Landscape Ecol Eng (2013) 9:59–66
DOI 10.1007/s11355-011-0177-9

ORIGINAL PAPER

Effects of different planting methods on the early establishment of two introduced tree species in the Mu Us Sandy Land of China

Takashi Otoda · Guosheng Zhang · Linhe Wang · Ken Yoshikawa

Received: 30 September 2010 / Revised: 6 May 2011 / Accepted: 30 August 2011 / Published online: 7 October 2011

Abstract We investigated the effects of planting density and relative ground height (distance from the water table) on the early establishment of two introduced tree species [Mongolian pine (*Pinus sylvestris* var. *mongolica*) and white poplar (*Populus alba* var. *pyramidalis*)] in the Mu Us Sandy Land of China; we used GLMM to analyze experimental effects. In total, 14 afforestation plots (seven plots per species) with variable relative ground heights were established on a shifting sand dune. Trees were planted at intervals of 3, 5, and 7 m, and the distances between neighboring trees were fixed within plots. Planting intervals and numbers of neighboring trees were treated as measures of planting density, and relative ground height was treated as an indicator of water supply stability. For both species, tree survival rates decreased with increasing planting interval; the number of neighboring trees had a positive effect on survival. The effect of relative ground height differed between species. Pine tree survival rates decreased with increased relative ground height, while the survival rates of poplar trees were unaffected. We recommend that pine trees be planted at high density on lower sectors of sand dunes to prevent wind erosion in early spring. Poplar trees should be planted at high density without reference to relative ground height for the provision of fuelwood.

T. Otoda (✉) · K. Yoshikawa
Department of Environmental Ecology,
Graduate School of Environmental Science,
Okayama University, 1-1-1 Tsushima-Naka,
Okayama 700-8530, Japan
e-mail: dev20202@s.okayama-u.ac.jp

G. Zhang · L. Wang
Inner Mongolia Agricultural University,
Huhhot, Inner Mongolia, China

Keywords Afforestation · Desertification · GLMM · *Populus alba* var. *pyramidalis* · *Pinus sylvestris* var. *mongolica*

Introduction

Desertification is a global environmental problem. Drylands cover about 40% of the global land surface, and 10–20% of these landscapes have transformed into desertified lands (MA (Millennium Ecosystem Assessment) 2005). More than about 250 million human inhabitants have been impacted by the process (MA (Millennium Ecosystem Assessment) 2005). As a consequence, the United Nations and countries facing the growth of desert lands have enacted a variety of countermeasures (Stringer 2008).

China is among the countries in East Asia suffering from desertification. Deserts and desertified land in China occupy an estimated 1.49 million km^2, about 15.5% of the total land area (Fullen and Mitchell 1994). Desertification is most intense in northern regions, where an estimated 3.3 million km^2 have been impacted (Zha and Gao 1997). Various anthropogenic causes of desertification include overgrazing, overcultivation, and overexploitation of fuelwood. These activities often trigger decreases in plant coverage, with consequent growth in tracts of shifting sand and increased frequencies of dust storms (Li et al. 2003a, b; Zhang et al. 2004, 2005).

Various efforts have been made to combat desertification in these areas of China (e.g., Fan and Zhou 2001; Liu and Zhao 2001; Zou et al. 2002; Yoshikawa 2010). One of the most common methods is the fixation of shifting sand dunes by afforestation. This procedure is expected to stabilize shifting sand dunes. It is also the first step toward the conservation and natural recovery of remnant vegetation, because fixation of shifting sand dunes can promote natural invasion and the establishment of indigenous plants (Li et al. 2009). In addition, such afforestation is expected to play a large role in the provision of resources such as fuelwood to local people, and the conservation of environments by providing windbreaks for local housing and croplands (Ffolliott et al. 1995; Orlovsky and Birnbaum 2002; Li et al. 2003b; Yu et al. 2006). For these reasons, afforestation has been practiced since the 1950s in various arid and semiarid regions of China (Liu and Zhao 2001; Ren et al. 2002; Wu and Ci 2002; Zou et al. 2002; Li et al. 2003a, b; Zhang et al. 2004).

