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TRADE-OFF BETWEEN SHRUB PLANTATION AND WIND-BREAKING IN THE ARID SANDY LANDS OF NINGXIA, CHINA

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Abstract

The effect and cost-benefit relationships of planted shelterbelts on reducing wind velocity and sand transportation rate (benefit) in relation to shrub height and density (cost) were studied in the Yanchi sandy land in NW China. The species-specific morphology of *Salix psammophila* C. Wang & Ch.Y. Yang was more effective in wind-breaking than *Caragana microphylla* Lam. while *Tamarix* cf. *chinensis* was least effective. Wind-breaking and reduction of sand transportation increased with shrub height, higher planting density, number of parallel rows in a shelterbelt but was always the greatest near ground. It declined with increasing distance from the lee-side of the belt. Shelterbelts composed of 1.5m tall *C. microphylla* at 1.5m planting distance in 3 rows per belt exhibited best effects on wind-breaking and sand fixation. In a modelling approach these effects could be generally expressed as manifolds of shrub height rather than absolute distances, and they were correlated to a cost (investment) factor given by shrub height and planting density. The highest benefit-cost relationship is now yielded by planting smallest shrubs in 1 to 2 rows per belt at a larger (optimal) distance between rows and belts. Obviously, the trade-off is more sensitive to costs than to benefits favouring many small shrubs with smaller individual effects rather than fewer larger shrubs with stronger effects. This implies the potential for an appropriate, controlled wood harvesting from these shelterbelts as long as near-ground re-sprouting is not affected, and the use of grasses when planting these belts.

Introduction

Drifting sand is a major problem of desertification and land degradation in arid and semi-arid regions. Overgrazing, lumbering and agricultural overuses destroy the protective natural vegetation cover and enhance sand mobility, thus accelerating desertification processes (Breckle *et al*., 2001). Frequently occurring dust and sand storms have catastrophic impacts on the environment and human health in arid and semi-arid areas of north-western China (Yang *et al*., 2001). Especially in spring high wind speeds in combination with low degraded vegetation cover and high availability of sand and fine-grain material at soil surface generate local and regional sand and dusts storms (Littmann, 2006). However, mobile sand dunes only contribute to local sand storm events and not to the continental dust storms (Wang *et al*., 2005), which are a severe threat for villages, irrigated farmlands, railways, highways and other infrastructures. Continuous loss of soil fertility in these regions continuously leads to a decrease of arable land along the desert margins (Zhu & Chen, 1994; Wang *et al*., 2006a; Hoffmann *et al*., 2008; Zhao *et al*., 2009) while single strong dust storm episodes may cause devastation. Controlling and reducing hazards of wind erosion in arid regions along the desert margins in north-western China is closely related to identifying of potentially endangered areas which act as source for drifting sand as well as to develop measures in terms of protection (Gao *et al*., 2007). In the last decades comprehensive rehabilitation of degraded drylands and desert reclamation programmes were launched in China (Sun & Fang, 2001; Veste *et al*., 2006), and planting methods in order to control drifting sands are widely practised and have a long tradition in China (He, 2001). Compared to other methods the use of plantations has several advantages: Costs of phytomelioration are relatively low at stable and sustainable effects, therefore it is suitable to be used on a large scale to improve soil conditions by enhancing soil carbon and nitrogen pools. Furthermore, plantations provide timber for the local communities, and they have positive effects on biodiversity. However, sand dune fixation by vegetation is only successful when wind speed is greatly reduced and sand transportation is minimized by an optimal shelterbelt design (Dong *et al*., 1996; Zuo *et al*., 2008).Water shortage is a major problem for development of a continuous sustainable vegetation cover. Therefore, drought adapted shrub communities are considered appropriate to maintain shelterbelt systems to break wind and fix sand. Furthermore, spatial variations of soil moisture and ground water distribution in desert sand dunes (Huang *et al*., 2001; Littmann & Veste, 2006) have to be taken into account when establishing plantations on landscape level. Various studies have been conducted to investigate the abilities of shrubs on windbreak and sand fixation. Mainly fast-growing trees like *Populus*, *Salix*, *Tamarix* and shrubs like *Artemisia ordoscata* and *Caragana* (Li *et al*., 2003b; Veste *et al*., 2006; Wang *et al*., 2008, Yang *et al*., 2006; Gao *et al*., 2004) are successfully used for shelterbelt construction, windbreak and control of desertification in sandy areas of China. Different species, growth forms, plant height and spatial patterns of shelterbelts all have various effects on controlling soil erosion by wind. Therefore the design of an optimal spatial pattern of shrubs to prevent wind erosion is not at all trivial but an important challenge in combating desertification. To be successful it has to consider and has to be adapted to local growing conditions. When shelterbelts are planted in an optimal way, plants can control wind erosion at low vegetation coverage at minimal necessary water use by plants, and they may influence microclimatic conditions in a positive direction (Dong *et al*., 1996). In this paper we present an approach to develop an optimized shrub spacing pattern for a shelterbelt system using several typical indigenous shrub species at Yanchi sandy land comparing benefits, and in a simple approach also costs for maintaining them. We studied the influence of different species and spatial patterns of shrubs arrangement on controlling soil erosion by wind with the aim to design appropriate optimized shelterbelt spatial patterns that are suitable for the Yanchi sandy land and which might act as a reference for future plant production practice and shelterbelt system constructions in sandy deserts.

Materials and Methods

Study site: The study area is located at the Yanchi sandy land (Zhou *et al*., 2006) within the Ningxia province (37°04′ - 38°10′N, 106°30′ - 107°41′E) covering an area of 7130 km² (Fig. 1). The north of the Yanchi country is exhibiting complex geomorphological dune types. Influenced by summer monsoon, the study area has semi-arid climate with an annual rainfall of approx. 280mm mainly between June and August. Potential evapotranspiration is 5-7 times higher than rainfall. This region is frequently affected by strong winds and drifting sands, especially during spring. The highest wind speed during March to May can arrive at 3.2 m/s .The presented experiment was performed early in April, when soil erosion by wind is the most severe, as leaves and branches of shrubs have not flushed completely.

