Taylor & Francis
Taylor & Francis Group

Plant Biosystems - An International Journal Dealing with all Aspects of Plant Biology

Official Journal of the Societa Botanica Italiana

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/tplb20

The effect of different watering regimes and fertilizer addition on the growth of tree species used to afforest the semi-arid steppe of Mongolia

Ser-Oddamba Byambadorj, Donato Chiatante, Khaulenbek Akhmadi, Janchivdorj Lunten, Batkhishig Ochirbat, Byung Bae Park, Gabriella S. Scippa, Antonio Montagnoli & Batkhuu Nyam-Osor

To cite this article: Ser-Oddamba Byambadorj, Donato Chiatante, Khaulenbek Akhmadi, Janchivdorj Lunten, Batkhishig Ochirbat, Byung Bae Park, Gabriella S. Scippa, Antonio Montagnoli & Batkhuu Nyam-Osor (2021) The effect of different watering regimes and fertilizer addition on the growth of tree species used to afforest the semi-arid steppe of Mongolia, Plant Biosystems - An International Journal Dealing with all Aspects of Plant Biology, 155:4, 747-758, DOI: 10.1080/11263504.2020.1779845

To link to this article: https://doi.org/10.1080/11263504.2020.1779845

PLANT BIOSYSTEMS - AN INTERNATIONAL JOURNAL DEALING WITH ALL ASPECTS OF PLANT BIOLOGY
2021, VOL. 155, NO. 4, 747–758
https://doi.org/10.1080/11263504.2020.1779845

The effect of different watering regimes and fertilizer addition on the growth of tree species used to afforest the semi-arid steppe of Mongolia

Ser-Oddamba Byambadorj[a,b*], Donato Chiatante[c], Khaulenbek Akhmadi[d], Janchivdorj Lunten[d], Batkhishig Ochirbat[d], Byung Bae Park[b], Gabriella S. Scippa[e], Antonio Montagnoli[c*] and Batkhuu Nyam-Osor[a*]

[a]Laboratory of Forest genetics and Ecophysiology, School of Engineering and Applied Sciences, National University of Mongolia, Ulaanbaatar, Mongolia; [b]Silviculture Laboratory, College of Agriculture and Life Science, Chungnam National University, Deajeon, Republic of Korea; [c]Department of Biotechnology and Life Science, University of Insubria, Varese, Italy; [d]Institute of Geography and Geoecology, Mongolian Academy of Sciences, Ulaanbaatar, Mongolia; [e]Department of Biosciences and Territory, University of Molise, Campobasso, Italy

ABSTRACT

The environmental restoration of the semi-arid steppe of Mongolia is currently being addressed by creating new plantations able to protect the soil from the advancement of desertification and to improve the economy of the population living there. The success of these interventions relies on a high survival rate and good long-term growth performance of the transplanted trees. In the present work we analyzed stem height and root collar diameter (RCD) over 10 years for two native tree species (*Populus sibirica* and *Ulmus pumila*) grown with different water regimes and fertilizers. The investigated duration is sufficiently long to provide a reliable indication of the adaptation of these tree species to the steppe's harsh environmental conditions. Results suggest that both species could be used for environmental restoration projects, although *P. sibirica* requires the support of additional irrigation to achieve the best growth performance. *U. pumila*, on the other hand, shows good growth performance even with rainfall as the only water source. However, the higher water use by *P. sibirica* trees seems to be compensated by a more rapid ground cover compared to *U. pumila*. The addition of fertilizers to the soil before transplantation does not improve the growth performance of either species.

ARTICLE HISTORY
Received 22 October 2019
Accepted 28 May 2020

KEYWORDS
Populus sibirica; *Ulmus pumila*; afforestation; desertification; aridity; growth performance

Introduction

Advancement of desertification endangers the semi-arid and arid lands of Mongolia (Tsogtbaatar 2013), where they cover around 72% of the national territory (MNET 2010). Therefore, conservation of these lands has become a major issue on the agenda of this country's government (GCF 2019). To date, only 8% of the total Mongolian territory is covered by forests, although a reduction of this value to 6.7% must be considered due to recent forest degradation as a consequence of mismanagement, illegal logging, forest fires and insect pests (Ykhanbai 2010; Ariunzul et al. 2017). Furthermore, due to the inner-continental geo-localization of the country, Mongolia is highly affected by adverse climatic conditions as a consequence of global climate change (Hessl et al. 2016).

A carefully managed plantation is the most rapid way to implement forest landscape restoration (FLR) (Stanturf et al. 2014, 2015) in areas with degraded environmental conditions where natural succession is not an option. Moreover, using container seedlings is a cost-effective alternative when the planting season is to be extended or adverse sites are to be planted (Montagnoli et al. 2018). For this reason, the Mongolian government has been making an effort to plant trees to fight desertification with the result that already 15% of the total unforested area has undergone some degree of afforestation (Tsogtbaatar 2004; Miyasaka et al. 2014). Therefore, at present, in the forest inventory of this country, the decrease in forested land is counterbalanced by an increase in afforested land (Tsogtbaatar 2004).

As part of the project to contrast desertification, the government of Mongolia, jointly with that of South Korea, has launched a project named *Green Belt* (Lee and Ahn 2016). This project aims to create a forest shelterbelt in the southern part of the national territory at the northern border of the Gobi desert, where the steppe regions meet the desert area. Besides contrasting the advancement of the desert, a further important aim of the forest shelterbelt is to limit the number and intensity of sandstorms that originate in the Mongolia desert, but also affect several surrounding countries.

Regarding this project, it cannot be overlooked that the use of shelterbelts to contrast desertification and sandstorms is still a matter of debate (Yu et al. 2010), given the ecological implications (Lu et al. 2018) deriving from the transformation of grasslands. At the same time, it is difficult to ignore that, in addition to soil protection, tree shelterbelts

CONTACT Batkhuu Nyam-Osor nbatkhuu@gmail.com Laboratory of Forest genetics and Ecophysiology, School of Engineering and Applied Sciences, National University of Mongolia, Ulaanbaatar, Mongolia
*These authors contributed equally to this work.

Published online 02 Jul 2020

provide the opportunity to develop agroforestry activities, which are beneficial to the poor economy of the populations that live there (Jo et al. 2014; Lee and Ahn 2016).

In the particular case of the arid and semi-arid regions of Mongolia, it has been suggested that the survival rate of the transplanted tree could be the limiting factor of afforestation operations, due to strong winds and the dry (and barren) nature of the soil (Jo and Park 2017). Besides, it has been observed that high survival rate and fast initial growth rate are often followed by a notable reduction in growth performance related to the depletion of soil resources (Cao et al. 2011; Polzella et al. 2019). It is clear, therefore, that the success of afforestation in these Mongolian lands requires an initial high survival rate of transplanted trees, followed by an adequate growth rate in the long term (Zhang et al. 2016). The analysis of these two aspects of plant growth is essential to establish all the aspects of management measures required to ensure the success of afforestation (Lu et al. 2018).

Populus sibirica hort. ex Tausch and *Ulmus pumila* L. (two native species) are most frequently used to afforest Mongolian arid and semi-arid lands (Jo and Park 2017). The genus *Populus* is generally much appreciated (Zsuffa et al. 1996) for its fast growth and re-sprouting capability but also the ease by which it can be bred and propagated through cuttings (Mao et al. 2008). Moreover, these trees have shown a strong adaptability to different environmental conditions, including a certain degree of drought (Kang et al. 1996; Yin et al. 2005a, 2005b; Mao et al. 2008). The Siberian elm (*U. pumila*) has also been successfully used to afforest Mongolian lands. However, given the poor nature of the soils, it is necessary to evaluate for both species whether the amount of nutrients present is sufficient to support their demand of phosphorus necessary for nitrogen fixation (Israel 1987). If this is not the case, it will be necessary to support the growth of these trees by employing fertilization measures.

Poplar has been used to afforest steppes in China (Inner Mongolia) for almost 20 years, which led to the positive conclusion that this tree gives a significant increase of above- and belowground carbon stock (Hu et al. 2008) in lands where this result is much needed. At the same time, these studies call attention to the high transpiration activity of this tree which considerably affects water consumption, lowering the ground table and diminishing overall soil moisture (Su and Shangguan 2018). In this respect, Yao et al. (2016) found that afforestation with *Populus* could lead to a soil moisture content (SMC) decrease in semi-arid or arid lands, in particular in the upper 30 cm of soil. Therefore, it is not surprising that several authors have called attention to the possible adverse environmental impacts of afforestation (Bruijnzeel et al. 2005) and recommended the selection of slow-growing tree species such as *Ulmus* (Lu et al. 2018). The *Ulmus* tree is known to survive and grow better, even under water-deficient stress, compared to more mesic-adapted species (Engelbrecht et al. 2005). Moreover, this tree was shown to be well-adapted to live also on poor soil affected by severe cold (Moore 2003). The only problem of using *Ulmus* in afforestation programs is an incomplete knowledge of all its morphological and physiological traits (Lee et al. 2017). Hence, on the basis of the above, it emerges that any attempt to afforest arid lands in Mongolia must be preceded by a careful analysis of a) the possible environmental impacts and b) the most important traits of the plant species to be used (for example it could be important to measure the balance between the levels of plant transpiration and precipitation) (Guo and Gifford 2002).