However, the procedures, particularly the large-scale afforestations (e.g., the Three Northern Regions Shelter Forest System Project), have failed in many cases because of very low survival rates among planted trees and shrubs (Cao 2008; Wang et al. 2010). This might be due to unsuitable procedures such as inappropriate decisions regarding the species planted, locations, and planting methods (Cao 2008). To solve these problems related to planting procedures, several studies have examined the effects of topographic position on the survival of planted seedlings and the adaptability of several tree species (e.g., Ren et al. 2002; Cao et al. 2007). However, few studies—except for that of Bhattacharjee et al. (2010)—have examined the effects of planting density and different intervals between planted trees and/or number of neighbors, let comparied the relative importance of planting density with that of topographic features. Improving ecological knowledge in relation to planting density and location will reduce the potential risk of afforestation failures and circumvent the additional costs associated with preplanting preparation or excessive irrigation after planting.

In this case study, we determined the effects of different planting methods on the early establishment of two introduced tree species in the Mu Us Sandy Land of China; we used a generalized linear mixed model (GLMM) approach for data analysis (Bolker et al. 2009). The main objectives were to determine the effects of planting density (planting interval and number of neighbors), the effects of topographic position (relative ground height), and the effects of tree species on plant survival. Based on the results, we provide recommendations for achieving successful afforestation.

Materials and methods

Study site

The study was conducted on part of an experimental site in the Mu Us Sandy Land Development Research Center (38°55′327″N, 109°10′931″E). The Mu Us Desert is in the southern sector of the Ordos Plateau, Inner Mongolia, China. This region is in danger of desertification as shifting and semifixed tracts of sandy lands have increased in area while fixed sandy lands have decreased since the 1950s (Wu and Ci 2002). The elevation is about 1320 m. The mean annual temperature recorded at Wushenshao meteorological station (located about 18 km north of the study site) is 7.3°C; the monthly mean temperatures in the coldest (January) and warmest (July) months are about −11 and 22°C, respectively (1997–2006). The mean annual precipitation is 309.9 mm (1997–2009), and most of the precipitation falls as rain from May to September. The soil is derived from Mesozoic sandstone (Hirobe et al. 2001), and the vegetation on shifting sand dunes is dominated by annual herbs such as *Agriophyllum squarrosum* (L.) Moq. and *Cynanchum komarovii* Al. Iljinski, but they are very sparsely distributed (Oyabu et al. 2007, 2008).

Plantation design

In late spring 2007, we afforested an area (600 m × 200 m) of shifting sand dunes that previously supported a sparse cover of natural vegetation. Mongolian pine (*Pinus sylvestris* L. var. *mongolica* Litv.) and white poplar (*Populus alba* L. var. *pyramidalis* Bunge) were selected for the experiments. These two species are widely used for afforestation in arid and semiarid areas of China.

We established 14 plots, seven for pine and seven for poplar, on northwesterly windward slopes of sand dunes. Three different planting intervals (3, 5, and 7 m) were tested for afforestation (Table 1). Distances between neighboring trees were equal within each plot (Fig. 1). A 5 m interval has generally been used in afforestation programs for sand-fixing and/or windbreaks in this area (L. Wang, personal communication).

Tree sizes and ages were, respectively, 1 m in height and 5 years for pine, and 3 m in height and 3 years for poplar. Pine trees with intact leaves and root systems were used, while poplar trees were pruned of leaves and twigs before planting, but with their roots left intact. We made efforts to minimize variation in tree size. Planting hole sizes were 50 cm in diameter and 50 cm in depth for pine and 50 cm in diameter and 80 cm in depth for poplar. The tree sizes we used are common and readily available in this area (L. Wang, personal communication). Sufficient water was supplied by irrigation just once after planting. We used no sand-fixation procedures.

The climate data obtained from Wushenshao Meteorological Station showed that precipitation from May to September was 343.3 mm in 2007, when the trees were planted, 361.6 mm in 2008 (1 year after planting), and 226.4 mm in 2009 (2 years after planting).

Field measurement methods

We censused trees in early summer, immediately after planting, and in September of 2008 and 2009 (1 and 2 years after planting, respectively). During the first census, all planted trees were numbered. We measured the relative ground height at locations where trees were planted; the lowest ground height in the tract including all plantation plots was treated as the zero elevation point against which all others were compared. The distance between the lowest ground height (zero elevation point) and the groundwater table was measured by digging a pit and found to be about 40 cm. The distance from the groundwater table of each tree was then estimated by adding 0.4 m to the relative ground height, assuming that the groundwater table is flat in the afforestation area. In the second and third censuses, survivorship of trees was assessed by the presence or absence of green leaves, and by the measurement of root collar diameters and live heights.

