Evaluation of young and adult tree plantations for biodrainage management in the lower Amudarya River Region, Uzbekistan

Asia Khamzina
e-mail: asia.khamzina@uni-bonn.de,
John P.A. Lamers
e-mail: j.lamers@zef.uzpak.uz,
Bart Wickel
e-mail: bwickel@xolo.conabio.gob.mx,
Yulduz Djumaniyazova
e-mail: yulduzoy@yandex.ru,
Christopher Martius
c.martius@uni-bonn.de

ABSTRACT

Designing efficient biodrainage plantations based on tree transpirative capacity to enhance the discharge of shallow ground water tables (GWT) demands a careful species selection. A field study examined leaf transpiration of young trees of nine species for the species assortment. Leaf transpiration rates of the young trees differed significantly among species varying between 0.52-1.17 µg cm^{-2} s^{-1}. Concurrently, at adult plantations of selected species the interaction between the trees and GWT was studied with GW observation wells for one vegetation season. The assortment highlighted the potential of *E. angustifolia,* which combined high transpiration, salinity tolerance, fast growth and production of nutritious feed. Performance of *Populus* spp. and *Ulmus pumila* was less consistent, but promising enough to make them potentially suitable candidates. The results of the GW monitoring under the adult plantations suggested that biodrianage, being a feasible option, but in the open system where irrigation and ground water is continuously supplied from agricultural fields in the surroundings, biodrainage was not effective in lowering the GWL permanently.

Key words: leaf area, multipurpose trees, observation wells, porometer, shallow saline ground water table, transpiration rates.

1 INTRODUCTION

Shallow saline groundwater (GW) tables and the associated soil salinity problems are common in the irrigated areas of Uzbekistan (SAIGAL 2003). These issues are particularly acute in Khorezm region, located in the southern part of the valley of the Amudarya River, which is presently the sole contributor to the Aral Sea. The planting of trees for improving the unfavorable natural drainage conditions, which in Khorezm are aggravated by the deterioration of the drainage network, may be a cost effective option or addition to the conventional drainage systems, which require large capital investments in equipment, operation and maintenance (HEUPERMAN et al. 2002). In addition to the lowering of the groundwater table, biodrainage plantations may offer other advantages such as combating wind erosion (THORBURN & GEORGE 1999) and provision of construction material, fodder and fuelwood (HEUPERMAN et al. 2002). Possible negative side effects are mainly related with the potential increase in salinization under the tree plantations (THORBURN et al. 1995).

Biodrainage methods consist of the strategic planting of trees with high transpirative capacity (HEUPERMAN et al. 2002). Transpiration rates of various local tree species in Uzbekistan have been studied previously (e.g. ELISEEV 1939) although solely by destructive methods. Yet, the used procedure of measuring harvested leaf weight differences over periods of three minutes (IVANOV et al. 1950) certainly has influenced the validity of the findings. Recent research showed that leaf transpiration is only one characteristic which should be complemented with other tree specific parameters such as tree water use, salinity tolerance and ability to produce rapidly high quality fodder and fuelwood as this may increase farmers’ willingness to plant trees in the first place (KHAMZINA et al. 2005, in press).

Although several assortment studies have been conducted (MAKHNO 1962; FIMKIN 1983), few field studies quantifying the effects of biodrainage have been performed so far, and were mainly reported from Australia, Pakistan, India and the US (HEUPERMAN et al. 2002). The present study compared leaf transpiration rates of nine tree species measured with a steady state porometer to identify the most water consuming species for use in biodrainage plantations. To complement the species assortment with a study of landscape-level biodrainage effects, the influence of adult plantations on the GW level was examined concurrently to assess the potential of biodrainage under the natural agro-ecological conditions in the Aral Sea region.

2 MATERIAL AND METHODS

2.1 Description of the study sites

The study on species selection was conducted in Khiva district at the Research Station of the Uzbek Forestry Research Institute located at 41°41′ N latitude, 39°40′ E longitude and at an altitude of 113 m. Experimental plantations were established on gleyic solonchak soil at two sites characterized by sand (hereafter the sandy site) and silt loam texture (loamy site), both underlain by a loam layer. The plantations measured 0.14 ha each and were located 500 m apart from each other. The pre-selected nine deciduous native and exotic species represented a variety of life spans and tolerances to drought and salt stress: apricot tree (*Prunus* a*rmeniaca* L.*)*, black poplar (*Populus nigra var. pyramidalis* (Rozan) Spach*),* black willow (*Salix nigra* Marshall*)*, Eastern catalpa (*Catalpa bignonioides* Walter*)*, Euphrates poplar (*Populus euphratica* Olivier*),* Russian olive (*Elaeagnus angustifolia* L.*)*, Siberian elm (*Ulmus pumila* L.*),* swamp ash (*Fraxinus pennsylvanica* Marshall), and white mulberry (*Morus alba* L.*)*. Fifty, one-year-old saplings of each species were randomly planted on the shoulder of a 40 cm deep irrigation furrow. The spacing of 1 m x 3.5 m avoided mutual shading during the experiment.