In a recent study, Sungsik et al. (2019) compared water use efficiency and biomass production in 10-year-old *P. sibirica* and *U. pumila* trees, which had been used to afforest a semi-arid land situated in Lun Soum (Tuv aimag of Mongolia). The obtained data showed that *U. pumila* is characterized by a better water use efficiency than *P. sibirica* although both species had an equal photosynthetic efficiency. On the other hand, the aboveground biomass accumulated in 10 years of growth resulted to be much higher in *P. sibirica* compared to *U. pumila*. These contrasting indications make it difficult to decide which tree species would be the best candidate for afforestation of arid and semi-arid lands in Mongolia. To answer this question, the present work extends the comparative analysis of growth performance of both trees by taking into consideration the kinetics of aboveground biomass accumulation during the first 10 years of growth. In particular, we have analyzed growth performance by means of two morphological traits: stem height (H) and stem diameter at the root collar (RCD). The growth performance was analyzed for plants treated with different watering regimes and in the presence of two different types of fertilizers: 1) COMPOST (i.e., sheep manure used as natural manure fertilizer), and 2) a mixture of PNK chemical fertilizers. Results indicated that both tree species examined could be used to afforestate semi-arid and arid lands. In particular, *P. sibirica* is a faster-growing species but more sensitive to restricted water availability, whereas *Ulmus* trees grow more slowly but show better resistance to water shortage. Therefore, decision-makers must choose between two possible options: a) to prioritize the formation of a ground cover at the cost of using more water; b) to save water at the cost of delaying ground cover. For both tree species, the addition of fertilizers to the soil was less important for obtaining a good growth performance.

Material and methods

The geographical position of the experimental site and soil properties

The experimental site (2 ha) is located at 47°52′15.43″N, 105°10′46.4″E, with an elevation of 1130 m within the forest nursery of the South Korea-Mongolia Joint *Green Belt* Plantation project in Lun soum, Tuv aimag, Mongolia, 135 km west of Ulaanbaatar, Mongolia (Figure 1a). In particular, the nursery is located on the right bank of the Tuul River, in a dry-steppe area densely populated and greatly degraded by intense livestock grazing. Its typical steppe soil, classified as dark kastanozem, is deep (more than 1 m) and immature, lacking horizontal development. The hardness of the topsoil is 4.5 kg cm^{-2}, while that of the subsoil is 1.7 kg cm^{-2}, as

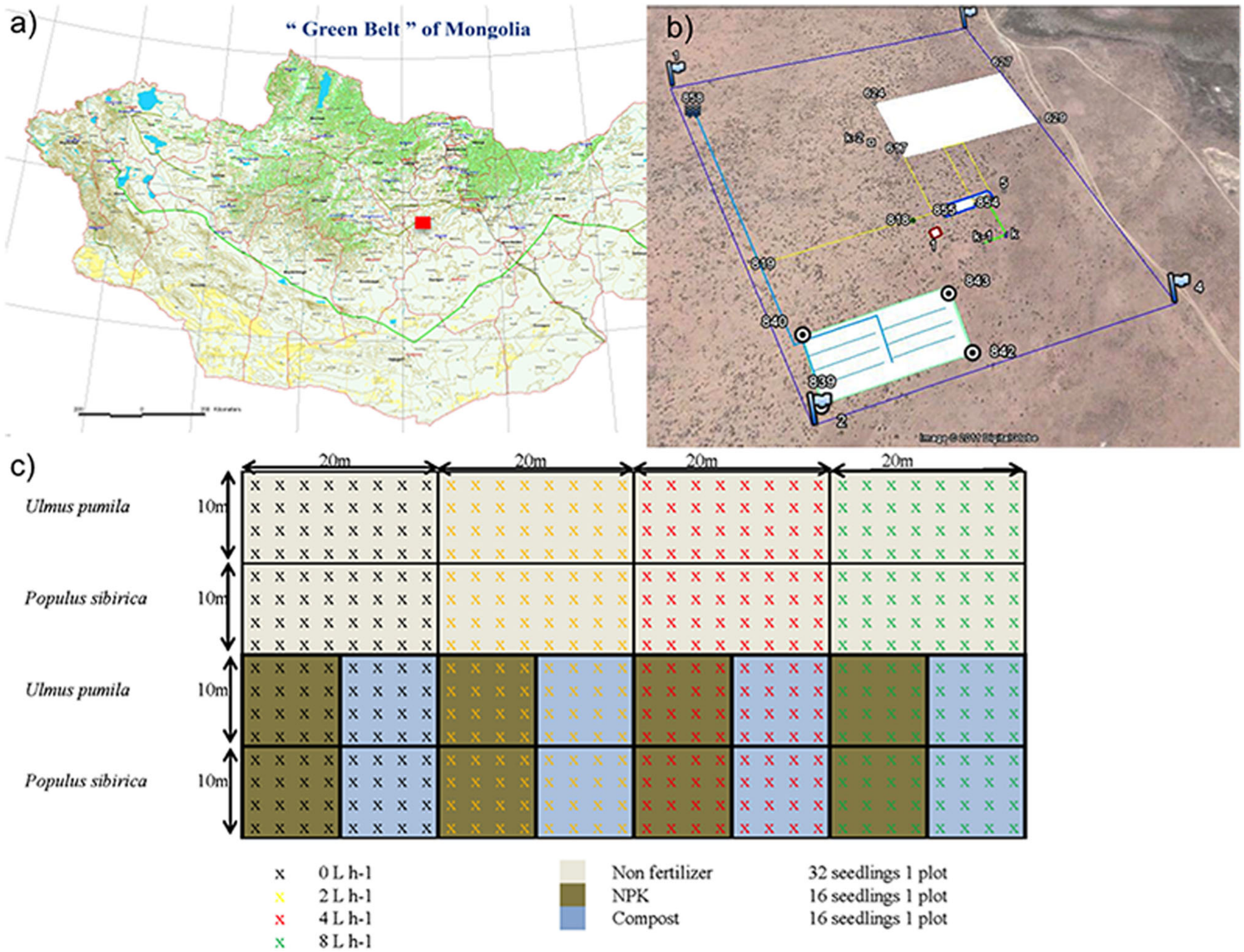

Figure 1. a) Map of Mongolia with a red square indicating the location of the experimental site; b) aerial photo with a close-up of the experimental site; c) planting scheme indicating plant species, number of seedlings and treatments.

the topsoil is drier than the subsoil. The particle size distribution analysis showed that the soil consists of 76.0% sand, 17.2% silt, and 6.8% clay, with an organic content of 2.8% (Kim et al. 2010). The cation exchange capacity (CEC) is 2.9 $cmol^{+}$ kg^{-1}, and the ionic composition is as follows: SO_4^{2-} (3.5 mg kg^{-1}); NO_3^- (0.9 mg kg^{-1}); Cl^- (120.8 mg kg^{-1}); Na^+ (83.0 mg kg^{-1}); K^+ (8.8 mg kg^{-1}); Ca^{2+} (40.0 mg kg^{-1}); and Mg^{2+} (4.6 mg kg^{-1}) (Kim et al. 2010).

Plant material

Two-year-old seedlings of *U. pumila* (grown from seeds) and *P. sibirica* Tausch (obtained from 20 cm cuttings) grown in the greenhouse and acclimated in the open nursery were obtained from the Greenbelt project nursery and transplanted in 60–70 cm-deep holes with a diameter of 50–60 cm. Immediately after transplanting, a sufficient level of watering was supplied to individual trees by compensating non-leakage (CNL) button drippers capable of delivering 1 gph (4 l h^{-1}). Emitters were placed at a distance of 10 cm from the seedling axis. After seedling stabilization, four different watering regimes were applied: 0 (control) l h^{-1}, 2 l h^{-1}, 4 l h^{-1}, and 8 l h^{-1}. The watering was done twice a week for 5 hours for the entire duration of the vegetative season (from the beginning of May to the end of August). In addition to the different watering regimes, two different types of fertilizers (500 g per tree) were mixed with natural soil to fill the holes before the seedlings were transplanted: NPK and COMPOST. NPK consisted of solid granules of the mixture of nitrogen, phosphorus, and potassium whereas COMPOST consisted of natural sheep manure. Twelve plots per plant species were prepared: 1 for control + 3 for watering regimes; 1 for control plus NPK + 3 for NPK with different watering regimes: 1 for control COMPOST + 3 for COMPOST with different watering regimes. Each plot measured 20 x 10 m; distance between trees in the plot was 2.5 m; trees were planted following rows distant 2.5 mt from each other. The number of seedlings per plot was 32 for control watering regime treatments or 16 for watering regime treatments with fertilizer addition. In the experimental field, the trees were planted with a north-south orientation to ensure maximum light availability during the whole day (Johnson & Brandle 2009) (Figure 1c). At transplanting time, elm seedlings were 51 ± 1.14 cm in height with a diameter at root collar (RCD) of 0.33 ± 0.01 cm (n = 64), whereas poplar seedlings were 68 ± 2.94 cm in height with 0.51 ± 0.02 cm RCD (n = 64). After transplanting in the field, the survival rate of seedlings was very high in the case of