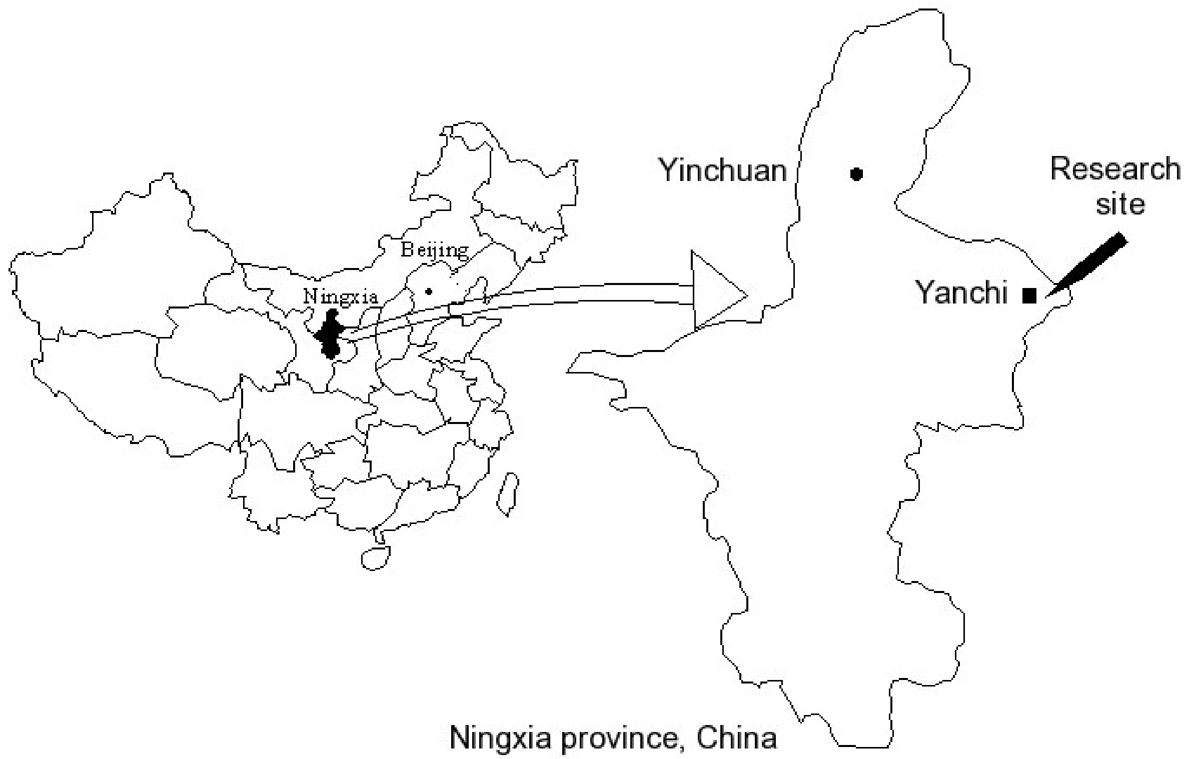

Fig. 1. Location of study site, Ningxia Province, China.

Plant materials: Three indigenous species were chosen, which are typical for the research area. *Caragana microphylla* Lam. (Fam. *Fabaceae*), *Salix psammophila* C. Wang et Ch. Y. Yang (*Salicaceae*) and *Tamarix* cf. *chinensis* (*Tamaricaceae*). These species were employed in 2 different types of experiments: Experiment A for a comparison of species and experiment B for comparing wind-breaking effects of different planting patterns. All plantations were located on a large smooth dune sloping 20° towards main wind direction; in order to reduce edge effects, the belts were extended to a belt length of at least 50m.

Experimental Design

Experiment A: Influence of species: *Caragana* was planted in two different densities (*Caragana* A, B) and compared to *Tamarix* and *Salix* arranged according to Table 1. In order to compare these species in terms of crown density, crown density was measured optically in a horizontal direction.

Experiment B: Influence of spatial pattern: Employing *Salix psammophila*, 3 groups of shelterbelts have been planted in the middle of the dune slope. The arrangement of the shelterbelts was vertically to the main wind direction. In order to reduce edge effects, each belt was 50m long. The spatial patterns of 3 shrub belts are given in Table 2, every belt consists of 1, 2 or 3 rows.

Measurement of wind velocity and transportation of sand: Wind velocity and direction were measured using PC-2F multi-channel auto-count telemetry (Jingzhou

Sunshine Technology Development Co. Ltd., China) and microclimate was recorded by an automatic weather station (HOBO H21-001, Onset Computer Corporation, Bourne, MA, USA).

Experiment A: Two places were chosen in which the vertical gradient of wind velocity was simultaneously recorded over a period of 30 minutes. One observation site was located within the shelterbelt, the other on open field. Wind velocity was measured every minute at 0.2m, 0.4m, 0.8m, 1.2m, 1.6 cm and 2.0m above ground.

Experiment B: Wind-cups were set up on open field and at different distances from the outer lee-side row at 1, 3, 5, 7, 10 and 15 times of shrub height. They were installed 0.5m and 2.0m in height separately. The observation points at open field were set up the same as that in belts. Wind velocity was recorded every minute and monitored as 5 minutes means. Sand collection instruments (Fig. 2) were employed at different observation points to determine the amount of sand transportation near ground according to Li *et al*., (2009).

Table 1. The parameters of the three species used in shelterbelts (experiment A).

Species	Location	Age of plants [a]	Belt length [m]	Pattern (plant spacing × row distance) [m×m]	Mean height [m]	Crown density [%]	Average crown extension [m×m]
Caragana A	1# site	8	210	2×3	1.55	55%	1.3×1.5
Ambigua B	1# site	5	100	2×5	1.40	40%	1.3×1.4
Salix psammophila	2# site	3	100	2×3	2.25	60%	1.8×1.8
Tamarix cf. *chinensis*	3# site	3	400	2×3	2.60	45%	1.5×1.6

Table 2. Spatial patterns of the three shelterbelts of *Salix psammophila* (experiment B).

Belt	Shrub height above ground [m]	Spatial patterns	Row spacing [m]
1	0.5	1 row, 2 rows, 3 rows	0.5
2	1.0	1 row, 2 rows, 3 rows	1.0
3	1.5	1 row, 2 rows, 3 rows	1.5

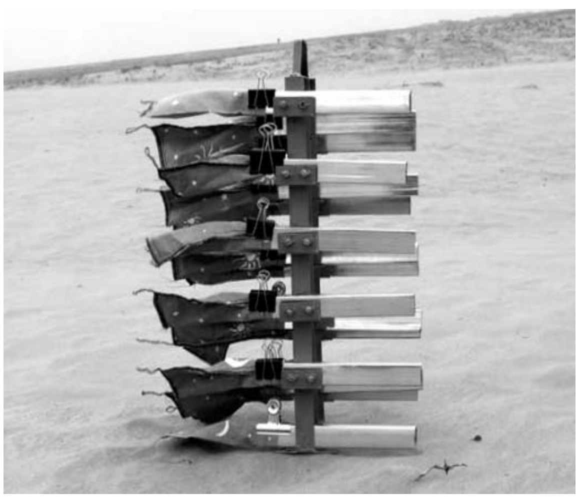

Fig. 2. Sand collection instrument.

