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**Degraded Tugai Forests under Rehabilitation in the  
Tarim Riparian Ecosystem, Northwest China:  
Monitoring, Assessing and Modelling**

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## SUMMARY

The Tarim River, located along the northern and eastern borders of the Taklamakan Desert in Xinjiang, Northwest China, is about 1320 km long and thus one of the longest continental inland waterways in the world. In an undisturbed state, it is accompanied on both sides by floodplain forests of Euphrates Poplar (*Populus euphratica* Oliv.), also known as “Tugai Vegetation” or “Tugai Forests”. These forests form typical desert riparian forests as the so-called “Green Corridor” and prevent the two deserts, the Taklamakan and the Kuruk-Tagh, from merging together.

At present, large areas that were originally *P. euphratica* riparian forests have disappeared, with the remaining areas in critical condition. Specifically, the greatest threats over the past few decades have been the rising water consumption in the upper and middle reaches and massive hydro-technical interventions (construction of embankments and dams) in the development of uncultivated land (including the direct clearance of forests) for cotton production. These have led to widespread destruction of the natural ecosystems, particularly in the lower reaches of the river where about 320 km of the floodplain forests are either highly degraded or dead as the result of nearly 30 years of river desiccation. As a consequence of these deteriorations, land desertification has been aggravated and has expanded in the region.

Because of the challenges facing this ecosystem, restoration measures with the diversion of “Emergency Ecological Water” have been implemented in the affected areas since 2000. This new process of recovery measures needs efficient and extensive long-term monitoring. In this thesis, current restoration measures as implemented to date are presented and hydrological dynamics as a function of water diversion are analysed. The structure, distribution and health status (referred to as “vitality”) of the dominant species *Populus euphratica* have been monitored by measuring eco-morphological parameters of more than 5000 trees in two sampling sites (a 100-ha permanent plot and five random sampling plots of 50-m radii) at Arghan village in the lower reaches of the Tarim River in the Xinjiang Uyghur Autonomous Region of China. The effects of restoration measures on the revitalization of degraded trees have been analysed and assessed by using individual-based repeated measurements of the tree data. From a long-term point of view, and taking labour intensity and the high cost of tree height measurements into account, a suitable height-diameter model for obtaining the tree height (TH) of *P. euphratica* based on the diameter at breast-height data (DBH) has been developed and evaluated.

The average annual groundwater depth within 300 m of the river channel at different transects (Yingsu, Karday, Arghan) recovered significantly after a second water diversion in 2001. The same rising trend in groundwater level was retained until 2004, started to decline until 2009, and then rose again until the end of the water diversion in 2011. The Mann-Kendall statistical

trend test was applied to the mean monthly and annual groundwater depth of six groundwater wells at different distances from the river on the Arghan transect. The trend test for the whole time series period from 2003 to 2011 indicated that there was a statistically significant decreasing trend for all wells, but that from January 2010 to December 2011 the groundwater level in all wells had a statistically significant increase. With the exception of a relatively favourable groundwater depth for floodplain forests within a 150 m distance of the riverbed, the groundwater depth at larger distances remained far below 5 m, causing most forest plants (with the exception of the *Tamarix sp.*) to suffer from water scarcity.

Analyses of forest structure, distribution and health status suggested that a maximum TH of 19 m was found within 0-20 m and 100-200 m of the river. By contrast, a maximum DBH of 126 cm was found within 500-600 m of the river. Trees with a TH of over 15 m and a DBH of over 60 cm appeared sporadically. The maximum CD (crown diameter) of 16.58 cm (one tree) was found next to the river bed. There was a relatively great variation in DBH when compared to TH and other eco-morphological parameters. On average, stand structure tended to be simpler as distance from the river increased. Trees classified as healthy and good accounted for approximately 40 % of all sample trees, with slightly and highly degraded trees representing nearly 60 %.

Some of the eco-morphological parameters of the trees vary differently with respect to the ecological water diversion measures. In particular, in the vertical (north-south) direction, the farther the trees are from the river, the weaker the response of ecological indicators. These parameters include: tree vitality classes (VS), crown diameter (CD), height to crown (HC), frequency of root suckers, number of young seedlings, and shoot growth, as well as newly developed crown types of *P. euphratica* trees. Generally, the floodplain forests within 200 m of the riverbed recovered remarkably, and those between 200 and 800 m from the river showed a medium response to the water transfer, while forests further than 800 m away from the riverbed showed lesser signs of recovery.

Following the evaluation and comparison of the results from ten commonly used models by means of multiple-model performance criteria (such as asymptotic *t*-statistics of model parameters, standardized residuals against predicted height, the root-mean-square error (RMSE), Akaike's information criterion (AIC), mean prediction error (ME) and mean absolute error (MAE)), Model (1):  $TH = 1.3 + a/(1 + b \times e^{-c \times DBH})$  and Model (6):  $TH = 1.3 + DBH^2/(a + b \times DBH + c \times DBH^2)$  are recommended as suitable choices for approximating the height-diameter relationship of *P. euphratica*. The limitations of the other models, resulting in poor performance for predicting TH accurately, are also discussed.

## ZUSAMMENFASSUNG

### **Regeneration degradierter Tugaiwälder im Auenökosystem entlang des Tarim, Nordwest-China: Monitoring, Bewertung und Modellierung**

Der Tarim verläuft entlang des nördlichen und östlichen Randes der Taklamakanwüste in Xinjiang, Nordwest-China. Er ist mit ca. 1320 km einer der längsten Inlandsflüssen der Welt. Im ungestörten Zustand ist er beiderseits von Auwäldern aus Euphratpappeln, den Tugaiwäldern, gesäumt. Diese Wälder sind die typische Vegetation der Wüsten-Auwälder und bilden den sog. "Grünen Korridor", der verhindert, dass die beidseitigen Wüsten Taklamakan und Kuruk Tagh zusammenwachsen.

Heute sind weite Teile der Euphratpappelwälder verschwunden, die verbleibenden Flächen sind gefährdet. Konkrete Bedrohung ist der steigende Verbrauch an Wasserressourcen am Ober- und Mittellauf sowie massive wasserbauliche Eingriffe wie die Eindeichung des Flusses. Ursache hierfür ist die Erschließung von Brachland für den Anbau von Baumwolle (inklusive der Rodung von Wäldern). Diese Eingriffe haben zu einer weitgehenden Zerstörung der natürlichen Ökosysteme insbesondere am Unterlauf geführt, wo auf ca. 320 km die Auwälder stark degradiert oder bereits abgestorben sind – ein Ergebnis von beinahe 30 Jahren fehlenden Abflusses. Folge hiervon ist die Ausbreitung der Desertifikation in der Region.

Aufgrund der Probleme, die sich für dieses Ökosystem ergeben, wurde 2000 mit der Renaturierung auf Basis einer „ökologischen Wasserumleitung“ begonnen. Dieser Prozess benötigt ein ausführliches und gleichzeitig effizientes Langzeitmonitoring. In der vorliegenden Arbeit werden die rezenten Renaturierungsmaßnahmen vorgestellt und die hydrologische Dynamik als Folge der Wasserumleitungen analysiert. Die Struktur, die räumlichen Charakteristika sowie der Zustand („Vitalität“) der Hauptart *Populus euphratica* waren Gegenstand eines Monitorings. Hierzu wurden ökomorphologische Parameter von mehr als 5000 Bäumen in zwei Stichprobenflächen aufgenommen. Diese befinden sich nahe dem Arghan am Unterlauf des Tarim in der Autonomen Uighurischen Provinz Xinjiang, NW China und setzen sich aus einer 100 ha großen Dauerbeobachtungsfläche und fünf zufälligen Plots mit 50 m Radius zusammen. Der Effekt der Renaturierung auf die Revitalisierung der degradierten Bäume wurde auf Basis von wiederholten Messungen an Einzelbäumen analysiert. Um langfristig den hohen Arbeitsaufwand und die hohen Kosten für die Messung der Baumhöhen zu reduzieren, wurde ein Modell für den Zusammenhang von Brusthöhendurchmesser und Baumhöhe für *Populus euphratica* entwickelt und evaluiert.

Der mittlere Grundwasserspiegel in drei Transekten (Yingsu, Karday, Arghan) innerhalb 300 m Abstand zum Fluss erhöhte sich in signifikantem Maße seit der zweiten Wasserumleitung 2001. Derselbe positive Trend bestand bis 2004. Danach sank er bis 2009 ab und stieg bis Ende der Wasserumleitung 2009 wieder an. Die Grundwasserdaten des Arghan-Transekts wurden

mithilfe des Mann-Kendall Trendtests untersucht. Für den Zeitraum von 2003 bis 2011 zeigte sich, dass der Grundwasserspiegel für alle Pegel signifikant abnahm. Für den Zeitraum von Januar 2010 bis Dezember 2011 ergab sich jedoch ein signifikanter Anstieg. Mit Ausnahme eines Korridors von etwa 150 m um das Flussbett, wo das Grundwasser ausreichend hoch für Auwälder ansteht, ist der Grundwasserflurabstand deutlich größer als 5 m, was bei den meisten Pflanzen (mit Ausnahme *Tamarix spec.*) zu Wasserstress führt.

Die Analyse der Waldstruktur, räumlichen Verteilung und Zustand ergab eine maximale Baumhöhe von 19 m in einer Zone von 0-20 m und 100-200 m um das Gerinne. Der größte Brusthöhendurchmesser von 126 cm wurde jedoch in einer Zone von 500-600 m gefunden. Bäume mit einer Höhe von mehr als 15 m und einem Durchmesser von mehr als 60 cm treten nur sporadisch auf. Der größte Kronendurchmesser (16,58 m, ein Baum) wurde direkt am Fluss gefunden. Der Brusthöhendurchmesser war im Vergleich zur Baumhöhe und dem Kronendurchmesser variabler. Im Mittel wird die Bestandsstruktur mit zunehmender Entfernung zum Fluss einfacher. Ca. 40 % der Bäume wurden als „gesund“ eingestuft, während 60 % leicht oder stark degradiert sind.

Einige der ökomorphologischen Parameter der Bäume verhalten sich in Bezug auf die Wasserüberleitung unterschiedlich. Besonders in Nord-Südrichtung ist die Reaktion der ökologischen Indikatoren mit zunehmendem Gerinneabstand schwächer. Diese Parameter umfassen die Vitalitätsstufe, den Kronendurchmesser, den Bodenabstand der Krone, die Häufigkeit von Klonen, die Anzahl an Jungpflanzen und Keimlingen sowie Sekundärkronen von *Populus euphratica*. Insgesamt erholte sich der Auwald in einer 200 m-Zone um das Flussbett sichtbar, zwischen 200 m und 800 m zeigte sich ein mittlerer Effekt während in mehr als 800 m Entfernung zum Gerinne die Anzeichen einer Erholung weniger deutlich sind.

Auf Basis von verschiedenen Kriterien wie dem Akaiikes Information Criterion (AIC), Mean Prediction Error (ME) und dem Mean Absolute Prediction Error (MAE) wurden zehn gemeinhin benutzte Modelle evaluiert und verglichen. Als Ergebnis zeigt sich, dass Modell 1 ( $H = 1,3 + a / (1 + b \times e^{c \times BHD})$ ) und Modell 6 ( $H = 1,3 + BHD \cdot (a + b \times BHD + c \times BHD^2)$ ) adäquate die Beziehung von Brusthöhendurchmesser (BHD) und Baumhöhe (H) sind. Die Einschränkungen der weiteren Modelle, die zu einer schlechten Performance in der Vorhersage der Baumhöhen führt, werden ebenfalls diskutiert.

# 中国塔里木河受损吐加依林生态系统的修复与重建

## ——监测、评估与模拟

### 内容提要:

有限的水资源是中国西北干旱区社会发展的重要支柱，是干旱区荒漠生态系统赖以生存和持续稳定的前提。由于全球气候变化和人类活动对该区域水文过程的影响和干扰，以胡杨林为主体的荒漠河岸林生态系统的退化和消失在干旱区已成为普遍问题，也成为我国西部大开发战略中极富挑战性的难题，引起了国内外政治界和学术界的高度关注。

塔里木河流域位于中国西北的新疆维吾尔自治区，地处天山和昆仑山之间。塔里木河沿着塔克拉玛干沙漠的北部和东部，最终流入台特码湖。其干流全长大约为 1320 km，是中国第一大内陆河，仅次于伏尔加河、阿姆河、锡尔河和乌拉尔河，为世界第五大内流河。当地所有经济活动，特别是农业生产和绿洲城市化以及自然生态系统主要依赖于塔里木河的水源。在不受人为干扰的状态下，塔里木河沿岸植被主要由以胡杨为主的荒漠河岸林组成，这些植被也被称为“吐加依林/Tugai forest”。塔里木河下游沿岸分布的吐加依林形成典型的绿色生态廊道，其具有防风固沙、水土保持、固碳减排等多种生态功能。更重要的是，这些稀疏植被在当地的生态与环境建设中起到不可替代的作用，即维持着当地脆弱生态系统的稳定性以及社会经济良好发展的持续性。

然而，在气候变化和人类活动的双重影响下，大面积的原始河岸林植被已经被退化或消失，分布面积不断缩小，长势逐渐变弱。具体而言，在过去的几十年里，在上、中游耗水量的持续增加，大规模水利工程（堤防和水坝）的建设，沿河农业生产（主要是棉花种植）的快速扩张（包括森林砍伐）导致了当地生态系统的严重退化。特别是下游河道长期断流，地下水位大幅度下降，以胡杨为主体的天然植被全面衰败，生物多样性锐减，胡杨荒漠河岸林生态系统严重受损，这导致了生态系统服务价值在范围、质量和数量上的下降，并使其对气候变化和自然灾害（沙尘暴、土壤盐渍化、荒漠化等）的抵抗能力降低，从而区域生态系统恶化，沙漠化程度加剧，灾害性浮尘天气增加，严重危及当地社会经济发展和人类生存环境。针对上述生态灾害和环境问题，从 2000 年 5 月开始，国家把塔里木河流域综合治理列入重大生态工程计划，累计投资 107 亿元人民币，修复与重建下游受损生态系统、保障区域生态安全。截至 2015 年底，向塔里木河下游已实施了 16 次人工应急调水，累计输水量达  $46.51 \times 10^8 \text{ m}^3$ 。随着社会各界对塔里木河下游人工输水工程关注度的日益高涨，对输水效益的争议不断，主要



