ^a | 0.040 |
| P value | | 0.682 | 0.000 | 0.000 | |
| Total P amount in three sites (mg P/m ²) | | 2.4±6.2 ^b | 39.2±20.2 ^a | 47.3±24.9 ^a | <0.001 |

Note: Means for different sand dunes in rows with the same letters are not significantly different. Within the same sand dune type in columns, * represents significant difference between different plant life forms ($n=15$).

Table 3 Herbaceous litter biomass and the amount of P in leaves and stems in three types of sand dunes

| | Parts | AD | SSD | SD | P value |
|--|-------|------------------------|-------------------------|--------------------------|---------|
| Litter biomass (g/m ²) | Leaf | 5.1±9.3 ^b | 15.8±7.2 ^b | 50.0±34.2 ^a | <0.001 |
| | Stem | 7.8±14.3 ^b | 32.6±13.0 ^{b*} | 100.5±73.4 ^{a*} | <0.001 |
| P value | | 0.487 | <0.001 | 0.008 | |
| Total litter biomass (g/m ²) | | 12.9±23.6 ^b | 48.4±19.5 ^b | 150.5±102.0 ^a | <0.001 |
| Litter P amount (mg P/m ²) | Leaf | 4.8±8.7 ^b | 23.0±15.4 ^b | 61.2±53.6 ^a | <0.001 |
| | Stem | 5.5±10.1 ^b | 32.3±14.7 ^b | 93.1±75.7 ^a | <0.001 |
| P value | | 0.798 | 0.057 | 0.132 | |
| Total litter P amount (mg P/m ²) | | 10.3±18.8 ^b | 55.3±29.6 ^b | 154.3±124.1 ^a | <0.001 |

Note: Different letters in a row indicate significant difference by LSR multiple test ($P<0.05$). Within the same sand dune type in a column, * represents significant difference between amounts of P in different plant parts ($n=60$).

The amount of litter P in stems was not significantly higher than those in leaves in AD, SSD, and SD ($P>0.05$, Table 3). The amount of P in leaves, stems, and their sum in SD were significantly higher than those in SSD and AD ($P<0.01$, Table 3). However, no significant difference was found between SSD and AD ($P>0.05$, Table 3). The total amount of leaves and stems P in SD was 2.8 and 15.0 times those in SSD and AD, respectively.

Total litter biomass and litter P amount were significantly different among the three types of sand dunes ($P<0.001$, Table 4). Among the three types of sand dunes, the litter biomass production and amount of P in SD were the highest while those in AD were the lowest.

Table 4 Total litter biomass and amount of P in the three types of sand dunes

| | Total litter biomass (g/m ²) | Litter P amount (mg P/m ²) |
|----------------|---|---|
| AD | 14.4±24.7 ^c | 12.6±20.6 ^c |
| SSD | 78.3±16.9 ^b | 94.5±27.1 ^b |
| SD | 186.5±60.5 ^a | 201.6±72.6 ^a |
| <i>P</i> value | <0.001 | <0.001 |

Note: Means with the same letters are not significantly different ($n=60$).

2.3 Leaf litter movement simulation

As shown in Fig. 3, no paper was found at the three AD plots during the first investigation. However, we found many paper pieces at the SD and SSD plots distributed within 0 to 12 m from the original location. Beyond 12 m, paper pieces were sporadically found at the SSD and SD plots.

The percentages of the paper pieces recovered from the three sites were 84%, 40.5%, and 24% of the total paper pieces for SSD and 81%, 47%, and 36% of the total paper pieces for SD after 60 d, 120 d, and 180 d, respectively. Therefore, the average number of paper pieces found left at the SSD and SD plots significantly decreased over time ($P<0.01$, Fig. 4).

The average number of the paper pieces recovered significantly decreased with the increase in moving distance. Within 0 to 2 m from the origin, the pieces of paper retrieved at the SSD plot after 60 d, 120 d, and 180 d were 147, 42, and 20, respectively (about 88%, 52%, and 41%, respectively, of the total). However, the numbers of paper pieces found within the 2 to 12 m range after 60 d, 120 d, and 180 d (Fig. 4) were 20,