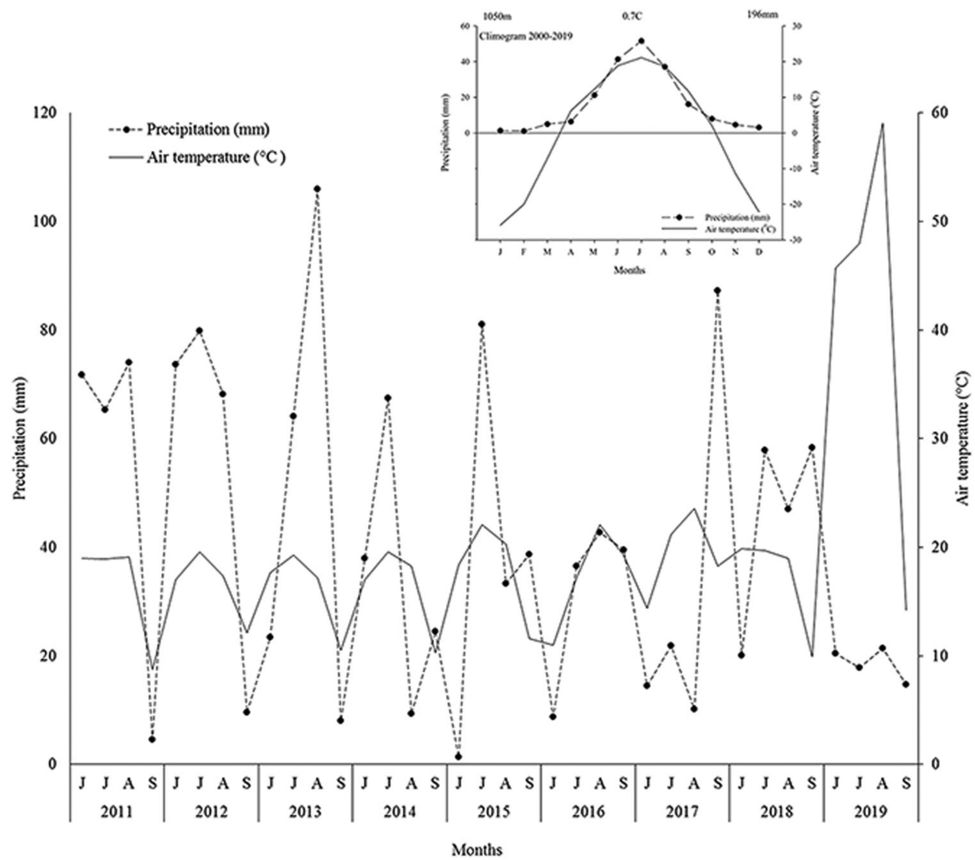

Figure 2. Inner panel. Monthly average air temperature (solid line) and rainfall (broken dotted line) for the period 2000–2019. Numbers indicate, respectively from left to right, study site elevation (above sea level), mean annual temperature, and mean annual precipitation. Data are obtained from the Lun soum weather station. Outer panel. Monthly average temperature (solid line) and rainfall (broken, dotted line) measured during the experiment (2011–2019) for the growing season only (June-September). Data were measured during the implementation of experiments.

elm, independently of the treatment used, whereas it was very low for poplar when trees received no water except for the natural amount of rainfall. The presence of fertilizers in the soil did not significantly change these results.

Climatic characteristics

The area is located in a semi-arid steppe region, with an annual average temperature of $0.6 \pm 0.45\,^{\circ}C$, and a summer average temperature of $16.29 \pm 0.41\,^{\circ}C$ (May–September; Figure 2, inner panel). Average annual precipitation during the whole experiment (2000–2019) was 196 mm, according to the Lun soum weather station, Mongolia (NAMEM 2019). Summer precipitation usually occurs between June and August and accounts for 80–90% of the total annual rainfall. The mean annual potential evapotranspiration is 752.12 mm (±30.68SD). The mean air temperature of the warmest month (July) is $16\,^{\circ}C$, while that of the coldest month (January) is $-22\,^{\circ}C$ (Figure 2). The length of the growing season varies between 110 and 130 days.

Growth measurement

Plant survival rate (%) in 2019 was calculated as the number of living plants for each species divided by the number of plants originally planted. Growth traits, such as stem height (H) and stem diameter at root collar (RCD), were measured during the period 2011–2019. Measurements were taken at 30 days intervals during the entire vegetative season. RCD was measured by a digital Vernier calliper (Thompson & Schultz 1995) at the base of the stem, while plant height was measured with a ruler (Basic aluminium Staff TS5-5MD, Korea).

Statistical analysis

Statistical analysis was computed by using the SAS software package, version 9.4 (SAS Institute Inc., Cary, North Carolina, USA). Two-way analysis of variance (ANOVA) with Duncan's multiple range test (DMRT) was used for multiple comparisons among the 2019 data. Permanent plots were considered as independent replicates. At each sampling date and within each plot, trees were measured and data were treated as mean. Stem height and RCD data were normally distributed. Analysis of variance (two-way ANOVA) for the effect of time and treatment on stem traits (H, RCD) was carried out with time and treatment as a fixed effect and plot as a random effect. We compared the linear regression lines for the relation between height and RCD for the two species using the analysis of covariance (ANCOVA), after analyzing the regression to elucidate significant differences between the two species.

Table 1. General linear model values (two-way ANOVA) obtained testing effects of time and treatment on tree height and root collar diameter (RCD).

Ulmus pumila					*Populus sibirica*			
	Source of variation				Source of variation			
	Time		Treatment		Time		Treatment	
Parameter	F	*p* value	F	*p* value	F	*p* value	F	*p* value
Height (cm)	1240.17	<.0001	61.83	<.0001	2995.42	<.0001	31.66	<.0001
RCD (cm)	1480.80	<.0001	80.50	<.0001	2088.40	<.0001	14.07	<.0001

Results

Plant traits measured during growth

Time and treatments significantly affected tree height ($p < 0.001$; Table 1) in both species. In elm, the 2 l h^{-1} watering regime initially (2011–2014) seemed to induce a difference in height compared to control samples (Figure 3 a), however, at a later stage of plant development (2015–2019) this difference was no longer evident ($p < 0.05$). Five years after transplanting, the growth rate (i.e., height increase over time) decreased (in poplar) or remained constant (in elm) (Figure 3 a and b, respectively). The final height values for control and 2 l h^{-1} treated trees were very close. In the case of poplar (Figure 3b), the 2 l h^{-1} watering regime seemed to considerably increase seedling height compared to the control for the entire duration of the treatment. Besides a difference in growth pattern between the two plant species, the final height achieved under the 2 l h^{-1} watering regime by poplar was double that of elm (Figure 3a, b). When the watering regime was increased to 4 l h^{-1}, a significant difference compared to the control (no watering) was observed for both elm and poplar trees (Figure 3a, b), although in poplar the height under both 2 l $h^{-1}$and 4 l h^{-1} regimes were similar for the entire duration of the experiment. In both species, the highest increase in height compared to control trees was observed when the 8 l h^{-1} treatment was applied (Figure 3a, b).

The initial addition of NPK fertilizer to the soil reduced the growth rate compared to control samples (no fertilizers) in both plant species, although this effect was more evident in poplar (compared to only watering reference in Figure 3 a-c, b-d). This inhibitory effect of NPK on stem height could be reversed by watering, with the highest recovery observed in both plant species when 8 l h^{-1} was used. In the case of COMPOST addition to the soil, no significant change in growth pattern was observed in both elm and poplar control plants (compared to only watering reference in Figure 3 a-e, b-f). Moreover, the addition of this fertilizer did not significantly modify the growth patterns obtained when different watering regimes were applied (compare panels a, b, e, and f in Figure 3).

Time and treatments significantly affected RCD ($p < 0.001$; Table 1) for both species. Figure 4 shows that the RCD of elm plants treated with different watering regimes increased for the entire duration of the experiment (Figure 4a), although during the initial growth phase (2011–2014) this increase was higher than in the last growth phase (2015–2019). The difference in RCD growth rate between control samples (no watering) and those undergoing different watering regimes was limited. In the case of poplar plants, all three different watering regimes applied were able to increase the RCD compared to controls (no watering), following a similar pattern for the entire duration of the experiment (Figure 4b). The addition of NPK fertilizer to the soil induced considerable differences in RCD both in elm and poplar plants (Figure 4c, d). In particular, the highest RCD increase in elm plants was obtained when the 2 l h^{-1} watering regime was applied, whereas in poplar the higher increase was observed when the 8 l h^{-1} watering regime was applied. The addition of COMPOST fertilizer did not affect the RCD of elm plants (Figure 4 e), independently of the watering regime applied, whereas a slight increase in RCD values was observed in poplar plants, which was not affected by different watering regimes (Figure 4f).