集中在：投入如此巨大财力物力的调水工程究竟能带来多少生态效益？如何定量胡杨等天然植被对输水的响应（长势和自修复能力）？输水量和输水方式是否合理？区域生态修复的潜力多大？....等问题，说明人工输水过程中的许多科学问题需要进一步深入调查和定量研究。

本研究首先基于塔里木河下游不同典型断面水文监测时间序列数据，对人工应急输水及其促使的地下水动态进行详细分析与评估。借鉴德国森林生态系统监测与评估体系，以塔河下游阿拉干断面生态监测样地长期序列数据（重复测量 5000 余棵胡杨生态、形态参数）为支撑，对其林分结构、不同水分胁迫下的空间分布特征和健康态势（即活力）进行了探讨。通过对单株长势时空数据对比，定量评估了输水对退化树木的恢复更新作用。从林业资源连续清查工作角度来看，测量树高所需时间长、成本较高。树高和胸径作为衡量林分生长的重要指标，其之间的模型在林业生产实践与科学研究中具有重要的作用。为了减轻测量胡杨树高的工作量和成本并为便于对生物量与碳储量的估算，本文采用地面实测的胡杨树高-胸径数据，用 10 个树高-胸径关系模型进行模拟和筛选，选出了两个适用于预测胡杨树高的最优模型并对其做了验证。

2000 年的第一次输水实施后，下游不同断面离河道 300 m 处的平均地下水位呈显著上升，其上升趋势一直持续到 2004 年，然后开始下降至 2009 年，2010 年第十一次输水实施直到 2011 年年底地下水位又开始呈现明显上升。本文采用的地下水埋深时间序列数据（2003 年至 2011 年输水结束为止）分析表明，在此期间，地下水位呈明显波动性特征。为了查明离河道不同距离地下水埋深的总动态趋势，采用了 Mann-Kendall 趋势性检验。结果显示，在 2003-2011 年期间，研究区不同离河道距离的地下水埋深呈显著下降趋势。除了近河道 150 m 范围内的地下水对河岸林植被生长发育较为合理之外，离河道较远处地下埋深仍然大于 5 m，这对大部分灌木和草本植被造成严重水分胁迫。

林分结构及其空间分布与树木活力分析表明，树高最大值（19 m）出现在离河道 0-20 m 和 100-200 m 范围内且株数极少。相反，胸径最大值（126 cm）出现在离河道 500-600 m 范围之内。树高高于 15 m，胸径大于 60 cm 的成熟健康胡杨林呈零星分布。在河床上只发现一颗最大冠幅（16.58 m）的胡杨树木。研究区胡杨胸径与树高或其他参数相比具有更大的变异性。总体而言，随着离河道距离的增加，林分结构趋于简单。长势等级分定为健康和良好的胡杨约占样地内总样本树木的 40%，衰弱木和枯立木约占 60%。

树木生态形态参数对应急输水表现出不同程度的响应。特别是，在河道垂直（北-南）方向上，离河道越远，树木的响应程度就越弱。主要参数包括：树木活力（VS），

冠幅 (CD), 枝下高 (HC), 根蘖率, 幼苗数量和新梢生长, 以及输水后重新产生的树冠类型 (原始树冠、二次树冠和复合树冠)。总体而言, 胡杨河岸林在离河道 200 m 的距离范围内恢复较为明显, 离河道 200-800 m 距离范围内呈中等响应, 离河道距离 800 m 以上其对输水的响应极弱。

通过多模型性能标准, 如渐近t统计模型参数, 对预测值的标准化残差, 均方根误差 (RMSE), Akaike 标准化残差 (AIC), 平均误差 (ME) 和平均绝对误差 (MAE), 对10个常用候选模型的预测精度进行校准、验证与评价, 选取了两个适用于胡杨树高-胸径模拟, 最后对其他模型的局限性做了详细讨论。

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# جۇڭگونىڭ غەربىي شىمالىدىكى تارىم دەريا ۋادىسى چېكىنگەن توقاي ئورمان ئېكوسىستېمىسىنى ئەسلىگە كەلتۈرۈش ھەققىدە تەتقىقات: مىقدارلاش، باھالاش ۋە مودېللاش

## قىسقىچە مەزمۇنى

بۇ دوكتورلۇق تەتقىقاتىدا، جۇڭگونىڭ غەربىي شىمالىدىكى شىنجاڭ ئۇيغۇر ئاپتونوم رايونى، بولۇپمۇ جەنۇبىي شىنجاڭ ئېكولوگىيەلىك مۇھىتىنىڭ سىجىل قوغدىلىشىدا ھەل قىلغۇچ رول ئوينايدىغان چۆل ئورمانلىرى ۋە توقاي ئۆسۈملۈك يېپىنچا بايلىقلىرىنىڭ ئاساسىي گەۋدىسى بولغان توغراق ئورمانلىرىنىڭ چېكىنىش سەۋەبلىرى، ھازىرقى ئەھۋالى ۋە كەلگۈسىدىكى تەرەققىيات يۈزلىنىشىنى چىقىش قىلغان ئاساستا، توغراق ئورمانلىرىنىڭ قۇرۇلمىسى، ھاياتى كۈچى ۋە ئۇنىڭ ئوخشاش بولمىغان يەر ئاستى سۇ شارائىتىغا قايىتىدىغان ئىنكاسى، ئېكولوگىيەلىك سۇ قويۇپ بېرىلگەندىن كېيىنكى يەر ئاستى سۇ ئورنىنىڭ دىنامىكىسى ۋە ئۇنىڭ چېكىنگەن توغراق ئورمانلىرىغا بولغان تەسىرلىرى ئىلمىي تەتقىقات ئۇسۇلىدىن پايدىلىنىپ مىقدارلاشتۇرۇپ چىقىلدى، ھەمدە ئورمانچىلىقتا كۆپ ئىشلىتىلىدىغان دەرەخ ئېگىزلىكى ۋە غول ئايلىنىشى ئوتتۇرىسىدىكى مۇناسىۋەت مودېللىرىنى ئاساس قىلىپ تۇرۇپ، تارىم دەرياسىنىڭ تۆۋەنكى ئېقىنىدىكى توغراق ئورمانلىرىغا ماس كېلىدىغان، دەرەخ غول سانلىق مەلۇماتلىرىدىن پايدىلىنىپ، ئېگىزلىكىنى ھېسابلاپ چىقىشقا بولىدىغان ماتېماتېكىلىق مودېل تاللاپ چىقىلدى.

تارىم دەرياسى جۇڭگونىڭ غەربىي شىمالىغا جايلاشقان بولۇپ، شىنجاڭ ئۇيغۇر ئاپتونوم رايونىنىڭ جەنۇبىي بۆلىكىدىكى تەكلىماكان قۇملۇقىنىڭ گىرۋىكىنى بويلاپ ئاقىدۇ. ئومۇمىي ئۇزۇنلۇقى 1320 كىلومېتىر ئەتراپىدا، دۇنيادىكى ئەڭ ئۇزۇن ئىچكى قۇرۇقلۇق دەريالىرىنىڭ بىرى ھېسابلىنىدۇ. دەريانى بويلاپ توغراق ئورمانلىرى (*Populus euphratica* Oliv.) تارقالغان بولۇپ، بۇ يەرلىك تىلدا يەنە «توقاي» ئورمىنى دەپمۇ ئاتىلىدۇ. بۇ تىپىك بولغان چۆل ئورمىنىنىڭ ئېكولوگىيەلىك رولى ناھايىتى چوڭ بولۇپ، تەكلىماكان ۋە قۇرۇقتاغ قۇملۇقلىرىنىڭ بىر- بىرىگە قوشۇلۇپ كېتىشىنى تىزگىنلەپ تۇرىدىغان بولغاچقا «يېشىل كارىدور» دېگەن نامى بار.

نۆۋەتتە، بۇ رايوندىكى توغراق ئورمانلىرىنى ئاساسىي گەۋدە قىلغان توقاي ئۆسۈملۈك يېپىنچىلىرى ئېغىر بۇزغۇنچىلىققا ئۇچرىدى ۋە يوقىلىش گىردابىغا بېرىپ قالدى. بولۇپمۇ، يېقىنقى 50 يىل مابەينىدە، تارىم دەرياسىنىڭ ئوتتۇرا ۋە يۇقىرى ئېقىنىدىكى يېزا- ئىگىلىككە ئىشلىتىلىدىغان يەرلەرنىڭ كەڭ كۆلەمدە ئېچىلىشى، ھەم شۇنداقلا دېھقانچىلىقتا زىيادە كۆپ سۇ ئىشلىتىش ۋە زور تىپتىكى سۇ تىزگىنلەش قۇرۇلۇشلىرىنىڭ (توسما، سۇ ئامبىرى قاتارلىقلار) تەسىرىدە، تۆۋەن ئېقىننىڭ 320 كىلومېتىرلىق بۆلىكىگە سۇ يېتىپ كېلەلمەي، بۇ رايوندىكى جانلىقلارنىڭ ياشاش شارائىتى بارغانسېرى ناچارلىشىپ، تەبىئىي چۆل يېپىنچا ئۆسۈملۈكلىرى ئېغىر دەرىجىدە چېكىندى ۋە قۇرۇپ كەتتى. نەتىجىدە قۇملىشىش تېخىمۇ ئېغىرلاشتى ۋە كۆلىمى بارغانسېرى كېڭەيدى.

تارىم دەرياسىنىڭ تۆۋەنكى ئېقىنىدىكى بۇزۇلۇۋاتقان توغراق ئورمان ئېكولوگىيەسىنى ئەسلىگە كەلتۈرۈش ئۈچۈن ئۆتكەن ئەسىرنىڭ 2000-يىلىدىن بۇيان تۆۋەن ئېقىنغا 15 قېتىملىق سۇ باشلاش قۇرۇلۇشى ئېلىپ بېرىلدى. بۇلارنىڭ چېكىنگەن ئورمان ئېكولوگىيەسىنى ئەسلىگە كەلتۈرۈشتىكى رولى ۋە تۆھپىسىنى ئىلمىي جەھەتتىن باھالاپ چىقىش پەقەت تەتقىقاتچىلارغا ئەمەس بەلكى ھەر ساھەدىكى مەنپەئەتدارلارغا نىسبەتەنمۇ ئىنتايىن مۇھىم بىر تېمىغا ئايلاندى. بۇ ماقالىدە، گېرمانىيىنىڭ ئورمان ئېكولوگىيە سىستېمىسىنى تەكشۈرۈپ باھالاش ئەندىزىسى ۋە لايىھەسىدىكى ئىلغار تەرەپلەردىن ئۆرنەك ئالغان ئاساستا، تارىم دەرياسىنىڭ تۆۋەنكى ئېقىنىدىكى توغراق ئورمانلىرىنى تەكشۈرۈش بازىسى -- ئارغاندىكى ئۇزۇن مەزگىللىك ئۆلچەپ چىقىلغان ئۆسۈملۈك، تۇپراق، سۇ قاتارلىق جۇغراپىيەلىك ۋە ئېكولوگىيەلىك سانلىق مەلۇماتلار ئىنچىكە ئانالىز قىلىندى، شۇنداقلا ھازىرغا قەدەر قوللىنىلغان تۆۋەن ئېقىن ئېكولوگىيەسىنى تۈزەپ ئەسلىگە كەلتۈرۈش چارىلىرى ۋە سۇ باشلاش قۇرۇلۇشىنىڭ ھىدرولوگىيەلىك ئۆزگىرىش جەريانى تەپسىلىي مۇلاھىزە قىلىندى. ئىككى ئۆلگە رايونىدىكى (100 گېكتار كۆلەمدىكى ئۇزۇن مەزگىللىك ئۆلچەش مەيدانى ۋە 5 دانە 50 مېتىر رادىئوسىلۇق چەمبەرسىمان ئۆلچەش مەيدانى) 5000 تۈپتىن ئارتۇق توغراقنىڭ ئورمان قۇرۇلمىسى، تارقىلىشى ۋە ھاياتى كۈچى، ئۇلارنىڭ ئېكولوگىيەلىك پارامېتىرلىرى ئۆلچەپ سېلىشتۇرۇلدى. بۇزۇلغان ئورماننى ئەسلىگە كەلتۈرۈش قۇرۇلۇشىنىڭ ئۈنۈمى ھەر بىر تۈپ توغراق ئۈستىدە ئېلىپ بېرىلغان سانلىق مەلۇماتلارنى ئانالىز قىلىش ئارقىلىق كۆرسىتىپ چىقىلدى ۋە باھالاندى. ئۇزۇن مەزگىللىك دالا تەكشۈرۈش خىزمىتىنى نەزەردە تۇتقان ئاساستا، كۆپ ئەمگەك كۈچى ۋە يۇقىرى ئىقتىساد سەرپ بولىدىغان دەرەخ ئېگىزلىكىنى ئۆلچەش خىزمىتىنى ئاددىيلاشتۇرۇش ئۈچۈن، توغراقنىڭ غول ئايلىنىشى ۋە ئېگىزلىكى ئوتتۇرىسىدىكى مۇناسىۋەت تەڭلىمىسىگە ئاساسەن، توغراقنىڭ ئېگىزلىكىنى ھېسابلاپ چىقىش ماتېماتېكىلىق مودىلى تۈزۈپ چىقىلدى ۋە تەكشۈرۈپ جەزملەشتۈرۈلدى.