Calculations

Data obtained from field observation in August are in the following used to calculate the windbreak effect of shrub belts and their relation to surface roughness. The relative decrease of wind velocity k is calculated after

$$k = (1 - u_i / u) \times 100$$ (1) Effectiveness of windbreaking

where u_i is the wind velocity behind a shrub, u is the wind velocity on open field at identical height.

For further comparison to other investigations, the aerodynamic properties of the shelterbelts are appropriate. Friction velocity u^* was estimated using the following equation (Dong *et al*., 2001; Li *et al*., 2003b):

$$u^* = k_c(u_1 - u_2) / \ln(z_1 / z_2)$$ (2) Friction velocity

where k_c is the dimensionless Karman constant (0.41) and u_1 and u_2 are mean wind speeds (m s^{-1}) for the 2 different heights z_1 = 2.0m and z_2 = 0.5m.

Surface roughness lengths of the different plantations of experiment B were estimated as suggested by Chamberlain (1983):

$$z_0 = 0.16\ u^{*2} / g$$ (3) Surface roughness length

where z_0 is the surface roughness length and g is the gravitational constant (9.8 m s^{-2}). However, this is only estimation, as this parameter refers to homogeneous plains rather than single shelterbelts. Nevertheless it provides a useful parameter to compare the situations behind the shelterbelt to such plains with similar aerodynamic properties (see results).

Modelling sand transportation rates: Sand transportation rates s at certain distances d behind a shelterbelt were fitted to an exponential model,

$$s = s_0 \times (1 - e^{-d \times (a - b \times r + c \times h)})$$ (4) Sand transportation rate

where s_0 is the sand transportation in the open field, and a, b, c are coefficients in a linear term for the exponent, depending on the number of rows per shelterbelt r and the shrub height h.

After fitting this equation to the actual data (R base package 2.11.0), the reduction in sand transportation behind a shelterbelt up to a certain distance d or up to infinity, is modelled as:

$$r(d) = \int_0^{d,\infty} s_0 - s \quad (5) \text{ Reduction in sand transportation}$$

For a sequence of shelterbelts, such calculations are only an approximation of real sand transportation rates, as with crossing each shelterbelt, sand transportation starts independently of what happened in front of them. However, this approach is assumed to be valid, as every decrease in that initial value would finally result in zero sand transportation for an infinite sequence of parallel shelterbelts.

Results

Characteristics of wind breaking by different species: In order to compare the impact of different plant architectures on wind velocity, four different plantations were compared in experiment A. First, the vertical wind profiles within these four stands were compared to the nearby open field. Fig. 3A shows the situation for *Salix psammophila*. As to be expected, wind velocity increased with height on open field as well as within the stands. Near ground, air movement was slowed down to less than half as compared to the open field, and this wind-breaking effect decreased at subsequently higher points of measurement (smaller distance between the two profile curves). The data for this species suggest a linear relationship for these first two meters above ground, but besides an overall decrease in wind velocity, the other stands (Fig. 3B-D) displayed slightly different characteristics. In the *Tamarix* stand, which was of a similar age as compared to *Salix*, wind-breaking was smaller and moreover, the linear relationship of wind speed to height was clearly less pronounced. Although the maximum wind speed was slightly lower at this site, this was likely an effect of different plant architectures, as leaf and twig biomass were concentrated on the lower layers of the stand. A similar change in wind velocity along the vertical profile could be observed in the two different stands of *Caragana* (Fig. 3C & D); with average stand heights of 1.55 m and 1.40 m respectively, they are lower as the 2 stands presented above. In both *Caragana* stands, a sharp decline in the windbreak effect (rise in velocity) was observed at an height between 0.8m and 1.2m, which is clearly below the top layer of the stand. In contrast, an effect on wind velocity was observed *above* the 2 stands of different densities, although it is low and likely to disappear with further heights. As expected, the difference between open field and shelterbelt is more pronounced in the denser *Caragana* stand (Fig. 3C) than in the more open stand (Fig. 3D) for the lower heights. 2.0m above ground, any differences are small.

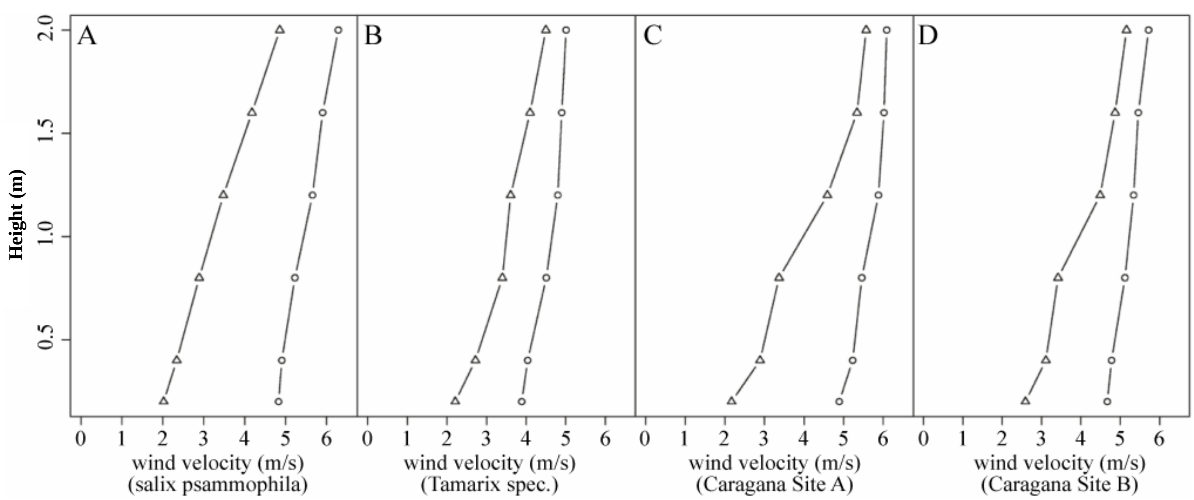

Fig. 3. Vertical wind profiles in the open field (○) and in the four different plantations (△) for species comparison (experiment A): Salix (A), Tamarix (B), Caragana Site A (C), Caragana Site B (D).