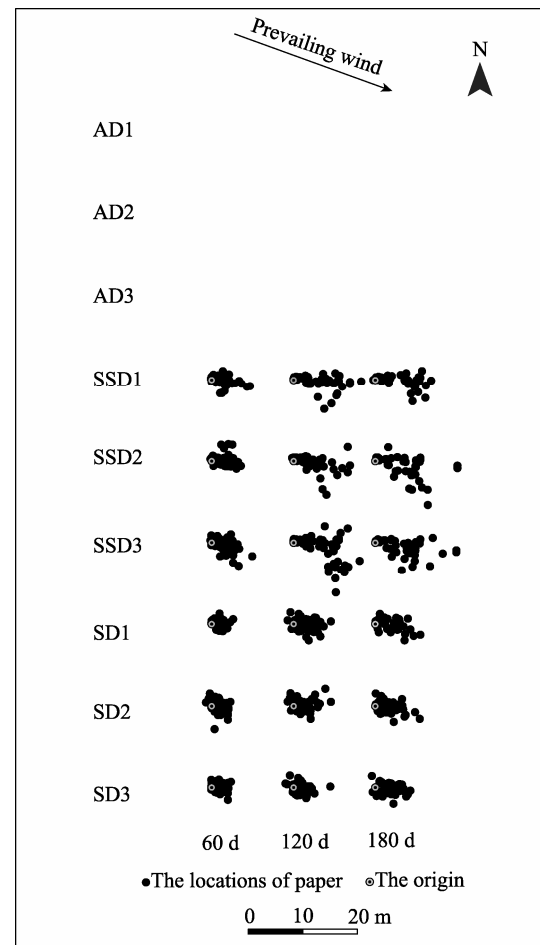


Fig. 3 The distribution of paper pieces after 60 d, 120 d, and 180 d at AD, SSD, and SD plots

39, and 29, respectively, equivalent to 11%, 48%, and 49% of the total. At the SD plot, the numbers of the pieces of paper retrieved within 0 to 2 m from the origin after 60 d, 120 d, and 180 d were 152, 75, and 34, respectively (about 94%, 78%, and 48%, respectively, of the total). Within the 2 to 12 m range, on the other hand, the numbers of the pieces of paper retrieved after 60 d, 120 d, and 180 d were 10, 20, and 37, respectively (about 6%, 22%, and 52%, respectively, of the total) (Fig. 4).

According to the leaf-litter dynamics experiment, the losses of leaf biomass by wind for AD, SSD, and SD were 6.6, 34.5, and 55.3 g/m², respectively (about 100%, 76%, and 64% of the total leaf biomass, respectively). The litter-biomass return rates for AD, SSD, and SD were 7.8, 43.8, and 131.2 g/m², equivalent to 54.2%, 55.9%, and 70.3%, respectively, of the

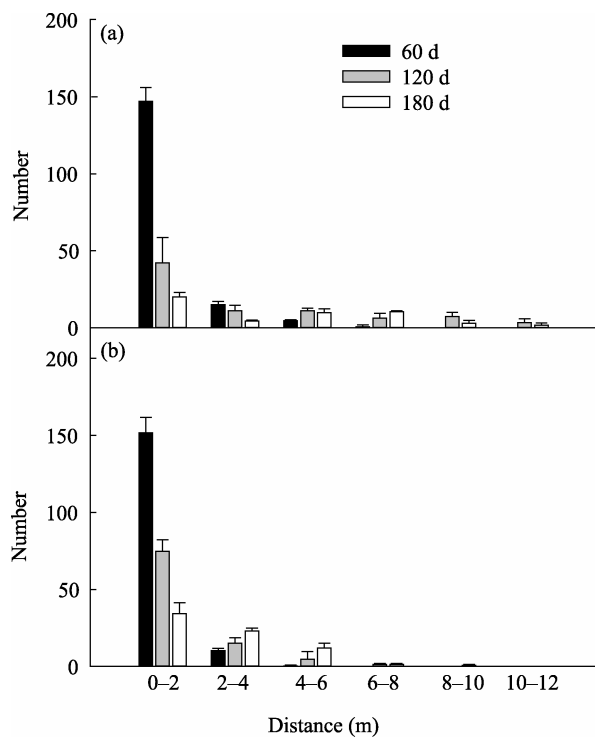


Fig. 4 Numbers of the paper pieces recovered and the distance of retrieval at three time intervals at SD (a) and SSD (b) plots. Distance (m) from the origin was measured. Bars represent Means \pm SD ($n=3$).

total litter biomass. The P loss in the same plots was 7.4, 46.9, and 69.8 mg P/m², about 56.4%, 49.6%, and 44.6%, respectively, of the total P. The returned P amount for AD, SSD, and SD was 5.5, 47.6, and 131.8 mg P/m², about 43.6%, 50.4%, and 65.4%, respectively of the total P (Table 5).