2000-يىلى بىرىنچى قېتىملىق سۇ باشلاش قۇرۇلۇشى تاماملانغاندىن كېيىن، تۆۋەنكى ئېقىندىكى يىڭسۇ، قارداي ۋە ئارغان كەسىملىرىدە، دەرياغا 300 مېتىر كېلىدىغان دائىرىدىكى يەر ئاستى سۈيىنىڭ ئورنى كۆرۈنەرلىك دەرىجىدە يۇقىرى كۆتۈرۈلگەن. بۇ ئۈچ كەسىمدىكى يەر ئاستى سۈيىنىڭ ئورنى 2004-يىلىغا قەدەر مۇقىم بولغان بولۇپ، ئۇنىڭدىن كېيىن 2009-يىلىغىچە بارا-بارا تۆۋەنلىگەن ۋە 2011-يىللىق سۇ باشلاش قۇرۇلۇشىنىڭ ئاخىرلىشىشىغا ئەگىشىپ ئاستا-ئاستا يۇقىرى كۆتۈرۈلگەن. 2003-يىلىدىن 2011-يىلىغىچە بولغان ۋاقىت تىزىمىدە، يەر ئاستى سۇ ئورنىدا روشەن كۆتۈرۈلۈش ۋە تۆۋەنلەش كۆرۈلگەن. ئارغان كەسىمىدە، دەريادىن ئوخشاش بولمىغان ئارلىققا ئورۇنلاشتۇرۇلغان ئالتە يەر ئاستى سۈيىنى تەكشۈرۈش قۇدۇقىدىكى سۇ ئورنىنىڭ ئايلىق ۋە يىللىق قىممىتىنىڭ ئۆزگىرىشى مان-كېندال (Mann-Kendall) ۋاقىت سېرىپىسى يۈزلىنىش سىتاتىستىكا ئۇسۇلى ئارقىلىق كۆرسىتىپ بېرىلدى. نەتىجە شۇنى كۆرسەتتىكى، ئارغاندىكى ھەممە قۇدۇقلارنىڭ يەر ئاستى سۇ ئورنى 2003-يىلىدىن 2011-يىلىغىچە بولغان پۈتۈن ۋاقىت ئارىلىقىغا نىسبەتەن ئېيتقاندا تۆۋەنلەش يۈزلىنىشىدە بولغان.

دەرياغا 150 مېتىر كېلىدىغان دائىرىدىكى، يەر ئاستى سۈيىنىڭ ئورنى توغراق ۋە باشقا ئۆسۈملۈك يېپىنچىلىرىنىڭ ئۆسۈشىگە ماس كېلىدىغان كىرىتىك سۇ ئورنى ھالىتىنى

ساقلىغان. دەريادىن نىسبەتەن يىراق بولغان كۆپ قىسىم جايلارنىڭ يەر ئاستى سۈيى چوڭقۇرلۇقى ئومۇمىيۈزلۈك بەش مېتىردىن چوڭ بولۇپ، بۇ يۇلغۇندىن باشقا ئۆسۈملۈك تۈرلىرىنىڭ نورمال ئېكولوگىيەلىك جەريانلىرىغا چەكلىمىلىك شەكىللەندۈرگەن.

توغراق ئورمانلىقىنىڭ قۇرۇلمىسى، تارقىلىشى ۋە ھاياتى كۈچى قاتارلىق جەھەتلەردە ئېلىپ بېرىلغان ئانالىز نەتىجىسىدە كۆرسىتىلىشىچە، ئەڭ ئېگىز بولغان توغراق 19 مېتىر بولۇپ، دەرياغا 20 مېتىر ۋە 100-200 مېتىر كېلىدىغان دائىرىگە تارقالغان. غول ئايلىنىشى ئەڭ چوڭ بولغان توغراقنىڭ غول دىئامېتىرى 126 سانتىمېتىر بولۇپ، بۇ دەرياغا 500-600 مېتىر كېلىدىغان دائىرىگە تارقالغان. ئېگىزلىكى 15 مېتىر، غول ئايلىنىشى 60 سانتىمېتىردىن ئاشىدىغان توغراقلار قائىدىسىز ھالدا تارقالغان. دەرەخ باراقسىنى ئەڭ چوڭ بولغان (16.58 مېتىر) بىر تۈپ توغراق دەريا قېنىغا جايلاشقان. توغراق غول ئايلىنىشى باشقا ئېكولوگىيەلىك پارامېتىرلىرىغا سېلىشتۇرغاندا، قىممەت ئېلىش دائىرىسى ناھايىتى ئۆزگىرىشچان بولغان. ئومۇمەن ئېيتقاندا، توغراق ئورمان قۇرۇلمىسى دەرياغا بولغان ئارلىقنىڭ ئېشىشىغا ئەگىشىپ ئاددىيلىشىشقا قاراپ يۈزلەنگەن. ھاياتى كۈچى ياخشى بولغان توغراقلارنىڭ ئومۇمى توغراقتا ئىگەللىگەن نىسبىتى 40 پېرسەنت، ھاياتى كۈچى ناچارلىشىۋاتقان ياكى ناچار بولغان توغراقلار 60 پېرسەنت ئەتراپىدا بولغان.

توغراقنىڭ ئېكولوگىيەلىك پارامېتىرلىرى سۇ باشلاش قۇرۇلۇشىغا ئوخشىمىغان دەرىجىدە ئىنكاس قايتۇرغان، بولۇپمۇ دەرياغا ۋېرتىكال يۆنىلىشتە، دەريا بىلەن بولغان ئارلىقنىڭ ئېشىشىغا ئەگىشىپ توغراقنىڭ ئۆسۈش پارامېتىرلىرىنىڭ (توغراقنىڭ ھاياتى كۈچى (VS)، دەرەخ باراقسىنى دىئامېتىرى (CD)، باراقسىنى ئېگىزلىكى (TH)، يىلتىزسىمان توغراق تەنچىلىرى ۋە نوتا توغراقلارنىڭ سانى ۋە شۇنداقلا ئىككىلەمچى دەرەخ باراقسىنى قاتارلىقلار) ئىنكاسى ئاجىزلىغان. ئومۇمەن قىلىپ ئېيتقاندا، دەرياغا 200 مېتىر كېلىدىغان دائىرىدىكى توغراقلارنىڭ ئەسلىگە كېلىشى كۆرۈنەرلىك بولغان، 200 مېتىردىن 800 مېتىرغىچە بولغان دائىرىدىكى توغراقلار ئوتتۇراھال دەرىجىدە ئەسلىگە كەلگەن، 800 مېتىردىن ئاشىدىغان دائىرىدىكى توغراقلارنىڭ ئەسلىگە كېلىشى ئىنتايىن ئاجىز بولغان.

10 خىل دەرەخ غول ئايلىنىشى ۋە ئېگىزلىك ئوتتۇرىسىدىكى ماتېماتىكىلىق مۇناسىۋەت مودىللىرىنى كۆپ تەرەپلىملىك مودىل باھالاش ئۆلچەملىرى (مودېل پارامېتىرلىرىنى سىمپسوتىك T سىتاتىستىكىلاش، مۆلچەرلەنگەن توغراق ئېگىزلىكىنى ئۆلچەملەشتۈرۈلگەن قالدۇق ئۆسۈلى ئارقىلىق تەكشۈرۈش، يىلتىز-ئوتتۇرىچە-كۇۋادرات خاتالىق پەرقىنى تەكشۈرۈش (RMSE)، ئاكائىكى ئۆچۈر ئۆلچىمى (AIC)، ئوتتۇرىچە مۆلچەر خاتالىق پەرقى (ME) ۋە ئوتتۇرىچە مۇتلەق خاتالىق پەرقىنى (MAE) تەكشۈرۈش قاتارلىقلار) ئارقىلىق تەكشۈرگەندە، توغراق ئېگىزلىكى ۋە غول ئايلىنىشى ئوتتۇرىسىدىكى  $TH = 1.3 + a / (1 + b \times e^{-c \times DBH})$  مودىلى ۋە  $TH = 1.3 + DBH^2 / (a + b \times DBH + c \times DBH^2)$  مودىلىنىڭ توغرىلىق دەرىجىسى يۇقىرى بولغان. ماقالىدە يەنە باشقا مودىللارنىڭ توغراق ئېگىزلىكى ۋە غول ئايلىنىشى ئوتتۇرىسىدىكى مۇناسىۋەتنى توغرا ئىپادىلەپ بېرىشتىكى چەكلىمىلىكلىرى ۋە سەۋەبلىرى توغرىسىدا تەھلىل ئېلىپ بېرىلدى.

قوللىنىلغان بۇ كىتاب ئاپتورنىڭ گېرمانىيە ئايشتات-ئىنگولشتات ئۇنۋېرسىتېتىنىڭ جۇغراپىيە ئىنىستېتۇتىدا ئېلىپ بېرىلغان بەش يىللىق تەتقىقات ئەمگىكىنىڭ نەتىجىسىدۇر. ئاپتورنىڭ بۇ تەتقىقات ماقالىسى 2015-يىلى 12-ئاينىڭ 9-كۈنى ئايشتات-

ئىنگولشتات ئۇنىۋېرسىتېتىدا ئۆتكۈزۈلگەن دېسرتاتسىيە ياقلاش يىغىنىدا مۇتەخەسسسلەرنىڭ ياخشى باھاسىغا ئېرىشىپ، «ئەلا دوكتورلۇق دېسرتاتسىيەسى» (magna cum laude) بولۇپ باھالاندى.

ئاخىرىدا، بۇ دوكتورلۇق تەتقىقات خىزمىتىنىڭ غەلبىلىك ئاخىرلىشىشىغا كۈچ چىقارغان شەخس ۋە ئورۇنلارغا ئالاھىدە رەھمەت ئېيتىمەن. ئالدى بىلەن دوكتور يېتەكچىم ھەم ئۇستازلىرىمدىن پروفېسسور دوكتور ئۈمۈت خالىق (Prof. Dr. Ümüt Halik)، پروفېسسور دوكتور بېرنىد سىفكا (Prof. Dr. Bernd Cyffka)، پروفېسسور دوكتور يوهاننىس كۈشلىرگە (Prof. Dr. Johannes Küchler)، ھەمدە گېرمانىيە پەن-تەتقىقات مىنىستىرلىكى (BMBF) نىڭ گېرمانىيە-جۇڭگو ھەمكارلىقىدىكى «جۇڭگو تارىم دەريا ۋادىسىدىكى بوستانلىقلارنى سىجىل باشقۇرۇش (SuMaRiO)» تېمىسىدىكى تەتقىقات تۈرىدىن ئۈچ يىللىق خىزمەت توختامى بېرىپ، مېنىڭ گېرمانىيەدىكى تۇرمۇش ۋە ئوقۇش ئىشلىرىمنى ئىقتىسادىي جەھەتتىن كاپالەتكە ئىگە قىلغانلىقىغا چىن كۆڭلۈمدىن رەھمەت ئېيتىمەن. ئۇنىڭدىن باشقا قىسقا مۇددەتلىك، جۇڭگو ۋە گېرمانىيە ئارىلىقىدىكى يول خىراجىتى ۋە دالا خىزمەت چىقىملىرىمنى كۆتۈرگەن جۇڭگو تەبىئىي پەن تەتقىقات فوندى (NSFC)، جۇڭگو دۆلەتلىك چەت ئەلگە چىقىپ ئوقۇشقا ياردەم بېرىش فوندى (CSC)، گېرمانىيە فولكسۋاگېن فوندى (VolkswagenStiftung) نىڭ EcoCAR تەتقىقات تۈرى ۋە گېرمانىيە باۋارىيە شىتاتى جۇڭگو ئالىي مائارىپ مەركىزى فوندى (BayCHINA) قاتارلىق ئورۇنلارغا ئالاھىدە تەشەككۈر ئېيتىمەن. ئاخىرىدا مېنى مەنئىي جەھەتتىن قوللىغان ۋە ئىلھاملاندۇرغان ئاتا-ئانام، قېرىنداشلىرىم، ھەر مىللەت ئۇستازلىرىم، جۇڭگو ۋە گېرمانىيەدىكى گۈرۈپپىداشلىرىمغا ۋە ساۋاقداشلىرىمغا چىن كۆڭلۈمدىن رەھمىتىمنى بىلدۈرىمەن.

تاھىرجان ھەسەن

گېرمانىيە ئايشتات

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## ABBREVIATIONS

TH	tree height (m)
DBH	diameter at breast height (cm)
CD	crown diameter (m)
HC	height to crown (m)
CL	crown loss (%)
DR	distance to the river (m)
V	tree vitality
V0	healthy tree
V1	good tree
V2	medium tree
V3	senesced tree
V4	dying tree
V5	dead tree
V6	fallen tree
TRAB	Tarim River Basin Administration Bureau
EWDP	Ecological Water Diversion Program

# 1 INTRODUCTION

## 1.1 GENERAL OVERVIEW

Rivers all over the world support natural environments, provide habitats for flora and fauna, contribute to the preservation of biodiversity and offer space for human activities (Hughes and Rood, 2003; Rood et al. 2003, 2005; Kasahara et al. 2009). In arid and semi-arid regions, socio-economic activities are highly dependent on water resources provided by rivers (Feng and Endo, 2001; Cui and Shao, 2005; Jiang et al. 2005; Shafroth et al. 2010), and these watercourses play a significant role in sustaining normal cycles of socio-economic systems as well as fragile floodplain ecosystems. Over the past decades, however, floodplain ecosystems have often been disconnected from their rivers as a result of population increase, economic growth, large-scale agricultural development, and mismanagement of river oases. Hence, natural vegetation along both sides of the river has been severely degraded (Woolsey et al. 2007; Wang et al. 2008; Chen et al. 2011; Thevs 2011; Tuck-Fatt and Doell, 2012).

The Tarim River is one of the largest inland rivers in the world, along with the Volga, Syr Darya, Amu Darya, and the Ural (Hai et al. 2006). It is mainly supplied by glacial and snow meltwater and by precipitation from the Tianshan mountains. Over the past 50 years, due to climate change and rapid socio-economic development, many tributaries have been disconnected from the Tarim River. At present, only the Aksu River, Yarkand River and Hotan River remain connected to the Tarim (Fig. 1.1).