Due to an adequate availability of irrigation water in the region throughout the study period, the presence of intensively irrigated rice fields in the vicinity, and a high GW table, the trees at the loamy site were only occasionally irrigated. The soil moisture at the sandy site remained close to field capacity; hence only one irrigation event was necessary at the onset of each vegetation season.

The GW table at the sandy site ranged between 0.7-1.3 m during the vegetation period, whereas the GW level at the loamy site varied from 1.0 to 1.3 m. The average GWT depth monitored at both sites was close to the long-term mean of 1.22 m for the region (IBRAKHIMOV et al. 2004). During both observation seasons the mean electrical conductivity (EC) of the GW was higher at the non-irrigated sandy site (4.3 dS m^{-1} vs. 3.3 dS m^{-1} at the loamy site). Both values exceeded the long-term mean salinity of 1.8 gl^{-1} (IBRAKHIMOV et al. 2004). Repeated chemical analysis showed that soil salinity at both sites did not increase significantly but remained slightly saline.

All data were subjected to the analyses of variance with the SPSS v11.0 software.

For monitoring the interaction of the GW and adult trees, a plantation was selected which consisted of sections of *P. nigra* L. and *U. pumila* trees respectively up to 10 and 6 years old. The plantations were located in Yangibazar district at 41°42′ N latitude, 60°35′ E longitude and at an altitude of 100 m. Trees were planted at 3 m x 1m giving a density of 3300 trees ha^{-1}. The *P. nigra* section covered an area of 70 ha, whereas *U. pumila* was planted on 5 ha. Over the observation period several occasional irrigation water applications were performed by farmers.

The area was instrumented with a network of observation wells. The texture analyses of the gleyic solonchak soil at each installation point showed in general a silt loam texture with a clay bank of varying thickness between 100 and 150 cm depth. Below this clay level the profile typically consisted of fine sand.

The GW table under the plantations ranged for the observation period from 1.2 to 2.2 m below the soil surface. The EC of the GW under plantations varied between 0.4-4.2 dS m^{-1} while the range of EC values under the open field was 0.4-2.8 dS m^{-1}.

Measurements of soil EC in the beginning and the end of the vegetation season indicated that the soil was of slight to medium salinity, although at the upper 40 cm horizon at some points EC reached values of over 25 dS m^{-1}. Soil EC at the open field was in average about twice as low as that at the plantation area.

2.2 Transpiration rate and leaf area of young trees

Leaf transpiration rates of selected individuals (eight trees per species) were measured with the steady state porometer (Li-Cor 1600) in-between irrigation events. Concurrently, irradiance (photon flux density), air temperature and relative humidity were measured by the porometer. Measurements were conducted three times during the growing season for five consecutive sunny days: shortly after the leaves flushed, in the mid-season and at the end of the season, which corresponded to 14, 16, and 18 months after transplanting (MaP) trees from the nursery into the experimental plots. From each tree, three to four sunlit leaves were measured every two hours during thirteen hours of sunshine duration. At the loamy site *P. euphratica* developed very narrow leaves inappropriate for the porometer cuvette. Due to time and equipment limitations, at the sandy site only *E. angustifolia, U.pumila* and *P.euphratica* could be measured. These had shown high growth and utility potential during the previous study season.

At the end of the vegetation season (19 MaP) the observed trees were completely defoliated and fresh leaf mass determined. Leaf sub-samples were weighed and transported in a cool-box to the laboratory where one side of the leaves was measured with a leaf area meter (Li-Cor 1200) in two replicates. Next, the total tree leaf area was calculated from the area/total mass ratio. Since mutual shading was avoided and trees of most species were not self-shaded, daily transpiration of the whole canopy could roughly be estimated using total leaf area (LA) of the measured trees.

2.3 Ground water table monitoring at the adult plantations

To determine the influence of the adult plantation on the GW, the most common method involving monitoring of GW fluctuations via observation wells (POLGLASE et al. 2002) was used. The study site was instrumented with ten observations wells located within and outside of the forested area. The wells were 3 m long PVC tubes, perforated over the lower 1 m section and covered with a filter sock. Four observation wells were equipped with an automatic sensor and covered with a metal cap protected with a padlock. GW level in the other wells was checked manually every ten days. Concurrently, GW samples were collected and EC was measured.

The sensors were programmed to measure the absolute depth of the groundwater from the soil surface each 30 minutes. Prior to installation, the pressure sensors were calibrated to the level observed at the moment of installation, and verified at various points in time to avoid instrument drift. Calibration occurred while taking a manual observation with a measuring tape equipped with a sounding device.

Two of the observation wells were placed outside the plantation: one at the open field and the other (equipped with a sensor) in-between the forest plantation and the open field. The relative change of GW level in each observation well was calculated and corrected according to the level observed at the open field, which was considered as the reference point. The measurement of the topographic position of the observation wells was included for making the position corrections to each observation.

3 RESULTS

3.1 Leaf transpiration rates

The daily leaf transpiration courses of most species showed one peak at different points during the day depending on the period of the season (Figure 1a, 1b). At 14 MaP the highest values recorded at the loamy site happened between 11:00-12:00 hrs. At 16 and 18 MaP water loss values at the loamy site peaked between 13:00-14:00 hrs but for *U. pumila*, *M. alba* and *S. nigra* a slight increase was observed between 17:00-19:00. The three species decreased their transpiration during the hottest time of the day. At the sandy site, at the early, middle and late season all measured species peaked at 11:00-12:00 hrs. At the end of the season a second peak was observed between 15:00-16:00 hrs.