Table 1 Details of plantation plots

Plot no.	Planting interval (m)	Plot size (m)	No. of trees	Relative ground height (m) Minimum–maximum (mean)
Pinus sylvestris var. *mongolica*				
1	3	20 × 20	56	0.1–2.4 (1.2)
2	3	20 × 40	112	0.1–2.4 (1.2)
3	5	25 × 55	77	2.0–4.1 (3.3)
4	5	25 × 25	33	2.1–3.4 (2.8)
5	7	30 × 35	33	0.1–4.1 (1.9)
6	7	30 × 35	33	0.2–4.7 (2.4)
7	7	30 × 35	33	0.1–4.5 (2.4)
Populus alba var. *pyramidalis*				
8	3	20 × 20	56	1.6–4.0 (2.8)
9	3	20 × 40	112	1.7–4.4 (2.9)
10	5	25 × 25	33	1.8–4.0 (2.8)
11	5	25 × 25	33	0.2–2.0 (1.0)
12	5	25 × 25	33	1.0–3.1 (2.4)
13	7	30 × 75	64	1.5–4.9 (3.3)
14	7	45 × 45	56	1.3–5.2 (3.1)

Statistical analysis

We determined first-year survival as the survivorship in 2008 of all trees planted in 2007, and second-year survival as the survivorship in 2009 of trees alive in 2008. Whole survival was defined as the survivorship in 2009 of trees planted in 2007.

We used planting intervals as measures of tree density. However, the effect seemed to vary depending on locations within plots (e.g., interior vs. edge; Fig. 1). We therefore used the number of neighboring trees as a factor. For example, a tree located in a plot interior had six neighbors, while one located at the plot edge had two to five neighbors (Fig. 1). The numbers of neighbors were fixed at the outset, but tree deaths reduced neighbor frequencies.

We used a GLMM approach to determine the effects of planting density and relative ground height on first- and second-year tree survival rates:

$$\log\left(\frac{P_{ij}}{1-P_{ij}}\right) = (\text{Intercept}) + \beta_{\text{PI}}\text{PI}_{ij} + \beta_N N_{ij} + \beta_{\text{RGH}}\text{RGH}_{ij} + \omega_i + \varepsilon_{ij}, \tag{1}$$

where i is the plot number, j is the number of individual trees, P_{ij} is the probability of survival, PI_{ij} is the planting interval between trees, N_{ij} is the number of neighbors, and RGH_{ij} is the relative ground height. β_{PI}, β_{N}, and β_{RGH} are fixed effect coefficients for PI, N, and RGH, respectively. ω_i corresponds to the random effect of the ith plot. ε_{ij} is the individual error factor for a given individual and plot. Equation 1 can be transformed into

$$P = \frac{1}{1+\exp[-f(\text{PI},\text{N},\text{RGH})]}, \tag{2}$$

where f(PI, N, RGH) is the linear predictor. Equation 2 indicates that the survival probability closely approaches 1 as the value of f(PI, N, RGH) increases.

For each species, first- and second-year survivals were used as response variables. Of the three explanatory

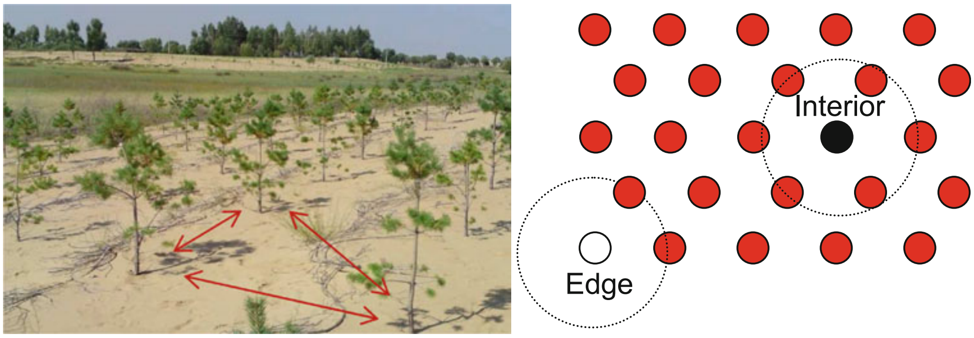

Fig. 1 Planting method: intervals between neighboring trees were fixed within plots. Interior trees had six neighbors; edge trees had two to five neighbors

factors, PI (3, 5, and 7 m) was treated as a three-level categorical variable; N (integer ranging from 0 to 6) and RGH were treated as numerical variables. If PI = 3 m, $\mathrm{PI}_{ij} = 0$, and if PI = 5 or 7 m, $\mathrm{PI}_{ij} = 1$ in Eq. 1. Differences among plots were treated as random factors that affected only the intercept.