The effect of fertilizer addition was also analysed in plants which received no additional watering (Figure 5). Results show that the addition of NPK to the soil resulted in lower height and RCD values for both poplar and elm species. This inhibitory effect seems to be stronger in the case of elm (Figure 5a, c) than in the case of poplar (Figure 5b, d). Plants grown with COMPOST addition showed similar value for both traits compared to plants grown without fertilizers.

Plant traits measured at the end of the experiment

The plant survival rate, expressed as the percentage of living trees over the total number of planted trees (Figure 6), was lowest (60%) for NPK-fertilized elm trees grown without irrigation. Survival remained low when 2 and 4 l h^{-1} water regimes were implemented (around 80%; Figure 6). In the case of COMPOST addition, the survival rate was comparable to that of plants that received only watering treatment. The survival rate of poplar trees was nearly 100% when plants received any of the watering regimes, independently of fertilizer addition. However, when no water regime was applied, poplar survival rate dropped to 40%, reaching the lowest value (10% circa) when plants had been fertilized with NPK.

The height and RCD achieved by plants at the end of the experiment (2019) varied significantly among the different treatments (Figure 7). Analysis of height showed that in elm the increase under the watering regimes is not significantly different from that of control plants which received watering only from rainfall (Figure 7a). Moreover, the addition of fertilisers (NPK and COMPOST) to the soil during transplanting had a negative effect on stem height if no watering regime was applied to the plants (Figure 7a). These findings are in accordance with the data obtained for the entire duration of the experiment (Figure 3 and 4). On the other hand, in case

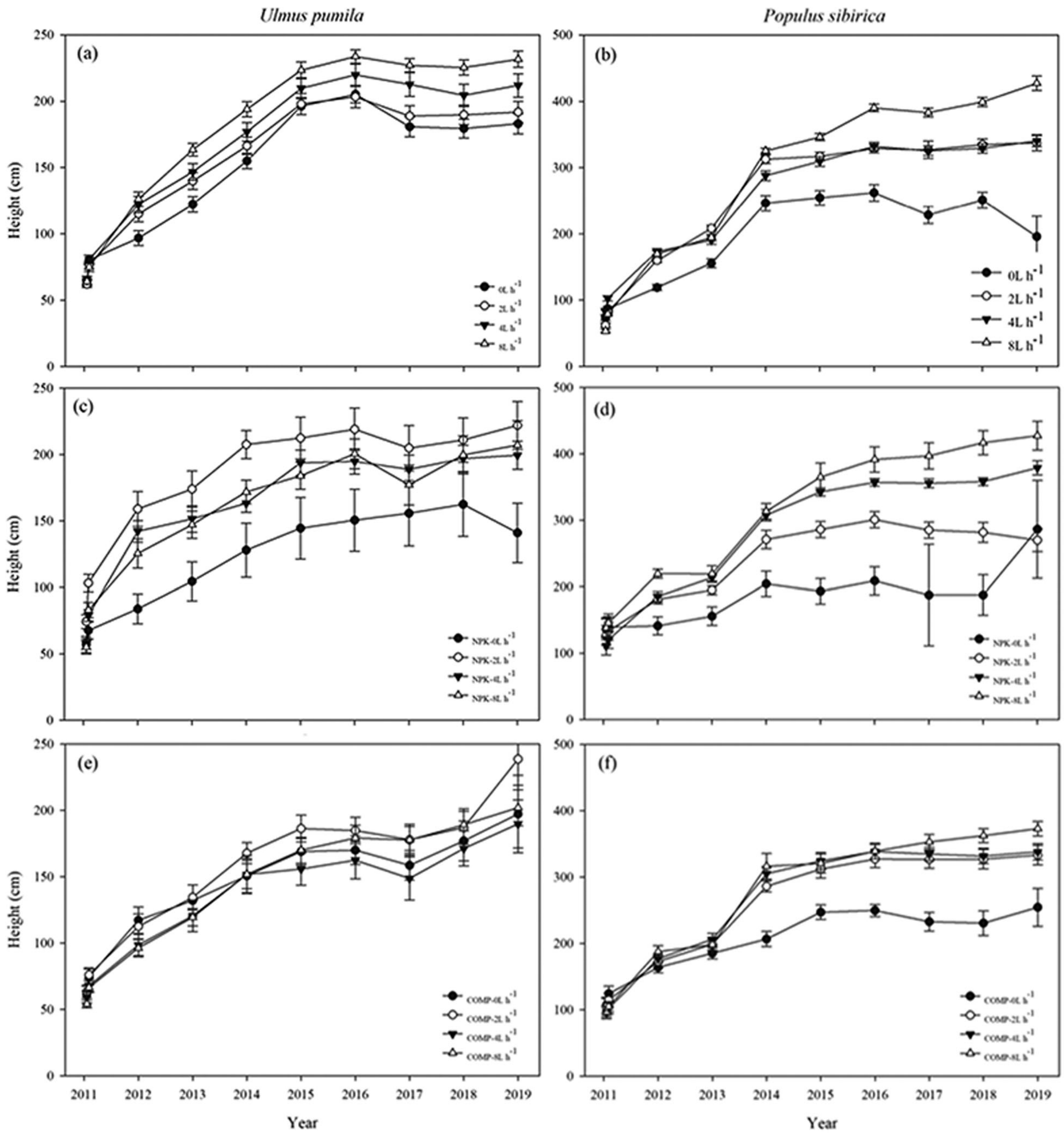

Figure 3. Plant height (cm) of *Ulmus pumila* (a, c, and e) and *Populus sibirica* (b, d, and f) measured from 2011 to 2019 on trees grown under four different water regimes with two different fertilizing treatments (COMPOST and NPK). Values are means of 32 trees for the watering regimes, and 16 for COMP and NPK (± 1 SE).

of poplar, a significant increase in height was found in plants treated with 2 l h^{-1}, 4 l h^{-1}, and 8 l h^{-1} watering regimes compared to the control (no watering), indicating that the additional water was necessary to ensure a better growth performance. The addition of NPK fertilizer also produced a significant increase in height (Figure 7b) despite the inhibition observed during the initial growth phase. A further increase in height could be observed in NPK-treated plants under additional watering regimes, although this increase was not statistically significant (Figure 7b). Similarly to NPK fertilizer, the addition of COMPOST resulted in a significant height increase of non-watered plants, which became of a higher magnitude when plants received water (Figure 7b).

Regarding RCD, the analysis of the data collected at the end of the 2019 vegetative season indicated that in elm plants only the treatment with the 8 l h^{-1} watering regime induced a significant increase compared to the control (Figure 7c). Poplar plants also showed a significant RCD increase when treated with the 8 l h^{-1} watering regime, independently of the addition of NPK fertilizer (Figure 7d).

Discussion

The advancement of desertification in the Mongolian territory requires the adoption of urgent measures aimed at protecting the soil (Tsogtbaatar 2004; Miyasaka et al. 2014). One