Transpiration rates per unit LA measured at 16 MaP (mid vegetation season) were similar to the values obtained at 18 MaP (late season) but superior to the rates at 14 MaP (early season) (Figure 1a).

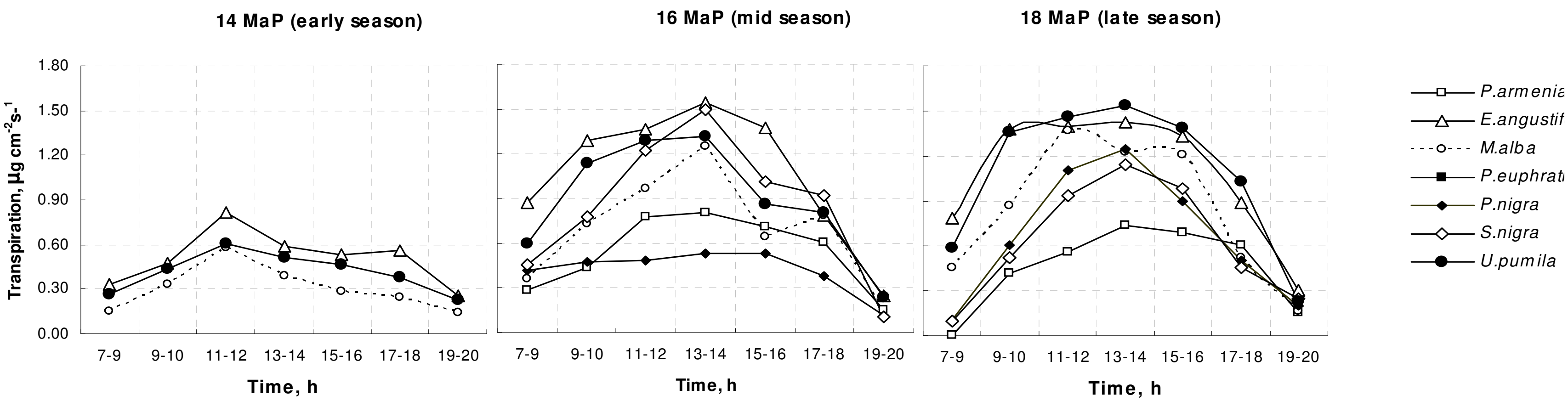

Figure 1a. Diurnal courses of leaf transpiration rates (µg cm^{-2} s^{-1}) measured with a steady state porometer at the beginning (14 MaP), middle (16 MaP) and end (18 MaP) of the vegetation season in trees grown at the loamy site.

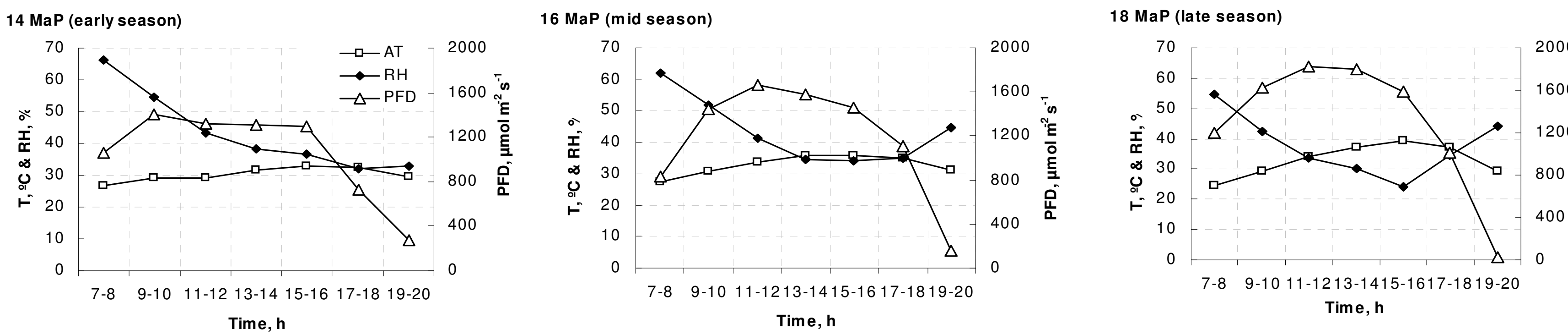

Figure 1b. Atmospheric parameters governing the water loss via leaf transpiration: air temperature (T, °C), relative humidity (RH, %) and photon flux density (PFD, µmol m^{-2} s^{-1}) measured with a steady state porometer in the beginning (14 MaP), middle (16 MaP) and the end (18MaP) of the vegetation season.

The rates were consistent with the mean air temperature and relative humidity during these periods. On the other hand, this sequence did not correspond with the irradiance given by in average higher values of photon flux density observed at the end of the season.