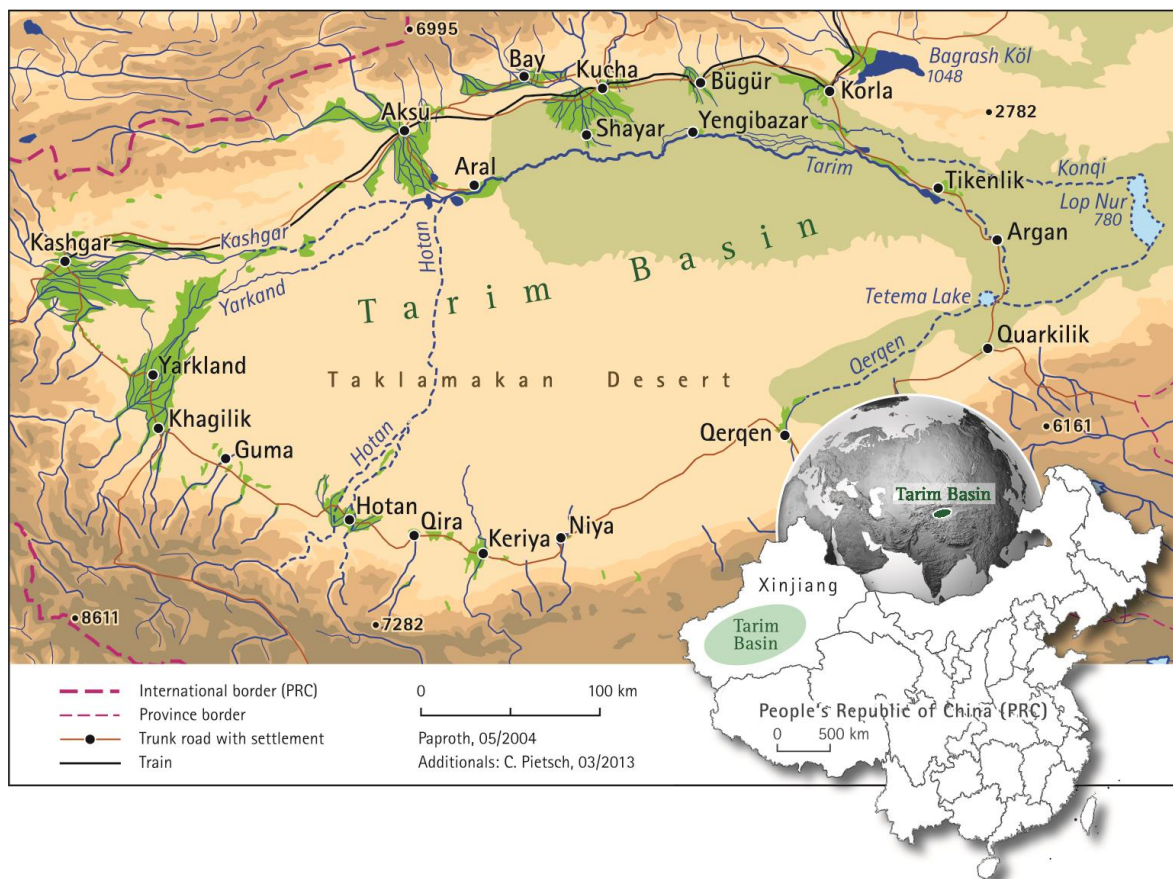


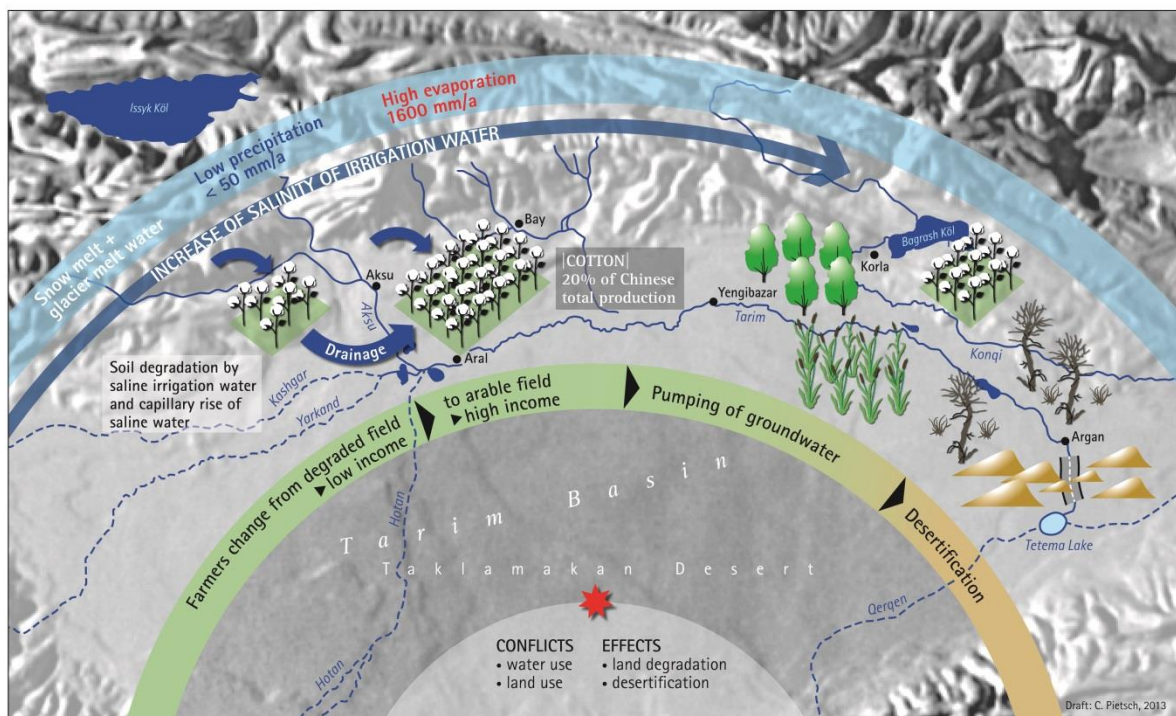
Fig. 1-1 Location of the Tarim River Basin.

The Aksu River is the primary water source, as its runoff makes up 73 % of the main stream of the Tarim (Halik et al. 2006; Chen et al. 2011). Floodplain forests distributed along the river are extremely important natural barriers supporting the ecological stability of these areas. *Populus euphratica* Oliv., found in the extremely dry areas of Central Asia, are the dominant species. More than 90 % of existing floodplain forests along the Tarim consists of this species (Song et al.2000; Huang 2002). These forests, as a safeguard for the cycle of all economic activities, provide a wide range of ecosystem services (ESS) and functions (ESF), such as protecting biodiversity, reducing the impact of sandstorms, moderating desertification, regulating oasis climate, fertilizing forest soils and maintaining ecosystem balance (Huang et al. 2010). Therefore, the protection of the floodplain forests is of crucial importance to the long-term social and economic development of the Tarim River Basin (Song et al. 2000; Ye, 2005; Wu and Tang, 2009).

Due to these unique natural conditions, all human activities and natural floodplain ecosystems directly or indirectly depend on the Tarim River as their key water supplier. Irrigation for crop production (mainly cotton) is the largest water consumer in the entire basin. Climate conditions in this region have been likely to be more conducive to increased river runoff during the recent years, but at the same time the number of agricultural areas with high water demand has been increasing rapidly as well (Song et al. 2000; Xu et al. 2008; Sun et al. 2011; Thevs 2011). Consequently, water scarcity in the downstream of the Tarim River has been exacerbated due to growing water demand for irrigation along the upper and middle reaches. Thus, the natural flood regime at the main stream has been completely altered, resulting in uneven distribution of river runoff, desiccation of rivers and lakes, groundwater level decline, vegetation deterioration and ecosystem degradation (Xu et al. 2008; Chen et al. 2010; Halik et al. 2011). The eco-hydrological processes in the lower reaches have been affected to a high degree as a consequence of the human changes in spatial and temporal patterns of natural water resources at the upper and middle reaches. The last 320 km of the main river channel and lakes have dried up, groundwater levels have declined, riparian vegetation has decayed, and desertification has increased (Halik et al. 2009; Zhuang et al. 2010; Chen et al. 2011; Zhang et al. 2012). The main problem of land and water management in the Tarim Basin is depicted in Fig. 1.2.

Since 2000, in order to restore and reconstruct these highly degraded floodplain ecosystems, the Chinese government has invested 10.7 billion RMB (approx. 1.8 billion US dollars) to implement the Ecological Water Diversion Program (EWDP) for the lower reaches of the Tarim River. The implementation of this project has produced positive effects on the environment. It was accompanied by extensive research conducted from different perspectives (Chen et al. 2004, 2006, 2008, 2010, 2011; Xu et al. 2007, 2008, 2009; Zhou et al. 2008a,b; Halik et al. 2009, 2011; Duan et al. 2010; Liu et al. 2012) in order to evaluate the effectiveness of this project. These research efforts have mainly focused on the restoration of hydrological process integrity (Wu and Tang, 2009; Chen et al. 2010), groundwater level recharge (Hou et al. 2007a,b; Ye et al. 2009a,b,c; Keilholz 2014) and the eco-physiological response of floodplain forests (Chen et al. 2004, 2006, 2008; Xu et al. 2008, 2009; Halik et al. 2009, 2011). This research has also revealed controversial issues regarding ecological water diversion practices. For example, there is the question of how to achieve maximum positive recovery of a degraded floodplain ecosystem by using the limited water resources rationally.

The main goal of this PhD thesis is to contribute to the sustainable management of the endangered Tarim riparian forest ecosystem. The specific objectives are to address the current ecological problems and forest degradation along the lower reaches of the Tarim River (particularly in Arghan), and the government’s effort to tackle these problems and to restore the highly degraded riparian ecosystem. More specifically, we examine the stand structure, distribution and status quo conditions of *P. euphratica* riparian forests along water-limited gradients in our permanent sampling plots at Arghan, analyze the spatial and temporal dynamics of groundwater depth and floodplain-forest recovery associated with water diversion, and evaluate the restoration effects and their limitations and challenges. In the final part of the thesis, the modeling of forest structure is carried out for the further purpose of long-term monitoring of this species. The results provide 1) holistic information about this species in the region; 2) scientific basis for potential recovery of the “Green Corridor” and for the optimization of future water diversion schemes; 3) last but not least, the research results also offer guidance to decision makers and forest managers for sustainable management of these existing endangered species.



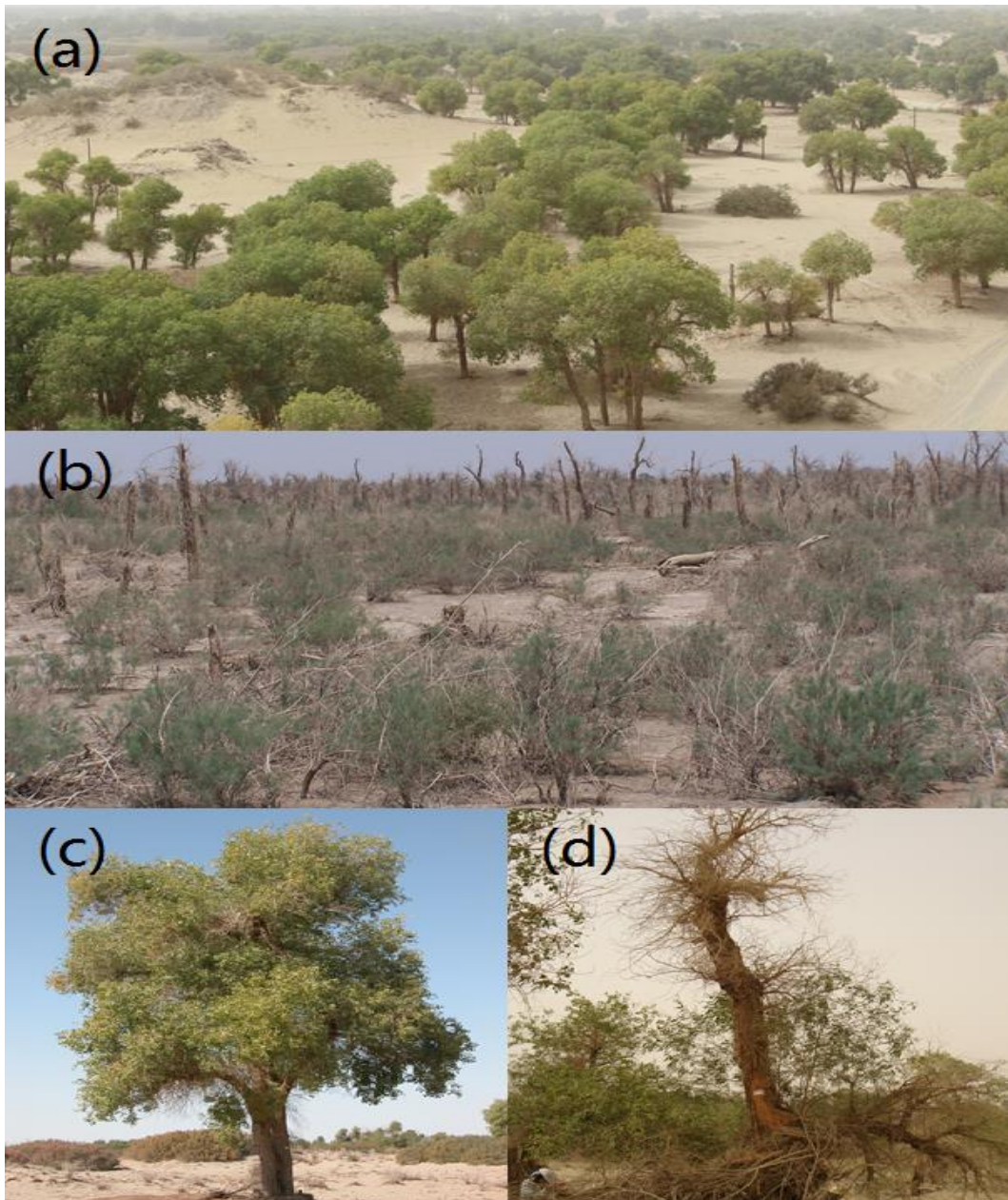
**Fig. 1-2** The major problems of land and water management in the Tarim Basin (Source: Cyffka et al. 2013).