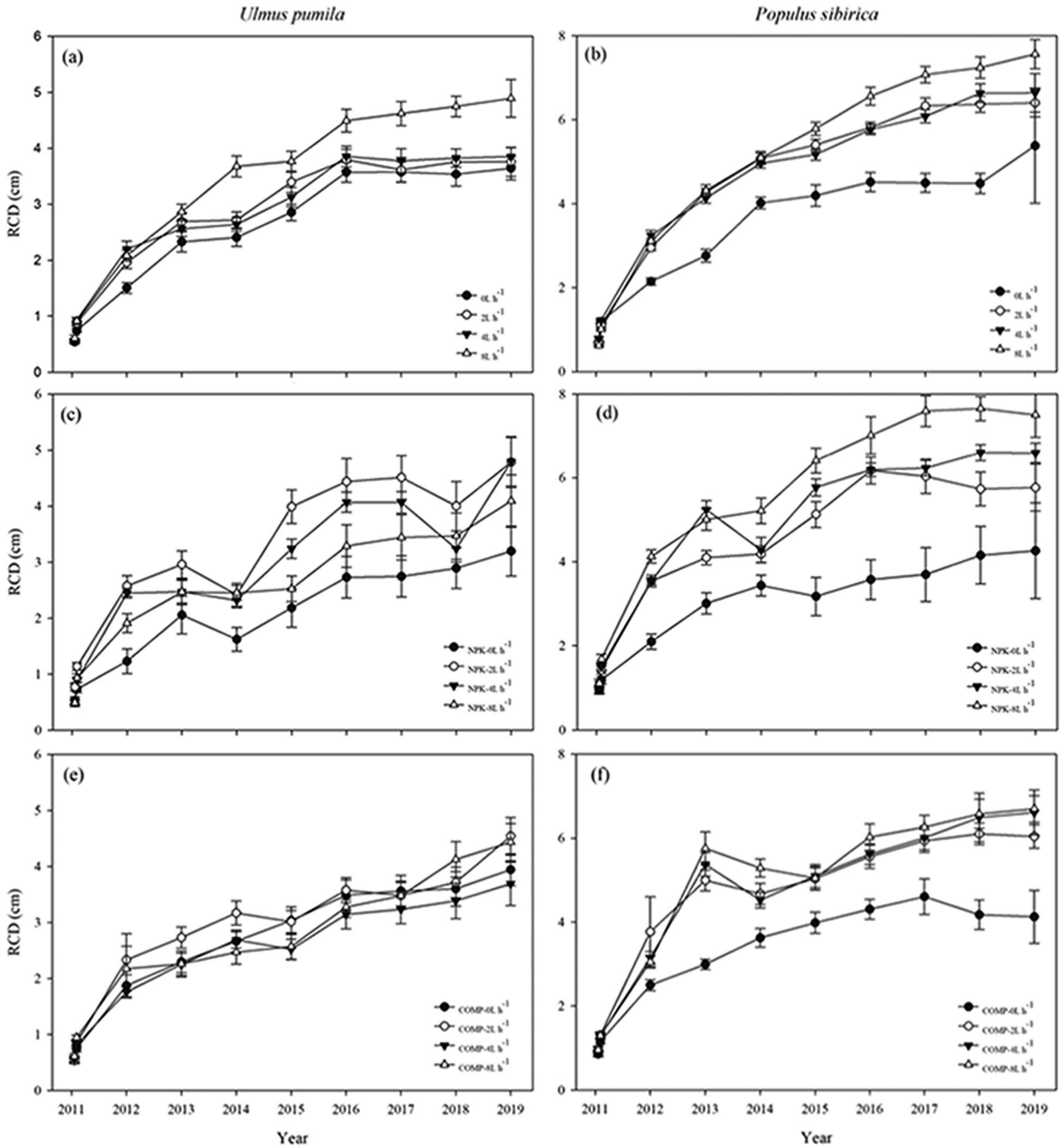

Figure 4. Root collar diameter (RCD; cm) of *Ulmus pumila* (a, c, and e) and *Populus sibirica* (b, d, and f) measured from 2011 to 2019 on trees grown under four different water regimes with two different fertilizing treatments (COMPOST and NPK). Values are means of 32 trees for the watering regimes, and 16 for COMP and NPK (± 1 SE).

of the actions deployed is the *Green Belt* project (Lee and Ahn 2016), which during the period from 2008 to 2017 has produced new plantations in the arid and semi-arid lands of Mongolia. This environmental restoration project, besides fighting desertification and sandstorms, also aims to promote the development of agroforestry activities as trees are planted following a scheme that establishes shelterbelts. These shelterbelts delimit internally to the plantation a number of farmlands where crops can be grown safely by taking advantage of the wind sheltering and water availability (Jo et al. 2014).

The efficiency and sustainability of shelterbelt plantations in controlling desertification and sandstorms of arid lands is still a matter of debate (Wu et al. 2019), despite it is evident that this type of environmental restoration also concerns the wellbeing of the local population which receives economic advantages and becomes directly involved in the management of these projects. However, more studies investigating the long-term growth performance of the trees used in these plantation attempts are needed to correctly (and definitively) assess the economic and social validity of this type of forest landscape restoration interventions (FLR, as defined by Stanturf et al. 2014, 2015).

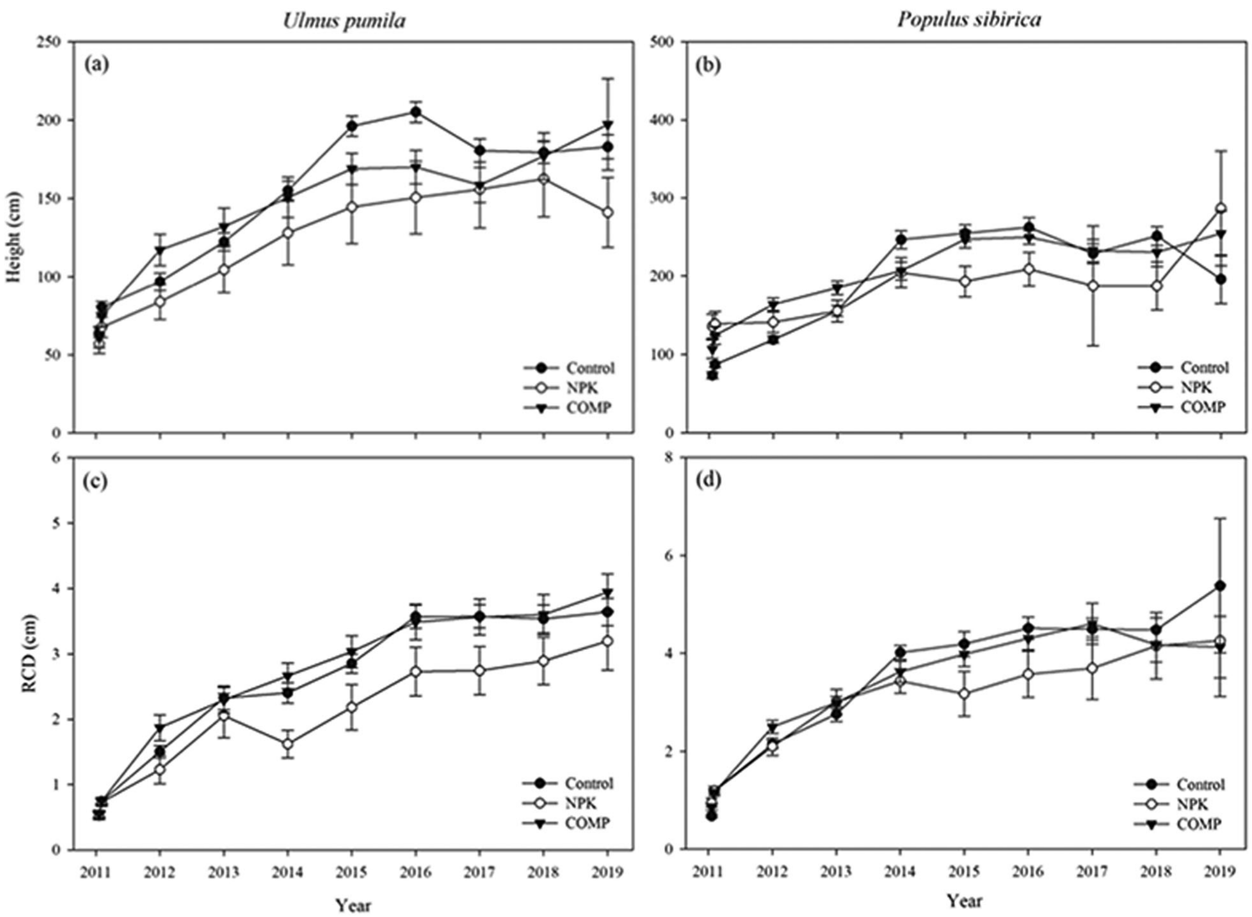

Figure 5. Plant height (cm) and root collar diameter (RCD, cm) of *Ulmus pumila* (a, c) and *Populus sibirica* (b, d) measured from 2011 to 2019 on plants grown with two different fertilizing treatments (COMPOST and NPK). Values are means of 16 trees for COMP and NPK (± 1 SE).

The data presented here represent the first attempt to evaluate the growth performance of two trees species, *P. sibirica* and *U. pumila*, used in the plantations of the *Green Belt* project (Lee and Ahn 2016). In particular, plantations were either left without attendance or subjected to management practices, i.e., different watering regimes and/or the addition of fertilizers to the soil. The growth performance of the trees was investigated through the analysis of two morphological traits: height and RCD. The evaluation period (10 years) was sufficiently long to enable a good prediction of the long-term sustainability of this type of FLR.

In the case of *P. sibirica*, earlier work by Lee et al. (2016) has shown that water shortage induces in these trees a significant decrease of growth, probably due to its negative effect on leaf water potential, transpiration rate, and photosynthetic yield. Nevertheless, the authors suggested that this plant species is characterized by a good adaptation of photosynthesis during drought, probably achieved through a mechanism of energy dissipation. Our data contrast with the latter statement, as the poplar trees in our experiment, were characterized by a very low survival rate if watering was not provided in addition to rainfall. Although there are only a few studies regarding the response of *U. pumila* to water shortage (Lee et al. 2016, 2017), it has been suggested that this plant species can be used to afforestate desert lands (Jo and Park 2017) given its high degree of adaptability to dry conditions (Engelbrecht et al. 2005; Jo and Park 2017). *U. pumila* is considered to be particularly adapted to live in harsh conditions, as it survives well also in the presence of very low temperatures (Moore 2003). The data presented here confirm the high resistance of *U. pumila* trees to water shortage as demonstrated by the fact that we find a very high survival rate even when plants received water only from natural rainfall.