2.4 Relationship between both the loss and return of litter P and total litter P

Significant linear regression was observed between both the loss and return of litter P and total litter P for AD, SSD, and SD ($P<0.01$, Fig. 5). The sum of the slopes of the two regression lines was equal to 1, and these slopes represented the rates of loss and return of litter P. The loss and return rates of litter P were significantly different among AD, SSD, and SD

($P<0.01$). The trend of loss rate was declining and that of return rate was increasing from AD to SD.

The intersection point of the two regression lines was the threshold at which the amounts of loss and return of litter P were equal. No intersection point was observed for AD, since the amount of total litter P was more than 0 mg P/m². The loss rate of litter P (0.52) was higher than the return rate of litter P (0.48), resulting in a higher amount of litter P loss than that of litter P return. The return rates of litter P were higher than the loss rates (0.32 and 0.17, respectively) for SSD and SD (0.67 and 0.83, respectively). The intersections of the regression lines were the two points of T_1 (85.5 mg P/m², 42.8 mg P/m²) for SSD and T_2 (110.6 mg P/m², 55.3 mg P/m²) for SD. If the amount of total P was lower than 85.5 mg P/m² in SSD and 110.6 mg P/m² in SD, the amount of P loss was higher than that of P return, and vice versa.

3 Discussion

3.1 The loss and return of litter P for different types of sand dunes

The loss and return of litter P varied across different sand dune systems because of precipitation, vegetation biomass, strong gales during the windy season (Hu *et al.*, 2009) and the decomposition rate of plant litter (Kemp *et al.*, 2003). Precipitation determines soil water content, which primarily limits vegetation biomass in sandy land. Modifications in the cover and biomass of herbs and shrubs occur because of competition for soil water (Li *et al.*, 2004; Lyne Ensign *et al.*, 2006). Many plants with low leaf biomass and, thus, decreased evapotranspiration, can survive in these areas (Singh, 2004) and reduce the litter biomass (Li *et al.*, 2004).

The vegetation biomass varied across different sand dune systems. Strong wind erosion and sand burial (Yan *et al.*, 2005) and low soil fertility (Su *et al.*, 2005) lead

Table 5 Returned litter biomass and P amount in the three types of sand dunes

| | Total litter (g/m ²) | Returned litter (g/m ²) | Total P (mg P/m ²) | Returned P (mg P/m ²) |
|---------|----------------------------------|-------------------------------------|--------------------------------|-----------------------------------|
| AD | 14.4 \pm 24.7 ^c | 7.8 \pm 13.8 ^c | 12.6 \pm 20.6 ^c | 5.5 \pm 10.1 ^c |
| SSD | 78.3 \pm 16.9 ^b | 43.8 \pm 5.1 ^b | 94.5 \pm 27.1 ^b | 47.6 \pm 14.7 ^b |
| SD | 186.5 \pm 60.5 ^a | 131.2 \pm 42.7 ^a | 201.6 \pm 72.6 ^a | 131.8 \pm 58.7 ^a |
| P value | <0.001 | <0.001 | <0.001 | <0.001 |

Note: Different letters in a column mean significant difference ($n=60$).

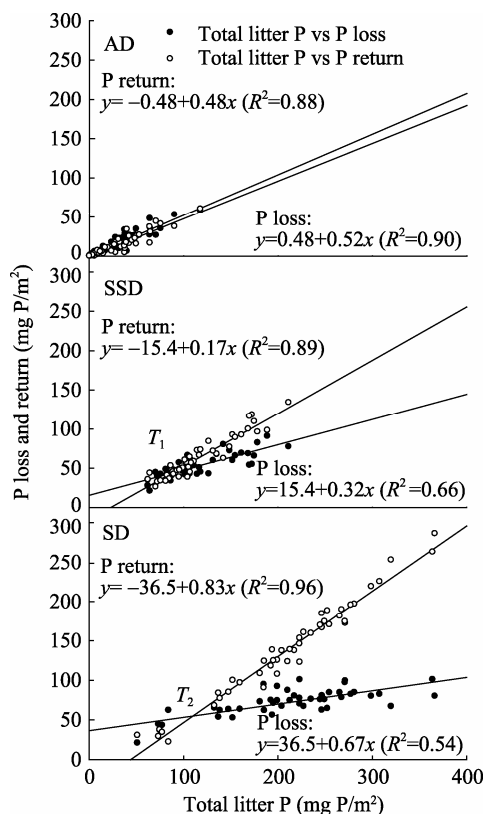


Fig. 5 Relationship between both the loss and return of litter P and total litter P for AD, SSD and SD.