## 1.2 *POPULUS EUPHRATICA* AS THE DOMINANT SPECIES IN THE TARIM RIPARIAN FORESTS

*Populus euphratica* Oliv., found in the extremely dry areas of Central Asia, is the dominant tree species considered in this work (Fig. 1.3). *P. euphratica* is the world’s most important gene pool, and is also known as the “leaf poplar”, “sycamore”, and “poon”, belonging to a new species of the genus *Populus*, family *Salicaceae*, a perennial deciduous forest tree (Wang et al. 1996). It is a remnant of the original Tertiary species (Wang et al. 1996). Qin R., (1959) has estimated that this species has existed for about 300 to 600 million years, and it has been



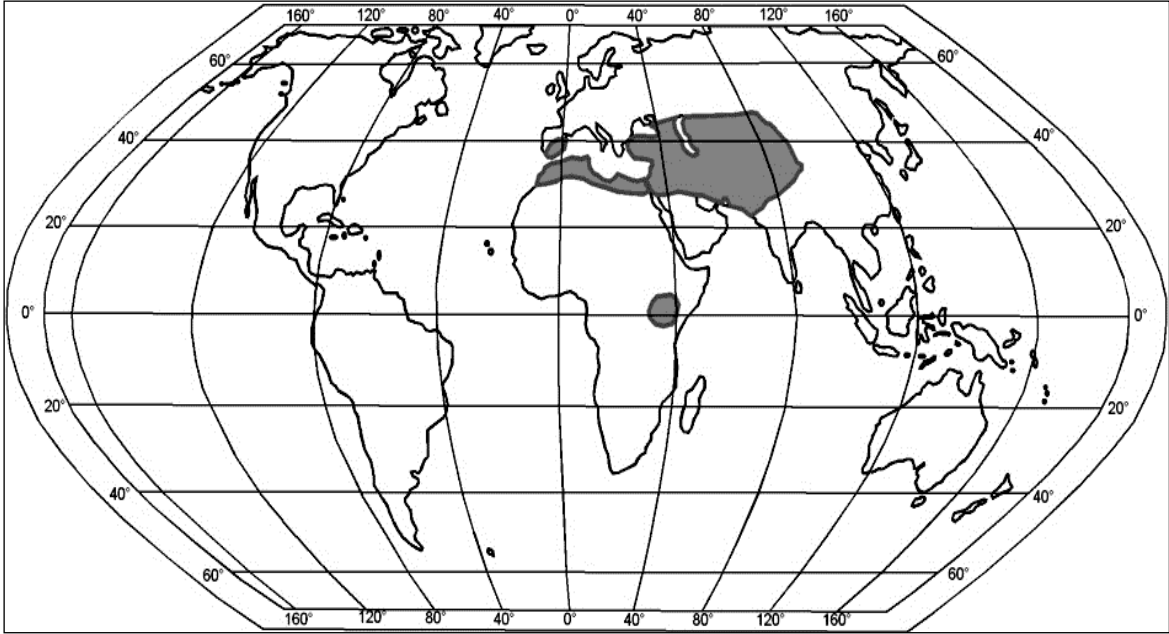
hailed as "living fossil" of ancient species by botanists (Wang et al. 1996). The *P. euphratica* was first described in 1801 by Olivier and named after the river Euphrates (Wang et al. 1996).



**Fig. 1-3** *P. euphratica* populations and individual trees: (a) relatively healthy population; (b) degenerated population of *P. euphratica* including *Tamarix sp.*; (c) individual *P. euphratica* tree with good vitality; (d) degraded *P. euphratica* tree. (Photos: Halik, 2004, 2011)

It is also on the Tentative List of the United Nations Educational Scientific and Cultural Organization (UNESCO). (For more information: <http://whc.unesco.org/en/tentativelists/5532/>). The distribution range of *P. euphratica* stretches across the three continents of Europe, Asia and Africa and is present in twenty countries surrounding the Mediterranean Sea (Fig. 1.4). A large proportion of this species is distributed in the arid and semi-arid desert areas of Northwestern China and Inner Mongolia (Tables 1.1 and 1.2). *P. euphratica* is mainly distributed in economically poor areas (Wang et al. 1996). 61 % of them are distributed in

Chinese territory (Table 1.1). In addition, the largest remaining stocks of *P. euphratica* can be found in Central Asian Countries, particularly in Kazakhstan. In China, approximately 91 % of the stands are distributed mainly in the Xinjiang Uyghur Autonomous Region (Table 1.2). Among them, nearly 90 % of the existing *Euphratica* forests in the Tarim riparian forest ecosystem are of this species (Song et al. 2000; Huang 2002).



**Fig. 1-4** Geographical distribution of *P. euphratica* in the world (Source: Chai et al. 2008).

**Table 1-1** Distribution and area of *P. euphratica* forests in different countries in the world (ha).

Count ries	China	Central Asian countries	Iraq	Iran	Syria	Turkey	Pakistan	Afghanistan	Spain	other	total
Area (ha)	395200	200000*	20000	20000	5818	4900	2800	n.d.	< 1.0	n.d.	648719
Percenta ge (%)	61.0	30.8	3.1	3.1	0.9	0.8	0.4	n.d.	—	n.d.	100

\*Estimated figure (Source: Wang et al. 1996).

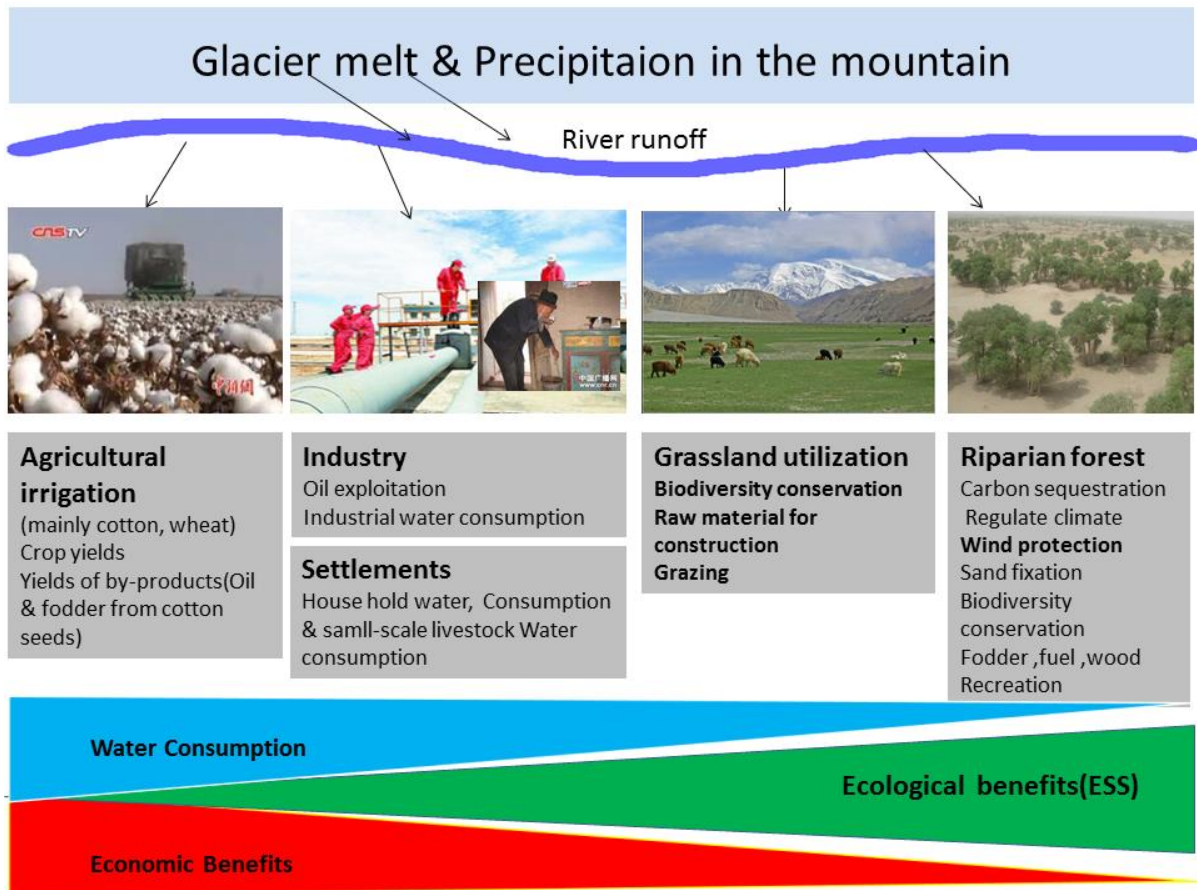
**Table 1-2** The distribution sites and areas of *P. euphratica* forests in China (ha)\*.

Location area (ha)	Xinjiang Uyghur Autonomies Region		Inner Mongolia	Gansu	Qinghai Ningxia	total
	Tarim Basin	Junggar Basin				
Area (ha)	352200	8000	20000	5000	sparse	395200
Percentage (%)	89.1	2.0	5.1	3.8	—	100

\* According to the statistics provided by the Forest Bureau of Ejina, Inner Mongolia. Presently, the total area of *P. euphratica* stands in Inner Mongolia (including sparse stands) amounts to 22700 ha (Source: Wang et al. 1996).

### 1.3 CONSERVATION OF THE RIPARIAN FOREST ECOSYSTEM IS THE KEY TASK

Like any other inland rivers in the world, the Tarim River is the key water source for all kinds of human activities (drinking, irrigation, industry, etc.) and for the natural riparian forest ecosystems in the Tarim River Basin (Fig. 1.5).

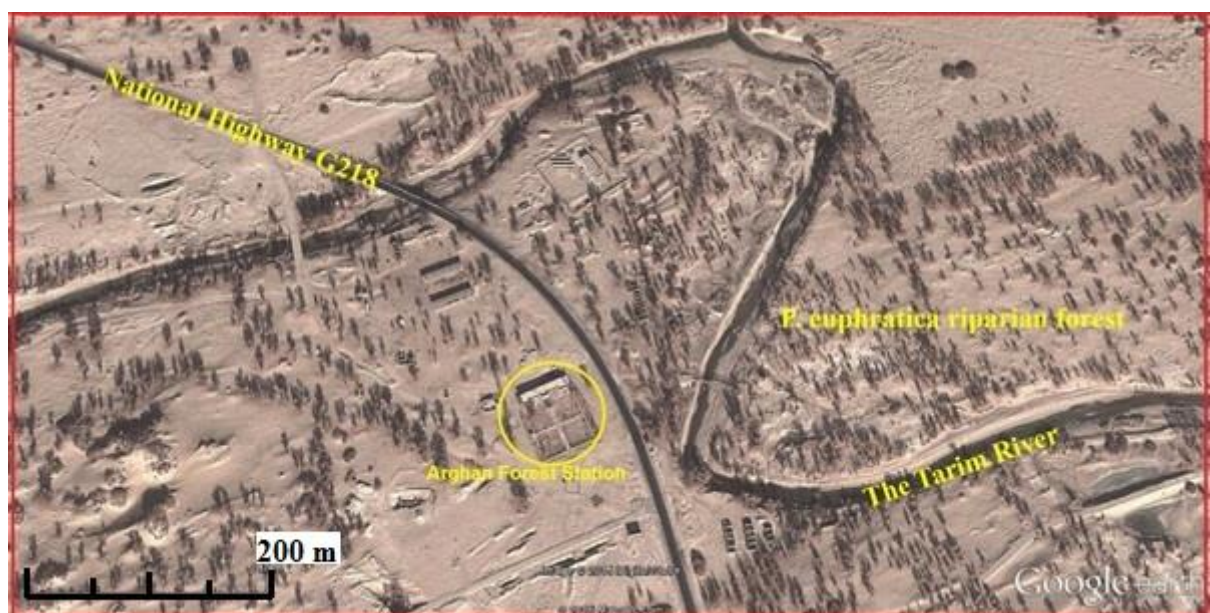
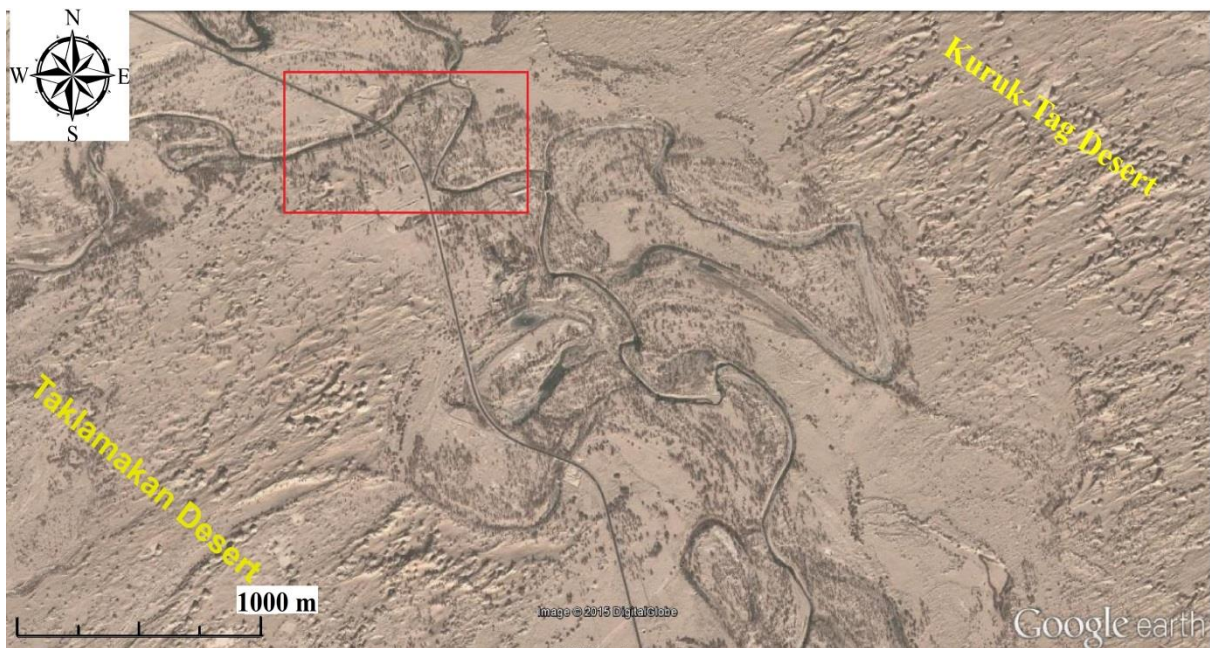


**Fig. 1-5** Water supply and the water use of different sectors along the river (slightly modified, Source: Thevs 2011).

*P. euphratica* riparian ecosystems along the Tarim River provide a wide range of ecosystem services, which have crucial impacts on the well-being of humans and the ecological security of the region. In addition to the impact of climate change, it is already clear that anthropogenic disturbances such as population growth, massive land reclamation, and the overutilization of water for agriculture and industries, as well as rapid urbanization, are all responsible for the degradation of the natural riparian ecosystem. Over the past decades, the natural flow regimes of the Tarim River have been significantly altered and their harmonious relationships with the riparian ecosystem have been affected and damaged. As a result, the original ecosystem service and ecosystem function (ESS/ESF) of the natural riparian forests could not be delivered sustainably. As mentioned above, the Euphrates poplar is the dominant species of the Tugai forests in the Central Asian deserts and plays an irreplaceable role in maintaining the sustainable development of these regions. One of the major ESS&ESF is the shelterbelt function and the prevention of desertification. Particularly in the lower reaches of

the Tarim River, the protective function of these species cannot be replaced with any other artificial measures.