ANOVA analyses revealed a significant effect of species on mean transpiration rate per unit LA at the loamy site (Figure 2). There, the most water consumptive species such as *E. angustifolia* and *U.pumila* transpired more than twice as much as the least water consuming species. At the sandy site where only three species could be measured, species specific differences were found at the onset of the season only, when *E. angustifolia* transpired significantly more water. Overall, the species showing the highest leaf transpiration were *E. angustifolia, U. pumila* and *P. euphratica* while *P. armeniaca* and *P. nigra* (during the hottest month, 16 MaP) showed the lowest transpiration rates.

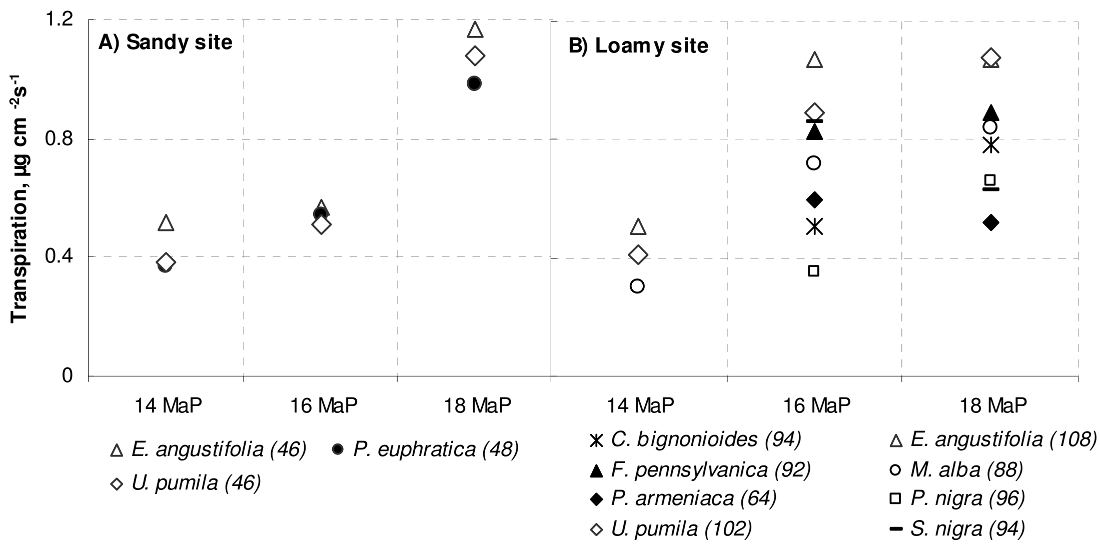

Figure 2. Mean daily transpiration rates per unit LA (µg cm^{-2} s^{-1}) at the beginning (14 MaP), middle (16 MaP) and end (18 MaP) of the vegetation season according to tree species and soil type. Between parentheses: the number of observations.

The transpiration per unit LA was transformed into whole-tree transpiration considering the leaf area per tree. Trees that had considerable leafy biomass were ranked in the upper quartile in daily transpiration at a tree level even if showing relatively low leaf transpiration as, for example, *P. nigra* Yet, *E. angustifolia* remained the most water consuming species transpiring 2.5-4 l day^{-1} at the age of three years at the end of the vegetation season. *P. euphratica* also showed relatively high values while the other species' daily transpiration did not exceed 0.9 l day^{-1} $tree^{-1}$.

3.2 Ground water level fluctuations under adult plantations and tree water use

Figure 3 shows the diurnal variation for a typical day in the early, middle and late vegetation season. An obvious diurnal influence of the trees on the ground water level (GWL) resulted in a drop of the GWL, which did not occur at the reference point at the agricultural field. The GWL started to drop below the reference at approximately 06:30 in the morning and rose again above the reference after 18:00. The GW table fluctuations were more erratic at the beginning of the season with the start of the irrigation events. During the midseason the daily curve became more consistent and had a prominent midday depression. Later in the season the GW loss decreased considerably and by the end of September the GWL drastically dropped with the cessation of the irrigation period. The GW daily and seasonal fluctuation trend negatively corresponded with the air temperature course which triggers the tree transpiration (Fig. 3).

