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**Exploring the potential of multipurpose tree species for
revegetating abandoned cropping sites in the lower Amu Darya
Basin**

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ABSTRACT

The land degradation due to soil salinization that results from elevated groundwater table (GWT) is common in intensively irrigated and poorly drained cropping areas in the lower Amu Darya Basin. Given the decreasing availability of fresh water for soil reclamation via salt leaching, farmers in the region tend to abandon highly salinized areas from cropping. To assess the potential of afforestation to rehabilitate the abandoned croplands, six tree species were examined through field experiments during 2010 and 2011 at two sites. The main focus was on species' survival, provision of ecosystem services (biomass production, replenishment of carbon (C) and nitrogen (N) soil stocks), as well as on the dynamics of soil salts and water. The empirical data were used to parameterize the field-scale, process-based model EPIC (Environmental Policy Integrated Climate model), which was subsequently used to simulate biomass growth and salt and water dynamics in tree plantations under shallow GWT conditions.

Both sites initially showed soil nutrient deficiency, high soil salinity ($10 - 12 \text{ dS m}^{-1}$) and moderately saline groundwater ($2-5 \text{ dS m}^{-1}$), but differed in texture (silty loam: G'oybu; loamy sand: Beruniy) and GWT depth. The latter fluctuated between 0.6 and $>2.8 \text{ m}$ in G'oybu and between 0.2 and 1.4 m in Beruniy. The tree plantations received deficit irrigation of 154 mm yr^{-1} . A survival analysis revealed differential response of tree species to plant-available water and salt content in the root zone. Afforesting abandoned croplands was most feasible with *Elaeagnus angustifolia* L., *Ulmus pumila* L., *Morus alba* L., and *Populus nivea x tremula* L. given their survival rates of 75 - 91% on both sites after two years. The major species of the native floodplain forest, *P. euphratica* Oliv. and *Salix nigra* Marsh., exhibited survival rates $<19\%$ and were therefore evaluated as not suitable for afforestation of the abandoned cropland. Overall, N_2 -fixing *E. angustifolia* was assessed as most promising among all species tested since it combined highest survival rates with largest aboveground biomass increments (up to $904 \text{ kg ha}^{-1} \text{ yr}^{-1}$). Its N_2 -fixation efficiency was estimated at 70 - 74% ($12 - 22 \text{ kg N ha}^{-1} \text{ yr}^{-1}$) with the ^{15}N natural abundance and the total N-difference method.

The afforestation impact on soil total N, C, and SOC was modest due to high inter-annual variability in soil characteristics, short observation period and modest addition of organic matter by young trees. Subtle but statistically significant increases in SOC stocks in the heavier textured soil in plots with higher biomass yielding species are first positive indications for future trends in soil C status. The decline in soil salinity that occurred in both afforestation sites and the reference cropland fields were associated with the fluctuating GWT rather than the impact of afforestation.

The EPIC model showed promise for simulating the processes in *P. nivea x tremula* plantation under deeper GWT conditions, given the percent bias ranging between -2.6 and 5.5%. The calibration results remain to be validated with independent datasets. The present findings revealed a limited capability of EPIC for the site with shallow, fluctuating GWT, requiring that the latter is accounted in the model on the daily basis. Furthermore, considering plant survival and aboveground biomass partitioning would enhance the capability of EPIC for application in forestry studies.

The overall assessment of tree species potential for revegetating long-term abandoned croplands showed that the land's productive capacity can be increased with selected species as opposed to a natural succession. However, afforestation remains associated with risks unless the availability of irrigation water during the initial establishment stage is warranted.

Das Potenzial von Mehrzweckbaumarten für die Rekultivierung von aufgegebenen Ackerflächen im unteren Amu Darya Becken

KURZFASSUNG

Im bewässerten Flachland des Amu Darya Beckens (ADB) verursachen hohe, saline Grundwasserspiegel (GWS) sekundäre Bodenversalzung, was die Produktivität des Ackerlandes mindert. Da die Verfügbarkeit von Frischwasser zur Salzauswaschung ständig abnimmt, geben Bauern regelmäßig stark versalzene Parzellen auf. Diese aufgegebenen, versalzene Parzellen können allerdings wieder nutzbar gemacht werden, indem sie in Baumplantagen aus salztoleranten Arten umgewandelt werden. Um ihre Eignung zur Rekultivierung von aufgegebenem Ackerland zu testen, wurden sechs Baumarten zwischen 2010 und 2011 in Feldversuchen auf zwei Versuchsflächen, G'oybu und Beruniy, getestet. Der Schwerpunkt der Untersuchung wurde auf die Überlebensraten der Baumarten und die Erbringung von Agro-Ökosystemdienstleistungen der Baumplantagen gelegt. Hierbei wurden sowohl die Produktion von Biomasse und die Anreicherung von Kohlenstoff- (C) und Stickstoffspeichern (N) im Boden–als auch Salzdynamiken erforscht. Mit den erhobenen Felddaten parameterisierte man das prozessbasierte, auf Feldebene arbeitende Modell "Environmental Policy Integrated Climate model (EPIC)". Dies wurde anschließend eingesetzt, um Salz- und Wasserdynamiken in den Baumplantagen mit niedrigem GWS zu simulieren.

Beide Versuchsflächen zeichneten sich durch Nährstoffmangel, hohe Bodensalinität ($10\text{-}12\text{ dS m}^{-1}$) und moderat salines Grundwasser ($2\text{ - }5\text{ dS m}^{-1}$) aus, unterschieden sich aber in Textur (schluffiger Lehm: G'oybu; lehmiger Sand: Beruniy) und der Tiefe des Grundwassers. Letztere schwankte zwischen 0.6 und >2.8 m in G'oybu und zwischen 0.2 und 1.4 m in Beruniy. In wieweit pflanzenverfügbares Wasser und Bodensalinität in der Wurzelzone die Überlebensraten der unterschiedlichen Baumarten beeinflusst, wurde unter Defizitbewässerung von 154 mm yr^{-1} im Rahmen einer Survival-Analyse getestet. Die Analyse zeigte gravierende artenabhängige Unterschiede in der Toleranz gegen Salzstress. Somit erwies sich das Aufforsten von aufgegebenem Ackerland als durchführbar mit dem Baumarten *Elaeagnus angustifolia* L., *Ulmus pumila* L., *Morus alba* L., und *Populus nivea x tremula* L., die nach zwei Jahren auf beiden Versuchsflächen Überlebensraten von $75\text{ - }91\%$ aufwiesen. Die typischen Arten der nativen Auenwälder, *Populus euphratica* Oliv. und *Salix nigra* Marsh., zeigten dagegen Überlebensraten von $<19\%$ und wurden deshalb unter den vorliegenden Gegebenheiten als nicht für die Aufforstung geeignet eingestuft. Insgesamt wurde unter allen untersuchten Arten der N-Fixierer *E. angustifolia* als vielversprechender Kandidat für die Aufforstung eingestuft, da hier sowohl die höchsten Überlebensraten als auch die größten überirdischen Biomassezuwächse (bis zu $904\text{ kg ha}^{-1}\text{ yr}^{-1}$) gemessen wurden. Die Effizienz der N-Fixierung wurde mit der ^{15}N natürliche Abundanz Methode und der Stickstoff Differenzmethode auf $70\text{ - }74\%$ ($12\text{ - }22\text{ kg N ha}^{-1}\text{ yr}^{-1}$) geschätzt. In Beruniy wurde nach zwei Jahren ein signifikanter Rückgang von organischem Boden C, gesamt N und Salinität sowohl in den Aufforstungs- als auch in den Referenzplots beobachtet. Folglich konnte zwei Jahre nach Aufforstung kein signifikanter Einfluss der Bäume auf die Bodeneigenschaften bestätigt werden, obwohl dies in anderen Zusammenhängen häufig beobachtet worden ist. Es wird allerdings angenommen, dass solche Einflüsse möglicherweise durch den schwankenden GWS überschattet wurden, welcher die beobachteten Jahresschwankungen in den Bodeneigenschaften verursachte.

Das Modell EPIC war bezüglich seiner Nutzung im ADB teilweise vielversprechend, da die Percent Bias der Simulationen zwischen -2.6 und 5.5% lagen. Die Ergebnisse lassen aller-

dings auf eine begrenzte Anwendbarkeit des Modells auf Standorte mit niedrigem GWS schließen, da EPIC die gemessenen Grundwasserschwankungen nicht simulieren konnte.

Die Baumeignungsbewertung für die Aufforstung von langfristig aufgegebenem Ackerland zeigte, dass die Produktivität des Landes gemessen an einer natürlichen Rekultivierung gesteigert werden kann. Die Menge der durch die Baumplantagen geleisteten Agro-Ökosystemdienstleistungen hängt signifikant von der verwendeten Baumart ab. Da während der Etablierungsphase der Bäume die Verfügbarkeit von Bewässerungswasser garantiert sein muss, bleibt die Aufforstung riskant. Um empirische Ergebnisse zu extrapolieren und somit Baumwachstum auf aufgegebenem Ackerland besser voraussagen zu können, sind erhebliche Änderungen in der Grundwasserkomponente von EPIC notwendig. Eine Möglichkeit wäre, Grundwasserinformationen in den Daily Weather File zu integrieren, was eine Angleichung des schwankenden GWS ermöglichen würde. Eine Kalibrierung und Validierung der Crop-Komponente für die getesteten Arten erfordert weitere Feldversuche, die besonders auf die Bestimmung artenabhängiger Pflanzenparameter ausgerichtet sind, wie dem Energy to Biomass Ratio.

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LIST OF ACRONYMS AND ABBREVIATIONS

ABI	Aboveground biomass increment
ADB	Amu Darya Basin
ANOVA	Analysis of variance
ARK	Autonomous Republic of Karakalpakstan
BBI	Belowground biomass increment
BNF	Biological nitrogen fixation
C	Carbon
CA	Central Asia
CPAW	Current plant available water
CDM	Clean Development Mechanism
CER	Certified emission reductions
CO ₂	Carbon dioxide
EC	Electrical conductivity
EPIC	Environmental Policy Integrated Climate model
GWT	Groundwater table
IR	Incidence rate
IRR	Incidence rate ratio
LAI	Leaf area index
MaP	Months after planting
N	Nitrogen
NDM	Nitrogen difference method
15NAM	¹⁵ N natural abundance method
Ndfa	Nitrogen derived from the atmosphere
NTFP	Non-timber forest products
P	Phosphorus
PBM	Process-based model
SAR	Sodium adsorption ratio
SOC	Soil organic carbon
TDS	Total dissolved solids

1 GENERAL INTRODUCTION

1.1 Afforestation for rehabilitation of degraded dryland ecosystems

Dryland regions are generally characterized by soils with frequent drought stress, low organic matter contents, low nutrient reserves, and especially low nitrogen (N) contents (Skujins 1991). Hence, primary production in dryland regions is often limited by the lack of plant nutrients and a low water availability (Zhang and Zak 1998; Lal 2001). Low and highly variable precipitation often hardly suffices to grow plants, which limits agricultural production and thus makes the use of irrigation inevitable. The costs associated with vegetation establishment within irrigation systems are high (Gupta 1995). Furthermore, in those regions where water for agriculture is supplied through irrigation, additional fresh water usually is required to combat soil salinization, a critical problem of virtually all irrigated lands (Kitamura et al. 2006) as it leads to soil degradation and yield reductions. In dryland regions where irrigation is not feasible, alternative land uses are usually limited to grazing activities (Noy-Meier 1973).

Various tree species have been seen to be more drought and salt tolerant than most agricultural crops due to their perennial nature and better adaptive capacity (Miyamoto et al. 2004; Khamzina 2006). Compared to annual crops, trees do not necessarily use more water (Grünzweig et al. 2003) and may even have a lower irrigation demand due to the effective uptake of shallow groundwater (Khamzina et al. 2008). The capacity of trees to reduce the groundwater table (GWT) level is the main component of biodrainage systems for water table control and is credited with the mitigation of secondary soil salinity (e.g., Heuperman et al. 2002). Tree plantations on poor soils also have been seen to reduce soil erosion and replenish soil-nutrient stocks (Danso et al. 1992; Katyal and Vlek 2000; Cacho 2001; Guo and Gifford 2002; Heuperman et al. 2002; Jiao et al. 2010) by modifying the quality and quantity of litter inputs, microclimatic conditions, and moisture and temperature in the soil (Bouwman & Leemans 1995). Especially N₂-fixing tree species bear promise for dryland afforestation purposes, since they are capable of thriving on low-N soils typical for dryland regions (Skujins 1991). Due to the positive impact on soil conditions and increased biomass production,

planting trees on degraded lands is worldwide recognized as an effective means for reducing the atmospheric carbon dioxide (CO₂) by carbon (C) sequestration in both woody biomass and soil (FAO 2000; Katyal and Vlek 2000; IPCC 2001; Smith and Scherr 2002; Jandl et al. 2007). In contrast to crops that are harvested annually, forest plantations establish a significant C sink due to their perennial nature and continuous input of organic residues to the soil (Laganiere et al. 2010). The C units sequestered through re- and afforestation can be traded through voluntary and mandatory markets (e.g., Clean Development Mechanism (CDM) of the Kyoto Protocol). In particular, due to a direct correlation between desertification and emission of CO₂ from soil and vegetation, dryland afforestation was assessed as an effective mitigation option linking the efforts of combating land desertification and reducing atmospheric CO₂ (FAO 2000; Lal 2001). Furthermore, the vast areas potentially available in dryland regions of the world and the ability of various trees to cope effectively with saline conditions and low soil-N stocks favour reforestation and afforestation as an option to make productive use of degraded lands in arid regions.

Nevertheless, such efforts have been mainly limited to the temperate zones (Martin et al. 2001) mostly due to the presumably low productive potential and cost effectiveness of dryland afforestation. For example, Zomer et al. (2008) excluded irrigated areas in their global land suitability assessment for CDM, as they assumed that the high productive value of crops in irrigated croplands cannot be achieved by tree plantations. Evidence exists that in arid regions, especially in those facing increasingly insecure irrigation water availability and soil salinity problems, afforestation could be an economically viable alternative to the highly water-demanding crop production on marginal cropland. For instance, findings in the degraded irrigated areas in the lower Amu Darya Basin (ADB) show higher potential financial benefit from afforestation than from annual cropping (Djanibekov et al. 2012a; 2013).

1.2 Potential and challenges for afforestation in the lower Amu Darya Basin

The ADB lies in the Aral Sea Basin where salinization affects an estimated 75% of all irrigated land (van Dijk et al. 1999). Salinization is boosted by the arid climate and the

shallow, saline GWT resulting from the intensive irrigation and the low irrigation efficiency (Ikramov 2004). Salt leaching and drainage are commonly practiced to fight soil salinization but annually require large amounts of fresh water and costly maintenance of the collector-drainage system. The lower ADB is particularly prone to an increasing scarcity of fresh water for irrigation and to leaching due to upstream water utilization and the deteriorating quality of the river water (main source for irrigation) due to the discharge of agricultural drainage effluent (Ibrakhimov et al. 2007; Tischbein et al. 2012). Therefore, the temporary or even permanent abandonment of highly salinized cropland parcels is observed in the lower ADB (Dubovyk et al. 2012a). In addition, negative impacts on the water availability for agriculture in the ADB are predicted as a consequence of climate change, although the timing and magnitude of these impacts is highly uncertain (Schlüter et al. 2010). Predicted was an increase in the frequency of extreme events (Glantz 2005) and shifts in the peak water flow (Savitsky et al. 2007). Furthermore, a general decrease by 15% in the river flow was estimated for 2050 resulting from a decline in the glacier area in the Pamir Mountains and the Hindukush (Agaltseva 2005).

The need for adaptation to the changing environment is only slowly being recognized, mainly as a consequence of the recent occurrence of extreme droughts (Schlüter et al. 2010). Furthermore, research findings from the Aral Sea Basin underline that the present lack of irrigation water is not only a biophysical phenomenon but is also caused by misallocation and over-irrigation of cash crops (Pereira et al. 2009). This highlights the need for an adoption of water-saving irrigation techniques and suitable land-use strategies, especially in the downstream regions, for water and salinity management (Djurabekov and Laktaev 1983). This need has been recognized by political leaders who see an increase in water availability by, for example, increasing water use efficiency, as a key factor for regional development prospects (Glantz 2005).

As opposed to the water-intensive reclamation by leaching of highly salinized cropland, an adaptive option of converting degraded cropland parcels to high-carbon stock systems of salt-tolerant tree species has been assessed as viable to generate ecosystem services and incomes in the lower ADB (e.g., Khamzina et al. 2012; Djanibe-

kov et al. 2013). This region, with its shallow GWT, is suitable for afforestation given the possibility to reduce the irrigation water demand of forestry by taking advantage of the relatively untapped groundwater resources. Even though tree plantations relied on irrigation during the establishment phase (e.g., Sandell et al. 1986; Khamzina 2006; Djumaeva et al. 2010), the groundwater uptake reduced the per-hectare irrigation demand to only a fraction of the amount required for annual crop cultivation (Khamzina et al. 2008). Furthermore, the income for farmers could be potentially generated through increasing the productive capacity of the degraded land and the provision of various tree products of commercial value (e.g., Lamers 2008b; Khamzina et al. 2008; 2012; Djumaeva et al. 2009; Djanibekov et al. 2012b).

The generated knowledge on suitable tree species, irrigation techniques and impacts of afforestation has been based on field research in marginal agricultural areas that were previously used for crop production despite low yields. Based on the findings of spatio-temporal analyses of cropland productivity dynamics in the lower ADB, Dubovyk et al. (2013a) highlighted that cropland parcels abandoned from cropping were the land degradation hotspots as the desertification processes there are exacerbated due to the absence of vegetation. These locations should be therefore primarily targeted by rehabilitation measures, but research on suitable options, such as afforestation, is required.

1.3 Research needs

To ensure effective and sustainable outcomes, afforestation as a revegetation measure for long-term abandoned cropping sites must be preceded by a suitability assessment of available tree species and of means to predict tree growth under prevailing stress conditions. Given the paucity of empirical data on tree-growth responses to the spatially variable environmental conditions observed on abandoned cropping sites in the ADB (Dubovyk et al. 2013), additional field trials are needed. In particular, the depth to the GWT exerts significant effects on tree growth (Mueller-Dombois 1964; Schaff et al. 2003) and can considerably influence the irrigation demand of tree plantations and thus the success of an afforestation enterprise. Furthermore, specific knowledge on

species response to water and salinity stress and to N deficiency is a prerequisite for initiating the revegetation of abandoned cropping sites affected by desertification. The capability of fixing atmospheric N by N₂-fixing trees helps to overcome the lack of N in the soil (e.g., Danso et al. 1992; Dommergues et al. 1995) and was confirmed in saline and moist soils (Khamzina et al. 2009; Djumaeva et al. 2011). However, it might be significantly hindered on drier sites, especially on those with low soil-phosphorus contents (Djumaeva et al. 2013). Still little is known about the efficiency of N₂-fixation under saline conditions and its importance for the success of dryland afforestation.

Without doubt, field experiments involving multiple tree species under a variety of site conditions and experimental treatments are the most reliable basis for site-specific recommendations on the species choice for afforestation. However, for practical and budgetary reasons it is not possible to establish experimental sites that cover all potential settings in drylands. Nevertheless, the empirical data gathered through laborious field experiments could be used for developing effective simulation tools to predict species performance for field situations for which only little empirical data is available. In this way, gaps in primary data sets could be overcome (Landsberg and Sands 2011). Although modeling cannot completely replace empirical research, tree-growth models are important scientific tools allowing useful, practical, and quantitative predictions of forest and tree growth and responses to environmental changes (Landsberg and Sands 2011). The type and complexity of a suitable model strongly depends on the scope of its purpose (Steiner et al. 1987; Porté and Bartelink 2002). In the context of irrigated cropland in the lower ADB, a model able to simulate tree growth under different depths to the GWT and soil salinity levels would support spatial planning of afforestation activities.

1.4 Objectives of the study

The overall objective of this study is to explore the potential of afforestation to revegetate long-term abandoned croplands in the lower ADB. In field trials, survival, growth, and biomass production of different tree species were monitored under deficit irrigation. A further aim was to select and calibrate a suitable model capable of predicting

tree-growth response to field conditions on long-term abandoned cropping sites in the lower ADB. The specific research objectives were to:

1. Assess the establishment and early growth of six tree species under deficit irrigation on abandoned cropping sites differing in depth to the GWT;
2. Quantify the N₂-fixation capacity of trees under saline conditions;
3. Analyze soil nutrient and salinity dynamics following afforestation;
4. Select, parameterize, and calibrate a field-scale, process-based model for site conditions and tree species in the study region.

1.5 Outline of the thesis

This thesis consists of seven chapters. Subsequent to this general introduction, and the description of the study region (Chapter 2), Chapter 3 reports on the results of afforestation experiments with six tree species on two long-term abandoned cropping sites. Chapter 4 provides an insight on the importance of N₂-fixation for successful revegetation of abandoned cropland. Chapter 5 continues with the analyses of the afforestation impact on soil characteristics. Empirical findings on tree productivity and dynamics of soil parameters are integrated in the modeling analyses in Chapter 6. The thesis ends with general discussion and conclusions in Chapter 7.

2 STUDY REGION

The study was carried out in two neighboring administrative territories in the north-west of Uzbekistan, Central Asia (CA). In the following, “the study region” refers to the area covering the Khorezm region and three southern districts of the Autonomous Republic of Karakalpakstan (ARK) namely Beruniy, Ellikkala, and Turtkul’ between 60°02’ and 62°44’ E longitude and between 40°62’ and 42°71’ N latitude, at an altitude of approx. 90–138 m a.s.l. (Figure 2.1).

Located in the lower reaches of the Amu Darya River at the rim of the Aral Sea Basin, the study region belongs to the populated areas immediately affected by the consequences of the Aral Sea disaster (ADB 2006). Its downstream location at the river supplying water to the irrigation systems makes the region particularly vulnerable to the disruption of the irrigation-water supply. Furthermore, the study region with its low-lying relief and flat topography is particularly prone to land degradation due to elevated GWT and secondary soil salinization. From this perspective, it is representative for many downstream regions with limited access to irrigation water in CA and beyond (Worbes et al. 2006).

Previous studies concluded that, besides the Dashoguz Region (Turkmenistan), water scarcity in the lower reaches and downstream of the Amu Darya River was - and is expected to be - worse in Khorezm and in the ARK (Glantz 2005).

2.1 Geographical information

Khorezm is Uzbekistan’s smallest administrative district and covers an area of about 560,000 ha including 270,000 ha arable land (Dubovyk et al. 2012a). Located in the northwest of Uzbekistan, Khorezm borders the Karakum and the Kyzylkum deserts to the southeast, Turkmenistan to the southwest, and the ARK to the north (Figure 2.1). The ARK borders Turkmenistan to the southwest, the Kyzylkum desert to the north-west and Kazakhstan and the Aral Sea to the north (Figure 2.1). The ARK covers an area of approximately 16.5 million ha of which about 14% consists of deserts and semi-deserts, and about 500,000 ha are arable. The three southern districts of the ARK in-

cluded in this study border the Khorezm region and the Amu Darya River (Figure 2.1). Together, they comprise an area of about 294,000 ha of which currently 140,000 ha are irrigated cropland (Dubovyk et al. 2013a).



Figure 2.1 Location of the study region (modified after Dubovyk et al. 2013b).

2.2 Climate

Belonging to the Central Asian semi-desert zone, the study area is characterized by an arid, extreme continental climate (Glazirin et al. 1999), i.e., dry and hot summers and cold winters with little precipitation. Annual temperatures in the region are characterized by a high annual amplitude reaching a minimum in January and a maximum in July (Figure 2.2). Annual precipitation with a long-term average of about 95 mm occurs mainly between November and March (Figure 2.2), and is exceeded at least 10-fold by the potential evapotranspiration (Ibrakhimov et al. 2007). Within the past 40 years, air temperatures in Uzbekistan increased non-cyclically due to global warming (Giese and Moßig 2004) although this was not confirmed for Khorezm (Conrad et al. 2012). Due to the arid climatic conditions, cropping relies entirely on irrigation.

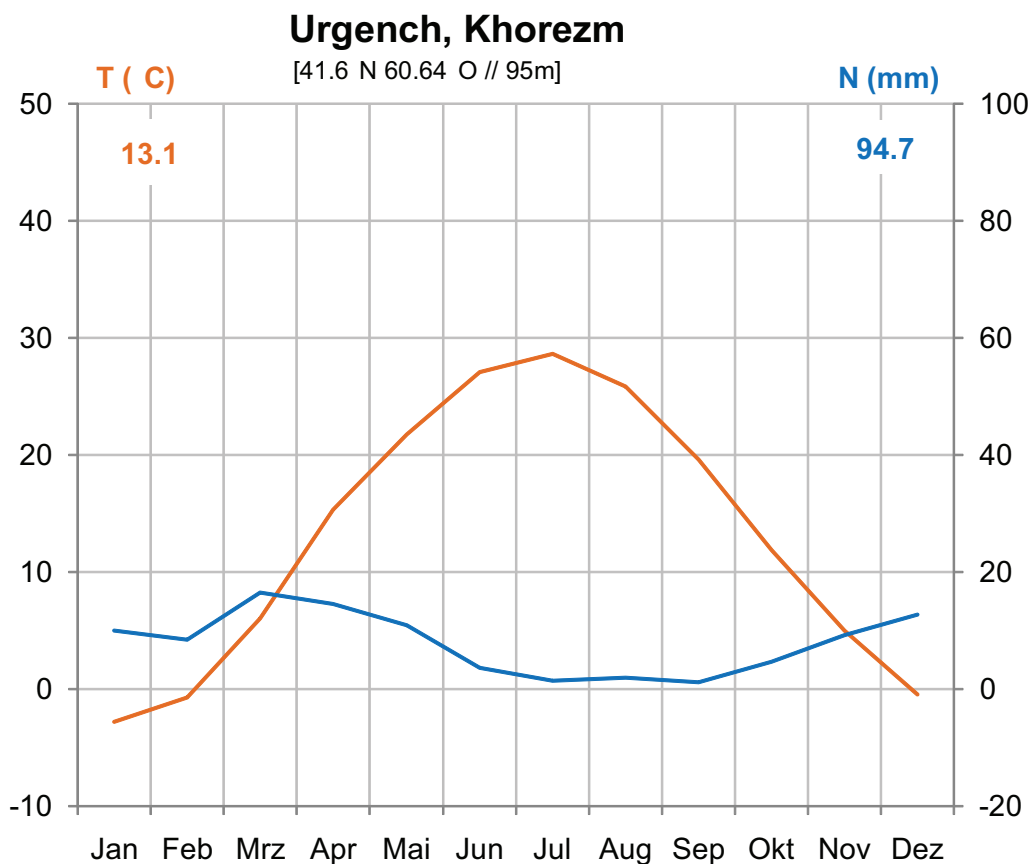


Figure 2.2 Walter-Lieth climate diagram, based on long-term data (1970-2007) of the meteorological station in Urgench, Khorezm region (source: Conrad et al. 2012). *T* temperature, *N* precipitation.

2.3 Relief and soils

The soils in the study region were formed by the meandering Amu Darya River carrying sediments that were deposited along the river channel and temporary streams. These alluvial layers are characterized by silty and sandy-loamy textures, usually 2-3 m thick and underlain by sand (Tsvetsinskaya et al. 2002; Ibrakhimov et al. 2007). The topography of the region is flat with insignificant slopes of less than 1% (Mukhammadiev 1982) and elevation points within the range of 112 – 138 m a.s.l. (Kats 1976). Dominant soil types in the study region are arenosols, cambisols, and fluvisols in the Khorezm region (FAO 2003), and mainly fluvisols in the irrigated area of the ARK (Mott-MacDonald 2011). Generally, the soils in the study region are naturally low in organic matter, which averages around 0.75% in the topsoil layers in Khorezm (Akramkhanov et al. 2012) and around 1% in the southern region of the ARK (Mott-MacDonald 2011), decreasing with increasing soil depth. Due to the overall poor fertility of the soils in the study region (Akramkhanov et al. 2012; Vlek et al. 2012), crop cultivation demands the intensive use of fertilizers (Khamzina 2006).

Mainly caused by the prevailing shallow GWT (Tischbein et al. 2012), the whole study region is affected by secondary soil salinization (Abdullaev 2003). Although salinity levels may vary according to land use and management systems (Akramkhanov et al. 2012), cropland productivity is generally reduced by salinity. An NDVI-based assessment revealed a significant decline in cropland productivity across 23% (94,835 ha) of the arable area in the study region between 2000 and 2010 (Dubovyk et al. 2013b). The most significant biomass decline was detected in cropland areas with reduced frequency of cropping and irrigation and therefore deeper GWT (Dubovyk et al. 2013a).

2.4 Irrigation and drainage

In the study region, most commonly practiced is furrow irrigation (Abdullaev 2003) with water withdrawn from the Amu Darya River, the main irrigation-water source in the region (Mukhammadiev 1982). The use of the groundwater for irrigation is precluded by its salinity and the necessity of pumping. In the past years, especially in the

downstream administrative districts, water allocated to villages and farmers has often been reported insufficient for irrigation and human consumption (Glantz 2005). Therefore, in water-scarce years, drainage- and groundwater are occasionally used for irrigation in some locations (Ibrakhimov 2004).

Drainage systems are mainly open, horizontal, and directed towards the Sarykamish Depression, which used to be linked to the Aral Sea (Conrad 2006). On the right bank of the Amu Darya, in the ARK, the drainage effluent is frequently discharged into the river. The irrigation and drainage systems in the study region were mostly constructed in the 1960s during the Soviet Union era (Kats 1976) for large-scale cotton (*Gossypium hirsutum* L.) production in CA (Tischbein et al. 2012). Today, these systems lack maintenance (Tischbein et al. 2012) resulting in an inefficient water management (Conrad et al. 2012; Tischbein et al. 2012) indicated by huge water withdrawals (Conrad 2006) as well as shallow GWT (Ibrakhimov 2004; Tischbein et al. 2012) and widespread soil salinity (Forkutsa 2006; Ibrakhimov et al. 2007).