From Fig. 1.6, it is not difficult to see that: (1) they form the so called “Green Corridor” to prevent the two deserts, the Taklamakan and the Kuruk-Tag, from merging together; (2) they are a natural effective shelter belt for the strategically important National Highway No. 218 which connects Xinjiang to inner China. In this context, the Chinese government has therefore declared the conservation of *P. euphratica* forests along the Tarim River as one of the eighteen key projects in their implementation of the UN Convention to Combat Desertification (CCICCD, 1996).



**Fig. 1-6** *P. euphratica* riparian forests distributed between the two main deserts of the Taklamakan and Kuruk-Tag. The research area in Arghan is circled on the map. The location of Arghan in the Tarim River Basin can be seen in Fig. 1.1.

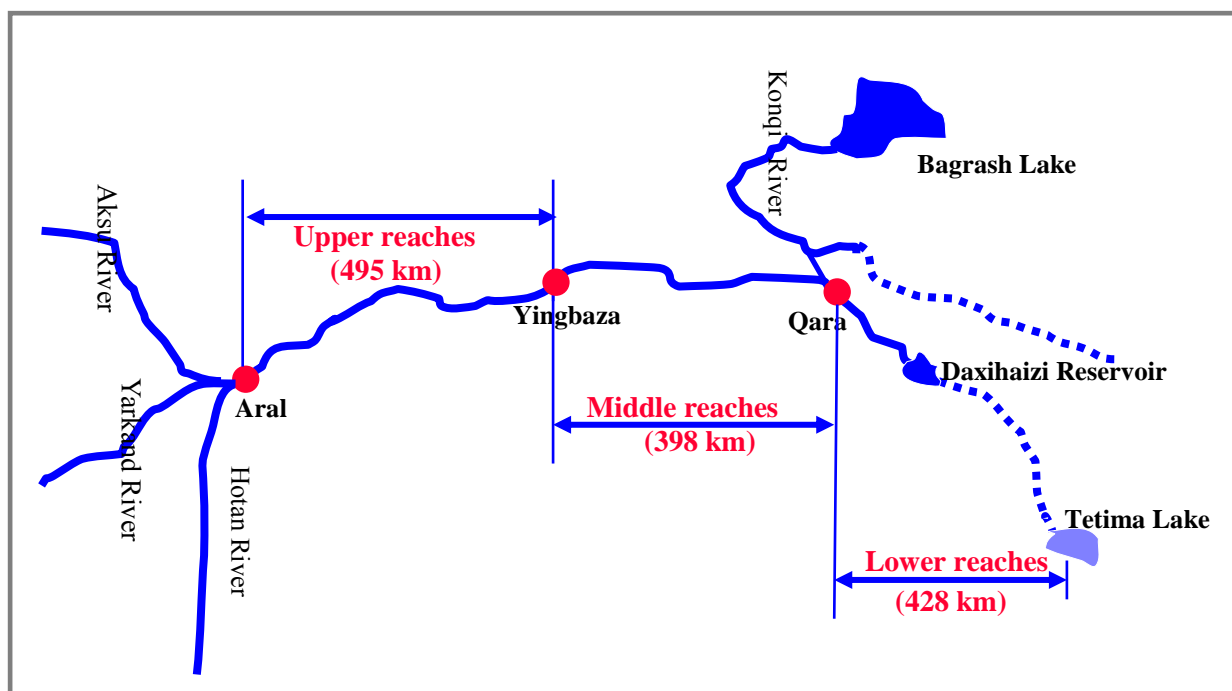
The present thesis consists of seven chapters. Chapter 1 has presented the research background and motivation. Chapter 2 introduces the study area in the lower reaches of Tarim and the plots of land under investigation, as well as the methods and data processing employed. Chapter 3 presents an overview of the restoration measures, their background and the groundwater dynamics that have resulted from the man-made ecological water diversion. Chapter 4 highlights the stand structure, distribution and vitality of the existing *P. euphratica* riparian forests at different hydrological conditions. Chapter 5 focuses on the change patterns in the eco-morphological parameters of the regenerated *P. euphratica* trees. Chapter 6 attempts to model forest structure for the purpose of long-term monitoring plans. A general discussion and conclusions with regard to each result are presented in Chapter 7.

## 2 MATERIALS AND METHODS

### 2.1 NATURAL OVERVIEW OF THE STUDY AREA

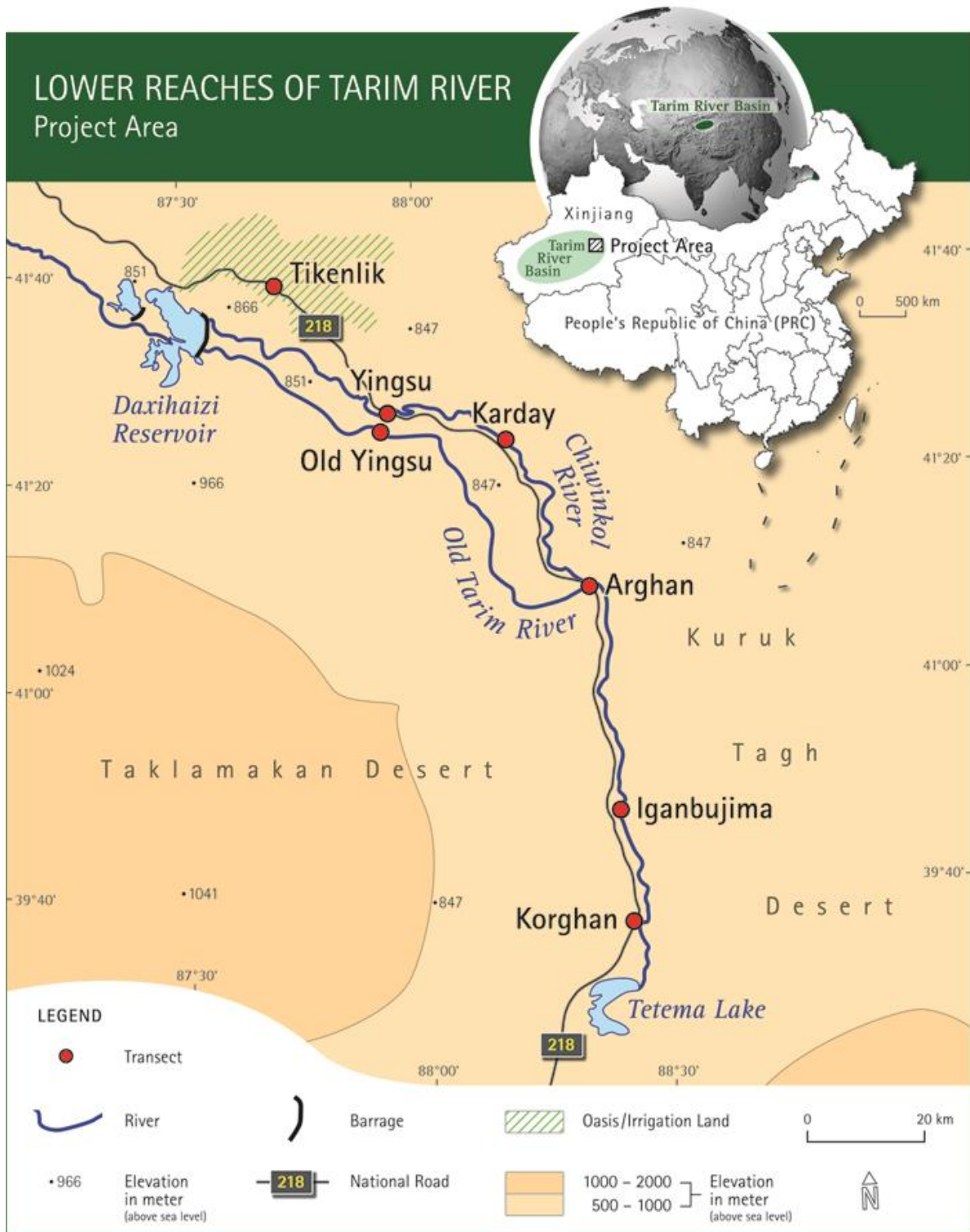
#### 2.1.1 GEOGRAPHY

The Tarim River is located in the Xinjiang Uyghur Autonomous Region (XUAR) in northwest China. The river basin ( $39^{\circ}24'08''$ -  $41^{\circ}03'40''$ N;  $86^{\circ}37'23''$ - $88^{\circ}30'00''$ E) is known for its rich natural resources and vulnerable ecosystems (see Fig. 2.1). The river's main stream, measured from the confluence of the Aksu, Yarkand, and Hotan rivers down to the terminal Lake Tetima (syn. Taitema Hu) is about 1321 km long (Fig. 2.1) (Chen et al. 2010; Lam et al. 2011). Our research area is located at Arghan village ( $40^{\circ}08'50''$  N,  $88^{\circ}21'28''$  E), between the Daxihaizi Reservoir and Tetima Lake (syn. Taitema Hu), in the lower reaches of the Tarim River (see Fig. 2.2).



**Fig. 2-1** Sketch map of the Tarim River and its three main reaches. (Source: Kurban 2013)

The riverbed is divided into two branches at a distance of 4.20 km from the Daxihaizi reservoir. The western branch is the old Tarim River; the eastern branch is the Qiwinkol/Chiwinkol River. The two branches are roughly parallel to one another, and converge at Arghan where vegetation coverage is relatively high and the effects of anthropogenic impacts, such as of grazing and fuelwood harvesting, are not significant at the sampling sites. Because of this, Arghan was selected as an ideal location for the evaluation of water diversion practices and their influence on the rehabilitation of riparian forest ecosystems.



**Fig. 2-2** Location of the study area at Arghan along the lower reaches of the Tarim River

### 2.1.2 CLIMATE

The Tarim River Basin area is located in an extremely arid climatic zone, being very hot in the summer and very cold in the winter. There are many thermal resources, there is a large temperature difference between day and night, and sunny and dry, at times sandy (sandstorm), weather is frequent. The annual precipitation is about 15–20 mm and the potential annual

evaporation is about 2,500–3,000 mm (Song et al. 2000; Xu et al. 2007; Wu and Tang 2009; Aishan et al. 2013). Fig 2.3 shows some of the climate characteristics of our research area at Arghan - the mean monthly maximum precipitation is seen to be less than 6 mm.

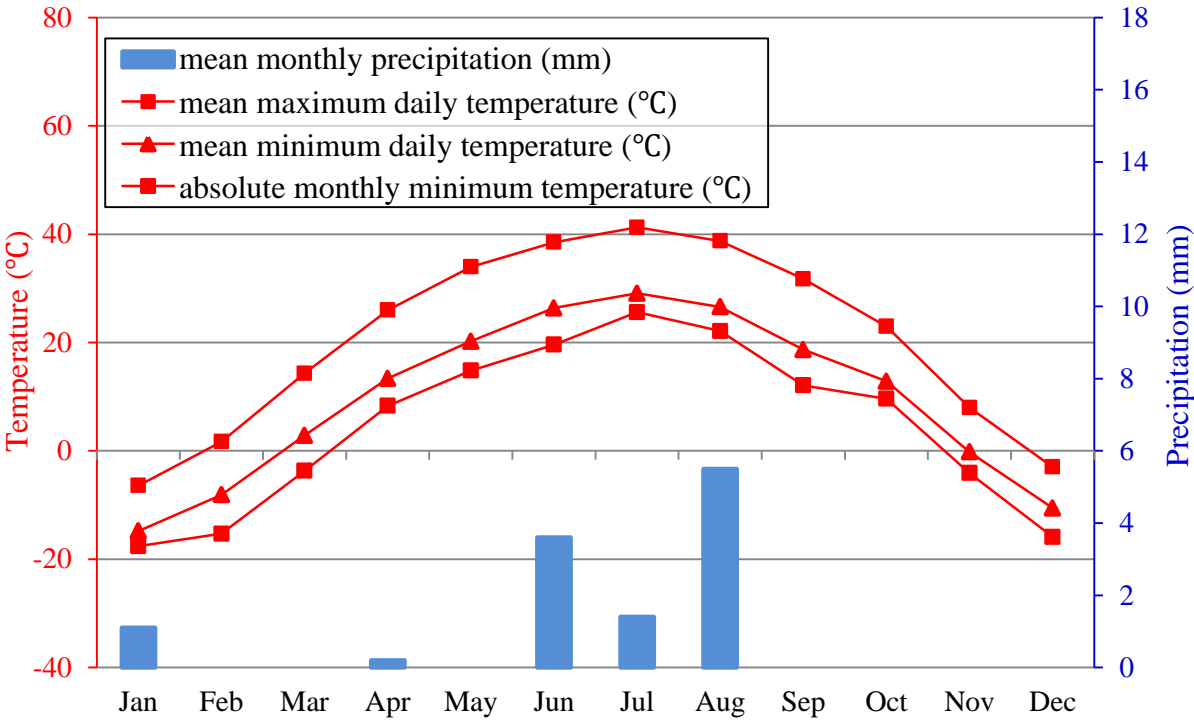


Fig. 2-3 Climate characteristics of the research area at Arghan.

### 2.1.3 TOPOGRAPHY AND GEOMORPHOLOGY

The downstream of the Tarim River is located in the eastern fringe of the Tarim Basin. The average above sea level (m.a.s.l.) is between 800 and 860 m (Song et al. 2000). Generally, the overall terrain is high in the west, low in the east, and slightly tilted from north to south. Thus, the river flows southeast from the Daxihaizi Reservoir to Arghan, and then turns south towards Tetima Lake. The slope of the terrain is about 3‰ (Song et al. 2000). There are three types of landforms (Fig. 2.4): a) Alluvial plains: these are located along both sides of river channel. Fluvial down-cutting is generally about 3-5 m (Zhao and Chen, 2008). Terrain is mostly flat; vegetation coverage is relatively high so that wind erosion and desertification is not so remarkable. b) Aeolian landforms: because of the intermittent water formed by rains, large barren patches are found in the certain areas, where vegetation is highly degraded, leading to strong wind erosion, with resulting erosion trenches and Yardang mounds. Aeolian landforms include sand and dunes with grass and shrubs, semi-fixed dunes, semi-mobile and moving sand dunes. c) Lacustrine plains (or lake plains): the terrain is very flat and dominated by sand and load sediments. In the dry lakebed, the surface often consists of a soft salt crust.