to significant variations in vegetation biomass (Su and Zhao, 2003; Zuo *et al.*, 2009a) and lower vegetation biomass (Zhang *et al.*, 2004) in AD. The vegetation biomass in SSD was higher than that in AD because of the better soil structure and larger seed bank and vegetation cover (Liu *et al.*, 2007). However, sand activity during the windy season and livestock grazing during the growing season reduce vegetation biomass (Li *et al.*, 2008). While the vegetation biomass in SD was the highest among the three types of sand dunes (Su and Zhao, 2003; Su *et al.*, 2004; Zhao *et al.*, 2008), the higher spatial variability of soil nutrients after the establishment of shrubs shifted SD toward a smaller vegetation biomass (Ridolfi *et al.*, 2008; Dong *et al.*, 2009).

Strong wind is the main reason for litter P loss in sand dunes during the windy season. Gales are powerful and frequent in the Horqin Sandy Land during the windy season (Wang *et al.*, 2005). Vegetation influences surface roughness length and wind resistance on sand dunes (Bressolier and Thomas, 1977). Leaf

litter is moved leeward by strong gales and blown away from sand dune communities with low vegetation cover toward dune slacks or other systems with high vegetation cover and low wind speed.

P in plant litter is released to top soil by decomposition (Moretto *et al.*, 2001; Regina, 2001; Costa *et al.*, 2004; Mubarak *et al.*, 2008). Decomposition of plant litter leads to P accumulation from deeper soil layers to the soil surface and promotes the reuse of P by plants (Yang *et al.*, 2004; Soares *et al.*, 2008). A lower plant-litter decomposition rate decreases P return, particularly in sand dunes. Plant material, soil, and air moisture are the main factors that influence plant-litter decomposition rates (Koukoura *et al.*, 2003), and the decomposition rate of litter buried in soil is higher than when on the soil surface in arid areas (Martinez-Yrizar *et al.*, 2007; Mubarak *et al.*, 2008). Placing litter on soil surface to measure the decomposition rate in sand dune systems thus provides simulation much closer to the actual circumstances. More than 50% of the litter mass and P content has been reported to remain after 2 years when litter is placed on the soil surface (Moretto *et al.*, 2001; Kemp *et al.*, 2003).

3.2 Relationship between both the loss and return of litter P and total litter P

The loss and return of litter P in the sandy soil of arid and semi-arid areas is strongly influenced by vegetation restoration. Vegetation restoration is characterized by the increase of plant biomass, that is, the increase in litter biomass and the amount of litter P. AD, SSD, and SD can be identified as the three stages of vegetation restoration. Plant species diversity, vegetation cover, and vegetation biomass increased during a restoration experiment conducted previously (Su *et al.*, 2005; Zhao *et al.*, 2007; Zuo *et al.*, 2009b). Thus, increasing vegetation biomass reduces wind disturbance on sand dune systems (Bressolier and Thomas, 1977; Liu *et al.*, 2005; Zhao *et al.*, 2006), leading to a decreased P loss rate and increased P return rate. The amount and rate of litter P loss could decrease further if wind resistance ability is increased by increasing vegetation biomass and litters remaining on the soil surface with decreasing grazing and trampling of animals. Consequently, the amount of returned litter P could be improved.

The loss and return of litter P in sandy soil is important for vegetation restoration in this area. P released by litter decomposition enters the soil and increases soil fertility under the plant canopy. P can be used by plants to increase vegetation biomass. If the loss of litter P increases, the return of litter P decreases, accelerating the loss of soil P, which is not conducive to vegetation restoration. Conversely, the increased return of litter P facilitates vegetation restoration.

4 Conclusions

In sand dune ecosystems, low vegetation biomass leads to low total litter P given the characteristics of soil and climate in such environments. Significant litter loss occurs in different sand dune types, leading to

litter P loss from the sand dune system. Increasing the vegetation biomass can increase the litter P return rate, thus decreasing litter P loss rate. Litter P return has a positive effect on vegetation restoration, whereas litter P loss yields negative effects on sand dune systems. Therefore, promoting vegetation restoration is necessary to improve the stability of sand dune ecosystems.

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