Groundwater table depths in the study region are highly dependent on seasonal leaching events, drainage, and irrigation intensity often leading to water logging and related yield reductions (Ibrakhimov 2004). In Khorezm, over 80% of all irrigated areas are reportedly characterized by GWT in the range of 1.2 – 1.5 m (Uzbek Soil Institute 2003), whereas in the southern part of the ARK, levels range from 1.0 – 2.0 m below the soil surface (Mott-MacDonald 2011). Abdullaev (1995) showed that in irrigated areas in the study region only a minor part of the groundwater is discharged to the collectors and percolated to deep soil layers while most of the water evaporates.

2.5 Land use

Since historical times, irrigated agriculture has played a key role in the study region allowing the local population to sustainably nourish themselves. With the development of centrally organized and managed agricultural production systems (*kolchoz* and *sovchoz*) during the Soviet Union era, CA, including the study region, fulfilled the primary agricultural role of producing cotton, fruits and vegetables largely for export to other Soviet republics (Worbes et al. 2006; Wehrheim and Martius 2008).

To this end, during the Soviet Union era, over several decades nearly the whole cropland area in the study region was used for cotton in rotation with alfalfa and experienced a steady increase in the area of irrigated lands (Tsvetsinskaya et al. 2002). Following Uzbekistan's independence from the Soviet Union in 1991, winter wheat replaced fodder crops and received high priority towards achieving national grain security (Wehrheim and Martius 2008). Nevertheless, cotton and wheat production in Uzbekistan is state regulated through a yield quota system, which is assigned to fixed land areas. Imposed yield levels are based on land "bonitet" classes representing the productive capacity of a field (Aminova and Abdullayev 2009).

Since Uzbekistan's independence, farm types and sizes have been restructured through a land reform carried out in four phases differing in speed and level of regulations (Djanibekov et al. 2012a). During the first phase (1991-1998), state farms (*sovkhoses*) were transferred into collectively owned production units (*kolchozes*). The main difference between these two farm types was the source of finance, which in the case of the *sovkhoses* came directly from the state, whereas *kolchozes* were self-financed (Djanibekov et al. 2012a). The second phase of land consolidation (1998-2003) was characterized by the transformation of *kolchozes* into agricultural shareholding cooperatives (*shirkats*), and the intensification of private farming (Djanibekov et al. 2012a). For that purpose, land was partly leased from the *shirkats* to private farms (Djanibekov 2008), which can be considered as first attempt of downsizing agricultural production units from large agricultural cooperatives into private farms (Khan 2005). The third phase of land consolidation (2003-2008) was defined as "decollectivization" and characterized by the intensified disaggregation of large *shirkats* into smaller private farms (Djanibekov et al. 2012a). The fourth phase aimed at the consolidation of small farms into larger ones and consisted of two steps. From autumn 2008-2009, small farms of less than 30 ha were amalgamated into medium-size farms. For that purpose, lease contracts were cancelled by the state and the land became part of bigger production units, typically joining 5-6 smaller farms into one large farm (Djanibekov et al. 2012a). The aim of the ongoing second step of the fourth phase (2009-present) is the further amalgamation of medium-sized farms (Djanibekov et al. 2013).

Aside from the large agricultural farms established on the basis of long-term leases with a commercial orientation in the study region, also *dekhans* existed, which are subsistence-oriented household plots limited by law to 0.25 ha (Wehrheim and Martius 2008) and were not part of the latest restructuring process (Djanibekov et al. 2012a).

Table 2.1 Farm types according to specialization in Khorezm and the three southern districts of Karakalpakstan (Beruniy, Elikqala, and Turtkul).

Specialization	Khorezm		Southern Karakalpakstan	
	Total number of farmers	Proportion	Total number of farmers	Proportion
Cotton/Wheat	2032	43%	776	75%
Livestock	471	10%	113	11%
Horticulture	1281	27%	98	10%
Vineyard	85	2%	-	0%
Vegetables	15	0%	-	0%
Melon/Watermelon	2	0%	-	0%
Sericulture	600	13%	8	1%
Poultry	86	2%	15	2%
Apiculture	10	0%	4	0%
Fishery	173	4%	7	1%
Others	7	0%	8	1%
Total	4762	100%	1029	100%

Source: Based on information from Farmers' Association of the Republic of Uzbekistan (2011); Elikqala and Turtkul District Divisions of State Natural Resource and Land Cadastre of the Republic of Uzbekistan (2011); Beruniy District Division of the Ministry of Agriculture and Water Resource Management of the Republic of Uzbekistan (2011).

Based on the politics of water management, Veldwish and Spoor (2008) distinguished three forms of crop production in the region: state-ordered production including cotton and wheat, (2) commercial production, particularly rice, but to a lesser extent also vegetables and fodder maize, and (3) household production on *dekhans* primarily for home consumption and small-scale sales at local markets. Most farmers specialize in cotton and wheat production or horticulture (Table 2.1) but tend to diversify their production when possible. The main annual crops grown in the region include cotton, wheat, rice, fodder maize, and vegetables, while perennial crops are grapes, apples, peaches, and other fruit trees (Table 2.1).

2.5.1 Forestry

In Uzbekistan, a total of 75 native tree species are to be found (FAO 2005). The forests are state owned and administrated through the Ministry of Agriculture and Water Resources and play only a minor role in the agricultural sector. Latest estimations suggest that the total forest cover hardly changed from 1990 to 2005 (Table 2.2). The lack of more recent inventories and the discrepancies between categories and definitions used in national forest inventories and international standards only allow approximate quantification of the current status and extent of Uzbekistan's forests (FAO 2005).

Table 2.2 Extent of forest and other wooded land in Uzbekistan.

FRA 2005 category	Area (1000 ha)		
	1990	2000	2005
Forest	3,045	3,212	3,295
Other wooded land	-	-	904
Forest and other wooded land	3,045	3,212	4,199
Other land	38,379	38,212	37,225
...of which with tree cover	-	-	-
Total land area	41,424	41,424	41,424
Inland water bodies	3,316	3,316	3,316
Total area of country	44,740	44,740	44,740

Data source: FAO, *Global Forest Resources Assessment (FRA) 2005*.

In the lower ADB, natural forests are restricted to a small transect of *tugai* floodplain forest along the Amu Darya River (Schlüter et al. 2005), and consist mainly of *Populus* spp. but also of *Elaeagnus* spp. and *Salix* spp. These fast-growing, deciduous forests strongly depend on the hydrological regime of the Amu Darya River (Kuzmina and Treshkin 1997). Consequently, the immense decrease in water discharge to the river in the last century has led to a strong degradation of the *tugai* forests (Rüger et al. 2005). Furthermore, trees in forest patches are often illegally cut during the winter to be used as firewood (Kan et al. 2008). Reportedly, the area covered by *tugai* forest has been reduced in the study region by about 90% in the past 60 years (Treshkin 2001).

Another natural forest type included in the present national forest classification in Uzbekistan is the so-called “desert forest” consisting of single shrubs, woody shrubs and herbs. Even though this forest type has important ecological functions such as the protection against erosion and the maintenance of biodiversity, according to international standards it is classified as “other wooded land” (Tupitsa 2010).

Pure tree plantations are rare in the study region and mainly consist of polarded *Morus alba* L. plantations for sericulture, and *Populus* spp. plantations, which are exclusively used for construction wood supply (Worbes et al. 2006; Tupitsa 2010). In the agricultural area, mostly fruit trees are grown, often interplanted with annual crops (Kan et al. 2008).

Multipurpose hedgerows planted at the field boundaries are common in the study region. Mostly planted as windbreaks to reduce wind erosion and improve the microclimate of the adjacent crop fields, multipurpose hedgerows may additionally provide silkworm fodder (*M. alba* leaves), wood for artisan work (*Salix* spp.), and construction wood (*Populus* spp. and *Salix* spp.) (Tupitsa 2010).

In addition, all trees in the study region are used for fuelwood (Worbes et al. 2006), which can be harvested from any tree species but differs in quality (Khamzina et al. 2006).

3 EARLY SURVIVAL AND GROWTH OF SIX AFFORESTATION SPECIES

3.1 Introduction

Setting aside marginal, irrigated cropland for afforestation with salt-tolerant, N₂-fixing tree species has been assessed as a low-input land rehabilitation measure in the ADB, where shallow GWT enable forestry practices with low irrigation input (Khamzina et al. 2012). The irrigation water and fertilizer resources thus saved could be used to intensify the resource use in productive agricultural areas and would hence compensate for the production losses that may occur due to the withdrawal of marginal cropland for afforestation (Martius et al. 2004). At the same time, additional financial benefits could be gained from non-timber forest products (NTFP) and C sequestration (Djanibekov et al. 2012b; 2013). Despite these promising findings, introducing trees is precluded by the current cotton-wheat policy that favors the cultivation of these crops on marginal land regardless of their low productivity (Djanibekov et al. 2012b). It therefore is of interest whether or not afforestation can be expanded to croplands that have been already abandoned from cultivation. There, the rehabilitation of the land's productive potential is particularly difficult due to the ongoing desertification (Genxu et al. 2004), which requires a specific assessment of suitable tree species and silvicultural techniques.

The vast body of research on tree species suitable for phytoremediation and dryland rehabilitation is summarized in the Forestry Compendium (CAB International 2010). Tree-species performance under water, salt, and nutrient stress conditions has also been addressed (e.g., Schonfield 1992; Tomar et al. 2004; Miyamoto et al. 2004; Archibald et al. 2006), but a direct comparison of the findings and their applicability in the ADB has little relevance for the choice of suitable species for afforestation of abandoned croplands in the study region. Previous studies in the lower ADB evaluated the performance of 10 tree species based on their physiological and socio-economic characteristics, but under adequately irrigated and slightly saline conditions (Khamzina et al. 2006; Lamers et al. 2006). The performance of several tree species on highly salinized croplands with shallow GWT was also assessed (Khamzina et al. 2008; 2009;

2012; Djumaeva et al. 2013) based on field research in marginal agricultural areas that were previously used for crop production. In particular, afforestation with the tree species *Elaeagnus angustifolia* L., *Populus euphratica* Oliv., and *Ulmus pumila* L. (Khamzina et al. 2006; Lamers et al. 2006) in areas with shallow, moderately saline groundwater reduced irrigation demand to between 3 and 30 % of the volume required for annual crop cultivation (Khamzina et al. 2008).

The depth to the GWT and associated salinity levels determine tree growth when irrigation water is deficit (Horton et al. 2001). A shallow GWT usually prevails within the irrigated lowlands in the ADB (Tischbein et al. 2012) but cropping sites long-term abandoned from cropping can be characterized by declined GWT due to ceased irrigation practices (Dubovyk et al. 2013a). The current study aims to determine if the previously observed performance of promising tree species in the lower ADB (Khamzina et al. 2012) still applies to abandoned croplands where degradation processes are no longer counterbalanced by agricultural inputs (Dubovyk et al. 2012b). It is hypothesized that other commercially important species also bear a potential for afforestation of abandoned cropping sites if small irrigation inputs are provided to cope with water and salt stress. The latter makes revegetation of the abandoned cropland a particularly challenging enterprise, thus the assessment has to prioritize species stress tolerance. As insecure water availability is the main reason for cropland abandonment in the study region (Tischbein et al. 2012), the feasibility of extending afforestation to such croplands needs to be assessed under deficit irrigation while accounting for the groundwater contribution to plant growth.

The initial survival rate under sub-optimal growth conditions is of core importance when evaluating a species' suitability for afforestation purposes, and influences the amount of biomass and tradable goods from a plantation in the long run. Particularly in short-rotation forestry, where stocking is constant till harvest, the plantation productivity depends on the biomass volume per tree and the number of trees per unit area surviving until the end of the rotation (Chambers and Borralho 1997). Thus, this study used survival rates as well as early biomass increment and partitioning in response to salt and water stress as indicators to evaluate the feasibility of multi-

species afforestation on long-term abandoned cropping sites differing in depth to the GWT during the first two years after planting.

3.2 Material and methods

3.2.1 Study sites

In 2010, two experimental tree plantations were established in the lower reaches of the Amu Darya River: (i) in the Khorezm region of Uzbekistan (G'oybu, 41°30'44.90"N, 60°34'05.60"E), and (ii) in the Beruniy district in the southern part of the ARK (Beruniy, 41°43'03.10"N, 60°49'18.58"E; Figure 3.1). Throughout the 2-year study (2010-2011), air temperature averaged 13.4 °C, reaching its minimum (-18.8 °C) in February and its maximum (42.4 °C) in August. Rainfall amounted to 51 mm yr⁻¹ during the observation period, and occurred mainly in the period from October till December. In May 2010, 30 mm of rainfall were measured during a period of two days (Figure 3.2).

The sites were selected due to their distinct differences in depths of GWT, with a significantly deeper water table in G'oybu compared to Beruniy. The study site selection was based on the region-wide, long-term hydrological survey by Ibrakhimov et al. (2007). This was followed by on-site visits, preliminary measurements and agreements with farmers and regional authorities for the afforestation experiments. The soil in G'oybu had a silt-loamy texture (20% sand, 6% clay, 74% silt) whereas lighter, sandy-loam soil was found in Beruniy (85% sand, 6% clay, 9% silt). The available water content in the rooting zone (top 60 cm), defined as the difference between soil moisture at field capacity and wilting point, amounted to 157 mm and 122 mm in G'oybu and Beruniy, respectively (Appendix 9.1). Both sites had been abandoned for ten years from cotton and rice cropping due to low yields. The examination of soil profiles at the onset of the experiment showed poor to very poor concentrations of macronutrients in the crop rooting zone in both sites (Table 3.1; Appendix 9.2). In 2010, fields surrounding the G'oybu site were cropped with water melon and maize, while in Beruniy, rice and cotton were the dominant crops on the neighboring sites. Year 2011 was characterized by a drought due to a reduced water intake from the Amu Darya for irrigation (Bekchanov et al. unpublished). In this year, a shift to less water demanding

crops was observed on neighboring fields in Beruniy, while in G'oybu there were no cropping activities at all.

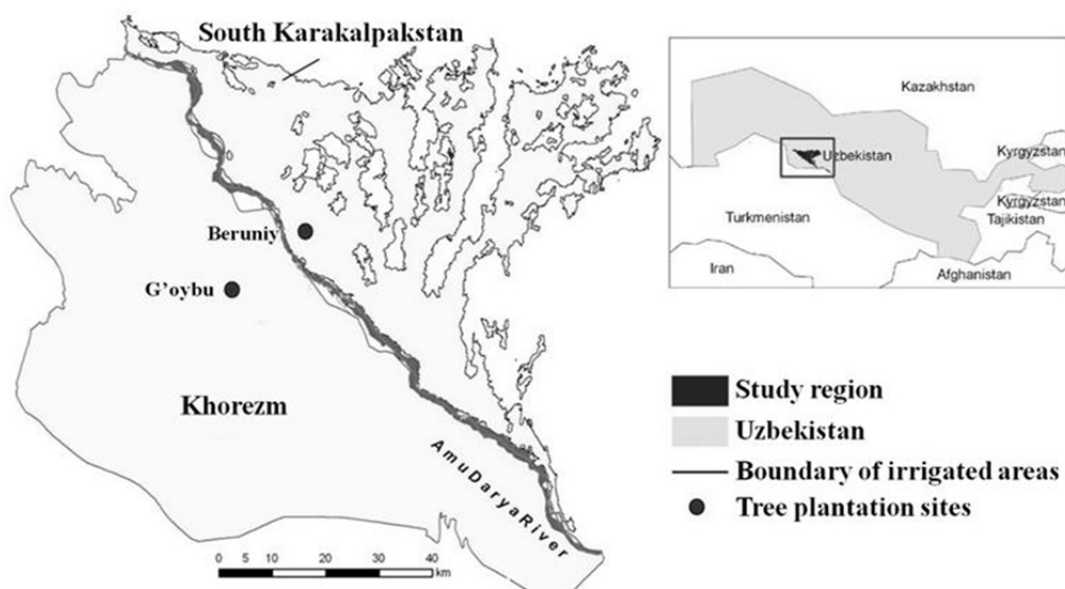


Figure 3.1 Location of the study region and the two study sites G'oybu and Beruniy.

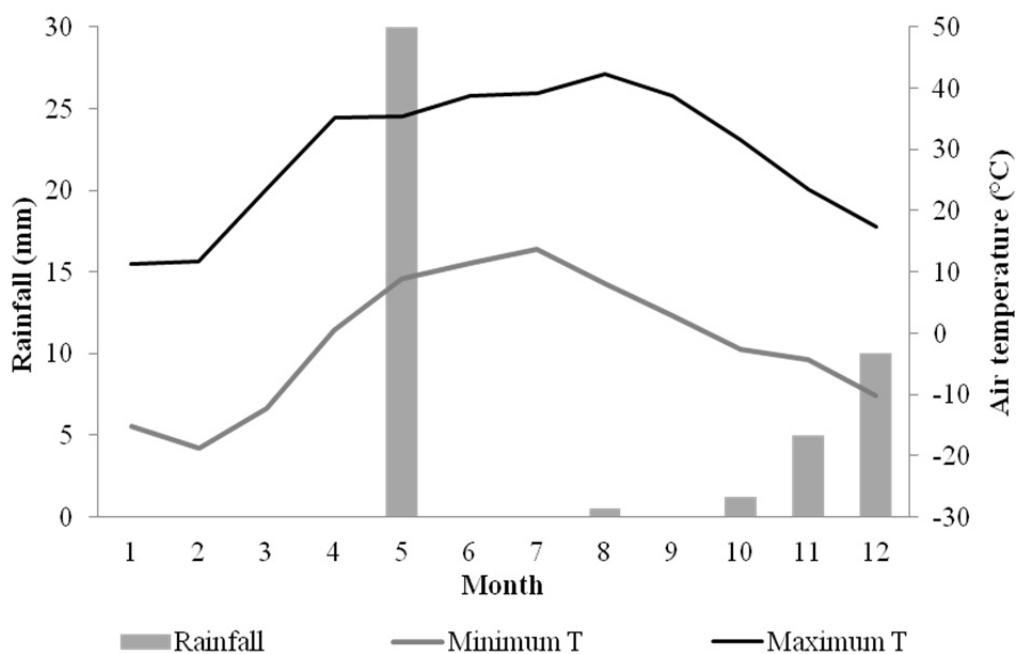


Figure 3.2 Meteorological parameters recorded during the study period from 5/2010 to 10/2011 in G'oybu.

Table 3.1 Soil total nitrogen (N), available phosphorus (P₂O₅), exchangeable potassium (K₂O), and total soil-organic carbon (SOC) at two study sites before afforestation in March 2010.

G'oybu							
Horizon cm	Total N %	P ₂ O ₅ mg kg ⁻¹	Evaluation ¹	K ₂ O mg kg ⁻¹	Evaluation ¹	SOC %	Evaluation ²
0-4	0.046	7.20	Very Low	163.70	Low	0.38	Poor
4-15	0.033	5.00	Very Low	72.20	Very low	0.24	Poor
15-30	0.018	4.70	Very Low	60.20	Very low	0.11	Very Poor
30-60	0.024	4.40	Very Low	72.20	Very low	0.19	Very Poor
60-81	0.020	7.20	Very Low	60.20	Very low	0.14	Very Poor
81-101	0.017	5.00	Very Low	72.20	Very low	0.11	Very Poor
101-115	0.016	5.30	Very Low	72.20	Very low	0.11	Very Poor
115-120	0.019	3.50	Very Low	72.20	Very low	0.13	Very Poor
120-150	0.012	4.10	Very Low	72.20	Very low	0.08	Very Poor
150-188	0.014	4.70	Very Low	72.20	Very low	0.10	Very Poor
Beruniy							
0-1	0.087	30.00	Low	207.10	Moderate	0.97	Rich
1-4	0.075	20.70	Low	223.90	Moderate	0.90	Increased
4-10	0.050	18.50	Low	207.10	Moderate	0.43	Poor
10-20	0.027	10.40	Very Low	240.80	Moderate	0.21	Very Poor
20-30	0.034	7.60	Very Low	257.60	Moderate	0.25	Poor
30-45	0.046	6.80	Very Low	192.60	Low	0.36	Poor
45-60	0.034	6.20	Very Low	163.70	Low	0.28	Poor
60-80	0.021	6.20	Very Low	101.10	Low	0.12	Very Poor
80-112	0.027	5.90	Very Low	149.30	Low	0.17	Very Poor

1: (Musaev 2001); 2: (Krasnouhova et al. 1988)

3.2.2 Tree species

Six tree species were selected for the experiment based on the previously assessed key physiological characteristics and multipurpose potential (Khamzina et al. 2006). All species were indigenous except for the introduced *U. pumila* and *P. nivea x tremula*, both widely planted in the study area for many decades (Table 3.2). *Populus euphratica*, *Salix nigra*, and *E. angustifolia* are natural phreatophytes and common species of the native riparian *tugai* forest where the shallow GWT is essential for ecosystem functioning (Tupitsa 2010). Earlier studies showed that *E. angustifolia* was capable of effective N₂-fixation in saline conditions, thus significantly increasing soil N stocks (Khamzina et al. 2009). Leaves of several species were assessed suitable as fodder for dairy livestock (Lamers and Khamzina 2010), while leaves of *Morus alba* are traditionally used as silkworm feed (Kan et al. 2008). Additional tree products include wicker from

S. nigra, and firewood, which could be harvested from all species but has the highest potential in species that tolerate frequent pruning and re-sprout readily (Lamers and Khamzina 2008).

Table 3.2 Characteristics of the multipurpose tree species included in the experiment.

Species	Family	Non-timber products
<i>Elaeagnus angustifolia</i> L.	Elaeagnaceae	Fruits, leaf fodder, honey
<i>Morus alba</i> L.	Moraceae	Fruits, leaf fodder (silkworms/cattle)
<i>Populus euphratica</i> Oliv.	Salicaceae	Fuelwood, leaf fodder
<i>Populus nivea x tremula</i>	Salicaceae	Fuelwood, leaf fodder
<i>Salix nigra</i> Marsh.	Salicaceae	Wicker, leaf fodder, fuelwood
<i>Ulmus pumila</i> L.	Ulmaceae	Fuelwood, leaf fodder, handcrafts

Modified after Tupitsa (2010)

3.2.3 Experimental set-up and measurements

The experimental sites were set up in a completely randomized block design. Prior to tree planting in March 2010, the sites had been cleared of sparse natural vegetation, represented by shrubby and herbaceous halophytes (*Tamarix* spp., *Cynodon dactylon* L., *Glycyrrhiza glabra* L., *Karelinia caspica* Pall., *Scrophularia leucoclada* Bunge.), levelled and leached of salts. Trees of the six species were planted in pure-species plots that were replicated three times, amounting to 18 plots at each site. Planting density was 6,666 trees ha⁻¹ within 10×10 m plots (1 m ×1.5 m spacing), with a 3.5-m buffer zone between the plots (Figure 3.3). The dense planting scheme was implemented to achieve higher biomass stock per unit of land area in a short time and to thus reduce the waiting period before NTFP could be harvested by the farmers.

After salt leaching, 12-month-old saplings were transplanted from a nursery onto the experimental plots at a depth of about 30 cm. For *S. nigra*, cuttings of 20 cm were used, as saplings were not available.

From March until October in 2010 and 2011, the trees were irrigated weekly at a rate corresponding to 10-15% of the evaporative demand, amounting to a total seasonal application of 154 mm. Different methods were used for implementing the deficit irrigation because of differences in the GWT level and hence in the expected water contribution from the groundwater at the two study sites. In G'oybu, with a

deeper GWT, irrigation was applied via a drip irrigation system consisting of stabilized high-density polyethylene hoses and one pressure self-compensating dripper (C.N.L. type) per tree, a water storage tank, and a 140-mesh disk filter (Figure 3.3). The irrigation rate was controlled by automatic measuring valves shutting down the water supply after the application of the pre-set volume of water. In Beruniy, traditional furrow irrigation (Abdullaev 2003) was applied as previously recommended for tree establishment at shallow GWT locations (Khamzina et al. 2006). Here, the water supply was measured with Cipoletti weirs allowing the estimation of the water inflow from the upstream water depth (Forkutsa 2006). Water depths in the weirs were maintained at the desirable level during the irrigation; water inflow was discontinued after applying the required amount. Whereas for the drip irrigation system, an irrigation interval of one week was used, the Beruniy site was irrigated every two weeks. Otherwise, the amount of irrigation water would not have been sufficient to fill the furrow along its entire length.

For the determination of the initial sapling biomass (above- and below-ground), ten saplings of each species from the planting material used for the plantation set up were randomly selected, separated into roots, stem, branches, and foliage fractions, dried and weighed with an electronic scale to the nearest gram. At the end of the growing season in 2010 and 2011, i.e., 7 and 19 months after planting (MaP), three trees per plot were harvested. The entire coarse root systems were excavated manually. Fresh sub-samples of a known fresh mass from each aboveground fraction were dried at 103 °C in a forced air convection oven until constant weight to allow the dry-weight estimation of the entire fraction. All coarse root systems were dried and weighed to avoid errors in weight estimates due to partial desiccation of roots during excavation. Biomass increment rates were defined as the difference between the average dry weight of the initial planting material and that at 7 and 19 MaP.

Sapling survival was assessed at 3, 9, 12, and 19 MaP by counting the number of living trees per plot. Dead trees were replaced once in March 2011 to maintain a homogeneous plot density in the experiment but were not analyzed.

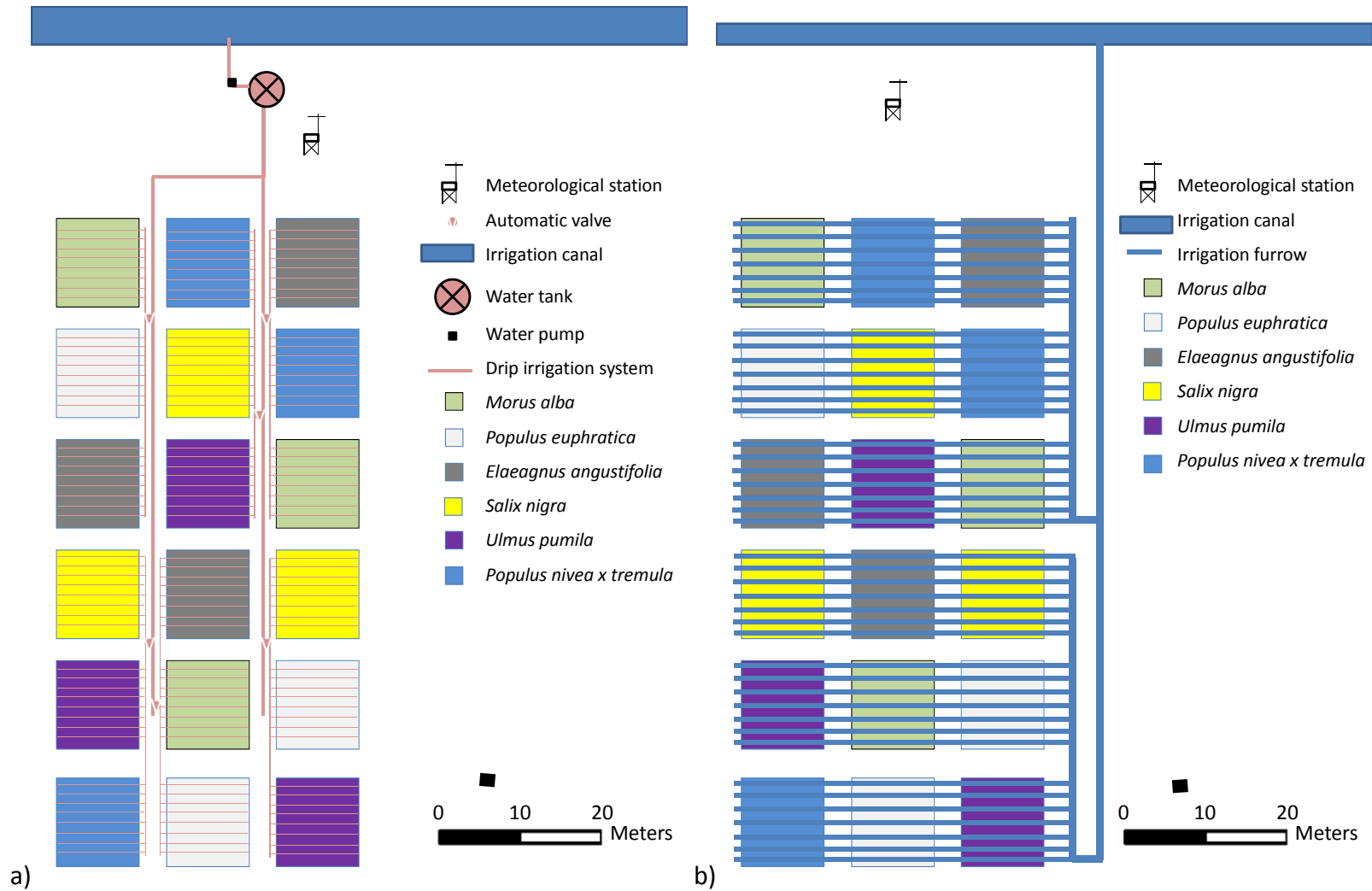


Figure 3.3 Schematic representation of the experimental set up at the G'oybu site (a) and the Beruniy site (b).

The GWT levels were measured in each plot monthly in observation wells installed to 200-220 cm depth. Groundwater salinity was measured with an EC meter each time. Soil was sampled monthly with an auger for measuring salinity and moisture in each plot in 20-cm layers down to 100 cm depth. As a proxy of soil salinity, the electrical conductivity of the saturation paste ($EC_{1:1}$) was measured with a portable EC meter and converted into EC_e using the relationship $EC_e = EC_{1:1} * 3.6$ established for soils in the Khorezm region (Shirokova et al. 2000). Soil moisture was measured gravimetrically and converted into volumetric units using soil bulk density values as determined for the examined soil pits. Current plant available water (CPAW) in the soil was calculated as the difference between the measured volumetric soil moisture and the moisture at the permanent wilting point (Goldammer et al. 1999). For that purpose, pF curves were determined in the laboratory with the pressure membrane method using samples collected from soil pits at both study sites at one MaP.

3.2.4 Statistical analyses

The effects of the species and study site factors on the above- and belowground biomass increment were estimated and tested with the analysis of variance (ANOVA) at a significance level of $p=0.05$. In case the ANOVA showed significant effects, this was followed by a Tukey post-hoc test to compare individual means.