**Fig. 2-4** Typical landscapes for the different types of landforms in the lower reaches of the Tarim River (Photos from top to bottom represent alluvial, aeolian and lacustrine landforms, respectively. Photos: Betz, September 2013).

#### 2.1.4 HYDROLOGY

Due to the unique geographical location of the Tarim River Basin (i.e., far away from the ocean and surrounded by high mountains), the water of the Tarim River is mainly supplied by the melting water from glaciers and snow in the mountains. There is almost no branch runoff

from the water flowing from the mountains and into the main stream of the Tarim River. Over the past few decades, the water flowing into the Tarim River's main stream has decreased from  $14.8 \times 10^8 \text{ m}^3$  in the 1960s to  $2.38 \times 10^8 \text{ m}^3$  in the 1990s as the result of significant reduction in the original water into the Tarim River because of unreasonable exploitation and fast increase in water consumption on the upper and middle reaches of the water-supplying rivers. After the construction of the Daxihaizi Reservoir in the 1970s, the Arghan area has become dried up until the start of the water diversion project in 2000. The amount of water in the terminal lake Tetima in the 1950s ( $4 \times 10^8 - 5 \times 10^8 \text{ m}^3$ ) was reduced to  $0.23 \times 10^8 \text{ m}^3$  in the 1960s. Since then, Tetima Lake has never been supplied with river water until the implementation of the water diversion project (Table 2.1).

**Table 2-1** Changes in water volume at each section in the lower reaches of the Tarim River before water diversion ( $\times 10^8 \text{ m}^3$ ).

Period	Qara			Tikenlik	Arghan	Tetima Lake
	Runoff from Tarim River	Runoff diverted from <i>Konqi River</i> *	The total runoff			
1957-1960	14.8	0.00	14.8	8.9	long-term flooding	4.00-5.00
1961-1970	10.39	0.00	10.39	2.88	Intermittent flooding	0.23
1971-1980	6.45	1.00	7.45	0.47	desiccated	desiccated
1981-1990	3.77	2.01	5.78	0.36	desiccated	desiccated
1991-1995	2.38	2.26	4.64	0.06	desiccated	desiccated
Average (1957-1995)	7.11	1.06	8.17	1.83	drying for 25 years	drying for 27 years

\*Note: Konqi River is also known as Kongque River or Kaidu River. (Source: Song et al. 2000 )

There are two main reasons for the reduction in the amount of water delivered to the lower reaches of the Tarim River. One reason is that the diversion of water for non-ecological purposes in the headstream has increased. The average annual runoff from three main water suppliers (the Aksu, Yarkand and Hotan Rivers) was  $194.00 \times 10^8 \text{ m}^3$  from 1957 to 2009, while the annual average water delivered to the main stream of the Tarim River was  $44.20 \times 10^8 \text{ m}^3$ . When the total amount of water in the headstreams was  $178 \times 10^8 \text{ m}^3$  over the period of 1957-1959, the amount of water into the Tarim River was  $49.40 \times 10^8 \text{ m}^3$ . By the years 2000-2009, despite the amount of water in the headstreams being increased ( $207.60 \times 10^8 \text{ m}^3$ ), the water supply to the Tarim River decreased to  $36.50 \times 10^8 \text{ m}^3$  (Table 4). Another reason is that water consumption in the upper and middle reaches has significantly increased, as has already been mentioned.

**Table 2-2** Total runoff in the three main water suppliers (Aksu/Yarkand/Hotan Rivers) and the amount of water flowing into the Tarim River ( $\times 10^8 \text{ m}^3$ ).

Period	Total runoff in Aksu, Yarkand and Hotan Rivers	The amount of water flowing into the Tarim River
1957-1959	178.00	49.40
1960-1969	188.90	50.60
1970-1979	192.50	45.20
1980-1989	185.90	44.80
1990-1999	204.70	42.50
2000-2009	207.60	36.50
Average (1957-1959)	194.00	44.20

Source: Song et al. 2000

As the result of multiple disturbances to the spatio-temporal distribution pattern of water resources along the entire Tarim River Basin, the lower reaches of the Tarim River past the Daxihaizi Reservoir had been completely disconnected from water supply for nearly 30 years. This led to widespread and severe degradation of the riparian forest ecosystem due to the negative effects of a sustained decline of groundwater levels. For example, the groundwater depth near Arghan dropped from 7.0 m in 1973 to 12.56 m in 2000; the decline was 5.56 m (Table 2.3).

**Table 2-3** Change in groundwater depth at different transects in the lower reaches of the Tarim River for different time periods before water diversion.

Location	Longitude	Latitude	Groundwater depth (m)		
			1973	1989	1997
Yingsu	E87°56.3' - E87°56.5'	N40°25.9' - E40°26.1'	6.00	8.00	9.44
Karday	E88°09.9' - E88°10.4'	N40°22.0' - E40°22.3'	5.86	10.00	11.13
Arghan	E88°20.8' - E88°21.5'	N40°08.5' - E40°08.7'	7.00	10.40	12.56
Yiganbujima	E88°22.5' - E88°22.7'	N39°47.2' - E39°47.3'	6.20	12.65	12.92
Korghan	E88°25.2' - E88°25.5'	N39°36.4' - E39°36.5'	2.33	3.10	5.69

Source: Xu et al. 2008.

## 2.1.5 VEGETATION

Zonal vegetation in the Tarim River Basin belongs to the class of typical desert vegetation characterized by temperate semi-shrubs and shrubs. However, non-zonal grassland vegetation can also be found in the lowlands on both sides of the river floodplains. This results in sparse vegetation comprised of riparian trees, shrubs and the herbaceous plants of this region (Table 2.4).

**Table 2-4** Main plant species in Arghan

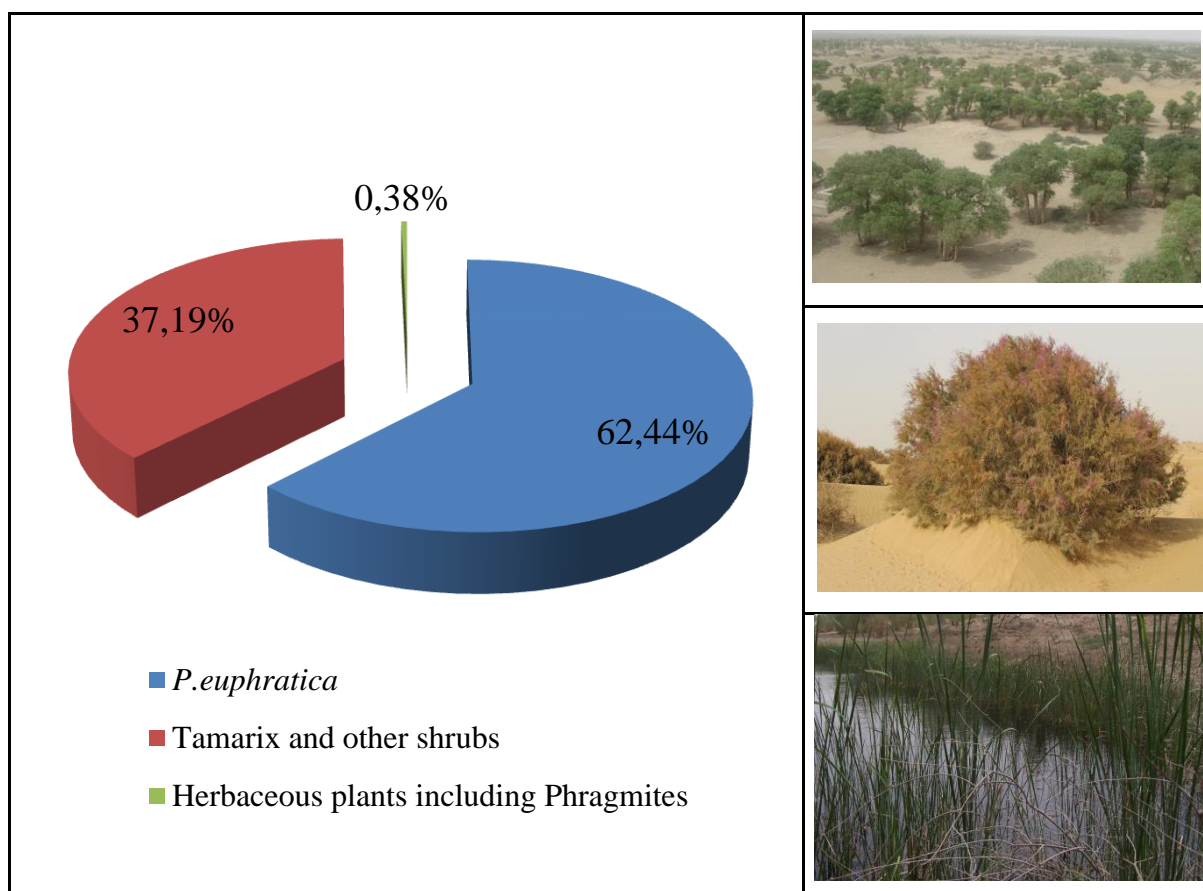
Plant groups	Family name	Botanical name
Annual herbaceous	<i>Chenopodiaceae</i>	<i>Salsola collina</i> Pall
Perennial herbaceous	<i>Gramineae</i>	<i>Phragmites australis</i> (Cav.)Trin
	<i>Typhaceae</i>	<i>Typha angustifolia</i> L.
	<i>Leguminosae</i>	<i>Alhagi sparsifolia</i> (B.Keller et Shap.) Shap.
	<i>Leguminosae</i>	<i>Glycyrrhiza glabra</i> Fisch.
	<i>Asteraceae/compositae</i>	<i>Karelinia caspica</i> (Pall) Less.
	<i>Asteraceae/compositae</i>	<i>Inula salsolodides</i> (Turcz.) Ostenf.
	<i>Apocynaceae</i>	<i>Poacynum hendersonii</i> (Hook. f.) Woodson
Subshrubs	<i>Chenopodiaceae</i>	<i>Halostachys caspica</i> (M.Bieb.) C.A.Mey.
Shrubs	<i>Tamaricaceae</i>	<i>Tamarix ramosissima</i> Led.
	<i>Tamaricaceae</i>	<i>Tamarix hispida</i> Willd.
	<i>Tamaricaceae</i>	<i>Tamarix hohenackeri</i> Bunge.
	<i>Tamaricaceae</i>	<i>Tamarix elongata</i> Ldb.
	<i>Solanaceae</i>	<i>Lycium ruthenicum</i> Murr.
	<i>Leguminosae</i>	<i>Halimodendron halodendron</i> (Pall.) Vass
Trees	<i>Salicaceae/willow</i>	<i>Populus euphratica</i> Oliv.
	<i>Elaeagnaceae</i>	<i>Elaeagnus angustifolia</i> L

Source: Aishan 2011.

This vegetation is also known as “Tugai vegetation”. Vegetation degradation is apparent, with desertification being very serious in the Arghan transect. The grassland vegetation between the Yingsu and Arghan transects had been nearly dried up, with the exception of some areas close to the river flooding zone. Large areas of dead vegetation such as *Lycium ruthenicum* Murr. and *Halimodendron halodendron* (Pall.) Vass could be seen on the surface. The main vegetation types are the desert poplar and the *Tamarix*, but most of them are either over-

matured or dead. In most cases, the *Tamarix* is distributed as the group of several tamarisks. The distribution width of the vegetation is gradually becoming narrower from Arghan to Yiganbujima, with a width of less than 2 km (Song et al. 2000). Many vegetation types are highly degenerated, and most of the poplar trees are over-aged and have already lost their top green branches. In addition, the *Tamarix* growing on the sand dunes appear to be dead. Table 2.4 shows the main vegetation types encountered in our study area - e.g., the main trees are *Populus euphratica* Oliv. and *Elaeagnus angustifolia* L.; the main shrubs are *Tamarix ramosissima* Ledeb., *Tamarix hispida* Willd., *Tamarix elongata* Ledeb., *Lycium ruthenicum* Murr., *Halimodendron halodendron* (Pall.) Voss., *Halostachys Caspica* (M. B.) C. A. Mey., *Poacynum hendersonii* (Hook. F.) Woodson., *Alhagi sparsifolia* (B. Keller et Shap.) Shap., *Glycyrrhiza inflata* Bat., *Karelinia caspica* (Pall.) Less., *Inula salsoloides* (Turcs.) Ostrnf., and *Hexinia polydichotoma* (Osten.) H. L. Yang (Zhang et al. 2005; Halik et al. 2006; Aishan et al. 2013 and 2015).

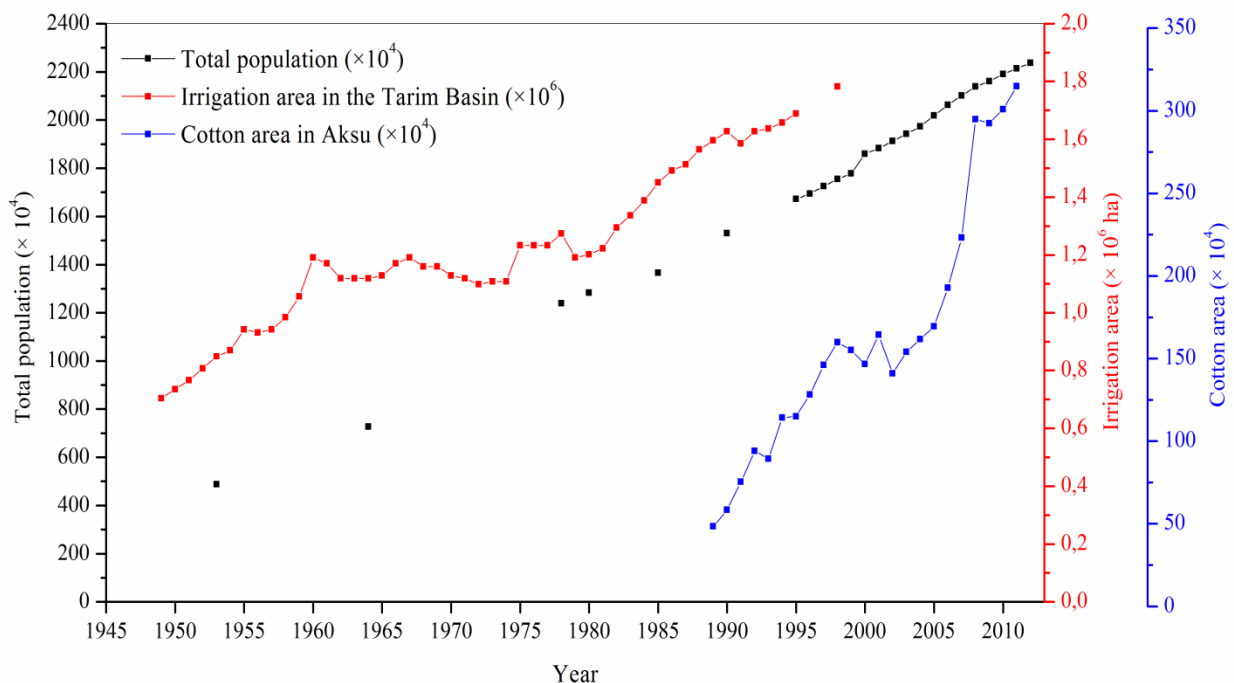
Herbal plants, such as *Salsola collina* Pall. and *Inula salsoloides* (Turcz.) Ostenf., predominantly grow close to both sides of riverbed. At distance of greater than 100 m from the river, apocynum, caspica, sparse leaves sparsifolia, licorice and other herbs, as well as dead roots of reed can be found. At distances greater than 600 m, one mainly encounters *P. euphratica* and *Tamarix*. More than 60 % of the *P. euphratica* trees act as the key species in our study area (Fig. 2.5) and are the main target of the restoration project being implemented at this moment.