During the 10 years of observation, the height of poplar control plants increased exponentially for the first 6 years of growth. After that time, only the highest watering regime treatment was able to ensure a further increase in height (although at a much lower rate than the initial one). Thus, in the absence of additional irrigation, the growth in height of this tree forms a biphasic pattern. At present, we cannot establish for how long this lower growth rate can continue before the trees reach a developmental limit when their own survival is put at risk. Unlike height, RCD increased at almost the same rate for all the 10 years of observation, even when plants received no water in addition to rainfall. These data suggest that when poplar trees are underwater shortage conditions they invest more biomass in diametral growth than in height thus changing the biomass allocation pattern. This type of growth response is probably obtained through a

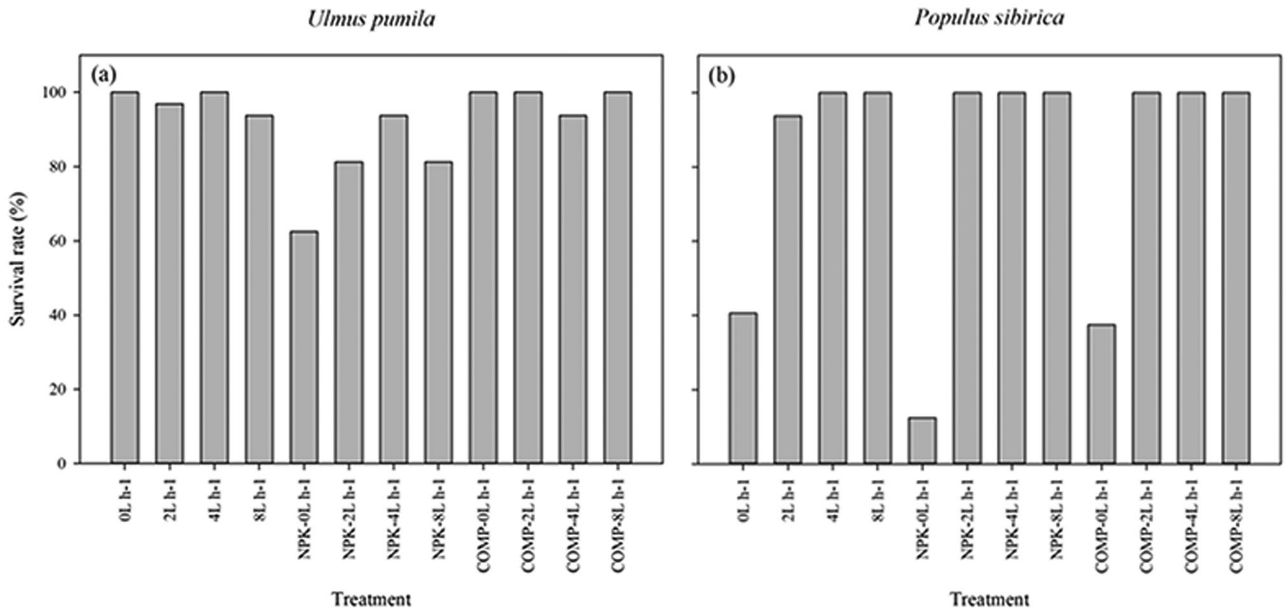

Figure 6. Plant survival (%) of *Ulmus pumila* (a) and *Populus sibirica* (b) measured at the last growing season (2019) on trees grown under four different water regimes with two different fertilizing treatments (COMPOST and NPK).

reduction of shoot-internode elongation (i.e., a reduction of the distance between two consecutive branching point). The continuation of RCD growth, even when plants are experiencing long-term water shortage, can be explained by the need of the tree to continue the production of new vascular tissue necessary to transport water to the new leaves. In fact, the reduction of stem height does not limit the annual production of leaf flushes. To test the validity of this hypothesis, future experiments are programmed that will focus on the analysis of vascular cambium activity in plants undergoing different treatments.

A growth pattern similar to that described for poplar was also observed in elm trees grown without additional watering, i.e., a biphasic growth rate for height and a continuous growth rate for RCD, suggesting that these two species employ the same mechanism of water use under drought conditions. The only interesting difference in growth pattern between these two plant species is that the absolute height and RCD values in poplar are twice as high than those of elm. However, to understand whether the higher height value achieved by poplar trees indeed corresponds to a higher value of biomass accumulated (i.e., carbon stored), it will be necessary to measure the wood density or dry weight of the stem. Evaluating this factor is important to establish which of the two tree species is the best candidate to be used in plantations, in particular, if the objective is not only to cover the land but also to obtain an increase in carbon storage.

Our data clearly suggest that, unlike in the case of poplar, the maximum rate of height and RCD increase in elm trees can be achieved with the lower irrigation regimes. This is an important result as it indicates that if the management of *Green Belt* plantations is to be programmed for a long period of time, then the use of elm becomes more sustainable (in term of water consumption) than that of poplar.

Our data further suggest that the addition of fertilizers to the soil before transplanting trees does not alter the biphasic growth pattern of plants grown without irrigation. Moreover, a slight decrease in height compared to controls was observed, in particular in the case of NPK. Cao et al. (2011) have suggested that, when establishing a new plantation in arid lands, a decrease in seedling growth rate could be related to a reduction in nutrient availability in the soil. That does not seem to be the case for our plantations, as we observed that tree growth rates decreased even when fertilizers but no additional water were given to the soil. Furthermore, the fact that watering reversed the negative effect of NPK means that the biphasic growth pattern is not caused by nutritional problems. At the same time, we cannot exclude that an alteration of the chemical, physical, and biological properties of the soil induced by this fertilizer affected the trees. To test this hypothesis, we have programmed the future analysis of soil properties in the presence or absence of fertilization.

In fact, it is known that when trees are planted in grassland, the nitrogen content of the soil increases, due to atmospheric nitrogen deposition and biological nitrogen fixation (Yang et al. 2011). Moreover, it has been shown that there is also an increase in carbon stock, as net primary production (NPP) increases due to higher nutrient availability (Li et al. 2012). Further improvement of soil properties following afforestation of grassland seems to derive from the fact that soil respiration increases, probably because of changes in soil temperature (shade effect) and water content (Perez-Quezada et al. 2012). Other works found that afforestation induces a considerable transformation of the microbial (Lauber et al. 2013), macrofaunal (Liu et al. 2013), and fungal communities (Helgason et al. 2009). Furthermore, an increase in soil organic carbon (SOC), total nitrogen (TN), total phosphorus (TP) has been observed (Yang et al. 2018). This