In summary, taking the overall differences of the four plantations, they can be arranged as *Salix psammophila* > *Caragana* A > *Tamarix* > *Caragana* B according to their effectiveness in wind breaking.

The general effect of stand density on wind breaking is addressed in further detail by relating the relative decrease of wind velocity *k* to the canopy density of the stand (Fig. 4), which also compensates for any differences in absolute wind speeds. As a first approach, a canopy density of 100% should decrease wind speed completely. Vice versa a canopy density of 0% should display no decrease at all. In Fig. 4 this is indicated by a dotted line, and near ground (0.2 m in height) this simple model is almost met by the observed values in all 4 plantations.

Of course, differences in the vertical direction have to be considered as shown before. 1.0 m above ground, where the wind breaking effect of the 2 *Caragana* plantations dropped sharply, *Salix psammophila* still displayed a higher decrease in wind velocity, and at 2.0m above ground, differences in the 2 stands of *Caragana* (with lower extend in height) but also *Tamarix* are hardly visible. At this height, only the *Salix* stand showed a more pronounced wind-breaking effect. Therefore optical density might be considered as a useful parameter for stand characteristics.

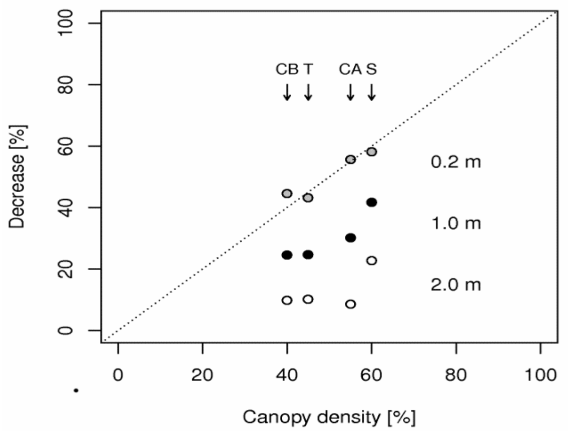

Fig. 4. Decrease in wind velocity in 0.2m, 1.0m and 2.0m height above ground as a function of canopy density. The values of the four plantations Salix (S), Tamarix (T) Caragana Site A (CA) and Caragana Site B (CB) are obtained from linear interpolation from Fig. 3. where necessary. A parsimonious linear approach is indicated by a dotted line (see text).

Windbreak effect of different special patterns of *Salix psammophila*: In the previous section, the greatest impact on wind velocity was demonstrated for *Salix psammophila*, but so far, only one kind of spatial pattern was investigated. Certainly different stand densities and structures display different wind breaking characteristics, a question, which is addressed in Experiment B, where nine different patterns of shelterbelts differing in height and planted either as single, double or triple rows, are compared.

The influences of different stand heights on wind breaking were illustrated in Fig. 5, where data on shelterbelts consisting of one, two or three rows were pooled. Starting at comparable values, any wind breaking effects clearly decrease with increasing distance to the shelterbelts. Behind the highest shelterbelt (h=1.5m) a wind breaking effect could be detected up to a distance of more than 20m, whereas for the lower shelterbelts (h=1.0 m and 0.5 m) a comparable effect was observed at an distance of only 7.5 m and 15 m respectively. Despite a small trend to an exponential curvature, these values where fitted to a linear model for further statistical analysis: The three different lines for the three different heights in Fig. 5A differed highly significantly ($p<0.001$), additionally the number of rows also showed highly significant but nevertheless slighter influence on this relationship ($p=0.001$). These different numbers of rows per shelterbelt were not distinguished in Fig. 5A but for a certain shrub height in all cases the windbreak effect of a shelterbelt consisting of three rows was higher than the one consisting of 2 rows and of one row respectively.

In order to eliminate any scaling effects, the distances were calculated as x-folds of shrub height (Fig. 5B). Now, the linear relationships of the wind breaking by the three different shrub heights to this distance were no longer distinguishable ($p=0.15$) as they were overruled by the effects of different numbers of rows per shelterbelt ($p<0.0001$).

Experiment B also investigated the characteristics of shelterbelts consisting of more than one row of shrubs in terms of wind-breaking. Therefore, the data for the shelterbelts differing in height were pooled. Fig. 5C shows the windbreak effect k for different absolute distances behind these shelterbelts in a way comparable to Fig. 5A. However, the data did not show any consistent pattern any more as they were spreaded over broader ranges. The linear relationship is also clearly broken and even exponential models failed to explain the observed values. Therefore, the data were also related to relative distances (Fig. 5D), where linear curve fitting was possible within the investigated distances. Compared to Fig. 5D, differences between the pooled data were visible, indicating the stronger impact of row numbers within this relationship between the two relative measures.

Sand transportation rates: The effect of different plantation patterns on wind speed is especially interesting in terms of preventing or reducing sand erosion. As shown in the previous section, these patterns are related to x-folds of shrub height. With increasing relative distance behind a shelterbelt, sand transportation rates should asymptotically approximate values observed on open field (Fig. 6A), which was determined as 2.264 g cm^{-2} min^{-1}. In contrast to the effectiveness in wind-breaking of shelterbelts with different heights, the curvatures of the sand transportation rates differed significantly ($p=0.007$) for the three different heights.

The underlying physical properties of any ground covers are frequently expressed in terms of surface roughness length. For the experimental setup of experiment B, which consisted of just one single shelterbelt but not a continuous homogeneous layer, could this parameter only be estimated (see methods section; Eq. 2 and 3). Nevertheless, all sand transportation rates were clearly related to such estimates in a linear fashion over the range of values (Fig. 6B; $r^2=0.86$, $p<0.0001$). Consequently, statistical analysis showed an influence of shrub height and row numbers within the shelterbelt on the sum of squares of this model of only 1.3% and 0.8% respectively. Only lowest sand transportation rates displayed a trend to an slightly exponential curvature, however, that range of values was not covered during these experiments.

As sand transportation rates were in the main focus of this work, it was necessary to predict this parameter under the various conditions as investigated here. To obtain one general model, a simple nonlinear model (see methods section; Eq. 4) was applied to the measured data (n=63) which resulted in the following coefficients (± SE) given in Table 3.