This analysis was conducted using the glmer function provided by the lme4 package in the R software package (version 2.10.1; R Development Core Team 2009). Values of maximum log likelihood were estimated by Laplace's approximation method. A GLMM procedure with a logit link function and a binomial error distribution was used for analysis. The choice of whether to accept or reject each explanatory variable for inclusion was made by model selection using Akaike's information criterion (AIC) (Johnson and Omland 2004).

Results

The RGH varied greatly among trees and within plots, ranging from 0.1 to 4.7 m for pine and from 0.2 to 5.2 m for poplar (Table 1). Given that the groundwater table is flat in the vicinity of this afforestation area, distances to the groundwater table ranged from 0.5 to 5.1 m for pine and from 0.6 to 5.6 m for poplar.

The overall first-year survival rate of pine trees was 83.8% (range: 54.5–99.1%), and that of poplar trees was 87.3% (range: 66.7–100%) (Table 2). The second-year survival rate was 90.8% (72.2–100%) for pine and 93.8% (75.5–100%) for poplar. Second-year survivals of both species tended to be higher than first-year survivals. First- and second-year survival rates of poplar were slightly higher than those of pine, leading to a higher whole survival rate of poplars throughout the experiment.

Model selection based on the AIC differed between species (Table 3). For first- and second-year pine tree survival, models including all three explanatory variables had the lowest AIC values. For poplar trees, PI and N were included in the best predictive model for first-year survival, while only PI was included in the best model predicting second-year survival. AIC values were lowest in models including PI in both species, suggesting that PI had the highest relative importance among the three explanatory variables.

With one exception, the values of the PI coefficients were negative for early survival in both species, indicating that the survival rates of trees planted at intervals of 5 and 7 m were lower than those planted at intervals of 3 m (Table 4). However, the 5 m PI coefficient for second-year poplar survival was 0.39 ± 1.17, which was not significantly different from zero. Coefficients of N were positive in the best models for first- and second-year pine survival and first-year poplar survival, indicating that the survival rates of trees with more neighbors (i.e., planted inside a plot) were higher than those with fewer (i.e., located at a

Table 2 First- and second-year survival and whole survival rates of pines and poplars in plantation plots

Plot no	Planting interval (m)	No. of trees	First-year survival			Second-year survival			Whole survival		
			Live	Dead	%	Live	Dead	%	Live	Dead	%
Pinus sylvestris var. *mongolica*											
1	3	56	54	2	96.4	54	0	100	54	2	96.4
2	3	112	111	1	99.1	110	1	99.1	110	2	98.2
3	5	77	59	18	76.6	49	10	83.1	49	28	63.6
4	5	33	26	7	78.8	20	6	76.9	20	13	60.6
5	7	33	26	7	78.8	20	6	76.9	20	13	60.6
6	7	33	18	15	54.5	13	5	72.2	13	20	39.4
7	7	33	22	11	66.7	21	1	95.5	21	12	63.6
Total		377	316	61	83.8	287	29	90.8	287	90	76.1
Populus alba var. *pyramidalis*											
8	3	56	53	3	94.6	53	0	100	53	3	94.6
9	3	112	112	0	100	109	3	97.3	109	3	97.3
10	5	33	29	4	87.9	28	1	96.6	28	5	84.8
11	5	33	30	3	90.9	30	0	100	30	3	90.9
12	5	33	22	11	66.7	22	0	100	22	11	66.7
13	7	64	43	21	67.2	38	5	88.4	38	26	59.4
14	7	56	49	7	87.5	37	12	75.5	37	19	66.1
Total		387	338	49	87.3	317	21	93.8	317	70	81.9

Table 3 Akaike information criterion (AIC) for models explaining first- and second-year survival rates of pines and poplars

Model	*Pinus sylvestris* var. *mongolica*				*Populus alba* var. *pyramidalis*			
	First-year survival		Second-year survival		First-year survival		Second-year survival	
	AIC	Order	AIC	Order	AIC	Order	AIC	Order
Null	286.7	8	175.5	8	260.3	7	143.0	5
PI	273.6	4	165.0	3	256.8	5	**136.8**	1
N	284.5	6	172.4	7	253.5	3	143.2	6
RGH	284.8	7	170.9	6	262.1	8	145.0	7
PI + N	271.8	2	162.5	2	**250.4**	1	137.5	2
PI + RGH	272.3	3	165.1	4	258.8	6	138.7	3
N + RGH	281.7	5	166.3	5	255.5	4	145.2	8
PI + N + RGH	**269.6**	1	**161.6**	1	252.4	2	139.4	4