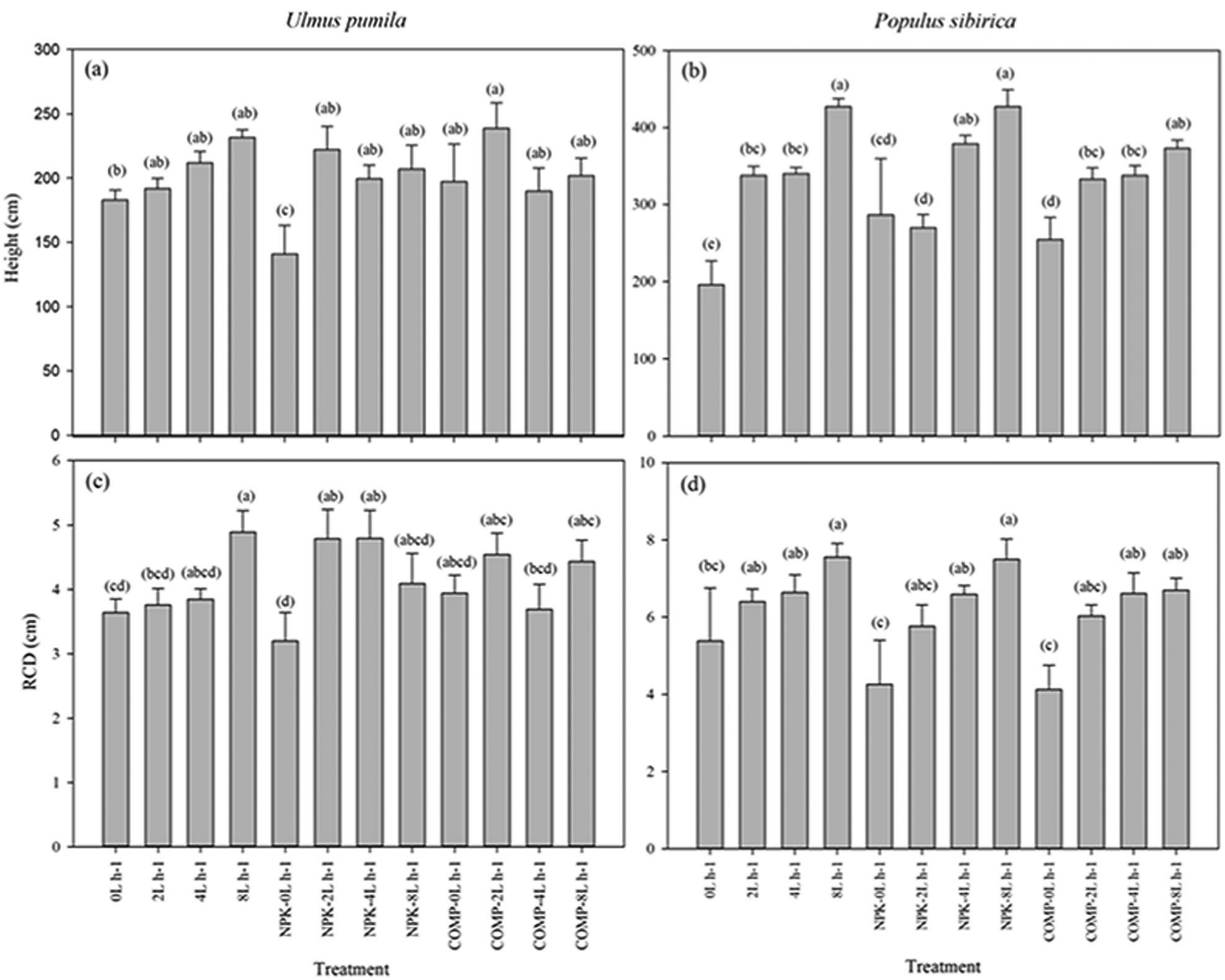

Figure 7. Plant height (cm) and root collar diameter (RCD, cm) of *Ulmus pumila* (a, c) and *Populus sibirica* (b, d) measured at the last growing season (2019) on trees grown at four different water regimes with two different fertilizing treatments (COMPOST and NPK). Each data is represented as mean (n = 32 for the watering regimes; n = 16 for COMP and NPK) ± 1 SE.

increase is achieved not only by the accumulation of plant litter with the consequent leaching of dissolved organic matter but also by root-soil interactions that take place in the rhizosphere and lead to acidification (Menyailo et al. 2002).

On the basis of the above considerations, we cannot exclude that several positive chemical and biological effects on soil properties have taken place as a consequence of our afforestation experiment. Furthermore, a modification of the physical structure of the soil might also have occured. In fact, physical changes of the soil as a consequence of the presence of roots with their exudates (Cullings et al. 2003; Scheibe et al. 2015) or the release of ions and organic matter following fine root turnover (Prescott and Grayston 2013) have previously been described. Moreover, an experiment conducted in the desert has shown that afforestation has a cooling effect on the soil during the day, independently of the season considered. At night, on the other hand, afforestation has a warming effect during winter, spring, and autumn but a cooling effect during summer. This phenomenon was attributed by the authors to the higher albedo of forested land compared to shrubland. However, other authors reported the occurrence of heat flux changes with a warming effect at daytime and a cooling effect at night (Wang et al. 2019). To assess any possible (positive or negative) effect of the physical, chemical, and biological properties of the soil on the growth pattern of poplar and elm used in our experiments, it will be necessary to explore the behaviour of the root system of these trees during growth. In this respect, one hypothesis that may well explain the biphasic growth pattern observed in the absence of additional watering could be that the physical nature of the soil makes it difficult for these plants to develop a root system able to sustain regular growth without additional irrigation (Cochavi et al. 2019). This type of knowledge could reveal potential soil improvement strategies necessary to enable a long-term continuation of the growth performance of these two trees in the absence of any additional watering treatments.

Beside nutrient depletion of the soil, direct competition (for some unknown environmental factor) between neighbouring plants could also have caused a decrease in growth rate observed in the absence of additional watering regimes. In regard to this, it must be considered that the distance between plants used in our plantations is certainly smaller

(2.5 m) than the one normally designed for a typical forest plantation. Unfortunately, it cannot be excluded that this high tree density may negatively affect plant growth at a later stage of development when plants will have achieved larger dimensions. The present experiment suggests that, if no additional watering regime treatment is selected as a management measure, a greater distance between plants should probably be adopted in this type of plantations.

Conclusions

To achieve long-term success in FLR, constraints related to local ecological (Bantis et al. 2019) and social conditions must be considered and investigated (Stanturf et al. 2014; Lu et al. 2018). The work presented here shows that the sustainability of new plantations established in the context of the *Green Belt* project requires a preliminary (and careful) evaluation of the growth performance of the tree species selected. Moreover, it is important to understand the nature of the relation existing between the selected tree and the soil of the area where afforestation is established. This approach is necessary to avoid that an erroneous selection of the plant species or wrong management procedures could lead to the failure of the intervention. With regard to the two species investigated here, *P. sibirica* and *U. pumila*, present results suggest that they have different requirements to achieve their best growth performance. Elm trees shows better adaptability to water shortage and, therefore, could be used when water is the limiting factor. Poplar trees, on the other hand, shows a stronger dependence of growth performance upon water availability but produces a more rapid ground cover. More investigations regarding belowground root development are needed before being able to make a well-considered choice of the best candidate tree to be used for these environmental restoration projects.

Acknowledgements

The authors gratefully thank the staffs of the Korea-Mongolia Joint "Green Belt" Plantation Project and the members of the Laboratory of Forest Genetics and Ecophysiology, the National University of Mongolia for their assistance in the laboratory and field works. AM and DC acknowledge the Department of Biotechnology and Life Science, the University of Insubria for providing the necessary support to the joint research project.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This research was supported by the Korea-Mongolia Joint "Green Belt" Plantation Project funded by Korea Forest Service, Republic of Korea.

ORCID

Ser-Oddamba Byambadorj http://orcid.org/0000-0002-0271-730X
Donato Chiatante http://orcid.org/0000-0003-4854-5408
Khaulenbek Akhmadi http://orcid.org/0000-0002-2307-3304
Janchivdorj Lunten http://orcid.org/0000-0002-7725-0281
Batkhishig Ochirbat http://orcid.org/0000-0001-6012-0395
Byung Bae Park http://orcid.org/0000-0002-0620-7374
Gabriella S. Scippa http://orcid.org/0000-0003-0573-1235
Antonio Montagnoli http://orcid.org/0000-0002-8921-0754
Batkhuu Nyam-Osor http://orcid.org/0000-0002-8683-8888

References

Ariunzul Y, Batchuluun T, Undram G, Bayanmunkh N, Batchimeg B, Gunjargal B, Erdenechimeg E. 2017. Mongolian forest cover change. Ulaanbaatar, Mongolia: Environmental Research Information and Study Center, Division of the Information and Research Institute of Meteorology, Hydrology and Environment.

Bantis F, Radoglou K, Brüggemann W. 2019. Differential ecophysiological responses to seasonal drought of three co-existing oak species in northern Greece. Plant Biosyst. 153(3):378–384.

Bruijnzeel LA, Gilmour DA, Bonell M, Lamb D. 2005. Conclusion – forests, water and people in the humid tropics: an emerging view. In: Forests, water and people in the humid tropics. Cambridge/New York: Cambridge University Press; p. 906–925.

Cao SX, Chen L, Shankman D, Wang CM, Wang XB, Zhang H. 2011. Excessive reliance on afforestation in China's arid and semi-arid agricultural regions: lessons in ecological restoration. Earth-Sci Rev. 104(4):240–245.

Cochavi A, Rachmilevitch S, Bel G. 2019. The effect of irrigation regimes on plum (*Prunus cerasifera*) root system development dynamics. Plant Biosyst. 153(4):529–537.

Cullings KW, New MH, Makhija S, Parker VT. 2003. Effects of litter addition on ectomycorrhizal associates of lodgepole pine (*Pinus contorta*) stand in Yellowstone National Park. AEM. 69(7):3772–3776.

Engelbrecht BMJ, Kursar TA, Tyree MT. 2005. Drought effects on seedling survival in a tropical moist forest. Trees-Struct Funct. 19(3):312–321.

GCF. 2019. Country Programme Mongolia - 19 March.

Guo LB, Gifford RM. 2002. Soil carbon stocks and land-use change: a meta-analysis. Global Change Biol. 8(4):345–360.

Helgason BL, Walley F, Germida JJ. 2009. Fungal and bacterial abundance in long- term no-till and intensive-till soils of the northern Great Plains. Soil Sci Soc Am J. 73(1):120–127.

Hessl AE, Brown P, Byambasuren O, Cockrell S, Leland C, Cook E, Nachin B, Pederson N, Saladyga T, Suran B. 2016. Fire and climate in Mongolia (1532–2010 Common Era). Geophys Res Lett. 43(12): 6519–6527.

Hu YL, Zeng DH, Fan ZP, Chen GS, Zhao Q, Pepper D. 2008. Changes in ecosystem carbon stocks following grassland afforestation of semiarid sandy soil in the southern Keerqin Sandy Lands. China J Arid Environ. 72(12):2193–2200.

Israel DW. 1987. Investigation of the role of phosphorus in symbiotic dinitrogen fixation. Plant Physiol. 84(3):835–840.

Jo H-K, Park H-M. 2017. Effects of pit plantings on tree growth in semi-arid environments. Forest Sci Technol. 13(2):66–70.