The rates obtained by the model could be compared to that of the open field, but it is important to keep in mind that any reduction of sand transportation does not necessarily result in a sand deposition of the same amount. Moreover, at a distance behind the shelterbelt of about 15 times shrub height, sand transportation is the same as on open field. Nevertheless, it can be assumed that the amount of fixed sand is proportional to the reduction of sand transportation, thus defining a measure for a benefit, which was given further attention in the next section.

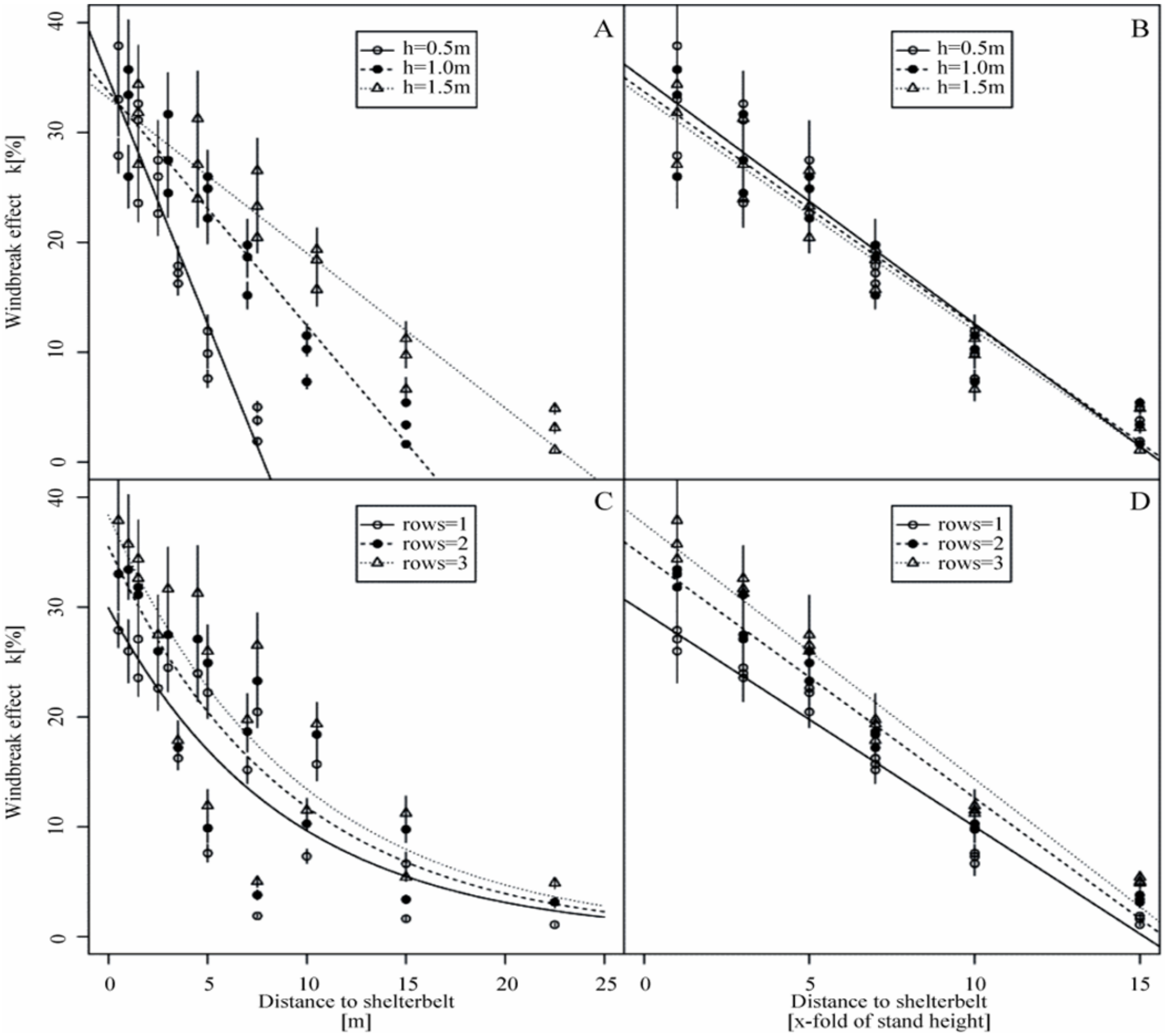

Fig. 5. Effectiveness of windbreak as a function of distance to the shelterbelt in absolute terms (A) and as x-folds of shrub height (B). Three different heights of the plantations are given to different symbols irrespective of the number of rows within a shelterbelt (1, 2 or 3) and fitted to separate linear functions (A: y1=34.9-4.5x; y2=33.7-2.1x;y3=33.1 -1.4x; B: y1=34.9-2.2x; y2=33.7-2.1x; y3=33.1 - 2.1x). Standard errors were given as vertical bars.

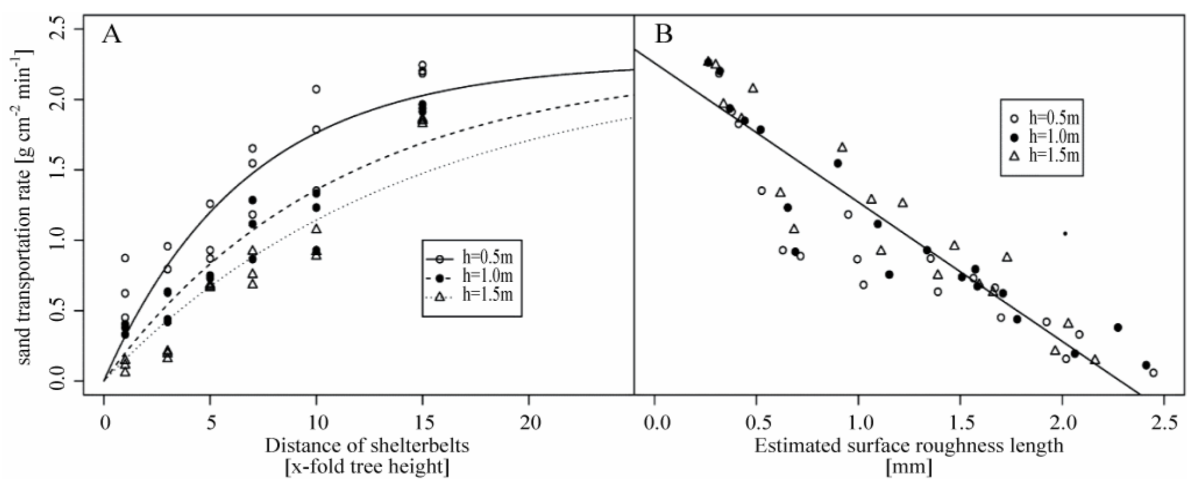

Fig. 6. Sand transportation rates at various distances behind shelterbelts of Salix psammophila (A). Sand transportation rate as a function of estimated surface roughness length. All values of the three different shrub sizes are fitted to one linear regression line (y=2.38x – 1.04) (B).