Maximum log-likelihood for each model was estimated with Laplace's approximation method. See Eqs. 1 and 2 for explanations of the model parameters. The four bold numbers in the table indicate the lowest AIC values

Table 4 Intercepts and coefficients of fixed effects (±SE) estimated using a GLMM approach to first- and second-year survival rates of pines and poplars

Species	Planting interval (PI)		No. of neighbors (N)	Relative ground height (RGH)	Intercept	AIC
	5 m	7 m				
Pinus sylvestris var. *mongolica*						
First-year	–2.59 ± 0.80**	–3.31 ± 0.76***	0.25 ± 0.12*	–0.30 ± 0.15*	3.65 ± 0.92***	269.6
Second-year	–2.93 ± 1.13**	–3.18 ± 1.09**	0.38 ± 0.16*	–0.38 ± 0.23^{ns}	3.93 ± 1.27**	161.6
Populus alba var. *pyramidalis*						
First-year	–2.34 ± 0.90**	–2.79 ± 0.92**	0.37 ± 0.13**	Not selected	2.33 ± 0.95*	250.4
Second-year	0.39 ± 1.17^{ns}	–2.51 ± 0.66***	Not selected	Not selected	4.00 ± 0.59***	136.8

Not selected indicates that the explanatory variable was excluded from the best model with minimum AIC

Significance levels by Wald's test: *ns* $P > 0.05$; * $P < 0.05$, ** $P < 0.01$, *** $P < 0.00$

plot edge). Deaths of neighbors probably reduced second-year pine survival.

RGH coefficients were negative in the best models for first- and second-year pine survival, although the coefficient for second-year survival did not differ significantly from zero (Wald's test: $P = 0.088$). Hence, the survival rates of pine trees decreased with an increased RGH. In contrast, RGH was not included in the best model predicting poplar survival, indicating that poplar survival was not affected by this variable.

Discussion

Model selection results demonstrated that of the three explanatory valuables studied, PI had the greatest effect on survival in both species (Table 3). Hence, more attention should be paid to the planting interval when afforestation is undertaken in sandy landscapes. Effects of variables differed between species, as discussed in detail below.

Effects of planting interval and number of neighbors

The GLMM demonstrated that a planting interval of 3 m led to higher first-year survival rates than intervals of 5 and 7 m in both species; the number of neighbors also had a positive effect on survival (Table 4). Hence, the facilitation effect of higher planting density swamped any negative effects of intraspecific competition. Even with 3-m intervals between plants, competition among trees did not seem to be high in the early establishment stage, probably because individual root systems did not spatially overlap through the duration of the experiment.

Rather, larger spacings between trees and fewer neighbors probably had little effect on soil surface fixation, perhaps leading to lower tree survival rates. Sparse vegetation and trees growing sparsely on sand dunes have little fixation effect on soil surfaces (Tsoar 2005; Cao 2008). In our experiment, surface sand around trees with larger intervals and fewer neighbors was more often blown away by the strong winds, enhancing the risk of exposing the root systems of the planted trees. This can lead to critical