Jo HK, Park HM, Kim JY. 2014. Agroforestry strategies reflecting residents' attitudes in a semi-arid region–focusing on Elsentasarhai Region in Mongolia. Korean J Environ Ecol. 28(2):263–269.

Johnson H, Brandle J. 2009. Shelterbelt design. [accessed 2019 Sep 15]. http://agriculture.vic.gov.au/agriculture/farm-management/soil-and-water/erosion/shelterbelt-design.

Kang JM, Kojima K, Ide Y, Sasaki S. 1996. Growth response to the stress of low osmotic p, potential, salinity and high pH in a cultured shoot of Chinese poplars. J for Res. 1(1):27–29.

Kim MS, Kim YH, Yang JE. 2010. Changes of organic matter and available silica in paddy soils from fifty-six years fertilization experiments. In: Proceedings of 19th World Congress of Soil Science, Soil Solution for a Changing World; August 1–6; Brisbane. p. 56–58.

Lauber CL, Ramirez KS, Aanderud Z, Lennon J, Fierer N. 2013. Temporal variability in soil microbial communities across land-use types. ISME J. 7(8):1641–1650.

Lee D, Ahn G. 2016. A way forward to sustainable international forestry cooperation: a case study of the 'greenbelt plantation project in Mongolia'. J Rural Develop. 39 (Special Issue):143–168.

Lee TY, Je SM, Kwak MJ, Akhmadi K, Tumurbaatar E, Khaine I, Lee HK, Jang JH, Kim HN, Ahn HJ, et al. 2017. Physiological responses of *Populus sibirica* to different irrigation regimes for reforestation in the arid area. S Afr J Bot. 112:329–335.

Lee TY, Woo S, Kwak J, Inkyin K, Lee KE, Jang JH, Kim IR. 2016. Photosynthesis and chlorophyll fluorescence responses of *Populus sibirica* to water deficit in a desertification area in Mongolia. Photosynt. 54(2):317–320.

Li D, Niu S, Luo Y. 2012. Global patterns of the dynamics of soil carbon and nitrogen stocks following afforestation: a meta-analysis. New Phytologist. 195(1):172–181. doi:10.1111/j.1469-8137.2012.04150.x.

Liu RT, Zhao HL, Zhao XY. 2013. Changes in soil macrofaunal community composition under selective afforestation in shifting sand lands in Horqin of Inner Mongolia, northern China. Ecol Res. 28(1):1–8.

Lu C, Zhao T, Shi X, Cao S. 2018. Ecological restoration by afforestation may increase groundwater depth and create potentially large ecological and water opportunity costs in arid and semiarid China. J Clean Prod. 176:1213–1222.

Mao H, Iwanaga F, Yamanaka N, Yamamoto F. 2008. Growth, photosynthesis, and ion distribution in hydroponically cultured Populus alba L. cuttings grown under various salinity concentrations. Landscape Ecol Eng. 4(2):75–82. doi:10.1007/s11355-008-0042-7.

Menyailo OV, Hungate BA, Zech W. 2002. The effect of single tree species on soil microbial activities related to C and N cycling in the Siberian artificial afforestation experiment. Plant Soil. 242(2):183–196.

Miyasaka T, Okuro T, Miyamori E, Zhao X, Takeuchi K. 2014. Effects of different restoration measures and sand dune topography on short- and long-term vegetation restoration in northeast China. J Arid Environ. 111:1–6.

MNET (Ministry for Nature, Environment and Tourism). 2010. National action program for combating desertification in Mongolia 2010–2020. National Report on the United Nations Convention to Combat Desertification. Fourth Conference of Parties.

Montagnoli A, Dumroese RK, Terzaghi M, Pinto JR, Fulgaro N, Scippa GS, Chiatante D. 2018. Tree seedling response to LED spectra: implications for forest restoration. Plant Biosyst. 152(3):515–523.

Moore LM. 2003. Siberian elm (*Ulmus pumila* L.). In: Natural resources conservation service plant guide. Washington, DC, USA: USDA. http://plants.usda.gov/plantguide/pdf/cs_ulpu.pdf.

[NAMEM] The National Agency for Meteorology and Environmental Monitoring of Mongolia. 2019. Weather data 2000-2019. [accessed 2019 Sep 25]. http://namem.gov.mn/eng/?p=56.

Perez-Quezada JF, Bown HE, Fuentes JP, Alfaro FA, Franck N. 2012. Effects of afforestation on soil respiration in arid shrubland in Chile. J Arid Environ. 83:45–53.

Prescott CE, Grayston SJ. 2013. Tree species influence on microbial communities in litter and soil: current knowledge and research needs. For Ecol Manag. 309:19–27.

Polzella A, De Zio E, Arena S, Scippa GS, Scaloni A, Montagnoli A, Chiatante D, Trupiano D. 2019. Toward an understanding of mechanisms regulating plant response to biochar application. Plant Biosyst. 153(1):163–172.

Scheibe A, Steffens C, Seven J, Jacob A, Hertel D, Leuschner C, Gleixner G. 2015. Effects of tree identity dominate over tree diversity on the soil microbial community structure. Soil Biol Biochem. 81:219–227.

Stanturf JA, Kant P, Lilleso J-PB, Mansourian S, Kleine M, Graudal L, Madsen P. 2015. Forest landscape restoration as a key component of climate change mitigation and adaptation. Vienna, Austria: International Union of Forest Research Organizations (IUFRO); p. 72. (IUFRO World Series, Vol. 34).

Stanturf JA, Palik BJ, Williams MI, Dumroese KR, Madsen P. 2014. Forest restoration paradigms. J Sustainable For. 33(sup1):S161–S194..

Su B, Shangguan Z. 2018. Decline in soil moisture due to vegetation restoration in the Loess Plateau of China. Land Degrad Dev. 30:290–299..

Sungsik C, Byambadorj S-O, Nyam-Osor B, Hyun Seak K. 2019. Comparison of water use efficiency and biomass production in 10-year-old *Populus sibirica* and *Ulmus pumila* plantations in Lun soum, Mongolia. For Sci Technol. 15:147–158.

Thompson JR, Schultz RC. 1995. Root system morphology of Quercus rubra L. planting stock and 3-year field performance in Iowa. New Forest. 9(3):225–236. doi:10.1007/BF00035489.

Tsogtbaatar J. 2013. Deforestation and reforestation of degraded forestland in Mongolia. In: The Mongolian ecosystem network. Tokyo: Springer; p. 83–98.

Tsogtbaatar J. 2004. Deforestation and reforestation need in Mongolia. For Ecol Manag. 201(1):57–63.

Wang L, Lee X, Feng D, Fu C, Wei Z, Yang Y, Yin Y, Luo Y, Lin G. 2019. Impact of large-scale afforestation on surface temperature: a case study in the Kubuqi Desert, Inner Mongolia based on the WRF model. Forests. 10(5):368.

Wu Y, Wang Q, Wang H, Wand W, Han S. 2019. Shelterbelt poplar forests induced soil changes in deep soil profiles and climates contributed their inter-site variations in dryland regions. Northeastern China Front Plant Sci. 10:220.

Yang Y, Luo Y, Finzi AC. 2011. Carbon and nitrogen dynamics during forest stand development: a global synthesis. New Phytologist. 190(4): 977–989. doi:10.1111/j.1469-8137.2011.03645.x.

Yang N, Ji L, Salahuddin Yang Y, Yang L. 2018. The influence of tree species on soil properties and microbial communities following afforestation of abandoned land in northeast China. Eur J Soil Biol. 85:73–78.

Yao Y, Wang X, Zeng Z, Liu Y, Peng S, Zhu Z, Piao S. 2016. The effect of afforestation on soil moisture content in Northeastern China. Plos One. 11(8):e0160776.

Yin C, Peng Y, Zang R, Zhu Y, Li C. 2005a. Adaptive responses of Populus kangdingensis to drought stress. Physiol Plant. 123(4): 445–451.

Yin C, Wang X, Duan B, Luo J, Li C. 2005b. Early growth, dry matter allocation and water use efficiency of two sympatric Populus species as affected by water stress. Environ Exp Bot. 53(3):315–322.

Ykhanbai H. 2010. Mongolian forestry outlook study. Food and Agriculture Organization of the United Nations regional office for Asia and the Pacific. Working Paper No. APFSOS II/WP/2009/21.

Yu P, Wang Y, Wu X, Dong X, Xiong W, Bu G, Wang S, Wang J, Liu X, Xu L. 2010. Water yield reduction due to forestation in arid mountainous regions, northwest China. Int J Sedim Res. 25(4):423–430.

Zhang JG, Lei JQ, Wang YD, Zhao Y, Xu XW. 2016. Survival and growth of these afforestation species under high saline drip irrigation in the Taklimakan Desert, China. Ecosphere. 7(5):e01285..

Zsuffa L, Giordano E, Pryor LD. 1996. Trends in poplar culture: some global and regional perspectives. In: Stettler RF, Bradshaw HD Jr, Heilman PE, Hinckley TM, editors. Biology of populus and its implications for management and conservation. Canada: NRC Research Press; p. 515–539.