The raw (unadjusted) survival data by species was analyzed using the nonparametric Kaplan-Meier estimator, a key method for analyzing censored survival data (Borgan 2005). Differences between the survival curves of individual species (overall and by site) were tested with a log-rank test. A post-hoc Bonferroni adjusted test was completed to identify the significance of the species effect on each site.

Incidence rates and incidence rate ratios adjusted for ties and dynamic subject effects were estimated with a Poisson model with random effects using generalized estimating equations and tested for their influence on the mortality rates. The relationships between soil salinity and CPAW with tree mortality were considered as target associations, adjusted for the eligible putative known confounders (site, plot, and species). Incidence rate ratios (IRR) were used to analyze the proportional change

in mortality rates when increasing independent variables by one unit (Long and Freese 2006). In the case of CPAW, exposition times were not included in the calculation due to their high variability under irrigation within the measurement intervals. Therefore, incidence rates of the CPAW were not considered in the analysis, but IRR were used as indicators for the CPAW influence on tree survival. All statistical analyses were performed using SPSS 15.0 and the STATA 12.0 software.

3.2.5 Species ranking

The species were ranked for their suitability for afforestation of abandoned croplands in the study area based on the Kaplan-Meier survival curves and the Tukey post-hoc tests of the above- and belowground biomass increments. The survival and growth rates significantly influence the amount of NTFP and the early independence from irrigation due to the groundwater uptake by roots. Based on the differing importance of these criteria, they were respectively weighted 3, 2, and 1 in the ranking.

3.3 Results

3.3.1 Environmental conditions of the afforestation sites

The GWT was significantly deeper in G'oybu than in Beruniy ($p=0.05$) during both growing seasons. During the 2010 season, the GWT fluctuated between 40 and 90 cm below the soil surface in Beruniy, and between 55 and 175 cm in G'oybu, dropping notably at both sites by the end of August (Figure 3.4). In 2011 in Beruniy, the GWT declined slightly, fluctuating between 60 and 120 cm and averaging 93 cm. In G'oybu, the level dropped below 200 cm, which was beyond the reach of the observation wells. In Beruniy, groundwater salinity averaged 3.8 dS m^{-1} in both growing seasons thus exceeding the 2010 average measured in G'oybu (2.5 dS m^{-1}).

Throughout the whole season 2010, the volumetric soil moisture in the rooting zone of 0-60 cm was significantly higher in Beruniy than in G'oybu (Figure 3.5). Nevertheless, no statistical difference in CPAW was observed between the sites, and both averaged 11% in 2010 ($p=0.81$) and 8% in 2011 ($p=0.48$), which was the result of different water holding capacity of the soils in the experimental sites. At both sites, soil

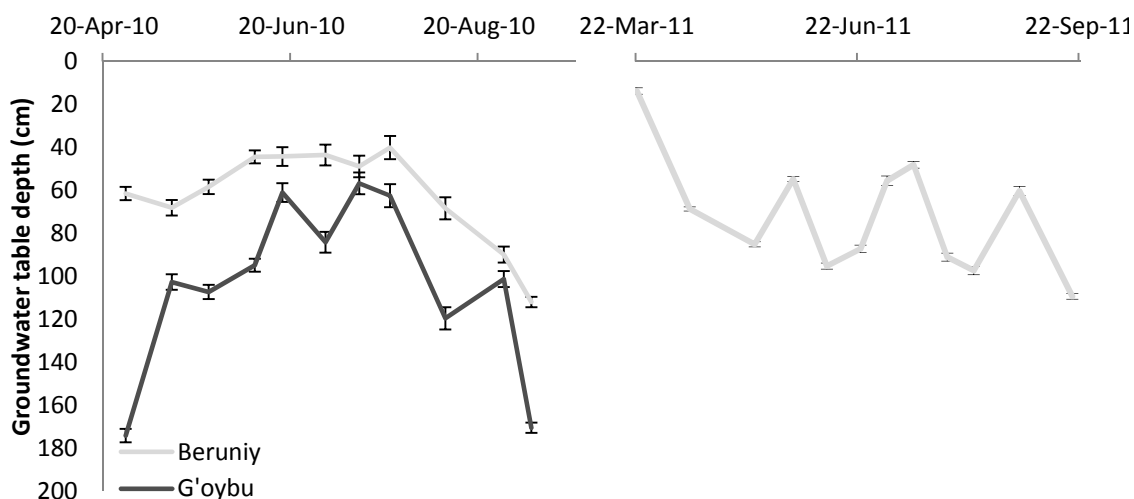


Figure 3.4 Annual course of the groundwater table at two afforestation sites measured with 18 observation wells per site during growing seasons in 2010 and 2011. The groundwater table in G'oybu in 2011 was below the 200 cm reach of the observation wells. Vertical bars indicate 95% confidence intervals.

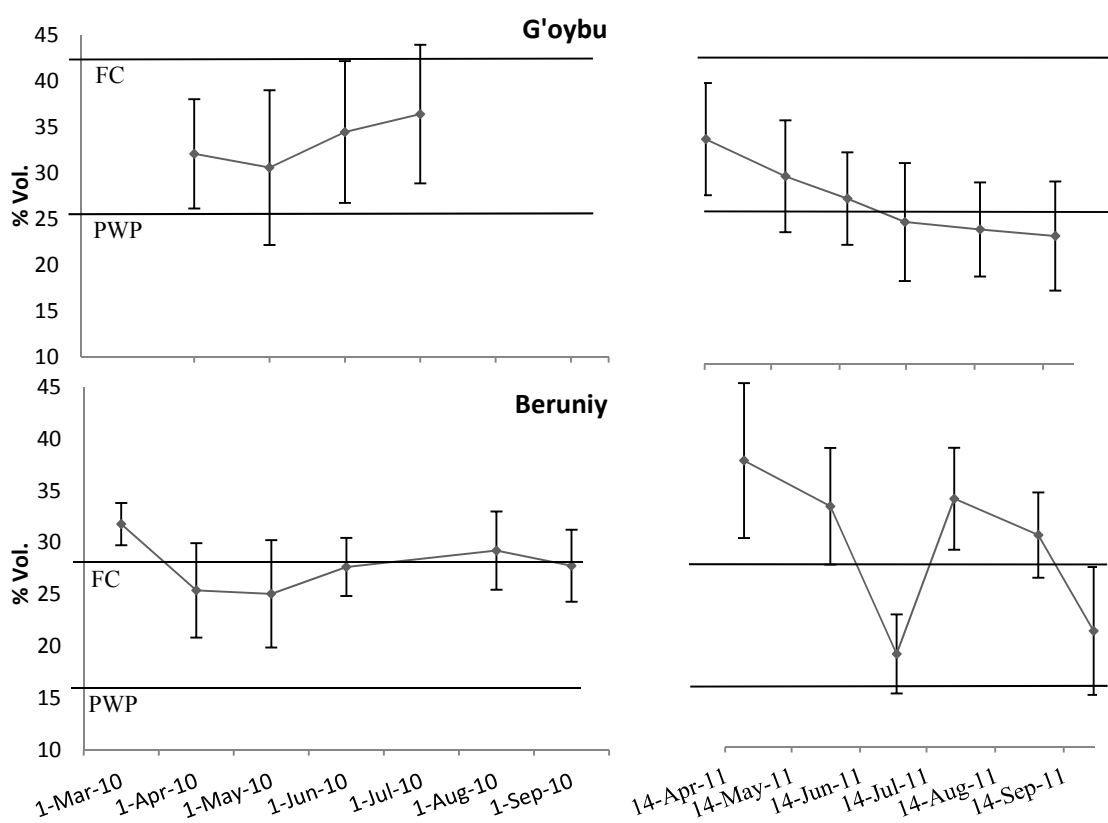


Figure 3.5 Volumetric soil moisture in the rooting zone (0-60 cm) at field capacity (FC), at the permanent wilting point (PWP) and as measured during the observation period on two study sites. Vertical bars indicate 95% confidence intervals.

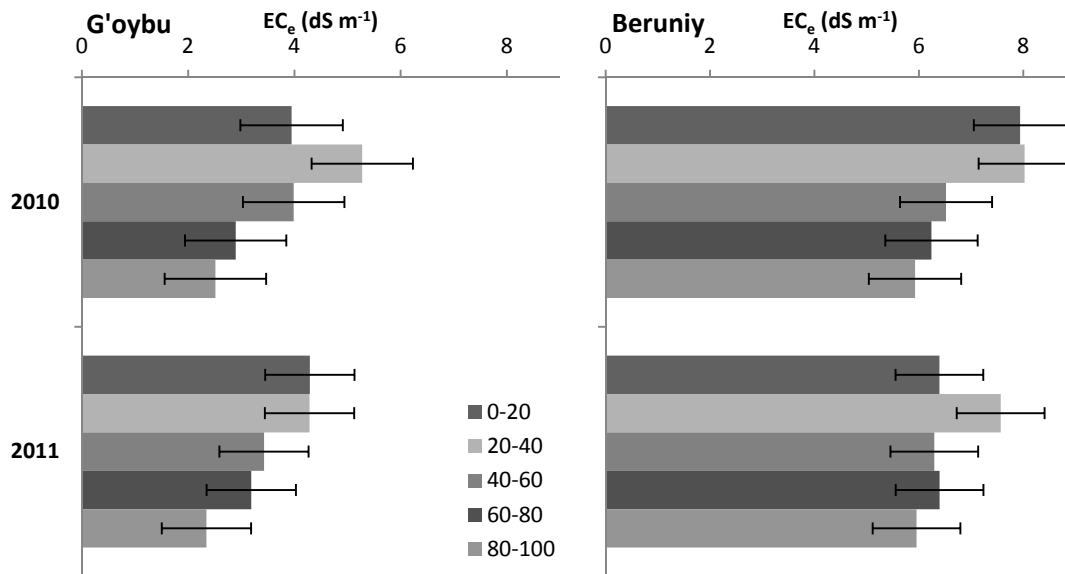


Figure 3.6 Mean of soil electrical conductivity (EC_e) measured monthly during the growing seasons 2010 and 2011 at two study sites according to 20-cm soil horizons. Horizontal bars indicate 95% confidence intervals.

moisture approached the wilting point in the midseason (July), thereafter recovering to the previous level and then dropping again in September in Beruniy. That was in contrast to G'oybu, where it remained at the low level till the end of the growing season.

Soil salinity, indicated by EC_e , varied depending on soil depth and time of the season (Figure 3.6). Generally, salinity levels in Beruniy, in conditions of the shallower GWT, exceeded those in G'oybu during the two-year observation period in all soil horizons ($p=0.05$). Within the soil profile, slightly higher salinity was observed in the topsoil (0-40 cm) on both study sites. During the first season 2010, Beruniy experienced higher salinity in the 0-20 cm and 20-40 cm horizons than below the rooting depth in the 80-100 cm horizon. During the 2011 growing season, no statistically significant differences were observed in Beruniy (Figure 3.6). The soil salinity in G'oybu was significantly higher within the 20-40 cm horizon (5.3 dS m^{-1}) than in the deeper horizons of 60-80 and 80-100 cm in 2010. During the 2011 growing season, the top 40-cm layers (both 4.3 dS m^{-1}) in G'oybu were significantly more saline than the deepest 80-100 cm horizon (Figure 3.6).

In Beruniy, the annual average soil salinity slightly declined from 6.9 dS m^{-1} to 6.5 dS m^{-1} , which is within the medium salinity range (Abrol et al. 1988). In G'oybu, the

inter-annual difference was also insignificant with annual averages of 3.7 dS m⁻¹ and 3.5 dS m⁻¹ in 2010 and 2011, respectively, thus revealing a slightly saline soil (Abrol et al. 1988).

3.3.2 Tree survival

During the 19-month observation period, 2,984 trees were included in the analysis; during the same period 1,580 trees perished (52.95%). Survival rates were higher in G'oybu than in Beruniy throughout the observation period. Comparison of the Kaplan-Meier curves revealed site-specific performances of the tree species (Figure 3.7).

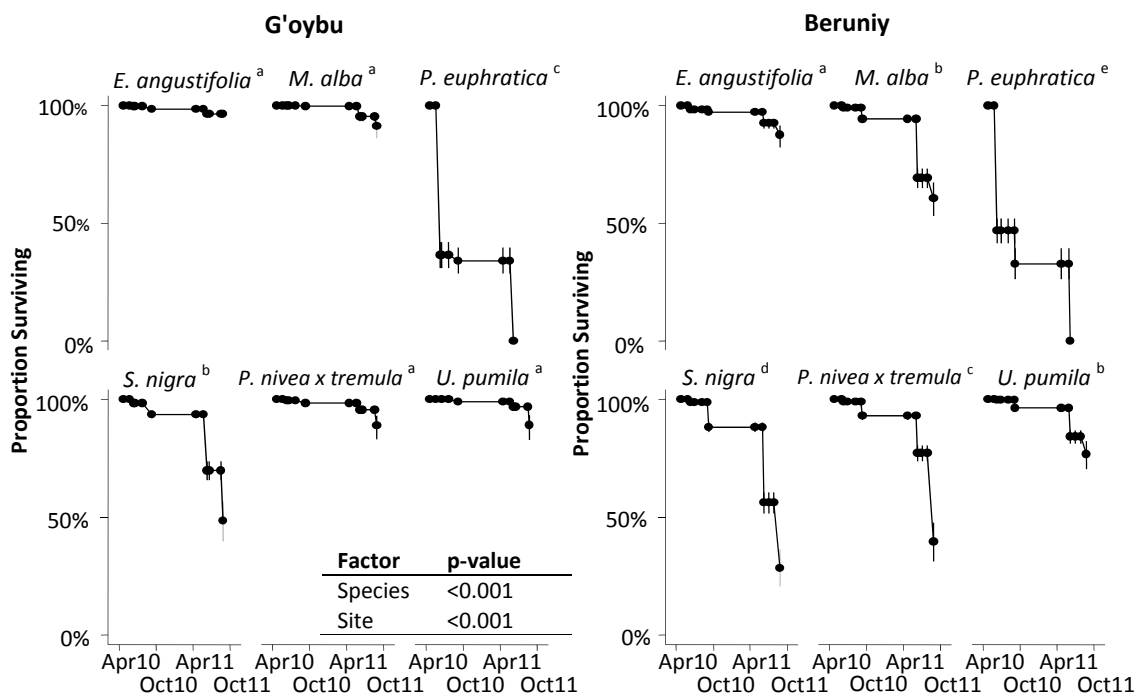


Figure 3.7 Kaplan-Meier survival curves according to species and study sites: log-ranking tests of equality of the main factors. Vertical bars indicate 95% confidence intervals. Caps are omitted to improve readability. Species with different superscripts differ significantly within one site.

In G'oybu, *E. angustifolia*, *M. alba*, *P. nivea x tremula*, and *U. pumila* showed similar survival rates exceeding those of *P. euphratica* and *S. nigra*. In contrast, in Beruniy, *E. angustifolia* outperformed all species whereas *U. pumila* and *M. alba* showed intermediate survival rates (Figure 3.7). Almost 60% of the *P. euphratica* trees on both

sites perished within the first months after planting, and a complete mortality was observed after the second growing period (Figure 3.7).

The CPAW and soil salinity in the rooting zone influenced species' survival rates with different intensity. In all species, increasing mortality was observed along with decreasing CPAW, but this significantly affected only *M. alba* and *U. pumila* (Table 3.3) under the observed range of CPAW (Figure 3.8). The impact of CPAW on these species was similar, as evidenced by their similar IRR_{CPAW} values (Table 3.3). All species except for *S. nigra* were significantly influenced by soil salinity in the observed range of up to 20 dS m^{-1} (in single plot measurements) with significant differences in estimated IRR_{ECe} varying from 1.01 (*U. pumila*) to 1.12 (*P. nivea x tremula*) (Table 3.3, Figure 3.8). *Ulmus pumila* was least impacted by the soil salinity, followed by *E. angustifolia* ($IRR_{ECe}=1.01$ and 1.07 , respectively). The effect of root-zone soil salinity on *M. alba* and *P. nivea x tremula* was much higher, as substantiated by the IRR_{ECe} values (Table 3.3).

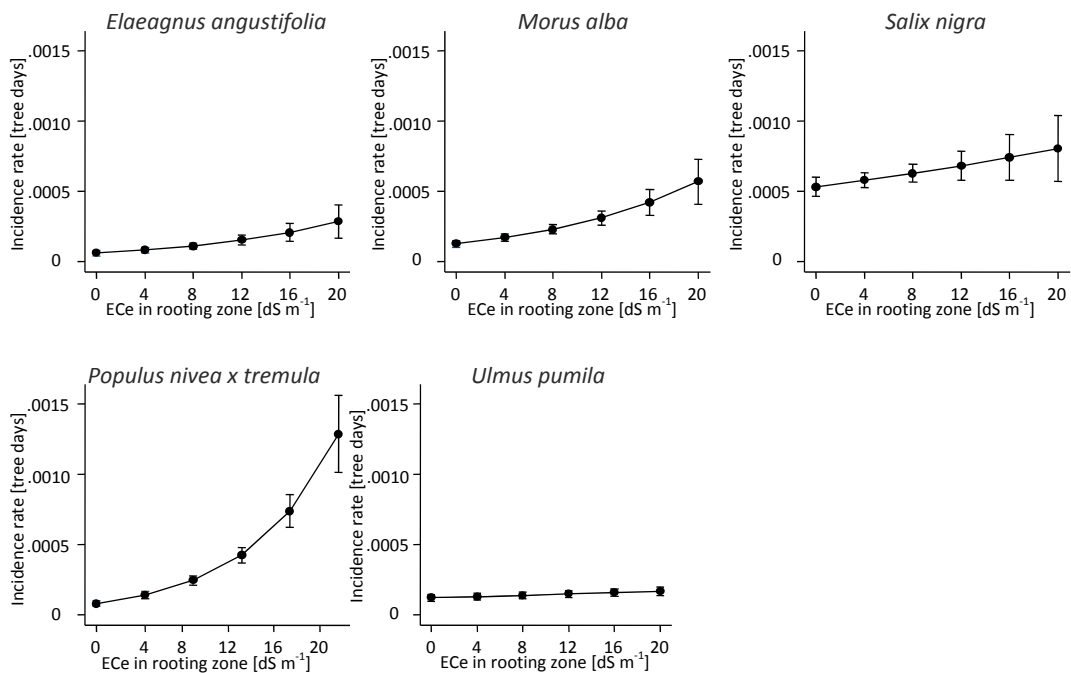


Figure 3.8 Incidence rate curves of the influence of average soil salinity in the rooting zone (EC_e) on the survival of five tree species. The vertical bars indicate 95% confidence intervals.

Table 3.3 Incidence rate ratios (IRR) and corresponding p-values of the correlation of tree survival with the root-zone plant available water (CPAW) and with the root-zone soil electrical conductivity (EC_e).

Species	IRR _{CPAW}	p-value	IRR _{EC_e}	p-value
<i>Elaeagnus angustifolia</i>	0.989	0.475	1.067	< 0.001
<i>Morus alba</i>	0.956	< 0.001	1.096	< 0.001
<i>Salix nigra</i>	0.991	0.400	1.014	0.268
<i>Populus nivea x tremula</i>	0.991	0.430	1.124	< 0.001
<i>Ulmus pumila</i>	0.957	0.013	1.014	0.003

3.3.3 Biomass increment

In both growing seasons, the produced above- and belowground biomass significantly varied according to tree species (Table 3.4; Table 3.5). Neither site nor interaction between site and species was statistically significant. At 7 MaP in G'oybu, *E. angustifolia* and *P. nivea x tremula* showed the highest aboveground biomass increment (ABI) among the species of 473 and 245 kg ha⁻¹ yr⁻¹, respectively. In Beruniy, no significant differences in species ABI were observed (Table 3.4). After the second growing season, biomass increments of *E. angustifolia* were higher than those of all other species on both study sites with ABI ranging from 900 to 1900 kg ha⁻¹ yr⁻¹ in G'oybu and Beruniy, respectively. Differences among the other species were statistically not significant (Table 3.4).

Table 3.4 Average aboveground biomass per tree at planting and increments after the first (7 MaP) and second (19 MaP) growing season according to tree species and study sites. Values with different superscripts in one column differ significantly.

Species	Total Biomass (kg ha ⁻¹) at planting	Aboveground Biomass Increment (kg ha ⁻¹ yr ⁻¹)			
		G'oybu		Beruniy	
		7 MaP	19 MaP	7 MaP	19 MaP
<i>Elaeagnus angustifolia</i>	195.1 ^b	473.4 ^a	1863.8 ^a	377.2 ^a	904.5 ^a
<i>Morus alba</i>	7.0 ^d	87.8 ^b	75.6 ^b	79.8 ^a	62.0 ^b
<i>Populus nivea x tremula</i>	251.9 ^a	245.1 ^{ab}	184.5 ^b	314.8 ^a	207.2 ^b
<i>Salix nigra</i>	61.9 ^c	14.2 ^b	11.8 ^b	28.3 ^a	99.1 ^b
<i>Ulmus pumila</i>	11.4 ^d	174.0 ^b	116.8 ^b	93.8 ^a	99.3 ^b
ANOVA (p-values)					
		7 MaP	19 MaP		
Species		<0.001	<0.001		
Site		0.690	0.470		
Species * Site		0.829	0.188		

Table 3.5 Average belowground biomass per tree at planting and increments after the first (7 MaP) and second (19 MaP) growing season according to tree species and study sites. Values with different superscripts in one column differ significantly.

Species	Total Biomass (kg ha ⁻¹) at planting	Belowground Biomass Increment (kg ha ⁻¹ yr ⁻¹)			
		G'oybu		Beruniy	
		7 MaP	19 MaP	7 MaP	19 MaP
<i>Elaeagnus angustifolia</i>	91.8 ^b	214.4 ^b	633.1 ^a	301.54 ^{ab}	376.6 ^a
<i>Morus alba</i>	11.0 ^c	87.4 ^b	63.3 ^b	87.7 ^{bc}	63.5 ^c
<i>Populus nivea x tremula</i>	193.9 ^a	426.0 ^a	223.0 ^{ab}	396.4 ^a	195.8 ^{ab}
<i>Salix nigra</i>	0.0 ^d	69.6 ^b	80.5 ^b	48.0 ^c	63.1 ^c
<i>Ulmus pumila</i>	17.6 ^c	230.1 ^b	147.7 ^b	138.5 ^{bc}	99.0 ^{bc}
ANOVA (p-values)					
		7 MaP	19 MaP		
Species		<0.001	<0.001		
Site		0.735	0.216		
Species * Site		0.541	0.270		

In terms of annual belowground biomass increment (BBI) at 7 MaP, *P. nivea x tremula* overtook all other species (396 - 426 kg ha⁻¹ yr⁻¹; Table 4). The only exception was *E. angustifolia*, which showed the highest BBI with a borderline difference for *P. nivea x tremula* at 19 MaP (Table 3.5).

3.3.4 Rooting depth

During the whole observation period, rooting depths of all species did not exceed 60 cm (Figure 3.9). Furthermore, no differences in rooting depths among species were observed, and site differences were negligible for both years at p=0.05. Whereas in Beruniy, rooting depths did not significantly increase over time, in G'oybu all species rooted significantly deeper during the second growing season (Figure 3.9).

Early survival and growth of six afforestation species

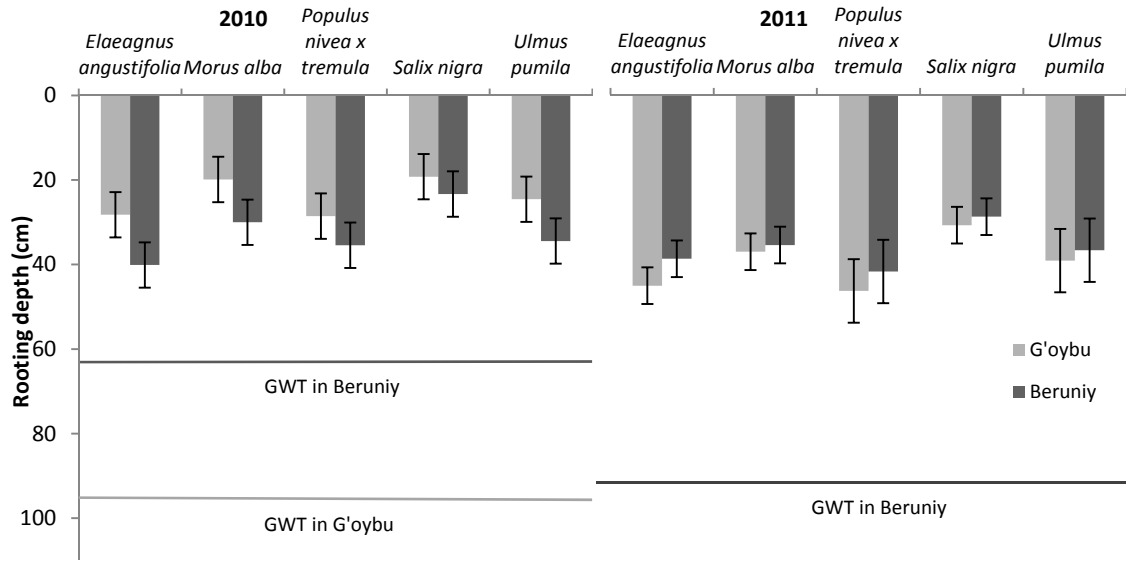


Figure 3.9 Maximum rooting depth of the tree species and average groundwater table depth (GWT) during the 2010 and 2011 growing seasons on two study sites. Vertical bars indicate 95% confidence intervals.

3.3.5 Species ranking

The ranking of species suitability for afforestation differed between the two study sites. Based on the weighted criteria of survival and biomass production, *E. angustifolia* ranked first at the end of the observation period at both study sites (Table 3.6). In G'oybu, *P. nivea x tremula* ranked second followed by *M. alba* and *U. pumila*. In Beruniy, *U. pumila* ranked second followed by *M. alba*. On both study sites, *S. nigra* was outperformed by all other species (Table 3.6). *Populus euphratica* was not included in this ranking due to its early mortality.

Table 3.6 Weighted ranking of tree species suitability for afforestation of abandoned cropping sites in Amu Darya lowlands.

Species	Rank	
	G'oybu	Beruniy
<i>Elaeagnus angustifolia</i>	1	1
<i>Morus alba</i>	3	3
<i>Populus nivea x tremula</i>	2	4
<i>Salix nigra</i>	4	5
<i>Ulmus pumila</i>	3	2

3.4 Discussion

3.4.1 Environmental conditions at abandoned cropping sites

The annual GWT fluctuations at the study sites followed the regional pattern driven by irrigation and leaching activities, with a shallow level observed during the irrigated period of crop growing and a declined GWT in the fall-winter period, after the cessation of irrigation (Ibrakhimov et al. 2007). The GWT subsidence in dry years, as evidenced in the years 2000/2001 in the study region (Ibrakhimov et al. 2007) and, to a lesser extent in 2008 and 2011, was also revealed by the measurements in the present study in 2011. In G'oybu, the drop in the GWT in 2011 as compared to the previous season was more severe due to the prevalence of uncultivated fallow cropland in the surrounds, whereas in Beruniy, cropping and irrigation of the adjacent fields continued, although shifting towards less water-demanding crops. These differences in GWT between the study sites were reflected in the soil moisture dynamics. The soil moisture in G'oybu steadily declined towards the wilting point in the drought year 2011, due to the tree water use and drastic reduction in the GWT contribution to the soil moisture content. In Beruniy, the decline was likely compensated by the underground inflow from the neighboring irrigated fields.

The deficit irrigation applied weekly at the afforestation sites counteracted the topsoil desiccation, thus supporting the survival and growth of the tree plantations. However, under conditions of declined GWT in G'oybu, larger amounts should have been applied to increase the moistened zone and stimulate root proliferation in depths below the observed 60 cm. Given the precarious availability of irrigation water in drought years, particularly in abandoned cropland parcels with deeper GWT (Dubovyk et al. 2012b), afforestation on such sites is associated with an increased risk of water stress.

A shallow GWT significantly contributes to soil salinity (Forkutsa et al. 2009) when it exceeds a certain threshold level, above which it rises by capillarity towards the soil surface (Hillel 2000). This effect was pronounced in Beruniy, where moderately saline GWT during the entire observation period exceeded 1.5 m, defined as the threshold level in Khorezm (Rakhimbaev 1992), and was also 1.5 times more saline

than in G'oybu. In consequence, the Beruniy site was characterized by higher soil salinity, at times above 8 dS m^{-1} hence beyond the tolerance of salt-sensitive plants (Kotuby-Amacher et al. 2000). This impacted tree survival and biomass production.

3.4.2 Tree survival and biomass growth in response to stress factors

Among the tested species, only *E. angustifolia* performed soundly on both N-poor sites, given its ability for N_2 -fixation (Khamzina et al. 2009). Next to the nutrient status, the depth to the GWT and associated moisture and, particularly, salt regimes may explain the monitored differences in tree survival between the sites, as observed regularly in shallow groundwater environments (Horton et al. 2001).

In conditions of declined GWT, as in G'oybu, the deficit irrigation ensured moisture in the topsoil, as evidenced by the observed survival rates of over 90% in most of the tested species, i.e., *E. angustifolia*, *P. nivea* x *tremula*, *U. pumila*, and *M. alba*. Nevertheless, survival rates of the latter two species were seen to depend on the amount of the soil moisture available in the rooting zone (as reflected in IRR_{CPAW}). This indicates a higher water demand of these species, possibly to counterbalance the adverse impact of salinity, the most important stress factor for plant growth in irrigated croplands (Hillel 2000).

Under the measured salinity range ($0\text{-}20 \text{ dS m}^{-1}$), all species except *S. nigra* were affected to a different extent. *Ulmus pumila* and *E. angustifolia* showed lowest IRR_{ECe} values illustrating a relatively high tolerance to soil salinity, as expressed in their best survival among the tested species at the more saline Beruniy site. This result is in line with the salt tolerance ranking by Miyamoto et al. (2004) who stated that *E. angustifolia* was able to tolerate salinity levels of $6\text{-}8 \text{ dS m}^{-1}$, and so was *U. parvifolia*, the only representative of *Ulmus* genus in this list. All other species included in the present experiment were classified by Miyamoto et al. (2004) as "sensitive", meaning that they start to show stress signs from 3 dS m^{-1} onwards. Although the salinity tolerance of tree species depends on the genetic potential, tolerance is known to increase in older trees as well as under more favorable soil moisture and nutrient conditions (Kozlowski 1997).