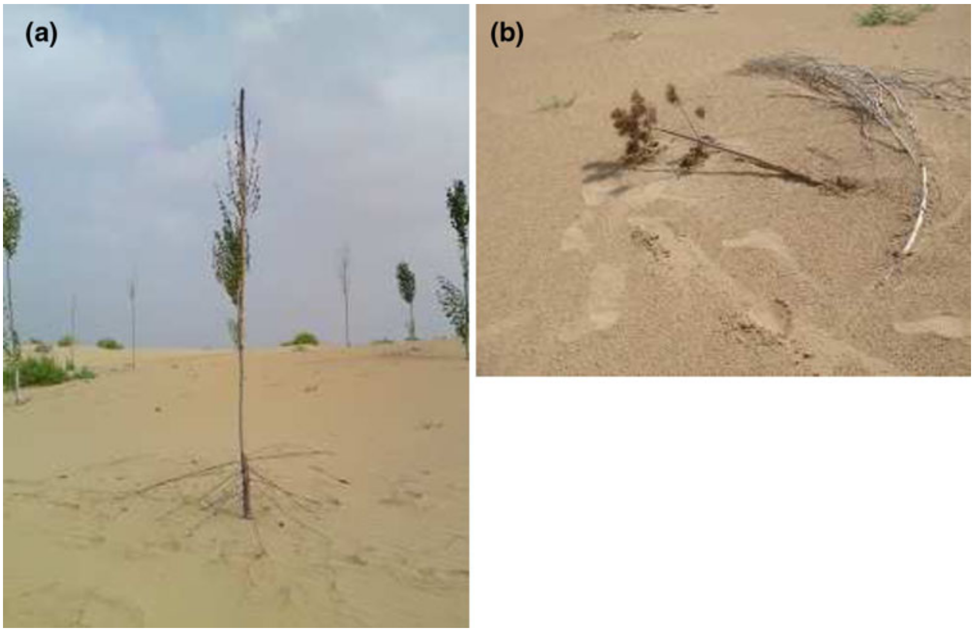

Fig. 2 Dead or dying trees that had fallen, exposing their root systems. **a** Dying poplar tree with exposed root system, **b** fallen dead pine tree

damage to the planted trees because their root systems are poorly developed shortly after planting. We also observed some fallen dead and dying trees in our experiment, with exposed root systems as the surface soil blew away (Fig. 2). Therefore, trees separated by larger intervals and with few neighbors are likely to be more vulnerable to wind erosion, leading to higher mortalities.

Effect of relative ground height

The GLMM predicted that the pine survival rate decreases with increased RGH (Table 4). In this experiment, the RGH might have been related to the degree of wind erosion and water availability, as discussed below.

As the afforestation was conducted on northwesterly windward slopes, trees planted on the lower sections within a plot may have been exposed to more wind erosion than those on the higher sections. Nevertheless, the survival rates of pine trees on the lower parts were higher than those on the higher parts (Table 4). Therefore, the degree of wind erosion might be less affected by the position within a plot than by planting interval and the presence/absence of neighbors.

Moreover, differences in RGH appear to affect the quantities and temporal fluctuations of available soil water in a shallow soil layer. When the groundwater table is deep, a rapid decrease in surface soil water occurs immediately following rainfall; the depth of the soil dry layer also increases because of the high infiltration rate of sandy soil (Tsoar 2005; Yang et al. 2010). When the groundwater table is shallower, the surface soil dry layer is not as deep (Masuda et al. 1988). Moreover, Masuda et al. (1988) demonstrated that the influence of groundwater on soil water content effectively extended to about 1 m above the water table, but not to >3 m, leading to a higher soil water content on lower sections, even during drier periods. Accordingly, trees planted on lower sections of a dune will obtain much more water and a more stable supply of it from the groundwater; a dry surface layer, however, occurs on the upper sections of a sand dune in dry periods and breaks up the capillary water flow, retaining some soil moisture. Such effects of different water availabilities on tree survival may have been overemphasized in our experiments because the small root systems of the planted trees shortly after planting would only have been able to access the shallow soil layer. In addition, this trend can be established because the natural invasion of indigenous plants has not yet occurred in the lower sections.

Notably, neither first- nor second-year poplar survival was affected by RGH. Poplar species are drought intolerant and have high water demand and consumption (Chen et al. 2004; Liang et al. 2006); poplar plantations often decrease the groundwater level (Wilske et al. 2009). Imada et al. (2008) demonstrated that *Populus alba* L. seedlings growing over a deep groundwater table did not adapt root morphology to soil water deficit (e.g., no increase in root surface area occurred to obtain more water). These previous studies seem to be inconsistent with our results. One possible explanation for this disparity is that we pruned poplar trees at an early stage. This treatment is commonly applied to reduce water loss through evaporation (Liu and Zhao 2001), and it may decrease poplar tree water demands, promoting better survival.

Further perspectives on the afforestation of shifting sand dunes

Our results provide some recommendations to improve the early establishment of pine and poplar trees. Regarding planting density, both pine and poplar should be planted at higher densities, with shorter intervals between trees (Tables 3, 4). Line planting in a few rows should be avoided because trees planted in this fashion will have few neighbors, leading to lower survival rates. As for topographic positions for planting, pine should be planted on the lower parts of sand dunes (Table 4), while poplar plantations might not need as much attention to RGH (distance from the groundwater table) (Table 4).