Table 3. Nonlinear model (equation in model section) comprising all shelterbelt designs with three different tree heights and 1, 2 or 3 rows per shelterbelt (n=63).

Coefficient	Value ± SE [g cm^{-2} min^{-1}]	Significance
a	0.146 ± 0.017	< 0.0001
b	0.035 ± 0.006	< 0.0001
c	0.028 ± 0.010	0.0110

Cost-benefit relationships: Using the relationship as described above, predictions can be made regarding the benefit of the shelterbelt, which is assumed to be proportional to the total amount of reduction in sand transportation. This could be related to the effort for maintaining the shelterbelt, most likely the amount of water drawn from the ground water level. For this first simple approach, it is assumed, that these costs are proportional to shrub size, that is: Shrubs of half the size compared to a shrub of 1.0 m in height, are assumed to result in half the costs, and shrubs of 1.5m in height result in 1.5 times these costs. If further information became available, this rough proportional approach can be easily improved by another height-cost relationship.

The results of this modeling approach resulted Fig. 7. Depending on shrub height and number of rows within a shelterbelt, lowest reductions in sand transportation rates are found on shelterbelts built up by one row and shrubs of lowest height, and they increase with shrub height (Fig. 7A). Obviously, the effort of maintaining such shelterbelts increases almost in parallel. Fig. 7B. illustrates this relationship, which is strictly linear in this case. In the last step, the ratios between the two previous graphs are calculated, as shown in Fig. 7C. Astonishingly, though single rows of small shrubs exhibited the lowest reduction of sand transportation rates, this is compensated by an even smaller effort for maintenance. Thus, the ratio of reduction per effort is higher under such circumstances for shrubs of about 0.5m in height and increased even more, when extrapolated to sizes below 0.5m. For medium sized shrubs of about 1.0m, which generally exhibit lower reduction/effort-ratios, the ratio decreased with row number. It was also remarkable, that the model suggests, that with the growing of these shrubs, the optimum shifts towards shelterbelts consisting of two rows of shrubs.

For sand transportation rates above a potentially infinite sequence of repetitively planted shelterbelts, various distances between them have to be considered. Fig. 8 illustrates the situation for shelterbelts consisting of one row of shrubs with different sizes. Obviously, the reduction of the sand transportation rate increases with shrub size and decreases with increasing distance between such shelterbelts (Fig. 8A). In parallel, the effort for maintaining such sequences of belts also increased with increasing shrub size and shorter distances between the shelterbelts (Fig. 8B). As the effect of shrub height on the effort of maintenance is stronger than on the reduction of sand transportation rates, the ratio behaved differently. As for a single row, shelterbelts with smaller shrubs show a better ratio of reduction to effort (Fig. 8C). The model also predicted, that when shrubs are growing, a sequence of shelterbelts with wider distances show better ratios of benefit per cost, at least for the investigated distances of about 15 to 20m.

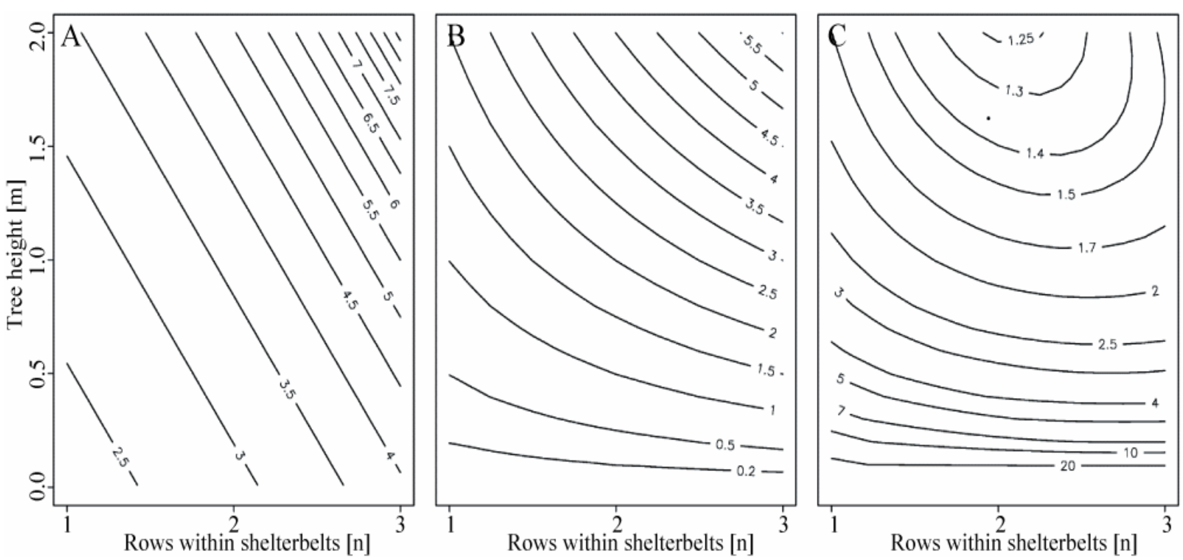

Fig. 7. Model of sand transportation behind a single shelterbelt as compared to the open field. A: reduction in sand transportation [kg m^{-1} s^{-1}] as a function of rows per shelterbelt and shrub height (values in graph). B: Effort of maintaining a certain running length of a shelterbelt [shrubs m^{-1}]. C: Reduction per effort [g s^{-1} $shrub^{-1}$] as a function of rows per shelterbelt and shrub height (the greater the number the more reduction).