In contrast to survival, the ANOVA revealed no significant site effect on biomass increments. The tree-biomass increments, above- and belowground, significantly differed only with respect to the species. The observed annual biomass increments for all species were up to five times lower compared to those in assessments of tree species' potential for afforestation of low-productive irrigated croplands in the same region (Khamzina et al. 2008; Djumaeva et al. 2013). The lower biomass production in the present experiment was likely the result of the cumulative stress observed at the abandoned cropping sites, including water deficit, known to negatively affect tree growth by inhibiting cell elongation and CO₂ uptake (Chapman-King et al. 1986). In contrast to the previous afforestation trials, where tree roots established access to the GWT moisture already during the first growing season, the root-groundwater interface was weaker in the G'oybu site with its relatively deep GWT. Although the rooting systems in G'oybu deepened in response to the GWT decline in the drought year 2011, most of the water demand was satisfied by the applied irrigation. Consequently, larger biomass increments can be expected with increased root contact with the groundwater following a rise of the GWT in subsequent, non-drought years.

3.4.3 Species ranking and implications for afforestation of abandoned cropland

The species ranking was generally in agreement with previous studies in the lower ADB that emphasized the potential of *E. angustifolia* for the afforestation of low-productive irrigated croplands (Khamzina et al. 2006; 2008; Djumaeva et al. 2013). Nevertheless, the pronounced differences in species survival between the two study sites imply that a broad generalization and extrapolation of the results obtained in marginal croplands to long-term abandoned cropping sites should be avoided when selecting appropriate candidates for afforestation of the latter. In particular, the sensitivity of *U. pumila* and *M. alba* to soil water depletion might require higher irrigation inputs when planting these species on abandoned cropping sites characterized by a lower GWT.

The declining survival of *S. nigra* was linked neither to moisture nor to salinity variation in the root zone. The probable reason for the observed mortality is that unrooted cuttings were used as planting material. When planted as rooted saplings in other afforestation trials on sandy and silt-loamy, slightly saline hydromorphic soils, *S.*

nigra showed similar survival rates to those of *E. angustifolia*, *U. pumila*, and *M. alba* (Khamzina et al. 2006). Therefore, the influence of the used planting material on tree survival on degraded lands should be studied.

The low survival rate of *P. euphratica* (<50%) was previously observed in tree plantations on marginal, highly saline sites and also on productive farmland with over 0.9 – 2.0 m deep GWT in Khorezm (Khamzina et al. 2008). This was also generally reported with respect to artificial propagation of this species outside its natural habitat, i.e., riparian forest (Wang et al. 1996). Long-term monitoring on the marginal site in Khorezm showed effective regeneration of *P. euphratica* via root suckering in consequent years (Khamzina et al. 2008). In contrast, trees in our study exhibited continuous mortality over the 2-year observation period, resulting in nil survival in the second, drought-affected year 2011. Given such a high sensitivity to water stress, the risk of which increases in abandoned cropping sites, *P. euphratica* is not recommended for the afforestation in such locations.

All in all, our afforestation experiments demonstrate the elevated risk of afforesting croplands that have been abandoned from cropping for a long period. Especially during drought years frequently occurring in the study region (Tischbein et al. 2012), both the accessibility of the GWT and the availability of irrigation water reduce and might not be sufficient for coping with salt stress during the early growth phase. This consequently limits the range of species to be included in afforestation of the abandoned cropping sites. Biomass production was likewise reduced, which might result in lower financial benefits than those estimated from afforestation of marginal croplands (Djanibekov et al. 2012b). However, the observed biomass production in the afforested plots is likely to be higher than on the abandoned cropping sites that were naturally revegetated by halophytic plants and showed sparse land cover (Dubovyk et al. 2012b). In this view, a cost-benefit analysis is strongly recommended before defining the overall viability of afforestation versus the natural vegetation succession on abandoned croplands and their use for grazing.

3.5 Conclusions

The results of the afforestation trials generally support the feasibility of extending afforestation efforts to cropland parcels that have been abandoned for a long period, but underline the importance of a site-specific assessment given the increased risk and input needs. A higher risk of the venture is particularly present in drought periods, which cause a decline in the GWT, thus requiring higher irrigation inputs to ensure early survival and growth of trees. On the other hand, tolerance to salinity stress was confirmed to be the factor determining tree survival under the observed moisture and nutrient status of the soils. Tree growth rates are expected to increase due to enhanced GWT in subsequent, non-drought years. The success of afforestation on abandoned croplands should therefore be evaluated over a longer observation period.

In agreement with previous studies in the Amu Darya lowlands, the most promising afforestation species appeared to be N₂-fixing *E. angustifolia* and, to a lesser degree *U. pumila*, which performed with relative consistency on both sites. *Populus nivea x tremula* and, to a lesser degree *M. alba*, should be considered for less saline sites only. Using cuttings as planting material is generally to be avoided on abandoned croplands. The modest growth rates observed demand the assessment of the economic feasibility of afforestation as opposed to leaving the land fallow for natural revegetation.

Since *E. angustifolia* was the only N-fixer among all tested species and outperformed all other species, it seems that N₂-fixation should be considered as a core selection criterion when seeking suitable afforestation species also for saline environments. The amount of N fixed by *E. angustifolia* needs to be determined in order to evaluate the competitive advantage in terms of the nutrient availability this species has over non-fixing species. In the following chapter, an analysis of the capability of *E. angustifolia* to fix N under saline and nutrient-poor conditions and the actual amount of fixed N by during the study period is presented.

4 NITROGEN FIXATION BY *ELAEAGNUS ANGUSTIFOLIA* L. IN THE REVEGETATION OF ABANDONED CROPLANDS

4.1 Introduction

Suitable tree species for afforestation of abandoned croplands besides being salt tolerant should be able to overcome a deficiency in soil nitrogen (N), which is one of the most limiting factors for crop production in the lower ADB (Kienzler et al. 2007). In this context, biological nitrogen fixation (BNF) is an efficient N source for leguminous crops (Peoples et al. 1995). Associated with trees, BNF is part of the functioning of many ecosystems from natural woodlands to plantations and agroforestry systems (Boddey et al. 2000), and is frequently used as an N supplier for intercropped non-N-fixing commercial woody crops (e.g., Danso et al. 1992). Furthermore, BNF plays an important role in land remediation (Zahran 1999) and rehabilitation of degraded soils (Dommergues 1995; Masutha et al. 1997). Nitrogen-fixation by trees can nevertheless be restricted by soil salinity and a lack of soil moisture affecting the symbiosis and the host plant growth, and by a deficiency in the soil nutrients, especially phosphorus (P), essential for the energy consuming process of BNF (Danso et al. 1992; Djumaeva et al. 2013).

Among all species in the current study, *Elaeagnus angustifolia* L., an actinorhizal tree species, was revealed to be relatively immune to the prevailing stress conditions on abandoned cropland, combining high survival rates with adequate biomass production (Chapter 3). The outstanding performance of *E. angustifolia* in comparison with that of the other tested species is most likely linked to its BNF ability. Particularly during the establishment phase of a plantation, the amount of N fixed strongly influences the early growth and further development of the trees (Khamzina et al. 2009, Djumaeva et al. 2010). Although the N-fixing capability of *E. angustifolia* in the study region was confirmed on salt-affected croplands in earlier studies (Khamzina et al. 2009; Djumaeva et al. 2010; 2013), the observed fixation rates varied with plantation age, and were significantly influenced by the amount of P in the soil (Khamzina et al. 2009; Djumaeva et al. 2010; 2013). Information on the N-fixing performance of *E. an-*

gustifolia on abandoned cropland, where water and salt stress was seen to significantly influence tree survival (Chapter 3), remains to be determined. Nevertheless, such information is crucial for assessing the suitability of *E. angustifolia* trees as an N source in afforestation systems, and the impact of tree plantations on soil nutrient fertility in the long run.

Quantifying N₂-fixation in trees remains difficult due to their large size and perennial nature (Danso 1995; Boddey et al. 2000). Additionally, estimations may differ according to the method used (Sellstedt et al. 1993; Boddey et al. 1995). To enhance the reliability of the estimates, combining different methods is recommended for the evaluation of the amount of N fixed. In addition, the choice of the non-N-fixing reference plant is known as a source of variability in BNF estimates (Unkovich et al. 2008), requiring several suitable species as a reference (Danso et al. 1992; Högberg 1997).

The relatively cheap and simple N difference method (NDM) is able to provide a time-integrated estimation of N fixation by comparing total N accumulation by N-fixing plants and non-N-fixing reference plants. Despite its limitations resulting from the principal assumption that N-fixing and non-N-fixing plants acquire the same amount of N from the soils, which in most cases is not robust, the NDM can give a preliminary approximation of the amount of N fixed (Unkovich et al. 2008). Since the NDM is most robust when used in low-N soils and when differences in growth between the N-fixing and reference plants are large (Unkovich et al. 2008), it can be used to obtain first estimates of amounts of N fixed in degraded croplands.

¹⁵N isotopic methods are currently regarded as most promising for the quantification of N₂-fixation in woody perennials (Boddey et al. 2000). These methods estimate the proportion of N derived from the atmosphere (%Ndfa) by comparing the natural abundance in ¹⁵N ($\delta^{15}\text{N}$) of the N-fixing plant to a non-N-fixing reference plant (Shearer & Kohl 1986). Originally developed for legumes, ¹⁵N isotopic methods were successfully applied to actinorhizal trees (e.g. Domenach et al. 1989; Sprent et al. 2000), including *E. angustifolia* (Khamzina et al. 2009; Djumaeva et al. 2010; 2013).

The current assessment aimed (1) to quantify the amount of N fixed by *E. angustifolia* in the two plantations established on abandoned cropping sites in the lower reaches of the Amu Darya River, and (2) to compare the results of the NDM and 15NAM to evaluate the robustness of the estimations and applicability of the two methods for tree plantations growing in arid conditions on cropland soils characterized by salinity and nutrient deficiency.

4.2 Materials and methods

4.2.1 Soil conditions

In G'oybu, available soil phosphorus (P_2O_5) was classified according to Musaev (2001) as very low over the whole soil profile. In Beruniy, it ranged from low in the top 10-cm to very low in deeper soil layers (Table 3.1). Initial pH values in the top 60-cm rooting zone were 8.0 and 7.6 in G'oybu and Beruniy, respectively. Whereas in G'oybu, no significant changes were measured during the 2-year study period, the measured pH values ranged between 7.5 and 8.1 in Beruniy for all tree plots and the reference site (Figure 5.8). Further information on soil properties prior to the afforestation is presented in section 3.3.1.

4.2.2 Plant sampling

The experimental set-up included pure-species plots completely randomized over the plantation area. Therefore all five non-N-fixing tree species in the afforestation trial (Table 3.2) served as reference plants in the quantification of BNF by *E. angustifolia*.

In September 2011, during the plantation harvest for the biomass measurements at the end of the second growing season (section 3.2.3), one tree in each plot was sampled to analyze N concentrations (% N) and $\delta^{15}N$ in all bio-fractions with a mass spectrometer (ANCA-SL/20-20SerCon, UK). Prior to the analysis, the samples were dried to constant weight at 60°C and finely ground.

4.2.3 Quantification of biological nitrogen fixation

Nitrogen difference method

The NDM relies on the differences between the amounts of N accumulated by an N-fixing and a non-fixing plant over a certain period of time. It assumes that two plants of similar phenology and structure use the same amount of N from the soil. The amount of N fixed by *E. angustifolia* was therefore calculated as:

$$\text{BNF} = N_{\text{yield fix}} - N_{\text{yield ref}} \quad (4.1)$$

where BNF ($\text{kg ha}^{-1} \text{ yr}^{-1}$) is the amount of N fixed from the atmosphere by the N-fixing species, $N_{\text{yield fix}}$ and $N_{\text{yield ref}}$ are the amount of N accumulated in the tissue of the N-fixing and the non-fixing reference plants, respectively, within one year. The average annual dry biomass increments per each tree fraction were multiplied with the corresponding measured % N to calculate the absolute N_{yield} per fraction. Fraction values were summed up per tree and converted into kg ha^{-1} considering the density of 6666 trees ha^{-1} .

¹⁵N natural abundance method

The 15NAM method exploits naturally occurring differences in $\delta^{15}\text{N}$ between plant-available N sources in the soil and gaseous N in the atmosphere (Boddey et al. 2000), relying on the commonly observed natural enrichment in ¹⁵N (heavy isotope of N) of soil mineral N compared to atmospheric N (Shearer et al. 1978). The percentage of N derived from the atmosphere (%Ndfa) was calculated based on $\delta^{15}\text{N}$ in plant tissues according to Shearer and Kohl (1986):

$$\% \text{Ndfa} = \frac{\delta^{15}\text{N}_{\text{ref}} - \delta^{15}\text{N}_{\text{fix}}}{\delta^{15}\text{N}_{\text{ref}} - \text{B}} \times 100 \quad (4.2)$$

where $\delta^{15}\text{N}_{\text{ref}}$ is the natural abundance in ¹⁵N of the reference (non-fixing) tree species, $\delta^{15}\text{N}_{\text{fix}}$ is the ¹⁵N natural abundance of the fixing species (*E. angustifolia*) and B is the $\delta^{15}\text{N}$ of *E. angustifolia* when entirely dependent on atmospheric N. Whole-plant $\delta^{15}\text{N}$ was calculated as weighted means of the tree fractions. As suggested by Peoples et al.

(2002), the smallest observed $\delta^{15}\text{N}$ in the experiment (-2.47‰) was used as the B-value due to the lack of an experimentally obtained B-value on *E. angustifolia* in literature. The annual amount of N fixed ($\text{kg ha}^{-1} \text{ yr}^{-1}$) was estimated by summing up the N content of each tree fraction multiplied with the calculated %Ndfa and considering the stand density of 6,666 trees ha^{-1} .

4.2.4 Statistical analyses

The effects of the experimental factors (species and study site) and their interaction on % N and $\delta^{15}\text{N}$ were tested with an ANOVA at a significance level of $p = 0.05$. Each tree was considered a replicate. In case the ANOVA showed significant effects, a Tukey post-hoc test by sites was done to compare individual means. The statistical analyses were performed using the STATA 12.0 software.

4.3 Results

4.3.1 $\delta^{15}\text{N}$

In G'oybu, statistical differences in $\delta^{15}\text{N}$ among tree fractions could be observed in *S. nigra*, *P. euphratica*, and *U. pumila*. The biggest differences of more than 5‰ were observed in *S. nigra* showing a $\delta^{15}\text{N}$ of -0.84‰ in leaves, which was significantly lower than in all other fractions (Table 4.1). The $\delta^{15}\text{N}$ of *P. euphratica* was highest in stem (1.79‰) and coarse roots (1.70‰), exceeding that in leaves by 3‰. The $\delta^{15}\text{N}$ values of *U. pumila* in G'oybu were homogeneous within the tree except for the foliar value, which was significantly lower than that of the other fractions. In Beruniy, no significant differences in $\delta^{15}\text{N}$ were observed among fractions in any species although the values, e.g., in *E. angustifolia*, varied from slightly positive to highly negative (Table 4.1). The overall ANOVA showed that weighted means of $\delta^{15}\text{N}$ differed between the sites ($p < 0.001$) and among the species ($p < 0.001$). Also, the interaction of these factors had a significant influence on weighted $\delta^{15}\text{N}$ ($p < 0.05$). In G'oybu, the weighted mean of $\delta^{15}\text{N}$ in N-fixing *E. angustifolia* (-1.20‰) differed by at least 2‰ from the positive $\delta^{15}\text{N}$ in the non-fixing species. In Beruniy, the weighted $\delta^{15}\text{N}$ of *E. angustifolia* (-1.46‰) significantly differed only from that of *P. nivea x tremula* (1.78‰) (Table 4.1).

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Table 4.1 $\delta^{15}\text{N}$ [‰] and nitrogen concentrations [%] in tree fractions and whole-tree weighted means in six tree species measured in the study sites at 19 months after planting. $\delta^{15}\text{N}$ and N contents with different superscripts in one column differ significantly for fractions. Weighted $\delta^{15}\text{N}$ with different capital superscripts differ significantly for species within each site.

$\delta^{15}\text{N}$, ‰												
Fraction	G'oybu						Beruniy					
	<i>Morus alba</i>	<i>Populus euphratica</i>	<i>Elaeagnus angustifolia</i>	<i>Salix nigra</i>	<i>Ulmus pumila</i>	<i>Populus nivea x tremula</i>	<i>Morus alba</i>	<i>Populus euphratica</i>	<i>Elaeagnus angustifolia</i>	<i>Salix nigra</i>	<i>Ulmus pumila</i>	<i>Populus nivea x tremula</i>
Leaves	-0.10 ^a	-1.13 ^b	-1.64 ^a	-0.84 ^b	0.90 ^b	1.77 ^a	0.02 ^a	0.58 ^a	-1.06 ^a	0.08 ^a	0.73 ^a	0.76 ^a
Stem	0.66 ^a	1.79 ^a	-1.05 ^a	1.31 ^b	2.06 ^{ab}	2.36 ^a	0.04 ^a	0.01 ^a	-1.55 ^a	0.71 ^a	2.06 ^a	2.24 ^a
Twigs	0.43 ^a	0.96 ^{ab}	-1.29 ^a	0.24 ^b	2.13 ^{ab}	0.86 ^a	-0.12 ^a	0.10 ^a	-1.72 ^a	-0.43 ^a	1.70 ^a	1.45 ^a
Coarse roots	1.32 ^a	1.70 ^a	-0.90 ^a	5.01 ^a	3.25 ^a	2.59 ^a	0.52 ^a	-0.16 ^a	-1.50 ^a	0.23 ^a	1.44 ^a	1.82 ^a
Fine roots	1.11 ^a	1.11 ^{ab}	-1.20 ^a	1.73 ^b	2.33 ^a	2.00 ^a	0.49 ^a	0.77 ^a	0.15 ^a	-0.35 ^a	1.66 ^a	2.28 ^a
Weighted mean	0.73 ^{BC}	1.12 ^{BC}	-1.20 ^C	4.33 ^A	2.19 ^{AB}	2.11 ^{AB}	0.16 ^{AB}	0.03 ^{AB}	-1.46 ^B	0.18 ^{AB}	1.46 ^{AB}	1.78 ^A
N, %												
Leaves	1.09 ^a	1.24 ^a	1.62 ^b	0.87 ^a	0.93 ^a	1.70 ^a	1.38 ^a	1.19 ^a	1.78 ^a	1.34 ^a	1.35 ^a	1.69 ^a
Twigs	0.51 ^b	0.37 ^b	1.03 ^c	0.38 ^b	0.47 ^b	0.40 ^b	0.55 ^b	0.32 ^b	0.93 ^a	0.34 ^b	0.60 ^b	0.66 ^b
Stem	0.41 ^b	0.29 ^b	0.91 ^c	0.37 ^b	0.40 ^b	0.21 ^b	0.41 ^b	0.27 ^b	0.89 ^a	0.33 ^b	0.49 ^b	0.36 ^b
Coarse roots	0.41 ^b	0.21 ^b	1.45 ^b	0.19 ^b	0.32 ^b	0.21 ^b	0.47 ^b	0.29 ^b	1.36 ^a	0.44 ^b	0.49 ^b	0.36 ^b
Fine roots	0.39 ^b	0.35 ^b	2.45 ^a	0.44 ^b	0.34 ^b	0.33 ^b	0.56 ^b	0.36 ^b	1.66 ^a	1.20 ^a	0.44 ^b	0.55 ^b
Weighted mean	0.57 ^B	0.41 ^B	1.29 ^A	0.25 ^B	0.46 ^B	0.31 ^B	0.62 ^B	0.45 ^B	1.36 ^A	0.48 ^B	0.65 ^B	0.57 ^B

4.3.2 Nitrogen concentrations

Nitrogen concentrations in the biomass differed among species ($p < 0.001$), fractions ($p < 0.001$), and sites ($p = 0.029$). Furthermore, the interactions between the species and fraction factors were important ($p < 0.001$) but not the interaction between site and species ($p = 0.056$). The average N concentration was highest in *E. angustifolia* at both sites (1.29 - 1.36%), whereas the differences among the other species were not significant (Table 4.1). Generally, N concentrations were higher in the leaves for all species except for *S. nigra* at Beruniy, whose foliar value did not significantly deviate from that of the fine roots. Furthermore, in G'oybu, nodulated fine roots of *E. angustifolia* showed a higher N concentration (-2.45%) in comparison to the other bio-fractions and overall in the dataset. This value was followed by that of leaves (1.62%) and coarse roots (1.45%). In Beruniy, differences in N concentrations among biomass fractions of *E. angustifolia* were not statistically significant (Table 4.1).

4.3.3 Nitrogen yields

At both study sites, total N yields were highest in *E. angustifolia* (16.60 – 30.76 kg ha⁻¹; Table 4.2). Among the reference species, *S. nigra* (0.23 – 0.86 kg ha⁻¹) and *M. alba* (0.86 - 0.90 kg ha⁻¹) had the lowest N yields at both sites, whereas N yields of the other species did not statistically differ in N yields despite the differences in the absolute values of up to 2 kg ha⁻¹.

At both sites, N yields in *P. nivea x tremula* and *P. euphratica* were highest in the leaf fraction (Table 4.2). In *E. angustifolia* and *S. nigra* significantly less N was accumulated in the stem. *Morus alba* and *U. pumila* did not show any differences in N yields among tree fractions (Table 4.2).

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Table 4.2 Total N yields in six species at the study sites G'oybu and Beruniy at 19 months after planting. Values with different superscripts in one column differ significantly for fractions. Values with different capital superscripts differ significantly for species within each site.

N yield kg ha ⁻¹ yr ⁻¹						
G'oybu						
Fraction	<i>Morus alba</i>	<i>Populus euphratica</i>	<i>Elaeagnus angustifolia</i>	<i>Salix nigra</i>	<i>Ulmus pumila</i>	<i>Populus nivea x tremula</i>
Leaves	0.44 ^a	1.20 ^a	8.91 ^a	0.05 ^a	0.48 ^a	0.82 ^a
Stem	0.06 ^a	0.22 ^b	5.32 ^b	0.00 ^b	0.11 ^a	0.29 ^b
Twigs	0.10 ^a	0.29 ^b	7.51 ^a	0.02 ^a	0.17 ^a	0.00 ^b
Roots	0.26 ^a	0.38 ^b	9.02 ^a	0.15 ^a	0.47 ^a	0.45 ^b
Total	0.86 ^C	2.09 ^B	30.76 ^A	0.23 ^C	1.24 ^B	1.57 ^B
Beruniy						
Leaves	0.30 ^a	1.80 ^a	6.61 ^a	0.41 ^a	0.50 ^a	0.97 ^a
Stem	0.08 ^a	0.32 ^b	1.50 ^b	0.07 ^b	0.13 ^a	0.36 ^b
Twigs	0.12 ^a	0.55 ^b	3.38 ^a	0.16 ^a	0.22 ^a	0.33 ^b
Roots	0.30 ^a	0.80 ^b	5.10 ^a	0.28 ^a	0.48 ^a	0.70 ^b
Total	0.80 ^C	3.47 ^B	16.60 ^A	0.92 ^C	1.33 ^B	2.36 ^B

4.3.4 Nitrogen fixation

Depending on the choice of reference species, the %Ndfa estimated with the 15NAM ranged from 61% (*M. alba*) - 81% (*S. nigra*) in G'oybu, and from 60% (*P. euphratica*) - 74% (*U. pumila*) in Beruniy, thus varying by 15 - 20% based on the choice of reference species (Table 4.3). Differences in %Ndfa by *E. angustifolia* were below 3% with the exception of %Ndfa derived using *S. nigra* as the reference species. At 19 MaP, similar amounts of N fixed were estimated in both sites in *E. angustifolia*, ranging from 19 - 25 kg ha⁻¹ yr⁻¹ in G'oybu and from 10 - 12 kg ha⁻¹ yr⁻¹ in Beruniy (Table 4.3).

Estimates of the NDM were significantly higher compared to those of the isotopic method, and ranged more narrowly among the reference species. The efficiency of N₂-fixation ranged from 93 - 99% in G'oybu and from 79 - 95% in Beruniy. This translated into 29 - 31 kg ha⁻¹ yr⁻¹ and 13 - 16 kg ha⁻¹ yr⁻¹ of N fixed in G'oybu and Beruniy, respectively (Table 4.3).

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Table 4.3 Proportion of N derived from the atmosphere [%Ndfa] and total amount of N fixed by *E. angustifolia* as calculated by conventional and isotopic method using five reference species.

Reference species	%Ndfa				Total N fixed, kg ha ⁻¹ yr ⁻¹			
	¹⁵ N natural abundance method		N difference method		¹⁵ N natural abundance method		N difference method	
	G'oybu Beruniy	G'oybu Beruniy	G'oybu Beruniy	G'oybu Beruniy	G'oybu Beruniy	G'oybu Beruniy	G'oybu Beruniy	G'oybu Beruniy
<i>Morus alba</i>	60.5	61.4	97.2	95.2	18.6	10.2	29.9	15.8
<i>Populus euphratica</i>	64.7	59.5	93.2	79.1	19.9	9.9	28.7	13.1
<i>Populus nivea x tremula</i>	72.4	70.2	94.9	85.8	22.3	11.7	29.2	14.2
<i>Salix nigra</i>	81.4	61.7	99.3	94.4	25.0	10.2	30.5	15.7
<i>Ulmus pumila</i>	72.9	74.2	96.0	92.0	22.4	12.3	29.5	15.3

4.4 Discussion

4.4.1 $\delta^{15}\text{N}$

In the present study, whole-tree mean $\delta^{15}\text{N}$ of *E. angustifolia* ranged from -1.20 to -1.46‰. Negative $\delta^{15}\text{N}$ values are per se an indicator of efficient N₂-fixation (Boddey et al. 2000), and therefore confirm the N-fixing capability of *E. angustifolia* on long-term abandoned croplands. The observed mean $\delta^{15}\text{N}$ was more negative than that observed by Djumaeva et al. (2013) (-1.81‰) during the first three years after establishment in a P-fertilizer trial. Nevertheless, during the three-year study period, Djumaeva et al. (2013) observed significant variations in the $\delta^{15}\text{N}$ values of *E. angustifolia*, which showed a significant increase in the third year. The values in the present study might also fall in the range of such variations, and are therefore comparable. Foliar $\delta^{15}\text{N}$ in G'oybu was -1.64‰, which is close to the values observed by Khamzina et al. (2009a) in the second growing season (-1.6‰) and that observed by Djumaeva et al. (2013) during the first three growing seasons (-1.77‰). In Beruniy, foliar values were less negative averaging -1.06‰.

Measured $\delta^{15}\text{N}$ values of the reference plants were slightly higher compared to literature values. Whereas $\delta^{15}\text{N}$ values in literature of *U. pumila* in the region ranged from 2.0 - 3.1‰ (Khamzina et al. 2009a, Djumaeva et al. 2010), in the present study

they ranged from 1.5 - 2.1‰ (Table 4.1). The same was observed for *P. euphratica* for which previously measured values ranged from 2.0 - 2.9‰ (Khamzina et al. 2009a) but which were lower (0.0 - 1.1‰) in the present study. These variations confirm the need to sample reference plants growing in the neighbourhood of the N₂-fixer (Boddey 2000), as $\delta^{15}\text{N}$ values vary spatially and over time (Khamzina et al. 2009a).

The lowest $\delta^{15}\text{N}$ whole-tree value of -2.47‰ measured for *E. angustifolia* is lower than reported B-values for other actinorhizal species ranging from -1.41 to -2.00‰ (Domenach et al. 1989; Tjepkema et al. 2000). It is however very close to the lowest field-observed $\delta^{15}\text{N}$ value (-2.53‰) in *E. angustifolia* growing in the ADB (Khamzina et al. 2009a). Although using the lowest field-observed $\delta^{15}\text{N}$ as B-value has been proposed as a legitimate compromise (Peoples et al. 2002), greenhouse measurement of the B-value specific to the *Elaeagnus* genus might improve the estimates based on the 15NAM.

4.4.2 Nitrogen concentrations and yields

Generally higher %N values in *E. angustifolia* compared to those of the reference species underline an elevated potential for soil-N-stock replenishment compared to other species. This especially applied to N stored in the annual fractions, as leaves and fine roots provide annual inputs of organic matter leading to a build-up of soil nutrients. In the case of *E. angustifolia*, in G'oybu and Beruniy a total of respectively 8.9 and 6.6 kg ha⁻¹ yr⁻¹ leaf-stored N reaches the soil via litterfall. Therefore, soil-nutrient stock dynamics in *E. angustifolia* plantations should be studied to quantify the impact of the biomass input on the soil characteristics.

4.4.3 Methodological issues in quantifying N₂-fixation by trees

Both the conventional and the isotopic method applied in the present study confirmed the capability of *E. angustifolia* to fix N under saline conditions and low soil P stocks, which is in agreement with earlier studies in similar environments (Khamzina et al. 2009; Djumaeva et al. 2010; 2012; 2013). Regarding the amount of N derived from the atmosphere, estimations in this study significantly vary with reference species and

methods used, indicating the need for the identification of the most reliable combination of these two factors for an accurate estimation.

Reference plant

Differences in %Ndfa estimations associated with different reference plants highlight the importance of involving a range of possible references and of their accurate selection (e.g., Boddey et al. 2000; Unkovich et al. 2008). Danso et al. (1986) and Hardarson et al. (1988) suggested that errors in BNF estimates due to the reference plants become insignificant when %Ndfa values range around 80%. The latter argument applies to the results of this study based on the NDM, which showed %Ndfa above 79% with variation depending on the choice of reference species. The isotopic method indicated %Ndfa below 80% with over 20% variance due to reference plants, in particular when comparing the values of *S. nigra* with those of other reference species. Generally, including several reference plants rather than a single one improves the accuracy of the results (Danso 1995), but there is a need for screening of the available references, as is indicated by this study with five non-N-fixing species.