Considering the prevention of wind erosion during early spring when strong northwesterly winds blow, pine plantations are expected to play an important role in fixation of the substratum, because this species is evergreen. In contrast, poplar plantations may be less effective at fixing sand dunes (even though the establishment rate is high and unaffected by RGH) because this species is deciduous and does not have leaves in early spring. Furthermore, the higher water demand of poplar trees could potentially cause water balance problems in arid and semiarid regions (Wilske et al. 2009; Cao et al. 2011).

Nevertheless, poplar plantations may be useful for providing fuelwood for local populations because the species is fast-growing and able to sprout from root and trunk suckers, in addition to its more favorable survival rate compared to that of pine (Table 3). Harvesting at regular intervals, aside from providing a continuous source of fuelwood, may lead to a reduction in water consumption by poplar trees. Therefore, we believe that exploring the effective utilization of poplar plantations is warranted because the purposes of afforestation should be to not only conserve the environment but also to improve the livelihoods of local people (Stringer 2008).

Yoshikawa et al. (2006) emphasized the importance of long-term follow-up and maintenance after afforestation to maximize its ecological functions. As our experiment lasted for only 2 years, further long-term monitoring of the survival and growth of planted trees is needed to provide more concrete suggestions for afforestation.

Acknowledgments We are grateful to Dr. K. Sakamoto, Dr. M. Hirobe, Dr. N. Miki, Dr. Y. Yamada, and Dr. Y. Ishii for their valuable comments. We are also grateful to M. Kataoka, M. Harada, and Y. Akaji for assistance in the field. Dr. L. Yang provided the climate data. Two anonymous reviewers greatly improved the early manuscript. This study was supported in part by the Global Environmental Research Fund of Japan's Ministry of the Environment (G-071), the Ministry of Education, Science, Sports and Culture, a Grant-in-Aid for Scientific Research (B) 17405001, and the Japan International Forestry Promotion and Corporation Center (JIFPRO).

References

Bhattacharjee J, Taylor JP Jr, Smith LM (2010) Optimum seedling productivity in cottonwoods: a function of neighbor distance. J Arid Environ 74:1018–1023

Bolker BM, Brooks ME, Clark CJ, Geange SW, Poulsen JR, Stevens MHH, White JSS (2009) Generalized linear mixed models: a practical guide for ecology and evolution. Trends Ecol Evol 24:127–135

Cao S (2008) Why large-scale afforestation efforts in China have failed to solve the desertification problem. Environ Sci Technol 42:1826–1831

Cao S, Chen L, Xu C, Liu Z (2007) Impact of three soil types on afforestation in China's Loess Plateau: growth and survival of six tree species and their effects on soil properties. Landsc Urban Plan 83:208–217

Cao S, Chen L, Shankman D, Wang C, Wang X, Zhang H (2011) Excessive reliance on afforestation in China's arid and semi-arid regions: lessons in ecological restoration. Earth Sci Rev 104:240–245

Chen R, Kang E, Zhang Z, Zhao W, Song K, Zhang J, Lan Y (2004) Estimation of tree transpiration and response of tree conductance to meteorological variables in desert-oasis system of Northwest China. Sci China Ser D 47:9–20

Fan S, Zhou L (2001) Desertification control in China: possible solutions. Ambio 30:384–385

Ffolliott PF, Gottfried GJ, Rietveld WJ (1995) Dryland forestry for sustainable development. J Arid Environ 30:143–152

Fullen MA, Mitchell DJ (1994) Desertification and reclamation in north-central China. Ambio 23:131–135

Hirobe M, Ohte N, Karasawa N, Zhang G, Wang L, Yoshikawa K (2001) Plant species effect on the spatial patterns of soil properties in the Mu-us desert ecosystem, Inner Mongolia, China. Plant Soil 234:195–205

Imada S, Yamanaka N, Tamai S (2008) Water table depth affects *Populus alba* fine root growth and whole plant biomass. Funct Ecol 22:1018–1026

Johnson JB, Omland KS (2004) Model selection in ecology and evolution. Trends Ecol Evol 19:101–108

Li FR, Zhang H, Zhang TH, Shirato Y (2003a) Variations of sand transportation rates in sandy grasslands along a desertification gradient in northern China. Catena 53:255–272

Li FR, Zhang H, Zhao LY, Shirato Y, Wang XZ (2003b) Pedoecological effects of a sand-fixing poplar (*Populus simonii* Carr.) forest in a desertified sandy land of Inner Mongolia, China. Plant Soil 256:431–442

Li YL, Cui JY, Zhang TH, Okuro T, Drake S (2009) Effectiveness of sand-fixing measures on desert land restoration in Kerqin Sandy Land, northern China. Ecol Eng 35:118–127