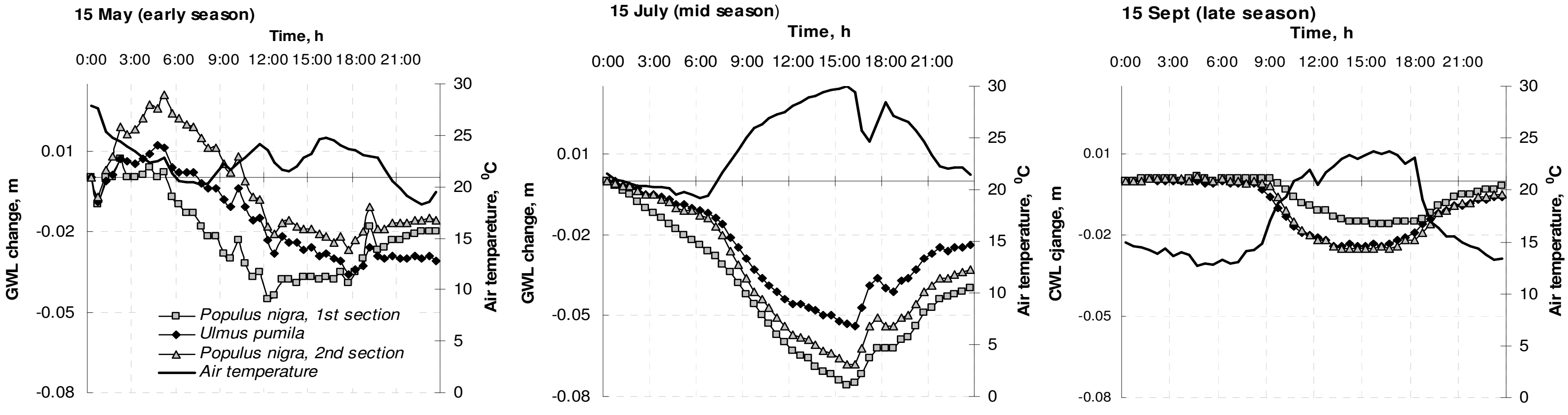

Figure 3. Diurnal GWL change under adult plantations (calculated using the open field as a reference) measured with automatic sensors and daily course of air temperature. Three exemplary days at the beginning (14 MaP), middle (16 MaP) and end (18 MaP) of the vegetation season are presented.

The GWL under the reference point was systematically higher than the average GWL under the trees, even though the irrigation events caused the GWL under the plantations to rise temporarily above the reference point. Despite daily fluctuations of the GWL under the plantations during the vegetation season, on the whole the GWL remained virtually unchanged at least for the monitored period of seven months. The salinity of GW both under the open field and the plantation had a tendency to decrease by the end of the season. The average EC of the GW under plantation was higher than that under the open field (Figure 4).

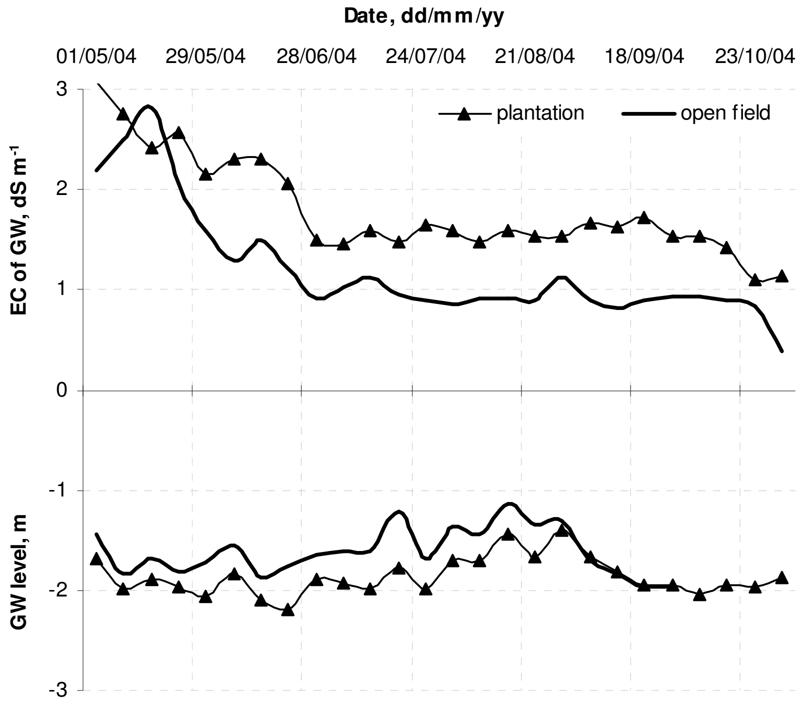

Figure 4. Seasonal dynamics of the GWL and EC of GW under the plantation and the open field.

Similarly, the EC of the soil under the plantation was observed higher in comparison with the reference point both at the beginning and the end of the vegetation season. No increase in soil EC was observed by the end of the season (Figure 5).

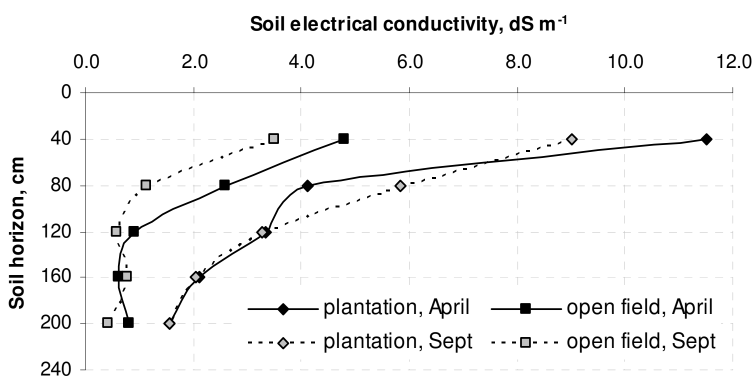

Figure 5. Soil EC at the plantation area and the open field in the onset and the end of the vegetation season.

The strong correlation of the GWL at all observation wells indicates that the soil hydrological characteristics are very similar throughout the study area and thus can be compared. The soil texture analysis confirmed this.