Non-fixing reference plants should have similar phenological characteristics and as a result similar patterns of N uptake by roots (Boddey et al. 2000). This criterion was poorly met by *S. nigra*, which was planted as unrooted cuttings. Furthermore, even a small variability in $\delta^{15}\text{N}$ of a reference plant depending on sampling location or plant parts can cause significant errors when using the 15NAM (Shearer and Kohl 1986). This restricts the suitability of *S. nigra* and *P. euphratica*, which showed spatial or within-plant variance in $\delta^{15}\text{N}$ thus altering the BNF estimations. Given that the use of the 15NAM requires a difference of at least $\pm 2\text{‰}$ in $\delta^{15}\text{N}$ to accurately quantify BNF (Unkovich et al. 2008), *P. euphratica*, and *M. alba* were least suitable as reference plants. *Populus nivea x tremula* and *U. pumila* showed consistent $\delta^{15}\text{N}$ on both sites, thus presenting the most reliable reference species among the studied species. *Ulmus pumila* has been shown to be a suitable reference plant for *E. angustifolia* when the 15NAM was applied in previous studies (Khamzina et al. 2009). In addition, it fulfilled

the above criteria of the reference plant at the Beruniy site, and can therefore also be considered as a fairly suitable reference species.

Method

The identification of *P. nivea x tremula* and *U. pumila* as the most suitable reference species reduced the original discrepancy among %Ndfa estimates with the 15NAM (70 - 74%) and the NDM (88 - 96%). The differences observed between the estimates of the NDM and the 15NAM stem from the basic assumption of the NDM that N fixer and reference plants acquire exactly the same amount of soil N, which cannot be guaranteed in our study given the higher root and overall growth rate of *E. angustifolia*. Due to a poor soil-N content, the growth of the reference plants was restricted (Chapter 3), while the additional soil N acquired by *E. angustifolia* was counted as biologically fixed, thus leading to an overestimation of N fixation based on the NDM (LaRue and Patterson 1981). The 15NAM obviates the above assumption and is generally recognized as a robust and direct technique for quantifying N fixation in woody perennials (Boddey et al. 2000). In the present study, it was therefore assumed to be the more reliable method among the applied ones. Its only limitation in this study remains the need to adjust for isotopic fractionation within the N-fixing plant (B-value). Even though the B-value is of less importance when %Ndfa is <50% (Unkovich et al. 2008), a threshold considerably exceeded in the present study, it represents a potential source of error. Published estimates for actinorhizal plants (Domenach et al. 1989; Tjepkema et al. 2000) did not cover the *Elaeagnus* genus. Therefore, additional trials will need to determine the B-value specific to *E. angustifolia* and thus refine 15NAM estimates.

4.4.4 Nitrogen derived from the atmosphere

The estimated range of %Ndfa when using the most reliable combinations of reference plants (*U. pumila* and *P. nivea x tremula*) and method (15NAM) of 70 - 74% compares with that measured by Djumaeva et al. (2010) of 68 - 79% when using *U. pumila* as reference plant and applying the A value method in lysimeter-grown 2-year-old trees. It is slightly lower compared to the results of a field trial in the same study region by

Khamzina et al. (2009a), who measured %Ndfa values of ~80% in 2-year old *E. angustifolia* with the 15NAM. Also applying the 15NAM, Djumaeva et al. (2013) estimated even higher %Ndfa values of up to 86 – 90% in *E. angustifolia* depending on the selected reference species in a P-fertilizer trial. The lower range determined with the 15NAM in the present study might be an effect of inhibited growth of *E. angustifolia* due to the observed stress factors at the study sites (Chapter 3) known to decrease BNF (Danso et al. 1992; Sprent and Parson 2000).

Despite higher salinity in the rooting zone at the Beruniy site (Chapter 3), site differences in estimated %Ndfa were not statistically significant. This indicates the persistence of *Frankia* symbiosis under slight-to-moderate soil salinity as reported for tree legume-Rhizobium symbiosis (Bala et al. 1990). Longer-term studies on *E. angustifolia* revealed that its ability for BNF not only enables self-sufficiency in N nutrition, thus facilitating early survival and establishment, but also increases soil available N stocks over time (Khamzina et al. 2009).

4.4.5 Nitrogen fixation

The estimated total amount of fixed N₂ ranging from 11.7 - 22.4 kg ha⁻¹ yr⁻¹ based on the most reliable reference species (*U.pumila* and *P. nivea x tremula*) and method (15NAM) at both sites falls within the range of the N₂-fixation values reported by Paschke et al. (1997) for actinorhizal species of 0.1 -200 kg ha⁻¹ yr⁻¹. Nevertheless, previous studies on N fixation of *E. angustifolia* in the region observed significantly higher fixation rates of 24 - 514 kg ha⁻¹ yr⁻¹ (Khamzina et al. 2009) and 25 - 342 kg ha⁻¹ yr⁻¹ (Djumaeva et al. 2013) within the first five and three years, respectively. These results are in line with the earlier reported biomass increments in the present study (Chapter 3), which were about five times lower than those reported in other studies in the region (Khamzina et al. 2009a, Djumaeva et al. 2013). Furthermore, in Beruniy, amounts of N fixed by *E. angustifolia* were about half of those estimated in G'oybu, which also coincides with the measured differences in biomass increments at the two study sites, even if these were not statistically significant (Chapter 3). Consequently, also the accumulated amount of total N in the trees was significantly lower.

4.5 Conclusions

Despite a discrepancy of approximately 20 - 30%, both applied methods confirmed the high efficiency of N₂-fixation by *E. angustifolia* under the given conditions. The estimated N₂-fixation rates of over 22 kg ha⁻¹ yr⁻¹ with the most reliable combinations of reference plants and method bear promise for *E. angustifolia* to satisfy its N demand and partly offset the impact of water and salinity stress prevalent on long-term abandoned croplands. The NDM seems to overestimate BNF in nutrient-poor soils significantly, thus limiting its suitability for BNF estimations in afforestation systems on degraded croplands. The 15NAM is not affected by soil characteristics and BNF estimations are reliable. Nevertheless, the study highlights the importance of an accurate selection of reference plants to be used with the 15NAM and the need for further research aiming at the determination of the B-value for *E. angustifolia* to eliminate an additional source of error in BNF estimations.

Since in this study, the capability of *E. angustifolia* to fix N from the atmosphere was clearly proven, it remains to be studied if this additional nutrient input into the agricultural system has a measurable effect on the soil characteristics already in the first years following afforestation.

5 DYNAMICS OF SOIL CHARACTERISTICS FOLLOWING AFFORESTATION

5.1 Introduction

In the previous chapters, clear differences in biomass production (Chapter 3) were determined among the tree species are shown, which are at least partly associated with the N₂-fixation capability of *Elaeagnus angustifolia* L. (Chapter 4). The increased input of organic material from the trees resulting from litter-fall deposition enhances the soil organic matter (SOM), which may consequently improve the water retention capacity and the fertility of the soil (Schlesinger 1999). Therefore, afforestation is often stated as a measure for replenishing soil nutrient stocks and land rehabilitation (e.g., Katyal and Vlek 2000; Cacho 2001; Guo and Gifford 2002). Nevertheless, changes in soil-nutrient stocks following afforestation might vary in direction and magnitude depending upon the time period since tree planting, previous land use, soil properties, and need to be examined for each species. Especially in plots of N₂-fixing *E. angustifolia*, soil-N dynamics might differ from that in plots of non-fixing species.

Afforesting degraded croplands in arid and semi-arid regions is also a recognized option for C sequestration in biomass and soil to reduce the atmospheric carbon dioxide (CO₂) and therefore mitigate climate change (e.g., Grünzweig et al. 2003; Nosetto et al. 2005). Particularly soils may represent a large C pool, containing about three times the quantity stored in terrestrial vegetation (e.g., Schlesinger 1997). Soil C sequestration is relatively slow and usually modest compared to the C accumulation in tree biomass following afforestation. However, the soil-C pools are more resistant to sudden changes in forest management (Vesterdal et al. 2002). Both pools are therefore to be accounted for when quantifying changes in the total C stocks of an ecosystem (Montagnini and Nair 2004). There is still a paucity of information specific to the impact of afforestation on the dynamics of soil C in degraded irrigated croplands (Post and Kwon 2000; Paul et al. 2002).

The changes in soil-C stock and their implications for soil fertility and C sequestration depend on the ratio between the amount of organic matter inputs and C outputs via processes such as mineralization (e.g., Lal and Kimble 1997; Nadelhoffer et al. 1999; Post and Kwon 2000; Six et al. 2002). Previous studies assessing soil-C dynam-

ics following afforestation showed changes occurring mainly in the topsoil (0-20 cm). Topsoil-C contents generally decreased during the first 5 years following afforestation, but recovered after about 30 years (Paul et al. 2002; Guo and Gifford 2002; West et al. 2004). The often observed initial decrease in soil C is attributed to the effects of soil disturbances, which trigger the decomposition of soil organic matter (Turner and Lambert 2000). At the onset of an afforestation enterprise (3-5 years following tree planting), this decrease in topsoil C is not yet offset by C input from tree organic residues due to the low biomass and a low rate of litterfall (Wilde 1964). Among factors influencing changes in soil-C stocks following afforestation the previous land use was emphasized (Paul et al. 2002) as it has a direct influence on the initial soil-C stocks. Under previously cropped sites, soil-C stocks tended to increase following afforestation, whereas under previous pastures, where soil-C stocks were higher, a negative tendency was commonly observed (Paul et al. 2002). Another important factor influencing soil-C-stock development following afforestation is the tree species used (Lugo et al. 1990; Paul et al. 2002). Under N-fixing species, 20 – 100% more soil C is stored compared to non-N fixers (Resh et al. 2002).

Previous research, also in Uzbekistan, has shown that soil-C changes triggered by a cropland afforestation mainly occurred in the soil organic carbon (SOC) component through changes in the quality and quantity of plant material input from the trees (Bouwman & Leemans 1995; Post and Kwon 2000; Lal 2003; De Gryze et al. 2004; Hbirkou et al. 2011) and through the cessation of plowing operations that generally reduce the SOC decomposition rate (Six et al. 2000; Del Galdo et al. 2003). SOC contents are low compared to total C stocks, and short-term changes in SOC might therefore not be noticeable when analyzing total C stocks (Six et al. 2002). Furthermore, losses in different soil-C fractions might counterbalance gains in other fractions resulting in a negligible net change in the total C. Analyzing different soil-C pools separately will therefore yield information about the soil-C dynamics following afforestation, which can serve as an early indicator for long-term impacts of afforestation on soil C (Six et al. 2002; Del Galdo et al. 2003). Therefore, the present study focused on the short-term SOC dynamics and total soil C.

Establishing tree plantations within irrigated agricultural landscapes characterized by a shallow GWT may exert significant effects on the water and salt balance (Schonfield 1992; Noretto et al. 2007; 2009). Depending on local hydro-geological conditions and arrangements of tree plantings in the landscape, afforestation can be used to cope with secondary salinization by lowering shallow saline GWT through the high water uptake and associated bio-drainage effect (Lal 2001; Rengasamy 2006). The capability of tree plantations to ameliorate salinized land depends furthermore on the tree species, their growth and water-use habits, and management (Del Galdo et al. 2003; Lal 2003).

In previous studies in the lower ADB, tree stands were seen to lower evaporation from the soil surface through shading, which in turn positively influenced the salt content in the surface soil already three years after afforestation (Khamzina et al. 2008). Hbirkou et al. (2011) also found significantly lower salinity in the topsoil of young afforestation sites in comparison to the neighboring abandoned cropland. Nevertheless, salt accumulation has occurred over time in the afforested plots and is generally reported for non-irrigated tree plantations in lowland areas with restricted groundwater outflow (Thorburn 1997; Archibald et al. 2006). Since soil salinity may significantly affect the survival of saplings and therefore the feasibility of afforesting degraded sites (Chapter 3), soil-salt regimes and dynamics should be known before drawing conclusions about the sustainability of afforestation of degraded croplands in the ABD lowlands.

In addition to the changes in the overall soil salinity (see Chapter 3), information on the type of salinity is of importance for deciding on salinity management strategies. Salinity may affect plant performance by reducing both water uptake and nutrient availability (Grattan and Grieve 1999, Pessarakli and Szabolcs 2002). For example, salinity dominated by Na^+ directly affects the plant- K^+ uptake, whereas high Cl^- concentrations reduce the NO_3^- uptake (Grattan and Grieve 1999). High concentrations of Na^+ in the soil directly affect the soil structure. Sodic soils are characterized by extreme swelling in wet conditions and by soil cracking in dry conditions, negatively affecting plant growth (Bernstein 1975). Soil salt leaching, commonly practiced in saline

croplands helps to wash out certain ions (e.g., Tischbein et al. 2012). The positively charged Na^+ ions are attached to the cation-exchange sites, and are therefore not washed out from the soil through leaching. The cost intensive amelioration of sodic soils requires a source of calcium (Ca_2^+) to replace Na^+ from the cation-exchange sites before the leaching (Qadir et al. 2003).

The objective of this part of the study was therefore to analyze changes in soil parameters, i.e., in C and N stocks, salinity, and sodicity in the rooting zone following afforestation of the long-term abandoned cropping sites, and to evaluate the impact of species on these dynamics during the initial two years.

5.2 Material and methods

5.2.1 Soil sampling

Soil sampling was performed at all experimental plots of both plantation sites (section 3.3). Of the six tree species monitored during two consecutive growing seasons in 2010 and 2011, *P. euphratica* failed to establish under the study conditions, and *S. nigra* was characterized by significantly lower survival and biomass increments compared to the rest of the tested species (Chapter 3). Therefore, these two species were not considered in the present analysis. Consequently, only the effects of *M. alba*, *E. angustifolia*, *P. nivea x tremula*, and *U. pumila* were studied. Detailed information on soil characteristics of the experimental sites and plantation set up is presented in section 3.3.1.

Before the establishment of the plantations in autumn 2009, and at the end of each growing season in September of 2010 and 2011, the soil was sampled with an auger in 20-cm layers down to 60-cm depth, which corresponded to the observed rooting zone (Chapter 3). At the same time, the soil of two adjacent abandoned cropping sites was sampled as reference. All soil samples were dried at 60 °C to constant weight in a drying oven and ground prior to chemical analyses.

Changes in salt regimes were determined by analyzing the electrical conductivity (EC) and the total dissolved solids (TDS) as indicators for the overall soil salinity (see Chapter 3). The salt-ion composition (Cl^- ; SO_4^{4-} ; Ca^{2+} ; Mg^{2+} ; Na^+ ; K^+) was determined in the laboratory with the full saturation extract analysis in a 1:5 ratio (Uzbek Soil Insti-

tute 2003). To classify the encountered soil salinity type, the Cl/SO₄ ratio in combination with the TDS was used as suggested by Kaurichev et al. (1989; see Appendix 9.4). As an indicator for soil sodicity, the sodium absorption ratio (SAR) was calculated as suggested by Funakawa and Kosaki (2007):

$$SAR = \frac{Na^+}{\sqrt{\frac{(Ca^{2+}+Mg^{2+})}{2}}} \quad (5.1)$$

Total C and N contents were determined via dry combustion with an elemental analyzer. The SOC was determined in a sulphurous extract according to the Tyurin method (Tyurin 1975). Soil pH was measured following ISO 10390 (2005).

As a result of soil tillage before tree planting and spatial variability, the soil bulk density under afforested sites may vary from that of the reference site and therefore bias the calculations of changes in soil C from fixed depths (Ellert and Bettany 1995). Soil total C, total N, and SOC were therefore related to the unit of mass rather than volume as suggested by Ellert et al. (2001). For that purpose, the measured contents in each soil layer were converted to stock values (Mg ha⁻¹) (Lee et al. 2009):

$$C_{stock_i} = C_{con_i} \cdot M_i \quad (5.2)$$

where C_{stock_i} is the C mass in layer i (Mg C ha⁻¹), C_{con_i} is the C concentration in the layer i (% C), and M_i is the dry soil mass (Mg ha⁻¹) in layer i calculated as:

$$M_i = BD_i \cdot T_i \cdot 10^4 \quad (5.3)$$

where BD_i is bulk density (Mg m⁻³), T_i is the thickness of soil layer i (m), and 10^4 is a unit conversion factor (m² ha⁻¹). This same calculation was also applied to soil total N and SOC.

Soil bulk densities at the tree sites and the reference plots were determined after the plantation was set up in April 2010. For that purpose, 100 cm³ of soil was collected in each 20-cm layer with a soil sampling cylinder and oven dried at 105 °C. Soil bulk density was calculated from the volume of the soil sample and the mass of the oven-dried samples. For data on SOC and N concentrations see Table 3.1.

5.2.2 Statistical analysis

Temporal differences in the measured parameters were analyzed with respect to the initial values measured in September 2009. For that purpose, the 2009 values were subtracted from the respective values in 2010 and 2011. The resulting differences (Δ 2010 and Δ 2011) were tested against zero with an ANOVA. Tree effects on the soil were additionally tested by comparing the estimated Δ 2010 and Δ 2011 among species and against the unplanted reference plot at each site with an ANOVA. In case the species effect was significant, a post hoc test (pairwise comparison) was used to determine mean differences. In the case of the parameters total C, total soil N, and SOC, the effects of the experimental factors “species”, “sites”, and their interaction were tested with ANOVA at a significance level of $p = 0.05$ in the topsoil (0-20 cm). For all other soil parameters (EC, SAR, Cl/SO₄ ratio, TDS, and pH), the analyses refers to the maximum observed rooting depth of 60 cm (section 3.3.4). Here the experimental factors “species”, “site”, and “depth” and their interaction were tested with ANOVA ($p=0.05$). All statistical analyses were performed using SPSS 15.0 and Stata 12.1.

5.3 Results

In G'oybu, bulk density in the topsoil (0-20 cm) of the tree plantation was 1.58 g cm⁻³ and slightly decreased with depth (Table 5.1). In Beruniy, the topsoil was characterized by a lighter bulk density of 1.46 g cm⁻³ compared to the deeper soil layers where it ranged from 1.59 to 1.67 g cm⁻³ (Table 5.1).

In G'oybu with increasing depth, a constant decrease in the clay content and increase in the sand fraction was observed (Table 5.2). Starting from 80 cm, a sandy soil texture was identified (Table 5.2). In Beruniy, according to the FAO classification “loamy sand” to “sand” was observed (Table 5.2). Down to 80 cm in the soil profile, sand fraction ranged from 77 to 95% whereas clay content ranged between 3 and 11%. In the 80 to 112 cm layer, sand content was lower (55%) and clay content higher (12%) than in the rest of the profile.

Table 5.1 Soil bulk density by depth at the study sites in G'oybu and Beruniy measured in September 2009.

Depth (cm)	Bulk density (g cm ⁻³)	
	G'oybu	Beruniy
0-20	1.58	1.46
20-40	1.56	1.59
40-60	1.53	1.59
60-80	1.51	1.57
80-100	1.53	1.67

Table 5.2 Soil clay, silt, and sand contents and classification of soil texture according to FAO by generic horizons at the study sites in G'oybu and Beruniy measured in September 2009.

Depth (cm)	Clay (%)	Silt (%)	Sand (%)	FAO
G'oybu				
0-4	15.8	73.2	11.0	ZL
4-15	14.9	71.1	14.0	ZL
15-30	5.4	82.2	12.4	Z
30-60	3.9	62.1	34.0	ZL
60-81	5.4	51.6	43.0	ZL
81-101	5.0	34.2	60.8	SL
101-115	4.0	22.1	73.9	LS
115-120	7.6	54.2	38.2	ZL
120-150	0.4	2.4	97.2	S
Beruniy				
0-1	11.4	11.6	77.0	SL
1-4	7.8	10.6	81.6	LS
4-10	5.8	8.5	85.7	LS
10-20	3.7	5.5	90.8	S
20-30	3.7	4.1	92.2	S
30-45	5.2	8.4	86.4	LS
45-60	6.9	10.8	82.3	LS
60-80	2.9	2.0	95.1	S
80-112	12.4	32.4	55.2	SL

Overall, the ANOVA showed highly significant differences in the changes between the sites for all measured parameters ($p < 0.001$). Therefore, the sites were analyzed separately. At both sites, the influence of tree species on changes in stocks of soil carbon (C), soil organic carbon (SOC), and nitrogen (N) in the topsoil (0-20 cm) between 2009 and 2010 ($\Delta 2010$) and 2011 ($\Delta 2011$) was not significant, except for $\Delta 2010$ in N-stocks in G'oybu ($p = 0.098$). Parameters analyzed in the rooting zone (EC,

SAR, Cl/SO₄ ratio, TDS, and pH) differed with soil depth at both sites except for the SAR, which showed no significant differences with respect to depth at the G'oybu site (Table 5.3). Nevertheless, within each site, the depth-related variability was independent from the tree species, as illustrated by the non-significant interaction between "species" and "depth" for all parameters (Table 5.3).

Table 5.3 Influence of tree species and soil depth and their interactions on changes in sodium absorption ratio (SAR), Cl/SO₄ ratio, total dissolved salts (TDS), and pH in the rooting zone (0-60 cm) between 2009 and 2010/2011 (Δ 2010/ Δ 2011) at the study sites in G'oybu and Beruniy. Displayed are p-values of the ANOVA. Significant p-values are marked in bold.

	SAR		Cl/SO ₄		TDS		pH	
	Δ 2010	Δ 2011	Δ 2010	Δ 2011	Δ 2010	Δ 2011	Δ 2010	Δ 2011
Species	0.160	0.619	0.170	0.017	0.630	0.021	0.235	0.003
Depth	0.075	0.191	0.022	0.005	<0.001	0.002	0.005	<0.001
Species*Depth	0.800	0.654	0.966	0.864	0.468	0.468	0.953	0.935
Species	0.076	0.001	0.475	0.012	0.201	0.022	0.822	<0.001
Depth	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.086	<0.001
Species*Depth	0.076	0.136	0.279	0.840	0.331	0.224	0.982	0.127

5.3.1 Soil C and N stocks

Initial total C stocks in 2009 were 80.6 and 56.1 Mg ha⁻¹ in G'oybu and Beruniy, respectively. On both sites, these stocks did not significantly change between 2009 and 2010/2011 (Figure 5.1). Furthermore, no significant species-related differences were observed.

The SOC appeared to be a more sensitive indicator of changes in soil-C status. In G'oybu, changes in SOC stocks were not significant in 2010 compared to 2009. Nevertheless, SOC stocks increased between 2009 and 2011 under *E. angustifolia* (+0.78 Mg ha⁻¹) and *U. pumila* (+1.06 Mg ha⁻¹), whereas they declined at the reference plot (-0.17 Mg ha⁻¹) during the same period in G'oybu (Figure 5.2). In Beruniy, with its sandy soil texture and lower initial SOC stocks, SOC stocks under all tree plots significantly declined (-3.8 - 5.6 Mg ha⁻¹) between 2009 and 2010. In contrast, the loss observed at the reference site (-2.20 Mg ha⁻¹) was not significant (Figure 5.2). Nevertheless, only the change in the *U. pumila* plot in 2010 at the Beruniy site (-4.00 Mg ha⁻¹) differed

significantly from that of the reference plot (Figure 5.2). The analysis of changes during the whole observation period 2009-2011 confirms that SOC concentrations in all species plots declined (Figure 5.2).

In 2010, soil-N stocks at G'oybu in all tree plots declined significantly compared to 2009, whereas no significant change occurred in the reference plot (-0.02 Mg ha^{-1}) (Figure 5.3). In the following year, even though the reference site and the *M. alba* and *P. nivea x tremula* plots showed a slight decline compared to the initial stocks, statistical differences in N-stock changes among species and the reference plot were not significant (Figure 5.3).

At the Beruniy site, soil-N stocks in 2010 under all species were significantly lower compared to the initial stock of 1.28 Mg ha^{-1} in 2009 but did not vary among each other. Also two years following afforestation, soil-N stocks were generally lower at all sampled plots compared to the initial values (Figure 5.3). Among the sampled plots, a significantly lower decline compared to 2009 was observed in the *P. nivea x tremula* plots amounting -0.22 Mg ha^{-1} (Figure 5.3).

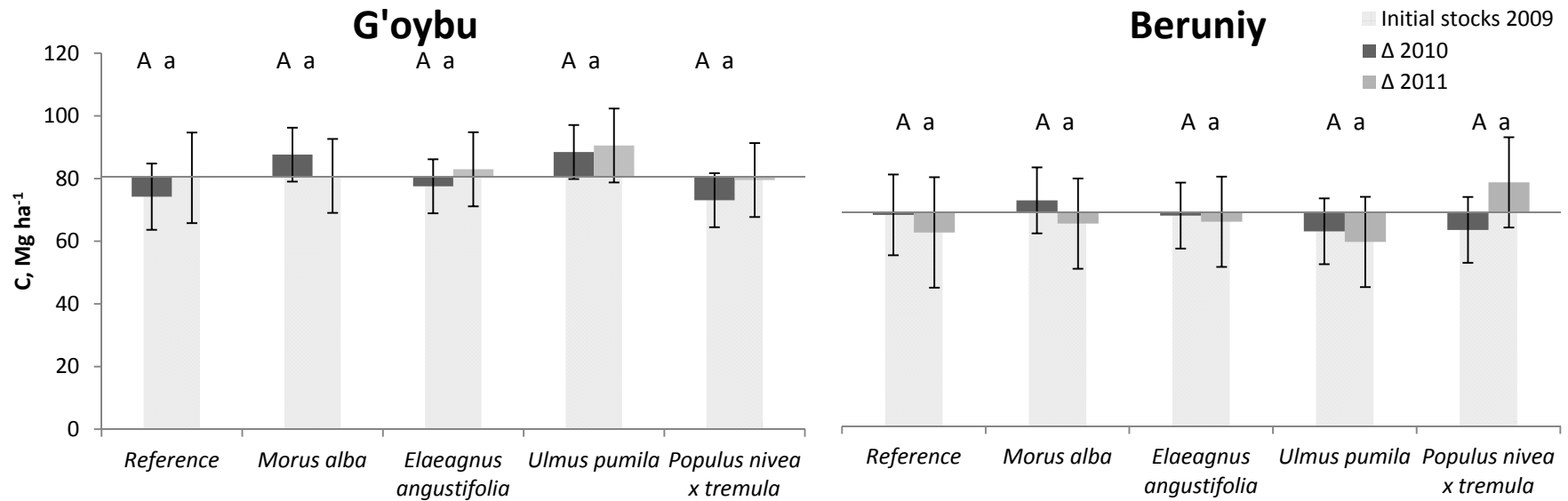


Figure 5.1 Soil total carbon (C) stocks in the top 20 cm under four tree species and a reference plot at the study sites in G'oybu and Beruniy. Displayed are initial soil total C stocks in 2009 and changes in 2010 (Δ 2010) and 2011 (Δ 2011) compared to the initial values. Error bars indicate the confidence intervals of the corresponding changes. Columns at one site with different capital and lowercase letters differ significantly in Δ 2010 and Δ 2011, respectively. None of the changes were significant at $p=0.05$.

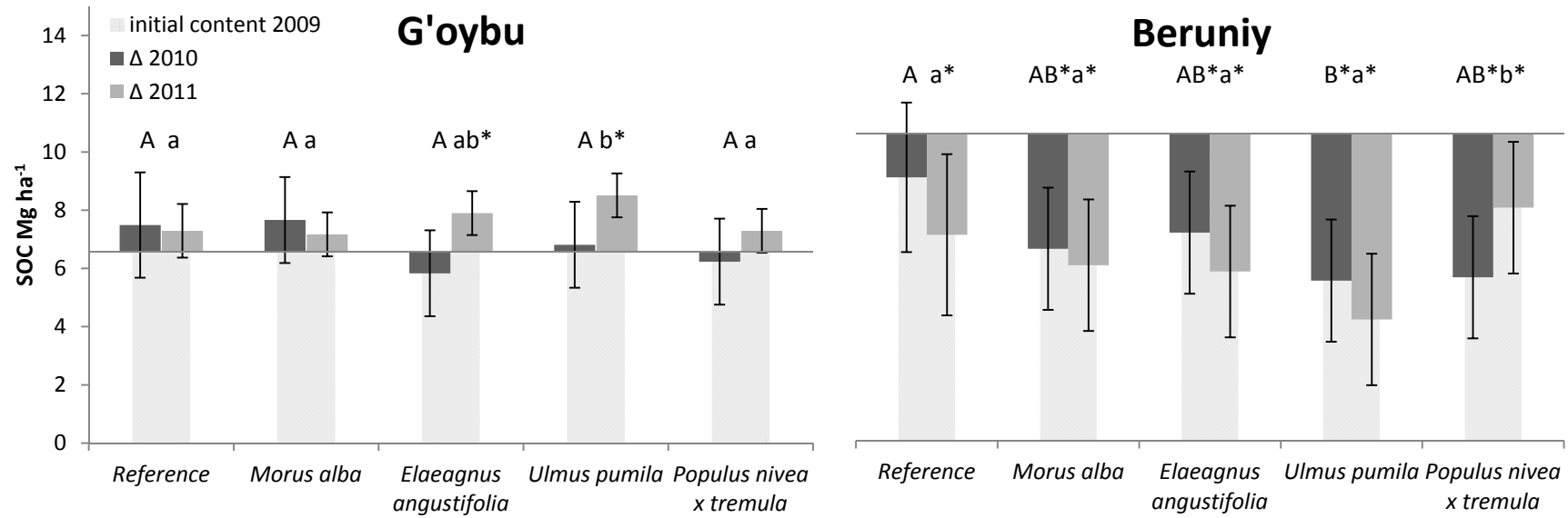


Figure 5.2 Soil organic carbon (SOC) stocks in the top 20 cm under four tree species and a reference plot at the study sites in G'oybu and Beruniy. Displayed are initial SOC stocks in 2009 and following changes in 2010 (Δ 2010) and 2011 (Δ 2011). Error bars indicate the confidence intervals of the corresponding changes. Columns at one site with different capital and lowercase letters differ significantly in Δ 2010 and Δ 2011, respectively. Asterisks (*) indicate significant changes at $p=0.05$.