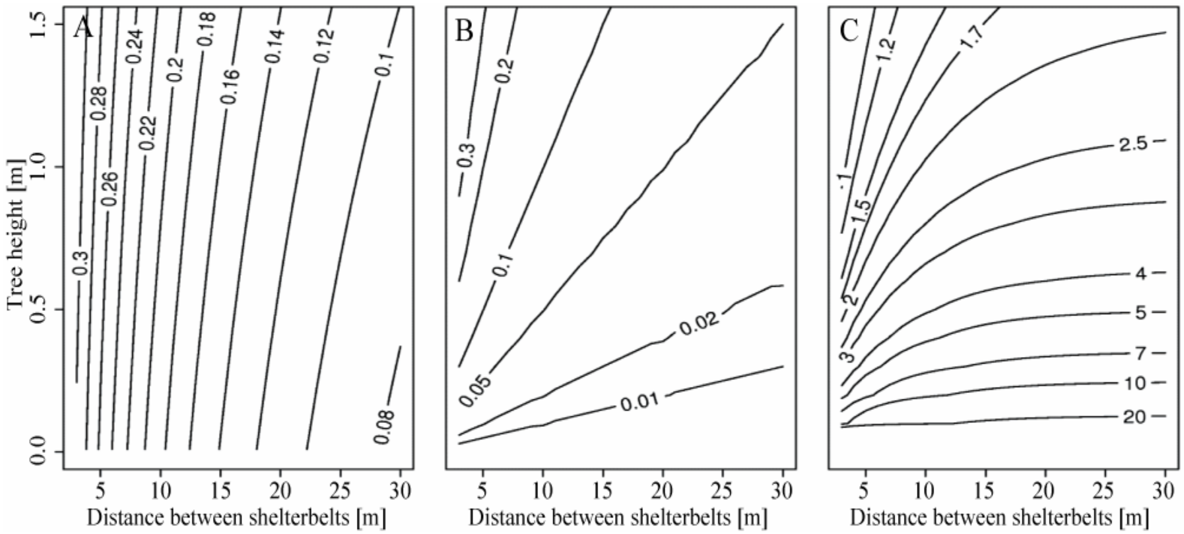

Fig. 8. Model of sand transportation across repetitively planted shelterbelts composed of one row each as compared to the open field. A: reduction in sand transportation [kg m^{-2} s^{-1}] as a function of distances between such shelterbelts and shrub height. B: Effort of maintaining a certain area of such a sequence of shelterbelts [shrubs m^{-2}]. C: Reduction per effort [kg s^{-1} $shrub^{-1}$] as a function of distance between shelterbelts and shrub height.

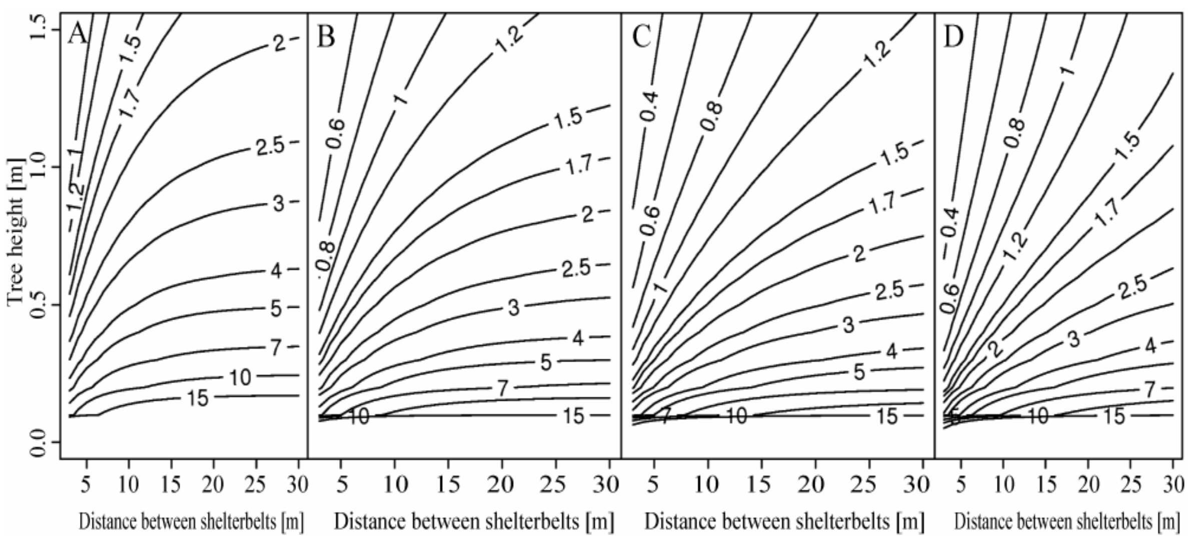

Fig. 9. Retention per effort [kg s^{-1} $shrub^{-1}$] across repetitively planted shelterbelts composed of one row each as compared to the open field like previous figure C. A: one row per shelterbelt B: Two rows per shelterbelt C: Three rows per shelterbelt D: Four rows per shelterbelt.

Finally, it is also of interest, whether such parallel shelterbelts are more cost-efficient, when they are composed of more then one row of shrubs. The underlying model was the same as for Fig. 8, but the ratio of reduction in sand transportation per effort was calculated for 1 up to 4 rows within a shelterbelt. For one row, Fig. 9A shows basically the same situation as that in Fig. 8C, but for better comparison, another scale was chosen. For a sequence of parallel shelterbelts consisting of two rows each (Fig. 9B), this ratio is about one third lower, as the benefit of an additional row does not compensate the effort. This trend is continued for shelterbelts consisting of three rows (Fig. 9C) and also when data are extrapolated to shelterbelts consisting of 4 rows (Fig. 9D).

Discussion

Vegetation is a very sensitive element in the landscape reacting to changes in other natural elements as land form, water, soil and climate (Wang *et al*., 2006b), especially in desertified areas (Lei H *et al*,2012). When vegetation cover is below 40%, as in the northern sandy lands of China, shelterbelts are important to prevent soil erosion by wind. Shrub communities increase ground roughness depending on their spatial patterns, slow down wind speed and enhance sand deposition. In this paper we analysed the effects of shelterbelts composed of different species to wind velocity. The investigated shelterbelts effectively reduce wind velocity lee-wards and especially below 1.0 m height near ground, wind velocity is decreased. With increasing height above the shelterbelts, the reduction of wind velocity reduction declined.