4 DISCUSSION

A careful selection of tree species is essential when considering trees for their use in potential biodrainage schemes within land areas with elevated saline GW tables and a flat topography in the Khorezm Region. Previous research concluded that for afforestation purposes, the appropriate tree species should combine high survival rates, quick growth, halophytic and xerophytic characteristics, and high utility value of firewood or foliage (KHAMZINA et al. 2005, in press; LAMERS et al. 2005, under review) since financial returns are key for farmer decision-making (LAMERS et al. 1994). For biodrainage purposes, water use and salinity tolerance is of primary importance (POLJAKOFF-MAYBER & LERNER 1999).

The examination of leaf transpiration rates of the various tree species allowed the comparison and selection of the most water consuming species for their use in biodrainage plantations. However, for the estimation of the extent to which tree plantations influence the GWL, a continuous monitoring of the GW dynamics under natural conditions and with mature trees is more appropriate.

4.1 Species selection

Extrapolation of leaf gas exchange measurements to the stand level and even to individual tree level is critically regarded due to high leaf-to-leaf and inter-specific variation in leaf gas exchange. McDERMITT (1990) stated that the transpiration rate measured in a porometer did not correspond with the *in situ* transpiration rate because the leaf and air temperature, the boundary level conductance and even the stomatal conductance and vapor pressure deficit values in the porometer differed from those in the field. This may explain our estimated values of up to 1 mm of tree daily water use, which are very low given the daily evaporative demand of about 5 mm and adequate soil moisture. However, HINGSTON et al. (1995) studied five plantations of *Eucalyptus* spp. in western Australia and arrived at daily WU values of 1-2 mm day^{-1}. Despite the possible inaccuracies when working with a porometer, the results can be used for comparisons among different species as they were concurrently measured. Yet, the extrapolated values are very rough estimates only.

Diurnal transpiration curves showed unrestricted water loss of some species (*E. angustifolia*) while *M. alba, S. nigra* and *U. pumila* were more sensitive to high temperature and irradiance and demonstrated a reduced transpiration during the hottest time of the day, which can explain the lower mean daily transpiration of these species.

Soil and water salinity can significantly reduce WU of plants (POLJAKOFF-MAYBER & LERNER 1999), which in conditions of the hydromorphic salt-affected soils in Khorezm, makes salt tolerance an important criterion for species selection. The level of salinity experienced in this study did, however, not affect the growth and transpiration of the most of the examined species, which were able to expel salts during water uptake (KHAMZINA et al. 2005 submitted). On the other hand, the higher values of groundwater EC at the sandy site than at the loamy site may have affected *P. armeniaca, C. bignonioides, F. pennsylvanica* and *M. alba.* These species have been reported as salt sensitive by MAKHNO (1962) and FIMKIN (1983) who based these conclusions on tree growth measurements. The transpiration of these species could unfortunately not be measured at the sandy site, but the observed visual signs of stress (scorching and dropping of leaves) indicate lower transpiration rates. The relatively high transpiration rates of *E. angustifolia* and *U. pumila* at the sandy site were in the range of their transpiration values at the loamy site, showing that those species were rather insensitive to the present degree of GW and soil salinity.

The highest tree transpiration extrapolated from the measurements of sunlit leaves was shown by *E. angustifolia* and *Populus* spp. However, actual daily transpiration of these species with a denser canopy compared to the others is expected to be lower due to self-shading and consequently reduced transpiration of the permanently and partly shaded leaves. The classification of the shaded and sunlit leaves is often debatable since they can interchange during the day due to the direction of the sun light (LARCHER 1995, pp 390 ff). Also the quantification of the area allocated to sunlit and shaded leaves is hardly standardized.

Advocates of biological drainage plantations often emphasize the low-cost aspects for the removal of excess water (SMEDEMA 1997). Moreover, biodrainage tree plantations do not demand the installation of physical structures, but can be implemented by farmers themselves who in addition may gain marketable products such as fodder and wood when adequate tree species are chosen. These aspects are considered to be a key element when one intends to convince farmers to introduce new technologies (LAMERS et al. 1994). However, the fruit species tested such as *P. armeniaca* and *M.alba* had a low potential for biodrainage purposes because of their salt sensitivity, low growth rates and resulting low dry matter production and water use. The tree species with highest transpiration rates and salinity tolerance, and therefore most promising for biodrainage purposes under the local agro-ecological conditions, proved to be *E. angustifolia*, followed by *U. pumila*, *P. euphratica* and *P. nigra*. In addition to the biodrainage potential, the fruit producing and N-fixing *E. angustifolia* and, to a lesser extent, *U. pumila* ranked also top as potential suppliers of high quality supplementary fodder (KHAMZINA et al. 2005, in press) and, therefore, may provide concurrent economic advantages to farmers.

However, *E. angustifolia* could not be included in the study of the tree plantations influence on the GWL, since in the region it does not occur in pure plantations but rather as one row strips (WORBES et al. 2005).

4.2 Trees and ground water interaction

The first analyses of the data from the GW observation network under the adult stand showed a diurnal fluctuation of the GWL, which was closely related to the diurnal course of the air temperature. Moreover, the analysis revealed that the GWL reacted directly to irrigation events and that the GWLs throughout the area are strongly linked and correlated.