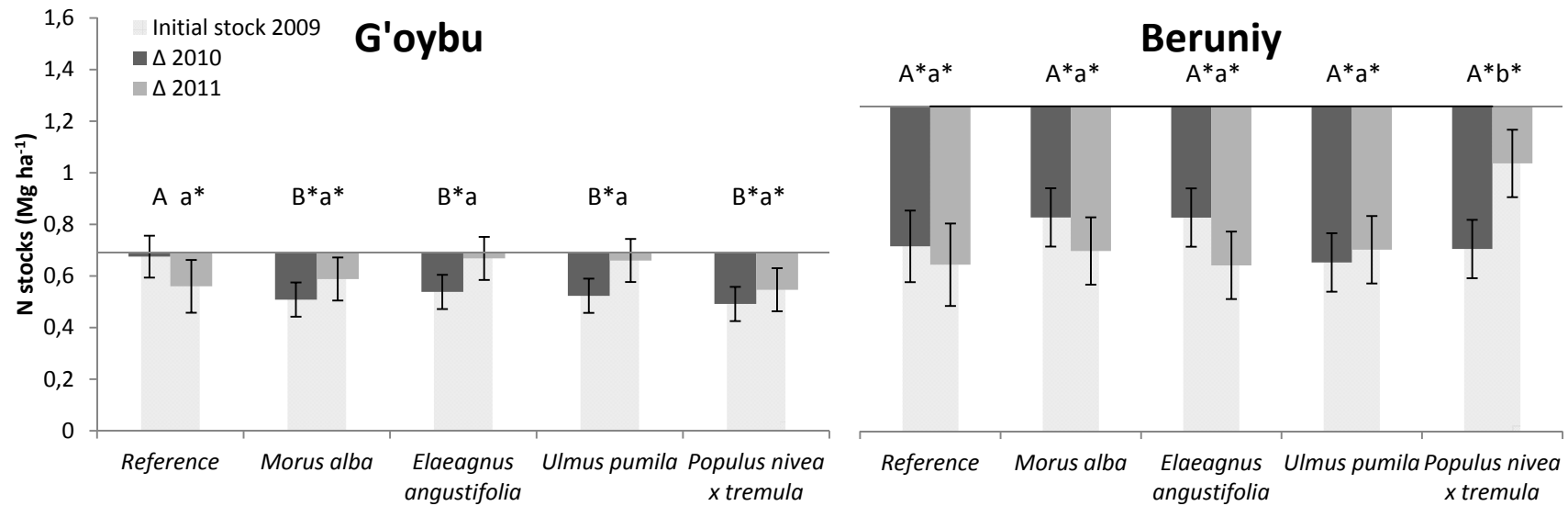


Figure 5.3 Soil nitrogen (N) stocks in the top 20 cm under four tree species and a reference plot at the study sites in G'oybu and Beruniy. Displayed are initial soil-N stocks in 2009 and changes in 2010 (Δ 2010) and 2011 (Δ 2011) compared to the initial 2009 values. Error bars indicate the confidence intervals of the corresponding changes. Columns at one site with different capital and lowercase letters differ significantly in Δ 2010 and Δ 2011, respectively. Asterisks (*) indicate significant changes at $p=0.05$.

5.3.2 Soil salinity and sodicity

The G'oybu site, with its lower GWT, experienced a lower initial salt load in the rooting zone than the Beruniy site (Figure 5.4). Over time, TDS declined at both sites but with a different magnitude. In 2010, one year following afforestation in G'oybu, the changes were insignificant for all species. In 2011, changes were significantly smaller in the *M. alba* (-0.17 Mg ha⁻¹) and *U. pumila* (-0.15 Mg ha⁻¹) plots than those in the reference plots (+0.11 Mg ha⁻¹; Figure 5.4). In Beruniy, values in 2010 were significantly lower for all plots, including the control, than in 2009. Compared to the reference plots, a significantly greater decline was observed in the *U. pumila* plots. Also in 2011, all plots at the Beruniy site were significantly lower in TDS content compared to 2009. The changes observed in the *P. nivea x tremula* (-1.21 Mg ha⁻¹) plots were significantly smaller than those at the reference plots (-1.42 Mg ha⁻¹), which did not significantly differ from those in the other species plots (Figure 5.4).

Observed changes in TDS stocks were highly correlated with the previously reported changes in EC_e values (Chapter 3), showing a R² ranging from 0.98 to 1.00 (Figure 5.5).

In 2010 in G'oybu, significantly higher Cl/SO₄ ratios compared to the initial value 0.23 measured in 2009 were observed for *M. alba* (+0.26), *U. pumila* (+0.30), and *P. nivea x tremula* (+0.41) (Figure 5.6). Nevertheless, only the latter value significantly differed from that measured at the reference plot in 2010 (+0.13). In 2011, except for *E. angustifolia*, all species and the reference site showed higher Cl/SO₄ values than before afforestation. In Beruniy in 2010, ratios were significantly lower for all species compared to 2009 where the ratio was 1.2 but species differences were not significant (Figure 5.6). Also in 2011, the Cl/SO₄ ratio of 0.38 observed at the reference plots was significantly lower than the values observed for all tree species. These did not significantly differ among species but were also lower compared to the initial 2009 value (Figure 5.6).

Appreciable differences in initial SAR values were observed between the two sites with much higher values in Beruniy (Figure 5.7). These decreased drastically following afforestation in contrast to the SAR values in G'oybu, which increased to a

much lower degree. Nevertheless, SAR ranges were far below the generally referred threshold of 13 cmol l^{-1} above which 15% of the adsorption sites are occupied by Na^+ and the soil is considered sodic (The U.S. Salinity Laboratory Staff 1954; Soils Survey Staff 1993).

Specifically, the initial SAR of 0.1 cmol l^{-1} in G'oybu increased in 2010 and 2011 for all species (Figure 5.7). Species differences in the magnitude of the changes were not observed in G'oybu over the entire study period (Table 5.3). In Beruniy, the SAR value in 2010 and 2011 was significantly lower than before afforestation in 2009, when it was 7.05 cmol l^{-1} . Significant species differences were only observed in 2011 at the Beruniy site, where *M. alba* showed a slightly smaller change of $-4.00 \text{ cmol l}^{-1}$ compared to the other species and the reference plots, where changes ranged from -5.66 to $-5.53 \text{ cmol l}^{-1}$.

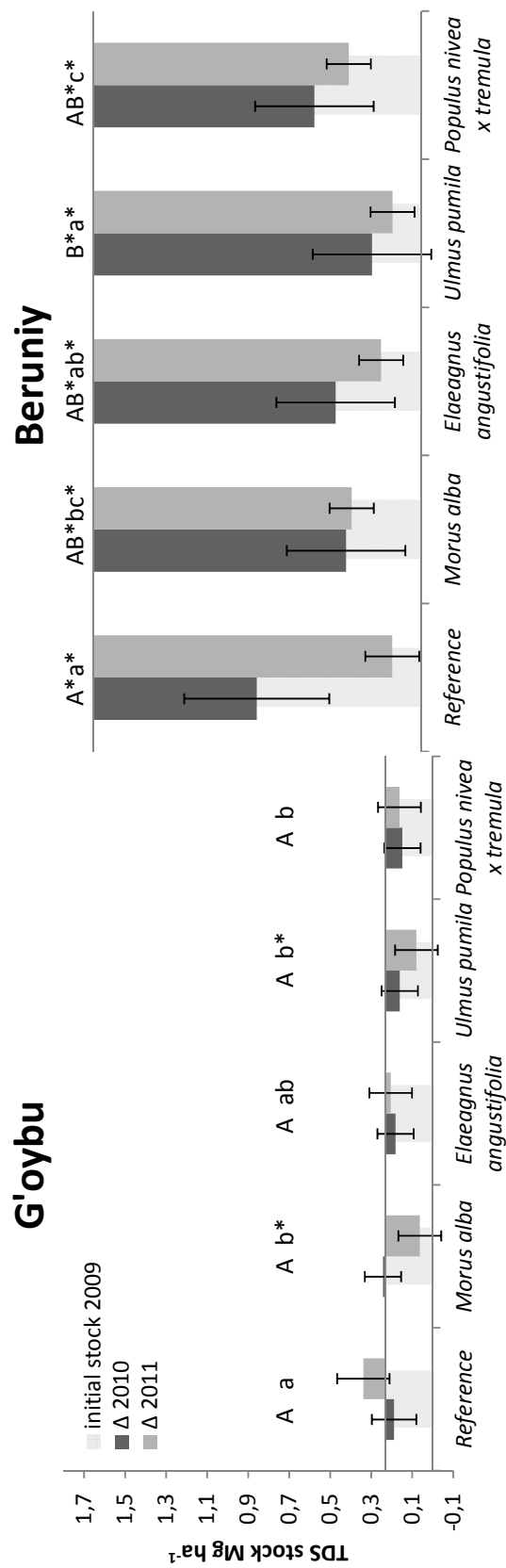


Figure 5.4 Total dissolved salts (TDS) in the rooting zone (top 60 cm) under four tree species and a reference plot at the study sites in G'oybu and Beruniy. Displayed are initial stocks in 2009 and changes in 2010 (Δ 2010) and 2011 (Δ 2011) compared to the initial 2009 values. Error bars indicate the confidence intervals of the corresponding changes. Columns at one site with different capital and lowercase letters differ significantly in Δ 2010 and Δ 2011, respectively. Asterisks (*) indicate significant changes at p=0.05.

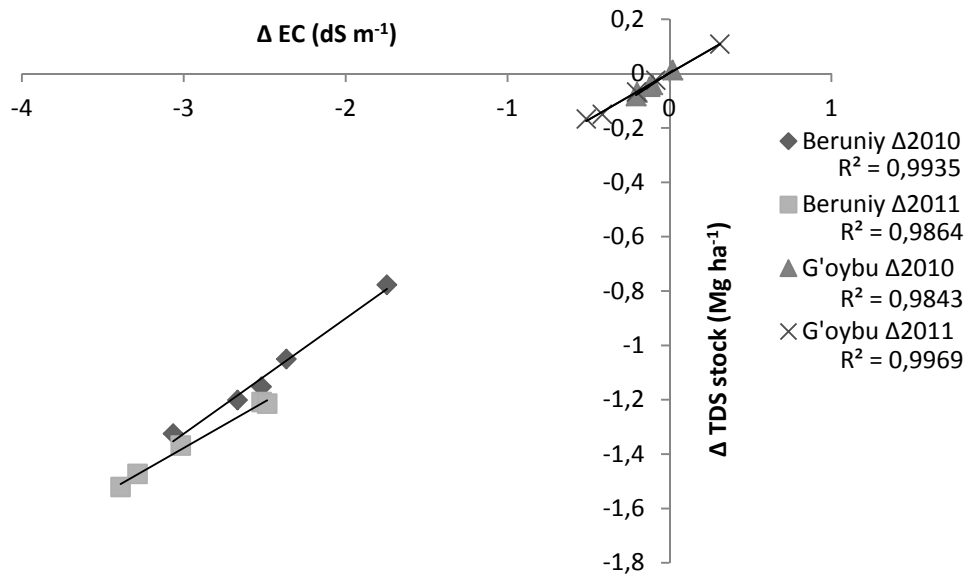


Figure 5.5 Correlations and R^2 of the correlations between the changes in the parameters TDS and EC at both study sites from 2009 to 2010 (Δ 2010) and from 2010 to 2011 (Δ 2011).

In 2010, one year following afforestation, changes in pH in G'oybu were not significant compared to the initial value of 8.00. In 2011, a slight increase of 0.14 was observed in the *U. pumila* plots (Figure 5.8). In Beruniy in 2010, significant changes in pH were measured for all species, whereas the pH in the reference plot remained unchanged. Nevertheless, the observed ranges did not significantly differ among species and the reference plots (Figure 5.8). In 2011, the changes in pH in the reference plot compared to 2009 (+0.26) were significant and higher than those observed in the *M. alba* (+0.80) and *E. angustifolia* (+0.10) plots. *Populus nivea x tremula* plots showed a statistically significant decrease in pH from 2009 to 2011 by 0.11 (Figure 5.8).

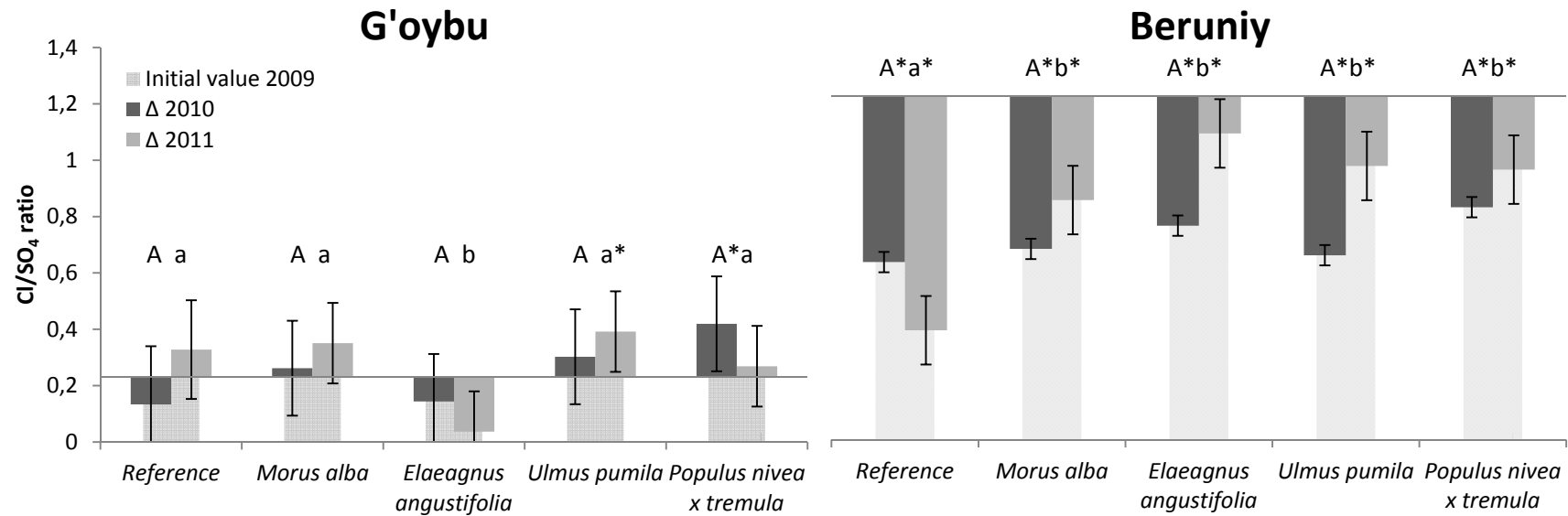


Figure 5.6 Cl/SO₄ ratio in the rooting zone (top 60 cm) under four tree species and a reference plot at the study sites in G'oybu and Beruniy. Displayed are initial values in 2009 and changes in 2010 (Δ 2010) and 2011 (Δ 2011) compared to the initial 2009 values. Error bars indicate the confidence intervals of the corresponding changes. Columns at one site with different capital and lowercase letters differ significantly in Δ 2010 and Δ 2011, respectively. Asterisks (*) indicate significant changes at p=0.05.

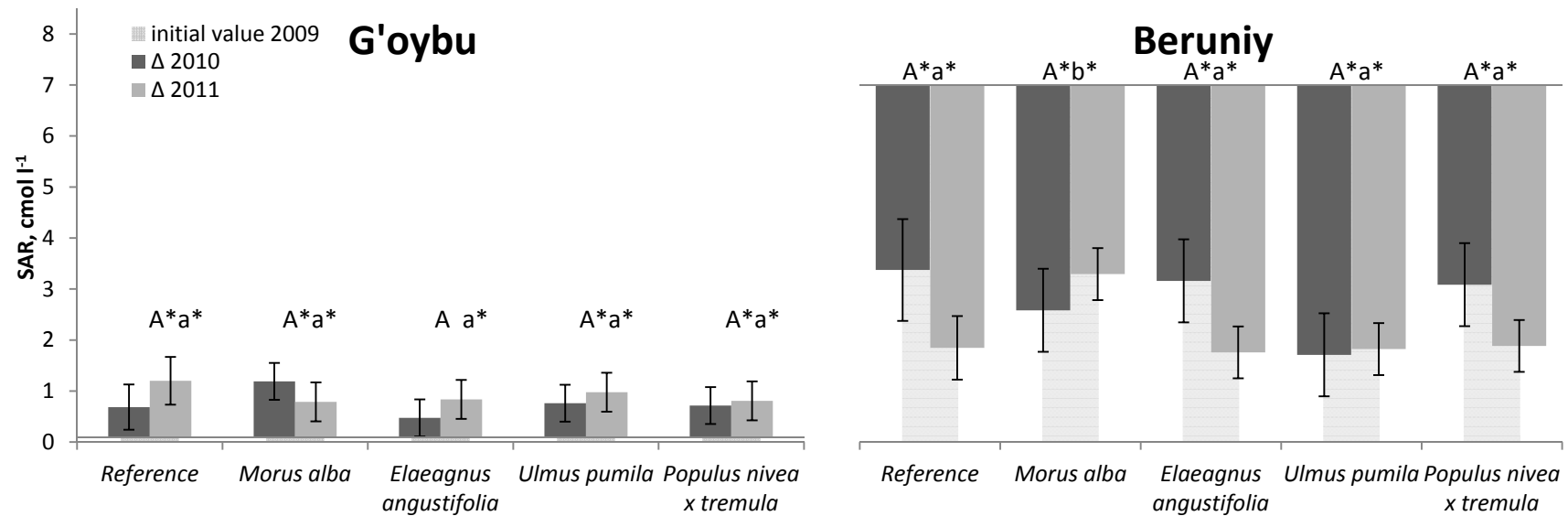


Figure 5.7 Sodium absorption ratio (SAR) in the rooting zone (top 60 cm) under four tree species and a reference plot at the study sites in G'oybu and Beruniy. Displayed are initial values in 2009 and changes in 2010 (Δ 2010) and 2011 (Δ 2011) compared to the initial 2009 values. Error bars indicate the confidence intervals of the corresponding changes. Columns at one site with different capital and lowercase letters differ significantly in Δ 2010 and Δ 2011, respectively. Asterisks (*) indicate significant changes at $p=0.05$.

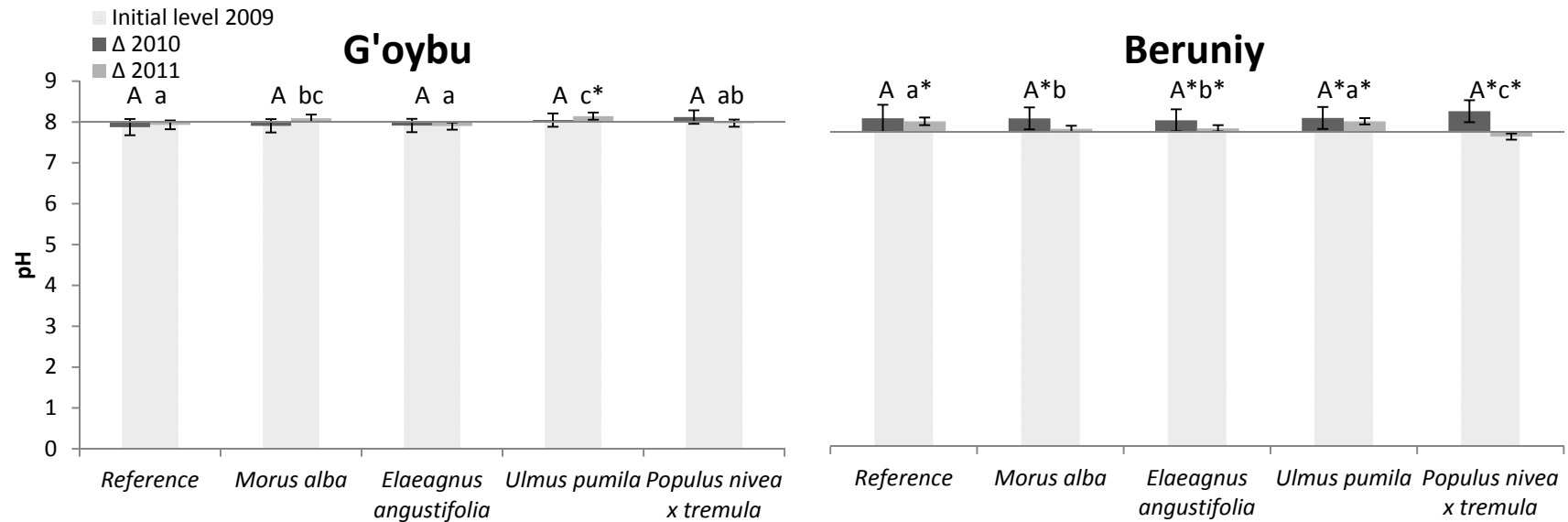


Figure 5.8 PH in the rooting zone (top 60 cm) under four tree species and a reference plot at the study sites in G'oybu and Beruniy. Displayed are initial values in 2009 and changes in 2010 (Δ 2010) and 2011 (Δ 2011) compared to the initial 2009 values. Error bars indicate the confidence intervals of the corresponding changes. Columns at one site with different capital and lowercase letters differ significantly in Δ 2010 and Δ 2011, respectively. Asterisks (*) indicate significant changes at $p=0.05$.

5.4 Discussion

5.4.1 Changes in soil nutrient stocks

Previous studies reporting initial decreases in soil-nutrient and soil-C stocks following afforestation attributed these to the mechanical disturbance of the soil during the site preparation and planting and the resulting accelerated decomposition (Turner and Lambert 2000; Paul et al. 2002) rather than to the impact of the trees. This observation was not confirmed in the current study sites where despite intensive land preparation, including the clearance of the natural vegetation on the sites, leaching, plowing, and levelling, no significant differences in total soil-C stocks between the plantation and the reference plot were observed within the first two years following afforestation. These findings, together with those of Paul et al. (2002), indicate that the initial decline in soil C after afforestation is likely to be smaller in soils with low initial soil-C contents, such as observed in abandoned croplands. Even though Paul et al. (2002) had excluded abandoned cropland in their studies, their overall findings highlighted the influence of the former land use and associated initial soil-C contents on the dynamics of the C stocks following afforestation especially in the short term (<10 years). On agricultural croplands, for instance, a frequent homogenization through ploughing leads to a (weak) concentration gradient of C in topsoil layers (Post and Kwon 2000), and hence initial soil C losses are usually of less importance. In the present study, initial soil-C and SOC stocks were already very low (section 3.2.1) allowing therefore only small C losses due to site preparation for tree planting.

Examining the organic fractions of total soil C that might allow detecting subtle changes in soil-C status already in a short period of time (e.g., Leifeld and Kögel-Knabner 2005) revealed changes in soil C status during the two-year study period. In the sandy Beruniy site, significant decreases occurred in the tree plots but also in the non-tilled control plots, which might have lost SOC due to lack of vegetation cover and erosion. A recovery of SOC after the second season following afforestation was indicated by a slight increase in the SOC level under *P. nivea x tremula* compared to the reference plots. In G'oybu, with its silt-loamy texture, the SOC increased in the *E. angustifolia* and *U. pumila*

plots and remained stable in the barren reference plot, presumably because the heavier soil there was less prone to erosion than that in Beruniy. The impact of species on changes in SOC is in line with the results of the biomass analysis (Chapter 3), indicating that species yielding higher biomass increase the soil organic matter pool due to decomposition of leaf litterfall and belowground material. The inter-annual variability of the surface SOC observed at the Beruniy site might also be a result of the observed fluctuations in depth to the GWT, which directly affects the salinity and moisture regimes across the entire soil profile (Chapter 3). As previously shown, both salinity and moisture directly influence C mineralization by affecting the soil microbial activity, which is crucial for the decomposition of organic matter and release of nutrients (Laura 1974; Pathak and Rao 1998).

Overall, the present results highlight the potential of afforesting degraded croplands with the purpose of C sequestration, particularly in heavier textured soils. There, the amounts of C accrued in the biomass (Chapter 3) by far compensate for possible initial losses in soil-C stocks caused by the disturbance of the soil during the land preparation for tree planting (e.g., Turner and Lambert 2000; Paul et al. 2002). On the other hand, the early detection of changes in SOC stocks remains challenging, because only a small part of the total organic matter pool responds to land-use changes in the short term (Post and Kwon 2000). Although the observed impacts on SOC stocks cannot be considered as an improvement in soil fertility, the observed tendency is a first evidence of enhanced SOC stocks under tree plantations in the long term. Therefore, the present results should be validated through longer-term research.

Judged by the lack of significant differences in soil-N stocks among the reference site and the tree plots, afforestation did not seem to impact soil-N stocks within the first years. This finding is in accordance with numerous previous studies, which could not detect any influence on soil N following afforestation (Compton et al. 1998; Jug et al. 1999; Ritter et al. 2003; Jaiyeoba 2001). Ritter et al. (2003) stated that changes in N-stocks occur slowly, and therefore long-term investigations are necessary in order to understand changes in soil properties and to predict future trends. The observed N losses when com-

paring the values before and after afforestation might have been due to inter-annual variability or even technical challenges during the laboratory analysis. The differences cannot be associated directly to the afforestation, since similar trends were also observed at the reference plots.

With respect to total soil C and N stocks, *E. angustifolia* did not offer significant advantages over the other species in the short run despite its confirmed N₂-fixation (Chapter 4). Previous studies reported that N-fixing species do not necessarily increase total soil N (Johnson and Curtis 2001; Resh et al. 2002; Paul et al. 2002). They even found significantly lower soil N under mixed stands of *Juglans nigra* and either *E. umbellate* or *Alnus glutinosa* than under pure *J. nigra* stands (Paschke et al. 1989). Previous studies in the Amu Darya lowlands however reported an almost 2-fold increase in plant-available soil N in four to five years following afforestation with *E. angustifolia*, and a consistent although subtle increase in soil total N concentrations (Khamzina et al. 2009).. The low impact of the tree plantations on soil total C and N stocks observed in the current study is probably a cause of the overall rather low biomass increments measured for all planted tree species during the initial two years (Chapter 3). Sanchez et al. (2004) postulated that under such arid conditions the increments in soil organic matter are proportional to the amount of organic material added.

5.4.2 Soil salinity dynamics

Soil salinity affected tree survival at both afforestation sites (Chapter 3). Even though soil salinity was initially higher at the Beruniy than at the G'oybu site, at both sites the EC declined over the two-year observation period. Initially, the soil at the G'oybu site was classified as slightly saline, with salinity of the chloride-sulphate type according to the classification based on the Cl/SO₄ ratio and the TDS by Kaurichev et al. (1989). The Beruniy site was characterized by a higher soil salinity which decreased significantly following afforestation. More specifically, initially classified as a solonchak with sulphate-chloride salinity according to Kaurichev et al. (1989), soil salinity in Beruniy changed towards slightly saline and

chloride-sulphate salinity type. Generally, a chloride salinity is more toxic to plants than a sulphate salinity (e.g., Eaton 1942; Bernstein and Hayward 1958; Bernstein 1975).

Soil-salinity decreases were at the margin of statistical significance in G'oybu, whereas in Beruniy the drop was highly significant. Accordingly, changes in SAR were small in G'oybu compared to those in Beruniy. Since at both sites changes in the reference plots did not significantly differ from those in the tree plots, the impact of the tree plantations and applied deficit irrigation on the soil-salinity regime was not statistically detectable. Only the distinct differences the CL/SO_4 ratio observed between afforestation and reference plots in Beruniy indicate changes in the salinity regime due to the furrow irrigation that influenced the ionic composition.

The commonly cited threshold of 13 cmol l^{-1} indicating sodic soils (Soil Science Society of America 2001) was by far not reached at the G'oybu site. Even with the much higher SAR at the Beruniy site, the threshold for sodic soils was not met either, thus characterizing a lack of sodicity. Furthermore, the significant decrease in the SAR at the Beruniy site was in accordance with the observed overall salinity decrease, and is therefore directly linked to it.

Overall, during the observation period, other external factors such as the fluctuating GWT might have been more determining the soil-salinity regime (Chapter 3). Tree plantations can impact soil moisture and salinity dynamics through their high water uptake, which can result in a salt build-up in the rooting zone (Heuperman 1999) or, in contrast lower the GWT and hence help to prevent the secondary-salinization process (Lal 2001; Rengasamy 2006). Also, the shading effect of the tree crowns can help to reduce the evapotranspiration of soil water and hence prevent soil salinization (Hbirkou 2011). Nevertheless, in the present study, the water use and shading effect of the young trees was likely modest but a decline in GWT due to drought in 2011 might partly explain the reduced capillary rise and thus soil salinization.

5.5 Conclusions

The overall impact on soil total N, C, and SOC directly linked to the tree planting on marginal lands was modest due to high inter-annual variability in soil characteristics, which occurred also in the reference plots, short observation period and young age of the tree plantations. In particular, the addition of organic matter, i.e., as leaves to the soil was not sufficient to significantly influence soil nutrient stocks. The subtle but statistically significant increases in SOC stocks in the heavier textured soil in plots with higher biomass yielding species (e.g. *E. angustifolia*) are first positive indications for future trends in soil C status. The soil C losses associated with soil disturbance during tree planting were mostly recovered already during the first two years since the afforestation. Consequently, this land use change has potential for C-sequestration purposes, also due to the C accrual in tree biomass.

The decline in soil salinity that occurred in both afforestation sites and their reference fields are likely associated with the fluctuating GWT rather than the impact of young plantations. Therefore, the influence of the GWT fluctuations must be accounted for when attempting to simulate the plant and soil dynamics in the study region. This underlines the importance of including a correct simulation of GWT dynamics and irrigation into a modeling exercise. Consequently, a suitable model for the prediction of plant growth under the conditions in the study region needs to be able to predict sudden abrupt changes in the GWT and the associated changes in soil-moisture and soil-salinity regimes.

6 EVALUATION OF THE EPIC MODEL FOR SIMULATION OF TREE GROWTH IN AFFORESTATION SYSTEMS UNDER SALINE CONDITIONS

6.1 Introduction

Afforestation was proven in this study to be a suitable measure to make productive use of long-term abandoned croplands under dryland conditions in the lower reaches of the Amu Darya River in an irrigated agricultural environment (Chapter 3; Chapter 5). The findings highlight the need for site and species specific recommendations (Chapter 3). Information on tree growth in dryland areas is generally sparse (Silver et al. 2001) and obtaining the required data from field experiments covering all potential settings in the study region is not feasible for practical and budgetary reasons. Modeling analysis is able to counterbalance in part gaps in field data through simulating plant-growth responses for a variety of field conditions (Landsberg and Sands 2011).

Therefore, tree-growth models are important scientific tools that allow useful, practical, and quantitative predictions of forest and tree growth and species response to environmental changes (Landsberg 1986; Landsberg and Sands 2011) and considered useful for forest management decisions (Peng 2000). Although tree-growth models cannot replace empirical research, their use could compensate the lack of long-term experience (Landsberg and Sands 2011) in dryland afforestation in irrigated agricultural settings and form a basis for land-use decisions.