Liang ZS, Yang JW, Shao HB, Hana RL (2006) Investigation on water consumption characteristics and water use efficiency of poplar under soil water deficits on the Loess Plateau. Colloid Surf B 53:23–28

Liu Z, Zhao W (2001) Shifting-sand control in Central Tibet. Ambio 30:376–380

MA (Millennium Ecosystem Assessment) (2005) Ecosystems and human well-being: desertification synthesis. World Resource Institute, Washington, DC

Masuda T, Kobayashi T, Yoshikawa K, Morimoto Y, Kobashi S (1988) Soil water conditions in the Mu-us desert, China. Bull Reveg Res 10:30–41 (in Japanese with English summary)

Orlovsky N, Birnbaum EH (2002) The role of *Haloxylon* species for combating desertification in Central Asia. Plant Biosyst 136:233–240

Oyabu T, Toda K, Mizuno Y, Nakashima A (2007) The appearance frequency by ground-water level and characteristic of photosynthesis rate of *Agriphylum squarrosum* (L.) Moq. (Shami) at Mu Us desert in Inner Mongolia. J Jpn Soc Reveg Tech 33:95–99 (in Japanese with English abstract)

Oyabu T, Toda K, Mizuno Y, Yoshimizu S, Horikawa M, Zhang GS, Miki N, Wang LH, Yoshikawa K (2008) The relation of groundwater level and distribution of *Cynanchum komarovii* Al. Iljinski indicate species of overgrazing in Mu Us sandy land in Inner Mongolia. J Jpn Soc Reveg Tech 34:33–38 (in Japanese with English abstract)

R Development Core Team (2009) R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna. ISBN 3-900051-07-0. http://www.R-project.org

Ren J, Tao L, Liu XM (2002) Effects of different microhabitats and stand age on survival of introduced sand-fixing plants. J Arid Environ 51:413–421

Stringer LC (2008) Reviewing the International Year of Deserts and Desertification 2006: what contribution towards combating global desertification and implementing the United Nations Convention to Desertification? J Arid Environ 72:2065–2074

Tsoar H (2005) Sand dunes mobility and stability in relation to climate. Phys A 357:50–56

Wang XM, Zhang CX, Hasi E, Dong ZB (2010) Has the Three Norths Forest Shelterbelt Program solved the desertification and dust storm problems in arid and semiarid China? J Arid Environ 74:13–22

Wilske B, Lu N, Wei L, Chen S, Zha T, Liu C, Xu W, Noormets A, Huang J, Wei Y, Chen J, Zhang Z, Ni J, Sun G, Guo K, McNulty S, John R, Han Z, Lin G, Chen J (2009) Poplar plantation has the potential to alter the water balance in semiarid Inner Mongolia. J Environ Manage 90:2762–2770

Wu B, Ci LJ (2002) Landscape change and desertification development in the Mu Us sandland, Northern China. J Arid Environ 50:429–444

Yang HL, Huang ZY, Ye YZ, Zhu XW, Dong M, Weng HB (2010) Effects of soil moisture profile on seedling establishment in the psammophyte *Hedysarum laeve* in the semiarid Otindag Sandland, China. J Arid Environ 74:350–354

Yoshikawa K (2010) New restoration engineering in northeast Asia. Glob Environ Res 14:37–46

Yoshikawa K, Sakamoto K, Hori S, Miki N, Huang SZ (2006) Growth of trees in a windbreak established in a desertification area in China (Yinchuan, Ninxia-Huizu Autonomous Region) 15 years ago. J Jpn Soc Reveg Tech 32:137–142 (in Japanese with English abstract)

Yu K, Li D, Li N (2006) The evolution of greenways in China. Landsc Urban Plan 76:223–239

Zha Y, Gao J (1997) Characteristics of desertification and its rehabilitation in China. J Arid Environ 37:419–432

Zhang K, Qu J, Zu R, Fang H (2005) Temporal variations of sandstorm in Minqin oasis during 1954–2000. Environ Geol 49:332–338

Zhang TH, Zhao HL, Li SG, Li FR, Shirato Y, Ohkuro T, Taniyama I (2004) A comparison of different measures for stabilizing moving sand dunes in the Horqin Sandy Land of Inner Mongolia, China. J Arid Environ 58:203–214

Zou XY, Li S, Zhang CL, Dong GR, Dong YX, Yan P (2002) Desertification and control plan in the Tibet Autonomous Region of China. J Arid Environ 51:183–198