Since no direct measurements of tree transpiration could be made at these sites, it is questionable if the GW drop was caused by the tree WU only. However, the comparison of the daily GW fluctuation under the reference point at the agricultural field and that under the forested area strongly suggests that the GWT depression below the plantations was most likely caused by the tree transpiration.

The preliminary results of accumulative amount of water loss during the first seven months indicated a rather large volume of water loss which exceeds the daily tree WU reported elsewhere (LANDSBERG 1999, HUEPERMAN et al. 2002). According to the review of HEUPERMAN et al. (2002), the highest annual tree WU determined in most studies in arid regions was not more than 3500 mm. Overall, the diversity of methods used to measure the tree WU and the frequency of measurements hampers a direct comparison of the results (Table 1).

Table 1. Tree water use of various species reported in arid and semi-arid regions

Region	Species	Method	Water use	Unit	Source
Turkmenistan	*Elaeagnus* spp.	Destructive	138	l	ELISEEV 1939
	Morus alba	gravimetric	275	day^{-1}	
	Populus spp.		346	$tree^{-1}$	
	Salix spp.		379		
Pakistan	*Eucalyptus* spp.	potential ET	137-143	l	ROITZSH & MARSUR
	M. alba		153	day^{-1}	Cited by BHUTTA &
	Populus spp.		45	$tree^{-1}$	CHAUDHRY 2000
western USA	*Populus* spp.	n/a	650-2350	mm	Cited by BHUTTA &
	Salix spp.		770-1350	$year^{-1}$	CHAUDHRY 2000
	Tamarix spp.		2200-2800		
Australia	*Eucalyptus* spp.	heat pulse	300	mm	MORRIS et al 1998
	E. globulus	hydrologic analysis	262-595	$year^{-1}$	HINGSTON et al 1995
	Corymbia maculata	n/a	675		THEIVEYANATHAN & BENYON 2000

The one-season findings of the GW observations under adult plantations suggests that during a year of sufficient water availability in the open system where GW is continuously influenced by the agricultural irrigation activities in the direct surroundings, and with a flat topography the examined plantations are not effective in lowering the GWL permanently. Longer term observations are recommended before drawing definite conclusions about the biodrainage potential of plantations since existing experience suggests that 3-5 years are needed to lower the ground water by 1-2 m (THORBURN & GEORGE 1999).

Salinity of the GW under the adult tree plantation, which was consistently higher than that under the open field, confirms a previous conclusion (THORBURN et al. 1995) that the salts, excluded from the root water uptake tend to accumulate under the plantations, particularly in GW discharge scenarios (HUEPERMAN et al. 2002), which is characteristic for the Khorezm region. However, the observed EC values of the ground water up to 4 dS m^{-1} and soil EC values averaging 4-5 dS m^{-1} are not likely yet to adversely affect the growth of 6-10 year-old trees, which are at least occasionally irrigated. Further observations are on-going to study if salt accumulation rates tend to increase.

It's very likely that the examined plantations have used the irrigation water in addition to the ground water. For the estimation of the GW uptake the stratification of the fine root biomass within soil horizons should be included in further observations. This data will also help understanding the salinity tolerance of the trees since salt sensitive species tend to localize the roots within less saline soil horizons (HEUPERMAN et al. 2002) particularly if surface irrigation is applied.

5 CONCLUSIONS

Leaf transpiration rates of three-year-old trees measured with the porometer significantly varied among species. Our findings, therefore, support the need for direct measurements of transpiration of the different tree species planted in hydromorphic salt-affected agricultural land in Khorezm rather than using indirect and species independent micrometeorological techniques.

The findings of the species assortment trial showed that *E. angustifolia* was the leading tree species with regards to its water use characteristics, followed by *U. pumila*, *P. euphratica* and *P. nigra.*

The findings of one-season observations from adult plantations suggested that the water table can be lowered by the trees when compared to GWL at the surrounding irrigated area. However, in the open system where irrigation and ground water is continuously supplied from agricultural fields in the surroundings, biodrainage was not effective in lowering the GWL permanently. In follow-up studies the precise monitoring of the GWT fluctuations should be complemented with direct tree measurements (e.g. sap flow meters) to verify the findings from the GW observation well network and estimate transpiration on a tree level.

The build-up of the often cited soil salinity under plantations remains unsolved and needs to be targeted before further recommendations can be given. From this perspective, the biodrainage may be a most suitable option when combined with conventional drainage systems and when involves multipurpose tree species which are adapted to the landscape and fit the farming practices.

6 ACKNOWLEDGEMENTS

The German Ministry for Education and Research (BMBF; project number 0339970A) and the Ministry for Schools, Science and Research of the State of Northrhine-Westfalia funded this study. The research was carried out within the framework of the ZEF/UNESCO landscape restructuring project.

7 REFERENCES

Bhutta, M.N. & Chaudhry, M.R. (2000) Biological control of waterlogging. Proceedings of the 8th ICID International Drainage Workshop, New Delhi, India. Vol. IV, Group V: pp 33-45.

Eliseev, L.V. (1939) Transpiration of woody species in irrigated conditions of Turkmen SSR. Forestry J 5. (in Russian).

Fimkin, V.P. (1983) Recommendations on assortment of tree and shrub species for salt-affected soils in Golodnaya Steppe. Middle-Asian Forest Research Institute, Ministry of Agriculture of Uzbek SSR, Tashkent, pp 1-13. (in Russian).