The type and complexity of a suitable model strongly depend on the scope of the model's purpose (Porté and Bartelink 2002). The careful choice of a suitable model and its parameterization and calibration to the site conditions are therefore required to ensure sound and reliable predictions (Steiner et al. 1987) allowing decision makers to choose the right action for a specific site. When selecting a model suitable for the current study region, of special interest was the model's capability of predicting the specific soil conditions resulting from prevailing shallow GWT and groundwater dynamics influencing both soil moisture and salinity in the rooting zone (Chapter 2). Furthermore, a suitable tree-growth model needs to include the influence of soil salinity on tree growth, which is highly signifi-

cant under irrigated dryland conditions and was seen to determine plant survival in the present study (Chapter 3). Therefore, the purpose of the selected model is to predict site-specific growing conditions including different textures, depths to the groundwater, and soil salinity levels, and their impact on tree growth.

6.1.1 Advantages of process-based models in the context of afforestation

Since the beginning of forest management, decision makers rely on models of different complexity to predict tree growth and the effects of the management decisions. The first forest models used were yield tables (e.g., Paulsen 1795), which allowed foresters to plan the optimal harvesting time. Based on observed data, yield tables belong to the group of empirical models consisting of equations describing statistical relationships among data with limited consideration of an object's internal structure, rules, or behavior (Korzukhin et al. 1996). Empirical models are well respected standard tools used in commercial management regimes and can give accurate predictions under specific conditions (Landsberg 2003). Therefore, yield tables still form the backbone of sustainable management particularly for plantation forestry despite a number of drawbacks (Porté and Bartelink 2002).

However, forest management is constantly changing and nowadays timber production is no longer the only conceivable forest use. The interest in NTFP and ecosystem services has been constantly growing and revenues from these sectors can even exceed revenues from timber production (e.g., Peters et al. 1989; Djanibekov et al. 2012b). With the increasing complexity of forest management strategies, the simplicity of empirical models, which initially was seen as an advantage, became more and more problematic (Landsberg and Sands 2011). Empirical models are generally site specific and often depend on the logically circular concept of site index. Based on measurements, the capacity to simulate the results of environmental stresses, such as drought or significant departures from the conditions pertaining during the period when the measurements were made, is usually lacking (Landsberg 2003). Due to the prevalent environmental stresses and lack of previous data for tree species growing on abandoned cropping sites in the ADB, an empiri-

cal model is not deemed sufficient for reproducing plant and soil processes observed in this study.

Where a higher degree of flexibility is required and the interest in forecasted outcomes differs from the classical forest parameters, empirical models are often substituted by process-based models (PBM). These models are based on the physiological processes that describe the system. Often unfamiliar to the forest manager, PBMs are not necessarily as accurate as empirical models and may require data that is unfamiliar or difficult to obtain. On the other hand, PBMs are usually based on a wide range of growth conditions, including non-commercial conditions, and are thus applicable to novel situations (Sands 2003). In addition, the possibility of combining PBMs with data obtained by remote sensing significantly increases the spatial applicability of these models (Landsberg and Sands 2011).

It is due to these advantages that for the purpose of modeling afforestation on long-term degraded cropland, where past experience is lacking, PBMs are more likely to meet the information challenges and are, therefore, the most suitable tool.

6.1.2 The Environmental Policy Integrated Climate (EPIC) model

The Environmental Policy Integrated Climate model (EPIC; Williams 1990), formerly known as Erosion Productivity Impact Calculator, is a PBM considered suitable for its application in drylands under arid conditions, including both, rainfed and irrigated agricultural areas (Williams et al. 2008a). The EPIC model is able to give satisfactory yield predictions in dryland regions after being calibrated to the location conditions (Steiner et al. 1987).

Unlike most forests models that project growth for individual trees (Porté and Bartelink 2002), the EPIC model is stand based and facilitates the up-scaling of plot predictions to a region due to the use of average canopy conditions as it is done in remote sensing (Ollinger et al. 1998; Plummer 2000).

Based on these advantages, EPIC was tested for predicting soil salinity and water dynamics in the presence of a shallow GWT under irrigation, a situation representative for

the site conditions in the study region. Furthermore, biomass simulations of the species “*Populus sp.*” included in the EPIC model were compared to field-observed values for *Populus nivea x tremula*, a local poplar hybrid species that showed promising biomass increments in field experiments (Chapter 3). Based on field-measured biomass and soil data from two experimental field trials in the lower reaches of the ADB (Chapter 3 and 5), this part of the study aimed to calibrate the model for *Populus nivea x tremula*.

6.2 Material and methods

6.2.1 Conceptual framework of the EPIC model

The EPIC model is a PBM developed by a multidisciplinary team (Williams et al. 1989), and can be used to assess the impact of weather, soil, water resources, and management strategies on agricultural production (Williams et al. 1990). Operating on a continuous basis, the field-scale model uses a daily time step and is able to utilize soil data, plant parameters, and weather conditions to accurately predict crop responses to environmental factors (Choi 2011). Since its development, the model has been continuously refined and expanded (Williams et al. 2008b), and currently consists of the following main sub-models (Williams 1995):

1. Weather generator
2. Soil water dynamics and hydrology
3. Erosion by wind and water
4. Nutrient (N, P, K) and carbon cycling
5. Soil temperature
6. Tillage
7. Crop growth
8. Crop and soil management
9. Economics

For the purpose of this study, not all of the sub-models were used. The components used in the present study are described in the following section.

Weather

The EPIC model requires the input of daily weather data, including precipitation, maximum and minimum air temperature, solar radiation and, as in this study the Penman-Monteith method (Monteith 1965) was used for estimation of the potential evaporation, also wind speed and relative humidity. A weather generator included in EPIC allows the user to generate or input the variable or combine the two options (Williams et al. 2008b). In case historical weather data for the simulated region is available, it can be used in two ways. First, it can be directly used in the EPIC simulation when the length of the historical data is the same as the simulation period. Second, the historical weather data can be used to generate monthly weather data, which serves as a basis for the generation of the EPIC weather input data (Steglich and Williams 2011).

Groundwater table dynamics

The EPIC model drives the GWT up and down between user-input maximum and minimum depths from the surface, without direct linkage to other soil water processes (Williams et al. 2008b):

$$WTBL = WTBL0 - X2 \cdot WTBL0 - XX) \quad (6.1)$$

$$X2 = \text{MINIMUM (PARM 88) or ABS(RTO)} \cdot X1 \quad X2 < 1.0 \quad (6.2)$$

$$RTO = (\text{SMRF} - \text{SMEO})/\text{SMEO} \quad (6.3)$$

for $RTO > 0.0$

$$X1 = 1.0$$

$$XX = \text{WTMN}$$

for $RTO < 0.0$

$$X1 = \text{PARM}(87) \cdot \left(\frac{\text{JULIAN DAY}}{\text{TOTAL NUMBER OF DAYS IN YEAR}} \right)^{\text{PARM}89}$$

$$XX = \text{WTMX}$$

where WTBL and WTBL0 are the groundwater levels (m) today and yesterday, respectively; SMRF and SMEO are the sum of daily precipitation and respectively soil temperature in

soil layer 2 for the antecedent period in mm. The user-specified antecedent period ranges from 5 to 30 days. WTMX and WTMN are the maximum and minimum possible distances from the soil surface to the water table (m), PARM(87) is a parameter slowing down the water table recession, PARM(88) is the fraction of the difference between WTBL and WTMX and therefore limits the daily water table movement, and PARM(89) is the exponent of the time ratio.

Plant growth component and plant parameters

The EPIC model is able to simulate about 100 different agricultural crops, pastures, and trees with one single growth function where every crop has unique values for the 56 model parameters (Williams et al. 2008a). Whereas annual crops grow from planting date to harvest date, perennial crops and trees extend their root systems throughout the years, except for the dormant winter period in continental climates. Thereafter, growth is triggered by the average daily air temperature and will be started when a plant-specific base temperature is exceeded.

The EPIC model uses an energy-/carbon-driven approach commonly used in plant growth modeling (McMaster et al. 2003; Ko et al. 2009). Potential biomass increase is estimated in daily steps based on the equation by Monteith (1977), and is mainly based on the light intercepted by the canopy (represented by the leaf area index (LAI) and light extinction factor) and a crop-specific energy to biomass conversion factor:

$$\text{DDM} = 0.001 \cdot \text{PAR} \cdot (\text{RUE} - \text{WAVP} \cdot \text{X1}) \quad (6.4)$$

$$\text{X1} = \max(\text{VPD} - 1, -.5) \quad (6.4a)$$

where DDM is the potential increase in biomass [$\text{t ha}^{-1} \text{d}^{-1}$], RUE is the crop-specific radiation use efficiency factor [$(\text{kg ha}^{-1})/(\text{MJ m}^{-2})$], VPD is the vapor pressure deficit [kPa], and WAVP is a crop parameter relating RUE and VPD.

Potential crop growth is usually not achieved, as plant growth is constrained by the plant's environment (Williams et al. 1989). Therefore, the EPIC model estimates

stresses caused by water, nutrients, temperature, aeration, and soil salinity factors. These stresses range from 0.0 to 1.0 and affect plants in several ways. The potential biomass predicted with Equation 6.4 is adjusted in daily time steps according to the stress factors using the equation:

$$\text{DDM}' = \text{DDM} \cdot \text{REG} \quad (6.5)$$

where DDM' is the actual daily biomass accumulation and REG is the factor regulating crop growth (minimum stress factor at day i). Aside from external stress factors, the model considers the influence of the phenological status of a crop by adjusting the parameters for leaf area growth and senescence, optimum plant nutrient concentrations, N_2 -fixation, partition of dry matter between roots and shoots, and consequently economic yield. The phenological development of a crop is based on the thermal time expressed in daily heat units using the equation:

$$\text{HU} = 0.5 \cdot (\text{TMX} + \text{TMN}) - \text{TBSC}; \text{HU} > 0.0 \quad (6.6)$$

where HU [$^{\circ}\text{C}$] is the number of heat units accumulated during a day, TMX [$^{\circ}\text{C}$] and TMN [$^{\circ}\text{C}$] are the maximum and minimum temperatures for the day, and TBSC [$^{\circ}\text{C}$] is the crop-specific minimum temperature at which growth occurs.

The actual biomass estimated by the model is divided into roots and shoots using the root/shoot ratio, which is a plant-specific input parameter. In the present study, the parameterized and calibrated parameter set for *Populus* sp. included in the EPIC model was used as a basis for the simulations of *P. nivea x tremula*.

Crop management

A simulation run in the EPIC model requires information on timing and type of field operations during the simulation period. For that purpose, the user creates a schedule of activities including all field operations selected from a predefined list. In the experimental plantations, the schedule included tree planting on 15 March 2010 and biweekly irrigation of

12.5 mm during the growing season from March till September. Even though the model allows simulation of competition for water and nutrients by weeds and for production loss through pests, these options were not activated since pests were not observed and there was weed control during the field experiment. The simulation period was set at two years starting in January 2010.

6.2.2 Input parameters

Parameters required by the model were measured directly in the field or laboratory as described in sections 3.2 and 5.2.1.

Weather data

A weather station installed at the beginning of the experiment at the G'oybu study site collected all the required parameters (section 3.2.1), which were then input to the model. The weather data were used to generate monthly weather data sets as a basis for the generation of the EPIC weather input data. These were used for the simulations at both study sites, since the local variability between the sites was assumed to be negligible.

Soil data

Soils were parameterized separately for each study site based on information on relevant physical and chemical parameters obtained from soil pits at the onset of the experiment (section 5.2.1). All other soil parameters were left blank and were calculated by the model through pedotransfer functions.

The EPIC model allows including up to ten soil layers. In this experiment, only five layers were needed to describe the soil profiles at both sites (Table 6.1). Maximum and minimum depths to the GWT were initially set according to the observations made during the study period and long-term monitoring of GWT in the region (Ibrakhimov et al. 2011) at 3.0 and 0.8 m, respectively, in G'oybu, and at 0.1 and 1.0 m in Beruniy. However, as a consequence of the lack of precipitation and the high temperatures during the growing

period, which control the GWT dynamics as described above, the GWT dropped to a minimum and remained there till the end of the simulation. Since the depth to the GWT significantly affects soil moisture and salinity regimes, its calibration is of crucial importance for the model outcomes.

Table 6.1 Parameterized soil properties at the G'oybu and Beruniy sites used in the EPIC model simulations.

Layer	Maximum layer depth (m)	Texture	Hydro-logical group	Wet bulk density (d/cm ³)	Soil water content at wilting point (%)	Soil water content at field capacity (%)	Sand content (%)	Silt content (%)	pH	SOC (%)	Cation exchange capacity
G'oybu											
1	0.13	SL	C	1.59	22.5	32.6	13.0	71.8	8.0	0.75	15.0
2	0.31	SL	C	1.59	24.3	34.1	13.8	79.8	8.0	0.58	6.8
3	0.49	SL	C	1.51	26.3	35.9	34.0	62.0	8.0	0.50	5.0
4	0.77	SL	C	1.45	26.0	35.1	39.5	55.7	8.0	0.73	5.0
5	1.00	SL	C	1.44	24.9	34.6	61.0	34.0	8.0	0.43	5.4
Beruniy											
1	0.30	S	A	1.5	15.5	25.89	88.9	6.3	7.5	0.36	8.1
2	0.50	LS	B	1.51	15.5	26.0	85.3	8.0	7.4	0.56	9.6
3	0.70	LS	B	1.57	14.2	25.6	88.7	6.4	7.8	0.43	5.5
4	1.05	LS	B	1.61	18.5	30.0	66.6	23.7	7.7	0.45	6.0
5	1.20	SL	A	1.68	20.9	34.2	55.2	32.4	7.7	0.51	6.4

6.2.3 Model calibration

Soil conditions

In order to correctly predict soil conditions, the EPIC model usually requires a regional adjustment (Steiner et al. 1987), which was done through the Parm editor without changing the original source code. Following the set-up of the model, including the parameterization of the soil conditions of both study sites with field-measured data and the run creation, the model was calibrated. This was done by improving the goodness of fit between the modeled and field-observed data on the soil conditions in the rooting zone during the growing seasons in 2010 and in 2011 through a graphical comparison (Figure 6.1 and 6.2). Adjusted parameters for the soil calibration are listed in Table 6.2.

Table 6.2 Default and adjusted values of the parameters changed during the calibration.

	Parameter	Definition	Default value	Adjusted value
Parm 5	Soil water lower limit	Regulates the lower limit of the water content in the top 0.5 m of soil and is expressed as fraction of the water content at wilting point	0.5	1
Parm 12	Soil evaporation coefficient	Governs soil evapotranspiration rate from the top 20 cm soil	1.5	5
Parm 62	Regulating coefficient	Increasing PARM62 increases the upward N and salt movement in the soil	0.5	0.8

In the EPIC model, yield-salt functions are based on the dependence of biomass production on transpiration under saline conditions as described by Maas and Hoffman (1977). Therefore, salinity conditions in yield-salt functions are related to soil-water salinity in the root-zone (Ranatunga et al. 2010). Since the aim of calibrating the soil component was to use the EPIC model to predict tree biomass accumulation at the study sites, the soil calibration targeted soil moisture and salinity as the main parameters for the calibration.

***Populus sp.* component**

The parameter set for “*Populus sp.*” included in the EPIC model was calibrated for the local poplar hybrid *P. nivea x tremula*. The most important crop parameters to be adjusted for that purpose are (Evelyn Steglich, personal communication):

1. Biomass to energy ratio (WA)
2. Leaf area index parameters
3. Salinity effect on growth (STX1) and salinity threshold (STX2)
4. Maximum rooting depth (RMAX)

In order to ensure the correct soil-plant interaction, the rooting depth and biomass partitioning were the first target parameters to be adjusted through changing the parameters RMAX and the biomass partitioning coefficient, which separates above- and belowground biomass, based on field data. In the next step, the leaf area index was compared to literature values and adjusted accordingly, since it was not measured during the experiment. The growth response to salinity and the salinity threshold (STX1 and STX2) were adjusted according to literature values, and the results of this study (Chapter 3). Since a regional adjustment of the WA is often required to fit the simulated to the observed biomass values (Steiner et al. 1987), this parameter was changed to the best fit, since literature was not available for *P. nivea x tremula*.

6.2.4 Model evaluation and validation

Model evaluation and validation were defined as the process of demonstrating that the parameterized model was able to make sufficiently accurate predictions, although the accuracy requirements may vary according to the overall modeling goal (Refsgaard 1997). Based on a review of relevant literature, Moriasi et al. (2007) concluded that in addition to a graphical evaluation, a model’s performance can be sufficiently evaluated by three quantitative statistics, namely the Nash-Sutcliffe efficiency (NSE), the percent bias (PBIAS), and the ratio of the root mean square error to the standard deviation of measured data (RSR). Following this approach, the precision of the calibrated model was measured through the following parameters (Moriasi et al. 2007):

1. Nash-Sutcliffe efficiency (NSE): A normalized parameter relating the magnitude of the residual variance (“noise”) with the measured data variance (“information”). It therefore indicates the fit of observed versus simulated data on a 1:1 line. NSE was computed following Nash and Sutcliffe (1970):

$$NSE = 1 - \frac{\left[\sum_{i=1}^n (x_i - y_i)^2 \right]}{\left[\sum_{i=1}^n (x_i - \bar{x})^2 \right]} \quad (6.7)$$

where n is the sample number, x is the observed, y the modeled parameter value, and \bar{x} the mean of the observed parameter values.

2. Percent bias (PBIAS): A parameter indicating the average tendency of simulated data compared to their observed counterparts (Gupta et al. 1999). Whereas the value indicates the magnitude of the bias, its sign defines if the model is over- or underestimating the real situation. PBIAS was calculated as:

$$PBIAS = \left[\frac{\sum_{i=1}^n (x_i - y_i) * 100}{\sum_{i=1}^n (x_i)} \right] \quad (6.8)$$

where n is the sample number, x is the observed, and y the modeled parameter value.

3. Root Mean Square Error (RMSE): A commonly used error index statistics (e.g., Vasquez-Amábile and Engel 2005). Root mean square error values close to zero express precision and reliability of the prediction for single estimation points (Gaiser et al. 2010). The RMSE was calculated as:

$$RMSE = \left[\frac{1}{n} \sum_{i=1}^n (y_i - x_i)^2 \right]^{0.5} \times \frac{100}{\bar{x}} \quad (6.9)$$

where n is the sample number, x is the observed, y the modeled parameter value, and \bar{x} the mean of the observed parameter values.

4. To include the variability of the observed data compared to the simulation error in the evaluations, the RMSE can be put in relation to the standard deviation of the measured data as suggested by Singh et al. (2004). The resulting model evaluation statistics, called the RMSE-observations standard deviation ratio (RSR) (Moriasi et al. 2007), in-

incorporates the benefits of error index statistics and includes a scaling/normalization, which allows its universal application (Moriassi et al. 2007). The RSR ranges between its optimal value of zero and a larger positive value. The RSR was calculated as:

$$RSR = \frac{RMSE}{STDEV_{obs}} = \left[\frac{\sqrt{\sum_{i=1}^n (x_i - y_i)^2}}{\sqrt{\sum_{i=1}^n (x_i - \bar{x})^2}} \right] \quad (6.10)$$

where n is the sample number, x is the observed, y the modeled parameter value, and \bar{x} the mean of the observed parameter values.

For the biomass increments of *P. nivea x tremula*, field-observed values were not sufficient to run a sound statistical analysis. In this case, the modeled outcomes were compared to the mean values and respective confidence intervals of the field values.

Even though validating a model is essential for its confident use, this is often not possible for complex models (Ranatunga et al. 2010). In this case, the refined functions should be related to the available data sets, thus providing an interim level of validation (Ranatunga et al. 2008). In the present study, the available information collected was not sufficient to validate the EPIC model. Consequently, extrapolating results from this study to other climatic and soil conditions should not be done without further validation. The EPIC model is a generally widely validated model (Williams et al. 1989), and providing a complete specific validation of the model was beyond the scope of the current study, which aimed to serve as a basis for further calibration and validation exercises.

6.3 Results and discussion

6.3.1 Soil conditions

Before calibration, the EPIC model generally underestimated soil moisture in the rooting zone (0-60 cm), whereas soil salinity was overestimated (Figure 6.1; Figure 6.2).

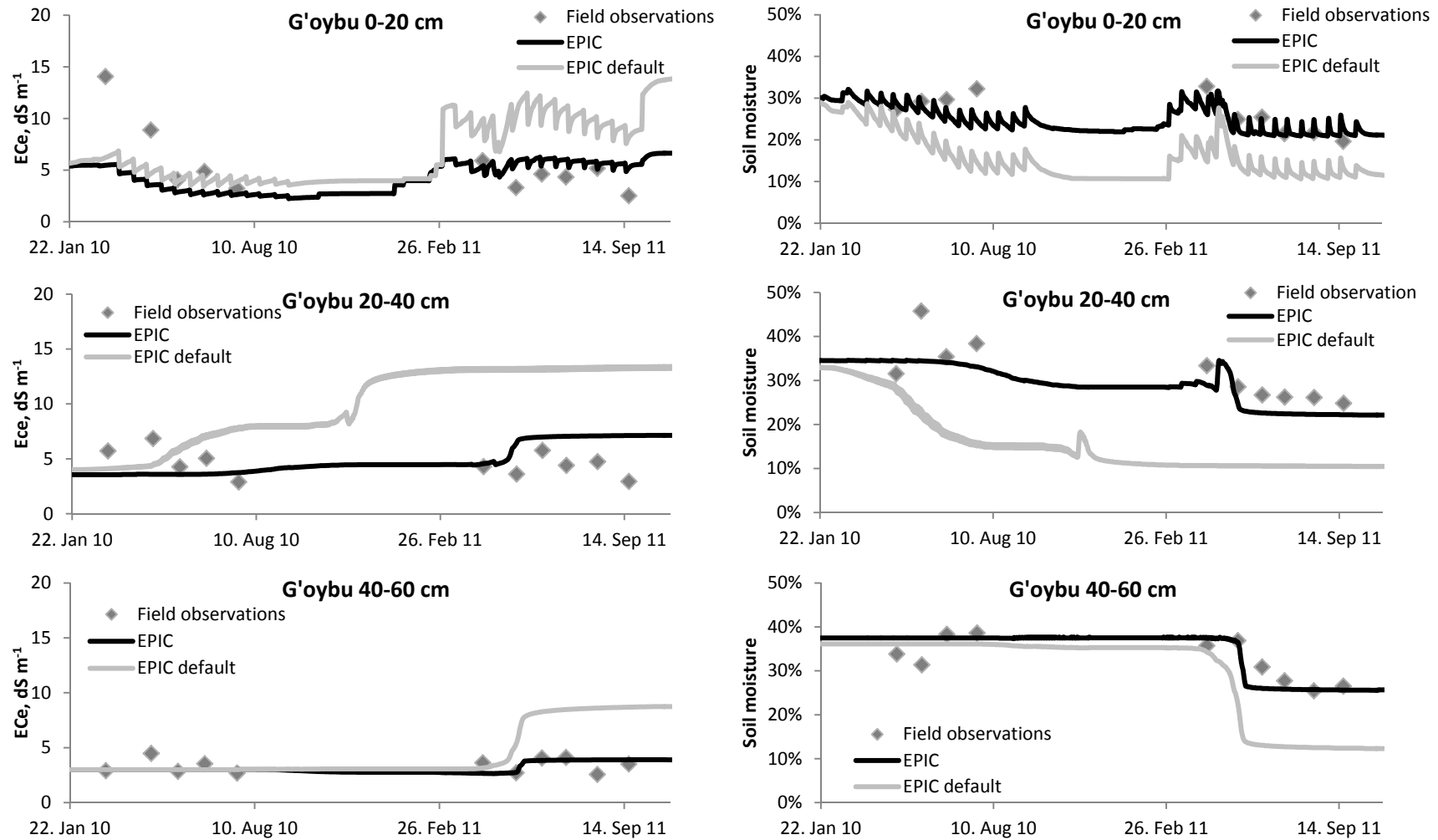


Figure 6.1 Measured and modeled soil moisture and electrical conductivity (EC_e) at the G'oybu site at different depths before and after calibration in the EPIC model. Error bars are not shown to improve the graph readability.

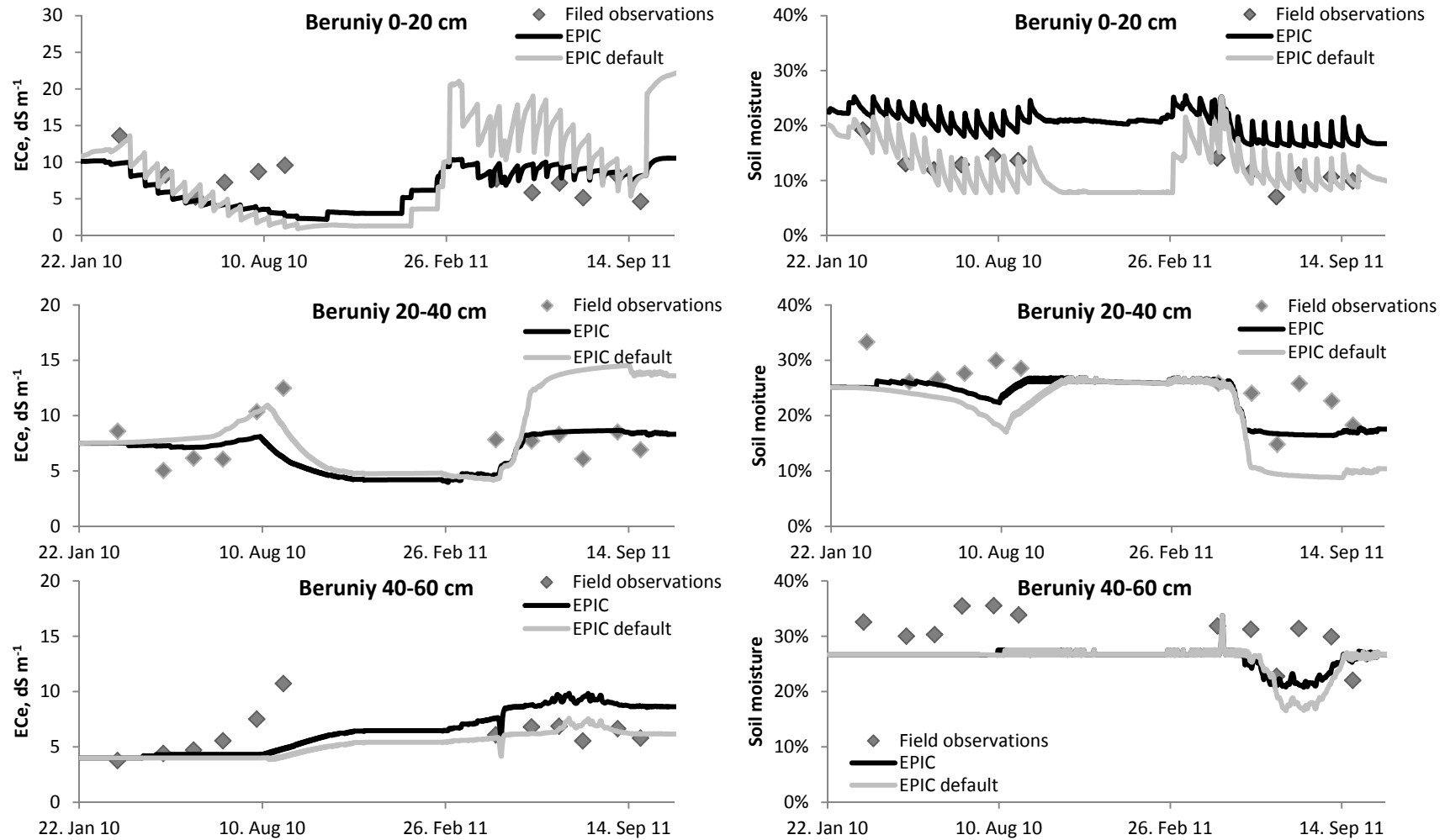


Figure 6.2 Measured and modeled soil moisture and electrical conductivity (EC_e) at the Beruniy site at different depths before and after calibration in the EPIC model. Error bars are not shown to improve the graph readability..

Soil moisture was calibrated by adjusting Parm 5, which regulates the minimum soil moisture in the top 0.5 m. Parm 5 was set at 1 to prevent the soil moisture from dropping below the permanent wilting point. Furthermore, to calibrate the salinity regimes in the rooting zone, Parm 12 regulating the soil evapotranspiration rate from the top 20 cm, and Parm 62 responsible for the upward N and salt movement in the soil profile needed adjustment (Table 6.2).

According to Moriasi et al. (2007), the simulation of a model is satisfactory if the NSE >0.5 , the RSR < 0.7 , and the PBIAS $< 25\%$. This was the case for the simulations of soil moisture in G'oybu and soil salinity in Beruniy following afforestation. Soil salinity simulations in G'oybu and soil moisture simulations in Beruniy were unsatisfactory according to the applied classification (Appendix 9.5), although the PBIAS values were in the category "very good" indicating only slight model deviations from the observed values.

In G'oybu, both measured and modeled soil salinity were in the category "medium saline" at the onset of the experiment and somewhat declined over the first growing season. Furthermore, at the beginning of the second growing season, slightly increased soil salinity was observed which was also correctly reproduced by the EPIC model (Figure 6.1). Since the EPIC model is poor in predicting extreme events and small-scale variations (Steiner et al. 1987), the modeled salinity ranges at the G'oybu site were assumed to be suitable as a basis for further calibrations in the plant sub-model.

The presumably unsatisfactory model performance in predicting soil moisture at the Beruniy site is a result of the modus by which the EPIC model simulates soil moisture in the presence of the GWT. Whereas field observations yielded soil moisture values exceeding the field capacity of the soil layers, in the EPIC model soil moisture is set at field capacity (Figure 6.2). Consequently, the EPIC model systematically underestimated soil moisture in the rooting zone at the Beruniy site (Table 6.3) as also indicated by the negative PBIAS (Gupta et al. 1999). Nevertheless, for the calibration of *P. nivea x tremula* it was not relevant whether soil moisture was at field capacity or beyond, since aeration stress was not assumed in the EPIC model. In both cases, the wa-

ter supply was ensured, so this soil moisture simulation was also assessed as satisfactory for the calibration of the plant component.