Because of different plant morphologies windbreak effects are in parts species-specific. In *Tamarix* plantations most stocking heights are below 1.2 m with strongest reduction effects below this height. In *Caragana*, the wind reduction effects between ground and 1.2 m are relatively homogeneous as *Caragana* A and *Caragana* B are the same species with a similar mean height. However, because of different stand densities their effects differ in magnitude. Larger branch density, coverage and height result in a higher surface roughness and increase wind-breaking effects. *Salix psammophila* exhibits larger height, coverage and branch density, so the wind breaking effects are larger than in *Caragana* and *Tamarix*. This could be confirmed by relating the density as derived from optical methods to the reduction in wind velocity. Comparing the overall effects of the four different species and densities of shelterbelts can be arranged as *Salix psammophila* > *Caragana A* > *Tamarix* > *Caragana B* according to their effectiveness in wind breaking.

Salix psammophila and *Caragana* scrubs and shelterbelts are the two most widely distributed tree species in the Yanchi sandy area (Gao *et al*., 2004). Furthermore, both species have good economic value. Already three year-old *Salix psammophila* plant roots can cover about 400m² with the shallowest roots reaching 5 m depth (own observations). Therefore, *Salix psammophila* has a reasonable endurance to drought and large ecological amplitude (Yamamoto *et al*., 2006). Nevertheless, heavily eroded landscape suffer from a loss in nutrients (Wang *et al*., 2006a) which can be a limiting factor for plant growth, so planting of the nitrogen-fixing *Caragana,* with is known to significantly improve soil fertility (Su & Zhao 2003; Zhao *et al*., 2007), might turn out to be more useful.

In the literature, *Salix psammophila* is well known for effectively building up shelter belts of good wind-breaking properties, and it is one of the best investigated species in the study region (Dong & Li, 1995). However, most studies were focussed on *Salix psammophila* barriers planted in a square grid design (Wang *et al*., 2008). Such plantations obviously result in higher costs for plantation and in terms of water requirement than designs in single or few belts. Besides this benefit, single belts show the drawback to affect wind velocity only locally. According to the few studies on single shelterbelts of *Salix psammophila* (Mctainsh *et al*., 1998; Dong *et al*., 2000; Zhao *et al*., 2006), any wind-breaking effects do not reach behind the shelterbelt for more than 12 to 15 times the shrub height, where wind velocity is the same as on open field. This is also observed at the study site presented here.

Therefore, plants of such shelterbelts should be arranged in an optimal way. By investigating different spatial patterns of this species, the effects on wind velocity could be related to parameters representing the costs of structures such as shrub height and planting density. From Table 3 it is obvious that all zonal arrangements of *Salix psammophila* shelterbelts reduce wind velocity near ground. The effects of windbreaking are related to height and patterns of shelterbelts, and, because all the experimental shrubs height are below 2.0 m, the windbreak effects are similar.

Sand storms move and accumulate soil (dust and sand) near ground. Erosion by wind is one of the most important factors resulting to soil desertification of arid and semiarid regions (Gao *et al*., 2006). In areas without vegetation coverage, wind-drifted sand threats the ground directly by moving dunes along the predominantly wind direction (Zhu *et al*., 1992). Therefore, the sand transport rate can be used to judge whether soil is eroded or accumulated. In this study a general equation of sand transportation behind such shelterbelts was used to predict the decrease of sand transportation under all investigated spatial patterns and at all distances behind a shelterbelt. The study also suggests a single negative linear relationship between sand transportation rate and surface roughness length behind all investigated shelterbelts. Only at lowest values of sand transportation, a trend to an exponential relationship might be identified, which would be expected for theoretical reasons and over a higher range of values (Li *et al*., 2003a).

The benefits of wind breaking and sand fixation are directly related to shrub height and spatial distribution patterns. For zonal shrub arrangements wind fields are stable, wind-breaking is more effective than for equal-spaced and randomly arranged shrub communities (Guo *et al*., 2006; Zhao *et al*., 2008). Zonal arrangements are an optimized spatial pattern in arid and semi-arid regions of northwest of China. Our data shows that shelterbelts of 3 rows in a belt, mean shrub height of 1.5 m and a distance of 1.5 m between two rows have the best effects of wind breaking and sand fixation.

Conclusion

The performed experiments raised considerations on the costs of such arrangements. The higher shrubs are and the more rows are planted, the higher the demands for water and nutrient will be. Those natural resources are limited in the dry lands. Therefore, in this first approach a linear relationship between shrub height, shrub numbers per area and any effort of planting and maintaining such patterns is assumed. Surprisingly, though highest shrubs showed strongest reduction in sand transportation rates, they generate an even higher effort of maintenance. Therefore, regarding single shelterbelts, the model predicts the highest ratio of sand retention per effort for smallest shrubs planted in one or two rows. This is supported by measured data, as every stand also affects air movement above plant height, as expected by theory (Dong *et al*., 2001). Furthermore, planting such shelterbelts repetitively one behind another, the smaller shrubs still exhibit the best cost-benefit ratio, especially when planted at larger distances. This is also predicted for repetitively planted shelterbelts consisting of more than one row. Apparently the ratio of benefit per cost is more sensitive on costs than on benefits under these circumstances, favouring many small shrubs with lower individual effects rather than larger shrubs with stronger effects. This implies further issues: First, as long as re-sprouting is not affected, any cutting of or feeding on such shelterbelts might be beneficial regarding subsequent use of resources as e.g. water. Secondly, extrapolating this prediction even further, the model suggests consider even smaller plant structures or plant species of smaller sizes such as grasses. It is imaginable, that in habitats, where such plants could reach the ground water, they might be a more suitable choice.

However, the underlying assumption of a linear relationship between shrub size and water use is only partly valid, as e.g. younger semi-arid shrubs of *Chrysothamnus nauseosus* showed lower long-term water use efficiencies and lower root shoot ratios. Whereas different sized shrubs of *Prosopis glandulosa* showed a similar response to moderate drought with rather small differences (De Soyza *et al*., 1996). Cutting shrubs and thus favouring roots, would alter the root-shoot-ratio even further, therefore the deviations to the model would be even stronger. On the other hand, the lower water-use-efficiencies of cut shrubs would result in higher yields of dry matter during the vegetation season, when water is available. Obviously, the presented modelling approach also neglects both any negative effects imposed by competition between shrubs and also economic benefits of planting the same shrub species in higher numbers. Therefore, how to choose a shrub belts spatial pattern with lowest costs and highest benefits needs to be further investigated (Yang & Wang, 2004). Especially water utilization of these stands is an open question, since the requirement for water during growth differs among species and depends on the temporal as well as spatial water availability in these areas both on the landscape and the local scale of sand dunes and slopes (Tsoar, 1990; Littmann & Veste, 2005; Veste *et al*., 2008).

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