Heuperman, A.F., Kapoor, A.S. and Denecke, H.W. (2002) Biodrainage - principles, experiences and applications. International Programme for Technology and Research in Irrigation and Drainage (IPTRID). Food and Agriculture Organization of the United Nations (FAO), Italy, 79 pp.

Hingston, F. J., Galbraith, J. H. and Dimmock, G. M. (1995) Evaluating the effects of soils and climate on the productivity of *Eucalyptus globulus* plantations on contrasting sites in south-west of Western Australia. Final Rep. Project, CSF-41A, RIRDC pp 67.

Ibrakhimov, M., Park, S.J. and Vlek, P.L.G. (2004) Development of groundwater salinity in a region of the lower Amu-Darya River, Khorezm, Uzbekistan. In: Ryan J., Vlek P.L.G., Paroda R. (eds) Agriculture in Central Asia: Research for Development. Proceedings of a Symposium held at the American Society of Agronomy Annual Meetings at Indianapolis, Indiana, USA. ICARDA, Aleppo, Syria, pp 56-75.

Ivanov, L.A., Silina, A.A. and Zelniker, Yu.L. (1950) About the method of fast weighing for determination of transpiration under natural conditions. Botanical J XXXV (2): 1-5. (in Russian).

Khamzina, A., Lamers, J.P.A., Worbes, M., Botman, E. and Vlek, P.L.G. (2005) Assessing the potential of trees for afforestation of degraded landscapes in the Aral Sea Basin of Uzbekistan. Agrofor Syst (in press).

Khamzina, A., Lamers, J.P.A., Martius, Ch., Worbes, M. and Vlek P.L.G. (2005). Biodrainage potential of nine multipurpose tree species in the lower Amudarya River region of Uzbekistan. Agrofor Syst (submitted).

Lamers, J.P.A., Michels, K. and Vandenbeldt, R.J. (1994) Trees and windbreaks in the Sahel: establishment, growth, nutritive and calorific values. Agrofor Syst 26(3): 171-184.

Lamers, J.P.A., Khamzina, A. and Worbes, M. (2005) The analyses of physiological and morphological attributes of ten tree species as determining components for their suitability in the rehabilitation of degraded landscapes in the Aral Sea Basin of Uzbekistan. Forest Ecol Manage (under review).

Landsberg, J. (1999) Tree water use and its implications in relation to agroforestry systems. In: Landsberg J. (ed) The ways tree use water. Water and salinity issues in agroforestry 5, RIRDC, pp 1-31.

Larcher, W. (1995) Physiological plant ecology. Ecophysiology and stress physiology of functional groups. Springer - Verlag Berlin Heidelberg, Germany.

Makhno, G. (1962) Elaboration of methods for forest management on salt-affected soils in Khorezm Region. Middle-Asian Forest Research Institute, Ministry of Agriculture of Uzbek SSR, Tashkent, 213 pp. (in Russian).

McDermitt, D. (1990) Sources of error in the estimation of stomatal conductance and transpiration from porometer data. HortScience 25 (12): 1538-1548.

Morris, J., Mann, L. & Collopy, J. (1998) Transpiration and canopy conductance in a eucalypt plantation using shallow saline groundwater. Tree Physiology, 18: 547-555

Polglase, P.J., Theiveyanathan, S., Benyon, R.G. and Falkiner, R.A. (2002) Irrigation management and groundwater uptake in young tree plantations growing over high watertables. Final report for the RIRDC/Land & Water Australia/FWPRDC/MDBC Joint Venture Agroforestry Program. 54 pp.

Poljakoff-Mayber, A. and Lerner, H.R. (1999) Plants in saline environments. In: Pessarakli M. (ed) Handbook of plant and crop stress. Marcel Dekker Inc. New York-Basel, pp 125-152.

Saigal, S. (2003) Uzbekistan: Issues and approaches to combat desertification. Asian Development Bank, Tashkent, Uzbekistan. Discussion draft, 51 pp.

Smedema, B. (1997) Biological drainage: myth or opportunity? GRID 11, 3 pp.

Theiveyanathan, V. and Benyon, R.G. (2000) Planting trees for sustainable rice production. In Onwood; research updates from CSIRO Forestry and Forest Products. No. 31: p. 5.

Thorburn , P.J., Walker, G.R. and Jolly, I.D. (1995) Uptake of saline groundwater by plants: Ananalytical model fer semi-arid and arid areas. Plant Soil 175:1-11.

Thorburn, P.J. and George, R.J. (1999) Interim guidelines for revegetating areas with shallow, saline water tables. In Thorburn P.J. (ed) Agroforestry over shallow water tables: The impact of salinity on sustainability. Water and salinity issues in agroforestry 4, RIRDC publication N 99/36: 12-17.

Worbes, M., Botman, E., Khamzina, A., Tupitsa, A., Ruzmetov, R., Martius, C. and Lamers, J.P.A. (2005) Strengthening the role of trees and forests in the landscape of the Aral Sea Basin: Scope and constraints. Discussion paper of the Center of Development Research, Bonn (forthcoming).