Table 6.3: Model performance parameters Nash-Sutcliffe efficiency (NSE), Percent bias (PBIAS), and Root Mean Square Error - observations standard deviation ratio (RSR). Displayed are EPIC model predictions and their evaluation for soil moisture and salinity conditions in G'oybu and Beruniy.

Site	Parameter	NSE		PBIAS (%)		RSR	
		Value	Evaluation	Value	Evaluation	Value	Evaluation
G'oybu	Soil moisture	0.57	Adequate ¹	5.49	very good ^{3,4}	0.66	satisfactory ⁵
G'oybu	Soil salinity	-0.23	unsatisfactory ²	3.45	very good ^{3,4}	1.11	unsatisfactory ⁵
Beruniy	Soil moisture	-1.71	unsatisfactory ²	-2.61	very good ^{3,4}	1.64	unsatisfactory ⁵
Beruniy	Soil salinity	0.83	very good ¹	2.45	very good ^{3,4}	0.41	very good ⁵

1 Saleh et al. (2000); 2 Motovilov et al. (1999); 3 Donigian et al. (1983); 4 Van Liew et al. (2007); 5 Moriasi et al. 2007

At the Beruniy site, the soil moisture regime was highly dependent on GWT dynamics (Chapter 3), which could not be correctly predicted in the EPIC model (section 6.3.2). This probably caused the significant overestimation of soil moisture in the top layer (0-20 cm) at Beruniy following calibration. Even though this is not relevant for the calibration of *P. nivea x tremula* in the present study, since water stress was not limiting this species growth (Chapter 3), it highlights the weak prediction of GWT dynamics and the need for further improvement of this component in the EPIC model.

6.3.2 Groundwater table dynamics

Groundwater dynamics play an important role in agriculture in the study region, since the prevailing shallow GWT significantly contributes to plant water supply as well as to secondary soil salinization (Tischbein et al. 2012). The groundwater availability also allows the establishment of tree plantations on marginal croplands, since the tree species with extensive rooting systems effectively utilize the groundwater (Khamzina et al. 2012). The depth to groundwater from the soil surface in the EPIC model is driven by precipitation and temperature (Williams et al. 2008). Since the depth to the GWT significantly affects soil moisture and salinity regimes, during the calibration process the minimum GWT depth was set at the average GWT depth observed at the sites during

the 2-year observation period of 0.8 m in G'oybu and 0.6 m in Beruniy; the GWT was kept at this level during the simulation period. Even though this adjustment allowed accounting for the influence of the GWT on soil conditions, it is evident that the seasonal variations will not be reflected by the EPIC model.

In the study region, seasonal variations in the depth of the GWT are strongly driven by leaching and irrigation activities (Ibrakhimov et al. 2007). Furthermore, inter-annual variations associated with the regional irrigation water availability are also prominent (Ibrakhimov et al. 2011). Especially during drought years, which frequently occur in the study region (Tischbein et al. 2012), the GWT can be significantly reduced as experienced in the year 2011. Since it is not possible to model external factors such as regional water availability at a field scale, the GWT minimums in this study were set at the average groundwater depth observed in the field during the first year; this yielded satisfactory soil moisture levels in the first year. In the second year, nevertheless, due to a low irrigation water availability, GWT tables declined at both study sites to different extents (Chapter 3). An adjustment of the GWT depth is, however, not possible since the model runs with one value for the whole simulation period and assumes relatively stable GWT levels. Even though this assumption still allows using the model for annual crops under the conditions in the study area, it significantly restricts the model's suitability for long-term simulations and hence, tree-growth modeling in the study area.

To increase the model's suitability for long-term simulations, an adjustment allowing a definition of annual maximum and minimum depths to the GWT would need to be included. A possible approach for this purpose could be linking groundwater characteristics with the daily weather files, which already allow the input of daily data sets into the simulations.

6.3.3 Crop component

The parameter RMAX, indicating the maximum rooting depth of the plants was set at 0.6 m. This was the maximum rooting depth observed and was reached in the EPIC simulation by the beginning of the second growing season. Even though this value

yielded the best model results for the observation period of two years compared to the field values it will need to be increased when modeling the long-time performance of *P. nivea x tremula*.

The root biomass is likewise important for an adequate representation of the nutrient uptake by trees. This is regulated through the biomass partitioning parameter at emergence “RWPC” that was set at 50% based on the observed biomass partitioning at the study sites (Chapter 3). The default value of 20% of the parameter “RWPC2” regulating the fraction of root weight at maturity remained unchanged due to a lack of data.

The EPIC model is based on the assumption that plant productivity is determined by photosynthetic efficiency in combination with light interception (Monteith 1977). Therefore, the produced biomass in the EPIC model is directly linked to the leaf area parameters regulating the amount of intercepted light, and to the biomass to energy ratio (WA). In the present study, leaf area parameters were not measured, and specific information on *P. nivea x tremula* is not available in literature. Nevertheless, the default maximum leaf area index (DMLA) for *Populus* sp. of 7.09 in the EPIC model was used. This value is in the same range as the DMLA of *P. tremula* of 7.13 measured by Rauner (1976), and was therefore assumed suitable for the present study. Steiner et al. (1987) postulated that the WA might require a local calibration to correctly predict yields. Also in the present study, the EPIC model tended to overestimate biomass increments, and the WA was changed from 40 to 30 kg ha⁻¹MJ⁻¹. This adjustment is relatively rough and was based on the best fit to the observed data. It therefore needs experimental confirmation.

Since the trees in the experiment were generally seen to suffer most from salinity (Chapter 3), for the calibration of *P. nivea x tremula* species-specific salinity-tolerance levels were changed. Salinity stress is regulated in the EPIC model with a salinity threshold at which any increase in salinity will cause a decrease in biomass production (STX2), and a parameter regulating the salinity effect on biomass (STX1; Steglich and Williams 2011). The salinity threshold STX2 in the model usually ranging from 0 to 9 dS m⁻¹ was set at 3 dS m⁻¹ in accordance with the results of Miyamoto et al.

(2004) who categorized *Populus* genus as moderately salt sensitive and starting to show severe damage through salinity in the range of 3-6 dS m⁻¹. In the present study, survival of *P. nivea x tremula* showed to be most strongly affected by salinity in comparison to all other species (Chapter 3). Therefore, the impact of salinity on growth was assumed to be relatively high; STX1 that usually ranges from 0 to 3 was set at 2. During the calibration, where observed values were compared to modeled results, STX1 and STX2 were adjusted to 1.9 and 3.1 dS m⁻¹, respectively, yielding best results.

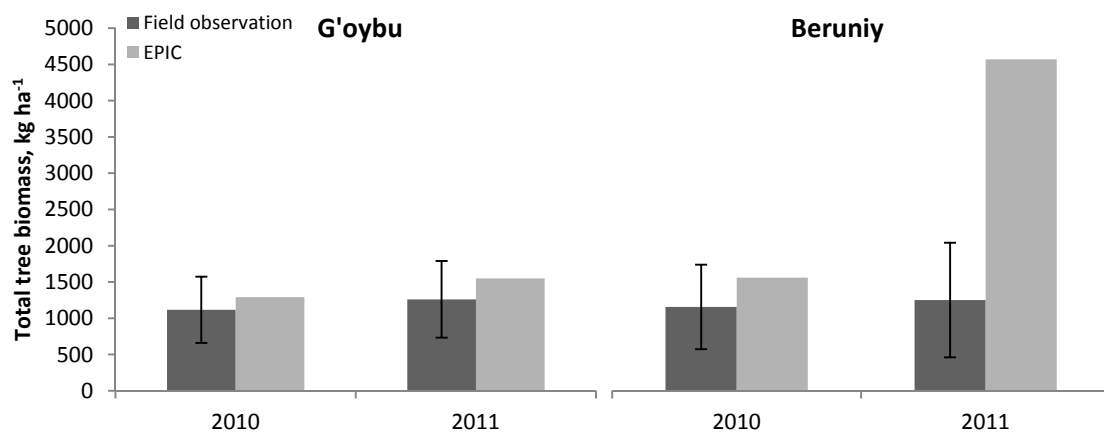


Figure 6.3 Field-observed and simulated data of *Populus nivea x tremula* biomass stocks after the first and second growing season. Error bars indicate 95% confidence intervals of the observed field data.

The calibration of the *Populus* sp. component yielded satisfactory biomass simulations within the field ranges at the G'oybu site (Figure 6.3). In the first year, also at the Beruniy site, biomass simulations were in the observed confidence interval thus confirming the calibration. Nevertheless, after the second season, simulated plant biomass at the Beruniy site was significantly higher than that observed in the field (Figure 6.3). The discrepancy between modeled and simulated values is probably a result of the problematic soil condition predictions at the Beruniy site, which can be associated with the above-discussed problem of GWT resulting in an overestimation of soil moisture in the topsoil. This additionally highlights the need to improve the groundwater component in the EPIC model, and underlines the limited suitability of the model for long-term simulations under the conditions in the study region.

Furthermore, the field biomass data showed a high variability (Figure 6.3), which complicates the calibration process. Therefore, more biomass data are required for an accurate calibration of *P. nivea x tremula*, which calls for additional field experiments under different conditions in the study region. The so-acquired data would furthermore allow a validation of the calibrated model that could not be done with the currently available dataset.

6.3.4 Suggestions for model improvements

Besides the previously discussed need to improve the groundwater component, two more model limitations of the EPIC model in the framework of afforestation were identified.

Survival

Tree survival determining plantation productivity and its economic value could not be modelled by EPIC, as the model does not consider tree mortality but assumes a constant stocking rate till the end of the simulation (Evelyn Steglich, personal communication). Including a tree-mortality sub-model could, therefore, significantly improve the model's accuracy and applicability in the planning of afforestation activities in the study region.

The results of the present study show that under the study conditions, early survival was most importantly limited by the salt concentrations in the soil (Chapter 3). Since the EPIC model predicts soil salinity levels in daily time steps, tree mortality could be linked up with the incidence rate (IR_{ECE}) and the incidence rate ratio (IRR_{ECE}) for salinity-induced tree mortality for the given site and climate conditions (Chapter 3). This would allow an accurate prediction of the final biomass production of the plantation, but would require further research in this field.

Biomass partitioning

Carbon partitioning remains a weak point in most current models, even though its basic mechanisms are relatively simple and well understood (Lacointe 2000). Due to

the growing interest in NTFP from tree plantations, there is a need for an accurate biomass prediction of different tree fractions. Even though the EPIC model includes the partitioning between above- and belowground biomass, the partitioning among different tree fractions should be considered in the model to increase its applicability.

Currently, biomass partitioning in the EPIC model is governed by two parameters (RWPC1 and RWPC2) describing an age-dependent allometric development curve of the fractions of biomass allocated to the aboveground part of the trees (Steglich and Williams 2011). Although allometric equations are determined for each species and therefore reflect species differences in biomass allocation, they are undoubtedly modified by environmental conditions (Landsberg and Waring 1997), expressed for example by reduced leaf area and production due to salt and water stress. Hence, improving biomass partitioning in the EPIC model and including the partitioning among tree fractions would probably further increase the applicability of the model for afforestation planning.

6.4 Conclusions

The use of the EPIC model for simulation of processes in afforestation systems established on degraded cropland within the irrigated agricultural areas of the lower ADB requires a regional calibration. The model's suitability strongly depends on the depth to the GWT and its dynamics. This was reflected in the regional calibration of the model that yielded satisfactory predictions of soil conditions at the G'oybu site characterized by a deeper GWT, whereas in Beruniy, where the GWT was more shallow and fluctuated during the growing season, the calibration resulted in inaccurate soil moisture predictions.

Consequently, also the calibration of the local poplar hybrid *P. nivea x tremula* was of limited success due to the overestimation of biomass production at the Beruniy site. Thus, the model should not be applied to other site conditions without further validation. To improve the model's applicability in the framework of afforestation projects, it is suggested to include survival and to detail the biomass partitioning component for tree fractions, which requires further research on these topics.

The model parameters obtained as a result of the calibration for the site conditions and for *P. nivea x tremula* serves as a first orientation for further calibration attempts and validation when sufficient data on afforestation systems becomes available.

7 GENERAL DISCUSSION AND OUTLOOK

Planting trees on degraded croplands in the lower reaches of the ADB has recently been suggested as a potential land-use option. This land-use change permits making productive use of otherwise unproductive lands (e.g., Khamzina et al. 2012) which are increasing in size because of ill-managed irrigation practices and climate change (Tischbein et al. 2012). Such tree plantations could be established with the help of (deficit) irrigation during about two to three years (e.g., Khamzina et al. 2012) and consequently depend on the shallow, saline GWT widespread in the ADB. The plantations could help to diversify rural incomes (Djanibekov et al. 2012b) and improve soil conditions at the afforested sites while mitigating the impact of global warming through C sequestration. Yet, previous research did not include long-term abandoned croplands in the ADB and had focused on a limited number of potential tree species only (e.g., Khamzina et al. 2012).

This study assessed multi-species afforestation as a land-use option for long-term abandoned croplands in the irrigated drylands of Uzbekistan, Central Asia, characterized by unfavorable site conditions, i.e., saline, nutrient-poor soils subject to water stress and with varying groundwater levels. For that purpose, field experiments were implemented on two abandoned cropping sites differing in soil texture and depth to the GWT representative for the lower reaches of the ADB. The growth dynamics and interaction with soil moisture and salinity dynamics were assessed throughout two years following afforestation. As a first step for the extrapolation of the site-specific results, the applicability of the EPIC model was evaluated for reproducing the field conditions prevailing in the ADB.

The findings, overall conclusions and recommendations for further research are discussed and summarized hereafter.

7.1 Afforestation of long-term abandoned croplands: feasible but risky

The findings of the present study generally confirm the possibility of expanding afforestation activities into long-term abandoned croplands in the ADB with deficit irriga-

tion, since most of the field-tested species survived during the field experiment (Chapter 3). Hence, deficit irrigation did suffice to ensure the survival of trees during the first two years following afforestation.

Nevertheless, challenges for afforestation activities were also identified. Survival rates of all species were significantly dependent on the soil salinity level and available soil water (Chapter 3). Both factors were seen to be highly variable in the study region (Chapter 3; Chapter 5), depending at least partly on the externally driven GWT (Chapter 5). This can present a risk for afforestation, as in the case of a lower GWT the initial irrigation period would be prolonged. On the one hand, this demands a secured water availability for a longer period and, on the other hand, it highlights the need for irrigation especially during dry periods when water availability is generally low and the GWT drops.

Furthermore, measured tree-biomass increments were much smaller than those reported in previous studies in the region (Khamzina et al. 2006; 2012; Djumaeva et al. 2010; 2013). Since a low biomass production negatively affects the productive potential and consequently the economic feasibility of afforestation (Chapter 3), an economic pre-assessment of afforestation versus leaving land fallow for a natural re-vegetation is recommended to determine the costs and benefits of action and inaction for land users on the most unfavorable sites.

When evaluating the impacts of afforestation, the replenishment of soil-nutrient stocks is a frequently mentioned environmental benefit of tree plantations. In the present study, significant changes in soil total C and N stocks could not be confirmed (Chapter 5). The likely reason is the rather modest biomass growth rates and input of organic residues to the soil during the observation period covering the first two years following afforestation (Chapter 3). Enhanced soil nutrient stocks may occur during further tree development when the biomass input to the soil becomes more significant and the water use of the trees considerably impacts the GWT and soil-moisture regime. The revealed increases in SOC stocks in the heavier textured soil at plots with higher biomass yielding species (e.g., *E. angustifolia*) are first positive indications for future trends in the soil-C status. The rapid recovery of soil C lost during the

field preparation for tree planting is in contrast to decade-long restoration of the losses observed in afforestation systems on presumably more productive agricultural land elsewhere (Six et al. 2000; Resh et al. 2002; Paul et al. 2002; Guo and Gifford 2002; West et al. 2004). These findings further highlight the general potential of afforesting the C-poor soils in Uzbekistan (Chapter 5). Longer-term studies should uncover further trends and impact of tree plantations on agro-ecosystem biomass and nutrient stocks.

7.2 Most promising afforestation candidate: *Elaeagnus angustifolia* L.

Significant differences in tree performance among species and between the study sites highlight the need for a careful species selection for afforesting long-term abandoned cropland in the ADB to increase the probability of success of afforestation activities (Chapter 3). Generally, the selection of appropriate candidates for afforestation of abandoned croplands depends on the site conditions, and it is therefore recommendable to field test more tree species while considering a wider range of the degraded landscape conditions. At present and in accordance with other studies in the lower ADB (e.g., Djumaeva 2011; Khamzina 2012), N₂-fixing *E. angustifolia* shows to be a well-fitting candidate for afforestation, combining highest survival rates with the highest biomass production during the initial two years (Chapter 3). The capability of fixing atmospheric N₂ was advantageous for the tree establishment and development on the N-poor soils (Chapter 4). Despite the discrepancy in results of the N difference and the ¹⁵N natural abundance method and variable estimates according to reference species (Chapter 4), even the most conservative figures confirmed the occurrence of BNF under saline and P-poor soil conditions. In case afforestation is envisaged, directing research to identify additional N₂-fixers also capable to establish and grow on salt-affected croplands could be beneficial to enlarge the basket of options for farmers to choose from.

N₂-fixing tree species might enrich depleted soil N stocks in the long run and serve as nursing plant for other valuable tree species not capable of BNF. *Ulmus pumila* was seen to be an additional promising candidate for afforesting degraded croplands as it performed with a relative consistency on both sites. Furthermore,

Populus tremula x nivea and, to a lesser degree *M. alba*, showed promising results at both sites. The overall findings suggest that the latter species should be considered for non-saline to slightly-saline sites only, since its survival was strongly influenced by soil salinity (Chapter 3). *Populus euphratica*, principle species of native riparian forest that occupied large areas in the lower ADB before conversion to the cropland failed to establish at both sites. It is therefore assessed as unsuitable when planning afforestation of abandoned croplands in the study region.

7.3 A challenge for afforestation in the ADB: fluctuating groundwater tables

In the present study, the importance of the GWT for the feasibility of afforestation ventures became very clear. Groundwater dynamics largely determined soil moisture and soil salinity during the entire observation period (Chapter 5). The fluctuations observed represent a high risk for the establishment of tree saplings, since regularly occurring GWT drops could negatively affect soil conditions and in turn reduce tree survival (Chapter 3). Furthermore, nutrient-stock dynamics also seemed to be directly influenced by the GWT fluctuations (Chapter 5); this aspect needs further research. The monitored inter-annual changes in soil parameters associated with the GWT fluctuations greatly exceeded those caused by the plantation set up and the influence of the trees (Chapter 5). The observed sudden drop in the GWT during the observation period furthermore implies that the initial irrigation period for tree plantations on croplands characterized by deep GWT might need to be extended beyond two to three years to ensure tree plantation establishment (Chapter 3; Chapter 5). It therefore becomes clear that in the ADB, GWT fluctuations present a risk for afforestation ventures and that when afforestation is planned in a specific region, the variability of the groundwater depth needs to be taken into account even though data (for example from statistical records available at local institutions) might be difficult to obtain.

7.4 The EPIC model in the study region: adaption needed!

When planning to introduce afforestation into the ADB, information on the management of tree plantations needs to become known, e.g., the optimal rotation period of

a plantation, which will vary with tree species and plantation purpose, i.e., timber production, fire wood, etc. Nevertheless, information on tree growth and especially on long-term tree performance under the site conditions that prevail in the study region is too sparse to give reliable recommendations for afforestation. Part of this information gap could be overcome by modeling. The EPIC model is potentially promising to extrapolate site-specific results of forestry experiments to other locations in the lower ADB, as it previously provided satisfactory yield predictions in dryland regions after being calibrated to local conditions (Steiner et al. 1987), and is capable of modeling tree growth (Williams et al. 2006). In the present study, following the successful calibration to the regional conditions (Chapter 6), the EPIC model was generally able to satisfactorily reproduce the conditions observed in the field experiment characterized by a deeper GWT (Chapter 6). In contrast, the findings showed the present limitation of the EPIC model for the site with shallow GWT, which is subject to significant fluctuations in irrigated lowlands (Chapter 5). Under such GWT conditions, soil moisture and salinity regimes were not simulated accurately leading to flawed predictions of the tree biomass (Chapter 6). The model's applicability to the lower ADB region could be improved significantly by improving the groundwater module. A first step in that direction would be to allow an annual adjustment of the groundwater parameters instead of setting a fixed value for the entire simulation period. Including GWT-depth data into the daily read weather file could also increase the model's suitability for long-term simulations of water and solute dynamics in irrigated environments with a shallow, fluctuating GWT (Chapter 6).

The plant growth component of EPIC would also benefit from some modifications to improve predictions for *P. nivea x tremula* and other species in the lower ADB. In particular, considering tree survival and aboveground biomass partitioning would enhance the model's capacity to predict the magnitude of NFTP at the end of a rotation period and as a result boost the model's general applicability for forestry systems (Chapter 6). These modifications are not only subject to technical solutions of EPIC itself but also require additional research on physiological parameters of relevant tree species. As a first orientation, the present findings (Chapter 3) could be used but

need to be supplemented with independent datasets for validating the calibration results (Chapter 6). This once more underlines the need for further field studies on tree performance on abandoned croplands in the ADB with a special focus on the required input parameters for the EPIC model.

7.5 Overarching conclusions for further research

Overall, it can be concluded that afforesting abandoned croplands under deficit irrigation is generally feasible in the lower ADB. Even though a general species recommendation for afforestation cannot be given, N_2 -fixing *E. angustifolia* performed best on both study sites among the explored species. N_2 fixation provides a competitive advantage when establishing plantations on abandoned croplands in the ADB and should be considered when selecting species for afforestation.

The fluctuating GWT presents a risk to the establishment of tree plantations by affecting irrigation and groundwater availability. The impact of the GWT on soil conditions, which significantly affects tree performance of all species, requires additional research and needs to be considered in any attempts to model tree growth in the study region. Here, the EPIC model showed reasonable potential and scope for improvement.

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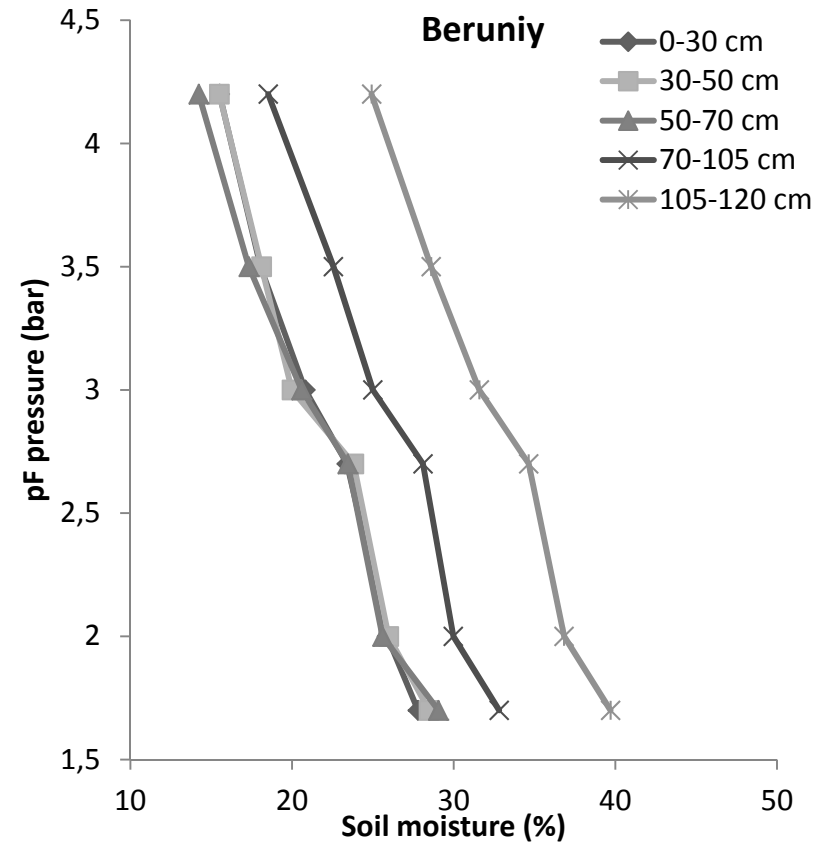
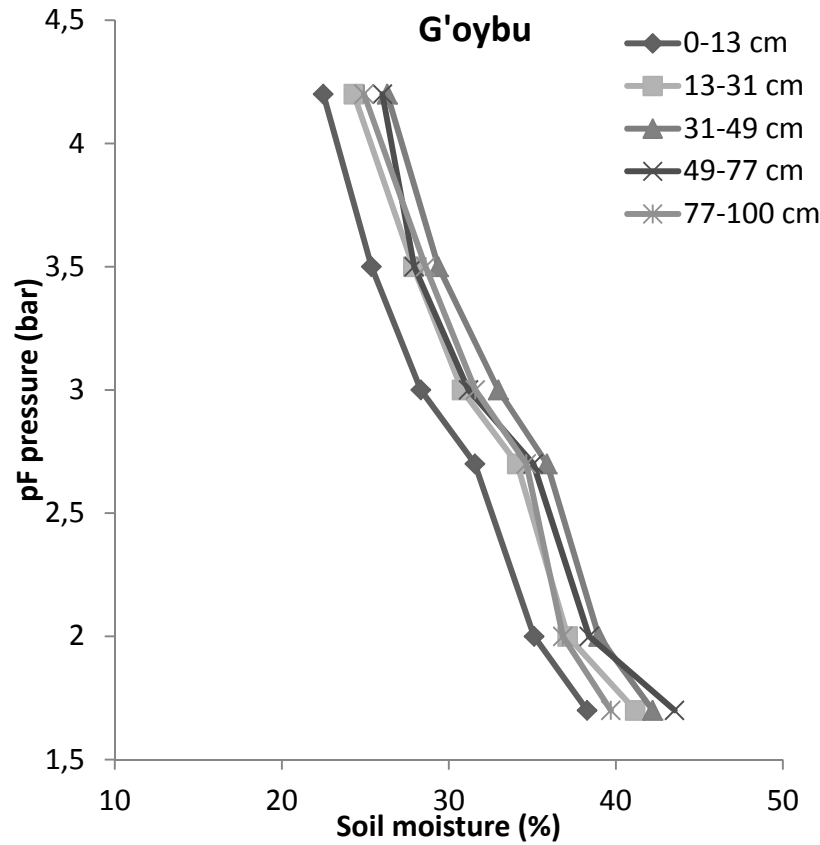
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9 APPENDICES

Appendix 9.1 Water retention (pF) curves of the study sites in G'oybu and Beruniy as determined in the laboratory from soil samples taken at the onset of the experiment.



Appendix 9.2 Classification of soil nutrient contents according to (a) Musaev (2001) and (b) Krasnouhova et al. (1988).

a)

Class	Available P₂O₅ [mg kg⁻¹]	Exchangeable K₂O [mg kg⁻¹]	N-NH₄ [mg kg⁻¹]
Very low	0-15	0-100	<20
Low	16-30	101-200	20-30
Moderate	31-45	201-300	31-50
Increased	46-60	301-400	51-60
High	>60	>400	>60

b)

Class	Humus [%]
Very poor	<0.4
Poor	0.4-0.8
Moderate	0.8-1.2
Increased	1.2-1.6
Rich	1.6-2.0
Very rich	>2.0

Appendix 9.3: Evaluation of soil salinity levels based on the electrical conductivity (EC_e) according to Abrol et al. (1988).

Salinity level	EC_e [dS m⁻¹]
Non saline	0-2
Slightly saline	2-4
Medium saline	4-8
Strongly saline	8-16
Very strongly saline	>16

Appendix 9.4: Qualitative salinity content and soil classification by salinity degree according to Kaurichev et al. (1989) by anions [cmol kg⁻¹].

a)

Salinity type	Cl ⁻ /SO ₄ ²⁻	HCO ₃ ⁻ /(Cl ⁻ + SO ₄ ²⁻)
Chloride	>2	-
Sulphate-chloride	1-2	-
Chloride-sulphate	1-0.2	-
Sulphate	<0.2	-
Carbonate-sulphate	<0.2	>1
Sulphate-soda	-	>2

b)

Class	Sulphate-Chloride	Chloride-Sulphate	Chloride	Sulphate
Non saline	<0.2	<0.25	<0.15	<0.3
Slightly saline	0.2-0.3	0.25-0.4	0.15-0.3	0.3-0.6
Moderately saline	0.3-0.6	0.4-0.7	0.3-0.5	0.6-1.0
Highly saline	0.6-1.0	0.7-1.2	0.5-0.8	1.0-2.0
Solonchak	>1.0	>1.2	>0.8	>2.0

b) (continued)

Class	Chloride-Sodium	Sulphate-Sodium	Sodium-Chloride	Sodium-Sulphate
Non saline	<0.15	<0.15	<0.15	<0.15
Slightly saline	0.15-0.25	0.15-0.3	0.15-0.25	0.15-0.25
Moderately saline	0.25-0.4	0.3-0.5	0.25-0.4	0.25-0.5
Highly saline	0.4-0.6	0.5-0.7	0.4-0.6	0.5-0.7
Solonchak	>0.6	>0.7	>0.6	>0.7

Appendix 9.5: General model-performance evaluation for recommended statistics modified after Moriasi et al. (2007).

Performance	RSR	NSE	PBIAS (streamflow)
Very good	0.00 ≤ RSR ≤ 0.50	0.75 < NSE ≤ 1.00	PBIAS < ± 10
Good	0.50 < RSR ≤ 0.60	0.65 < NSE ≤ 0.75	±10 ≤ PBIAS < ±15
Satisfactory	0.60 < RSR ≤ 0.70	0.50 < NSE ≤ 0.65	±15 ≤ PBIAS < ±25
Unsatisfactory	RSR > 0.70	NSE ≤ 0.50	PBIAS ≥ ±25

Legend: RSR indicates the ratio of the root mean square error to the standard deviation of measured data; NSE indicates the Nash-Sutcliffe efficiency, PBIAS indicates the percent bias.

Appendix 9.6: Experimental plantations after planting in 2010 in (a) G'oybu with drip irrigation and in (b) Beruniy with furrow irrigation. (c) Analysis of soil pit and height inventory in an *Elaeagnus angustifolia* L. plot.

a)



b)



c)



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