**Fig. 2-5** Proportions of different vegetation types in the study area at the Arghan section. Source: Wang 2008.

## 2.2 SOCIO-ECONOMIC CONDITIONS

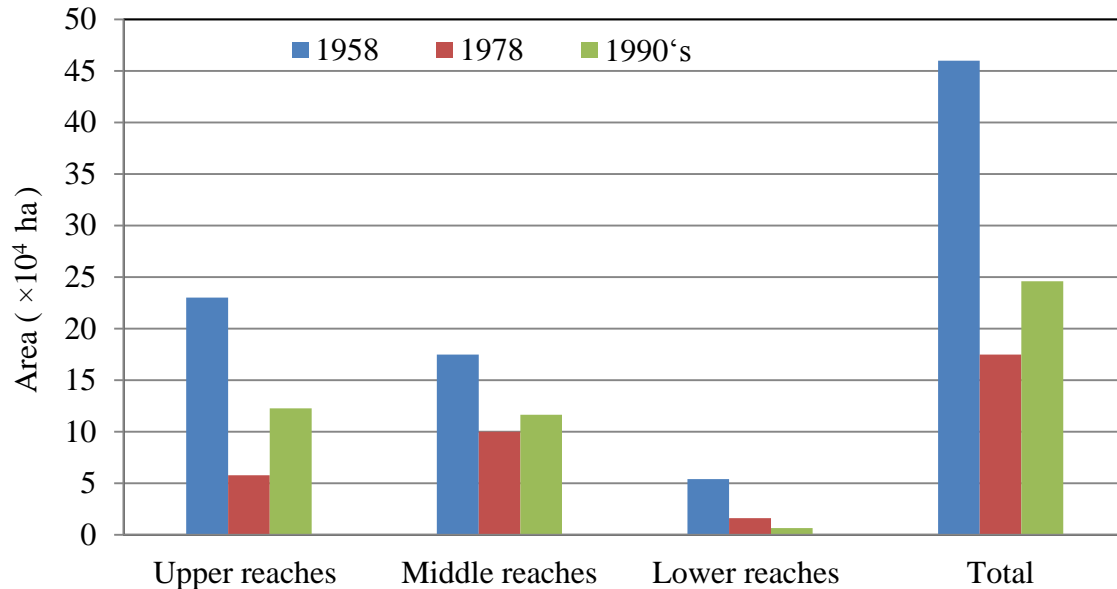
Since many human activities and the development of natural ecosystems depend highly on both surface water and groundwater water availability as provided by the Tarim River, any form of unsustainable water use can easily lead to severe water conflicts and ecological consequences. Fig.2.6 shows the changes in annual total population, irrigation area in the Tarim Basin, and the cotton production area in Aksu. The annual total population had increased from about  $4.873 \times 10^6$  in 1953 to  $22.328 \times 10^6$  in 2012, rising by about 4.58 times when compared to the total population in 1953. The irrigation area in the Tarim Basin also expanded, from approximately  $0.7 \times 10^6$  ha in 1949 to about  $1.80 \times 10^6$  ha in 1998, with an average annual growth area of  $22 \times 10^3$  ha. Feike et al. (2015) found that the cotton area in the Aksu region experienced a large increase over the period of 1989-2011 (from  $50 \times 10^4$  ha to  $350 \times 10^4$  ha).



**Fig. 2-6** Change in the annual total population, the irrigation area in the Tarim basin and the cotton production area in Aksu. Data source: total population data for the years 1953 and 1963 ([http://en.wikipedia.org/wiki/Demographics\\_of\\_China](http://en.wikipedia.org/wiki/Demographics_of_China)); the rest of the total population data (Tuergong 2014); data for the irrigation area in the Tarim Basin (Zhou et al. 2000); data for the cotton area in Aksu (Feike et al. 2015).

Such a rapid enlargement in population growth and reclamation of irrigation land (mainly cotton fields) had negative effects on the river hydrological system (with the continued reduction of flows to the Tarim River) and had consequently changed the sustainable coexisting balance between natural the riparian forest ecosystem and the Tarim River. Particularly, the dependence of the lower-Tarim riparian forest ecosystem, dominated by *P. euphratica*, on the river flows, river channel movement, the size of flooding area and favorable groundwater depth, as well as on the soil water content, was highly disturbed. Accordingly, the total area of *P. euphratica* riparian forests decreased from  $45.98 \times 10^4$  ha in

1958 to  $24.59 \times 10^4$  ha in the early 1990s (Fig. 2.7). More seriously, large areas of *P. euphratica* in the lower reaches of the Tarim River decreased in size from about  $5.4 \times 10^4$  ha in 1958 to  $0.67 \times 10^4$  ha in the early 1990s; almost 87.6 % of *P. euphratica* forest area had been lost.



**Fig. 2-7** Area of the *P. euphratica* forests along the upper, middle and lower reaches of the Tarim River (Data source: Giese et al. 2005).

The irrigation areas in the lower reaches of the Tarim River are mainly found in Lopnur county and Division 2 (state-owned farm), with irrigated areas of Division 2 being the main part of the “Green Corridor”, which includes the state-owned farms 31, 32, 33, 34, 35 and 36. At the same time, they are, as the main agricultural producer, an important part of the regional economy. Owing to the high water needs arising from agricultural irrigation, the water in the Tarim River is always subject to meeting these demands. In addition to the degradation of the natural riparian ecosystem, the socio-cultural system with which it is closely connected has also been disturbed. For instance, the abandoning of the Loplik village due to water shortage in old Yingsu in the lower reaches of the Tarim River is a typical example of cultural degradation. According to Hoppe (2006), the village had been given up in the early 1960s and is currently in ruins. After nearly 50 years of decay, the village and its architecture still offer clear evidence of the Loplik culture that used to thrive along the lower reaches of the Tarim River (Fig. 2.8). As Halik (2006) explained, this situation might change in the coming years since the lower reaches are scheduled to receive water supplies from the ongoing water diversion practices. It is worth noting that as the water diversion project to the lower reaches of the Tarim River has progressed, the degraded ecological environment has seen significant improvements, and there has been an increasing trend in livestock activities along the river. However, in the current hydrological regime, no resettlement of the old Yingsu has taken place, despite 15 years of “ecological restoration” in the region.



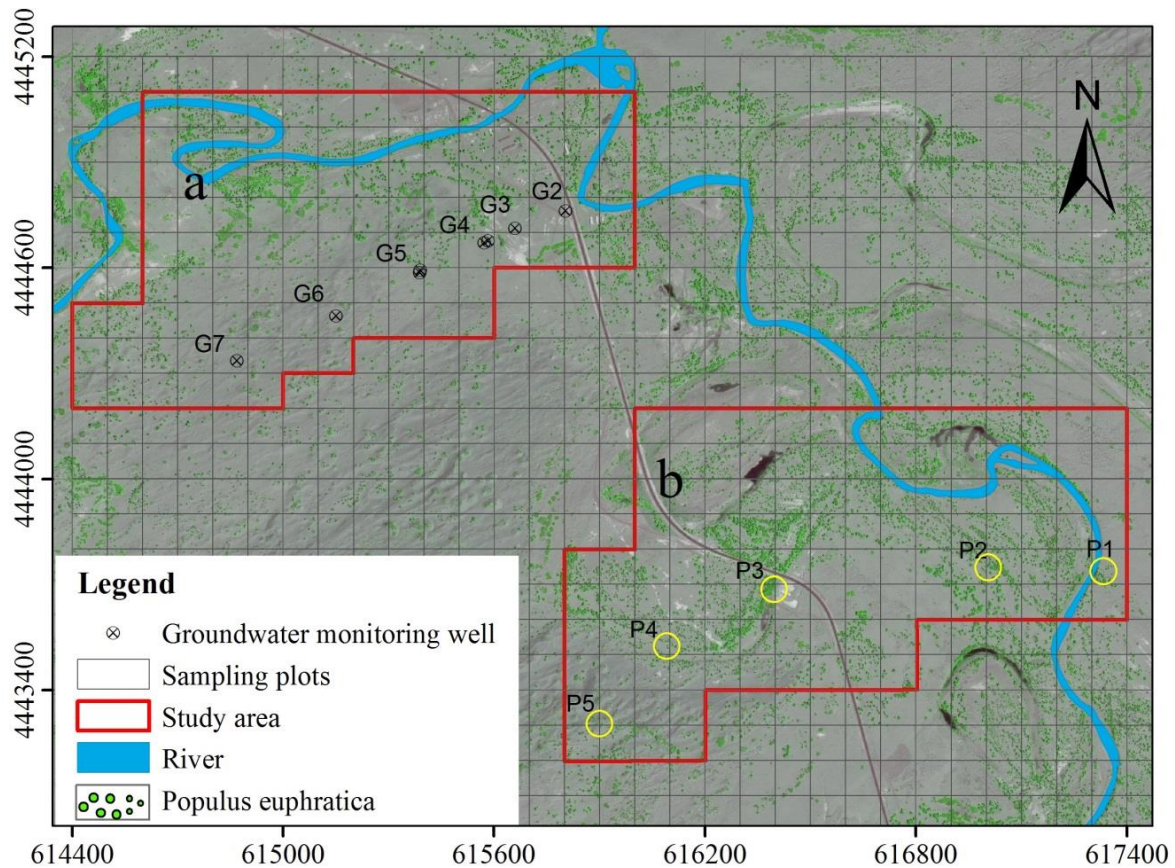
**Fig. 2-8** Parts of the abandoned Loplik village in Yingsu, in the lower reaches of the Tarim River (Photo: Halik, May 2015).

## 2.3 PLOT DESIGN AND DATA COLLECTION

### 2.3.1 DESIGN OF LONG-TERM INVESTIGATION PLOTS

To monitor riparian forest conditions for long-term purposes and to assess the response of eco-morphological parameters of *P. euphratica* trees under current forest management, two long-term ecological investigation plots were set up at the Arghan transect (188 km to Daxihaizi reservoir) in July 2004 by cooperative research groups of the Xinjiang University and the Berlin Technical University (Fig. 2.9). Taking into account the distance from the river channel, tree density and surface conditions, one permanent sampling site (Fig. 2.9a) with total area of 100 ha (100 square plots, each  $100 \times 100$  m in size) and one random sampling site (Fig.2.9b), with five 50-m radius circle plots at different distances from the river channel, were established. Plots P1, P2, P3, P4 and P5 were set up at different distances from the river channel.





**Fig. 2-9** Locations of the two study areas at Arghan: (a) permanent sampling plots, and (b) random sampling plots. Map based on QuickBird image taken in 05. July 2005, grid size: 100 m×100 m.

### 2.3.2 MEASUREMENT OF TREE PARAMETERS

Field measurements for almost 5,097 *P. euphratica* trees within these plots were conducted in the growing season of vegetation from 2004 to 2011 by extensive terrestrial investigations in combination with high-resolution (60-cm) QuickBird satellite images. Before the establishment of this monitoring base, mean (low-resolution) satellite images (TM/ETM+, SPOT and CBERS) had been used for monitoring the dynamics of riparian vegetation (Zhou et al. 2008a, b; Liu et al. 2013). Due to the heavy workload of field investigation and harsh growth conditions, sampled trees at Site A (Fig. 2.9a) had been measured once every 5 years (detailed forest inventory data for the years 2004 and 2011 were available for this plot), whereas trees at Site B (Fig.2.9b) had been measured once every 3 years (detailed forest inventory data for the years 2004, 2007 and 2011 were available for this plot). Major parameters such as vegetation coverage, canopy density, tree height (TH), diameter at breast height (DBH), crown diameter (CD), crown loss (CL), number of new shoots, root suckers, and geographical coordinates, as well as digital photos, were observed for each tree during the vegetation season at the permanent observation plots.

### 2.3.3 COLLECTION OF HYDROLOGICAL DATA

Data for volume and time of 12 water diversion events and groundwater dynamics since the initiation of the project in the year 2000 have been supplied by the Tarim River Basin

Administration Bureau (TRAB). They were collected at long-term groundwater monitoring wells at 10 transects<sup>1</sup>, at 90 ° to the main water flowing channel between Daxihaizi Reservoir and Tetima Lake (Table 2.5).

**Table 2-5** Layout of groundwater monitoring wells along the lower reaches of the Tarim River.(DR stands for “distance from the river”)

From Daxihaizi (km)	Transect	Code of the monitoring wells	DR (m)	Layout of the monitoring wells	G218 National Highway distance (km)
60	Yingsu (C)	C2 C3 C4 C5 C6 C7	50 150 300 500 750 1050		929
110	Karday (E)	E1 E2 E3 E4 E5 E6	50 150 300 500 750 1050		951
190	Arghan (G)	G2 G3 G4 G5 G6 G7	50 150 300 500 750 1050		984
328	Korghan (I)	I1 I2 I3 I4 I5 I6	50 150 300 500 750 1050		1048
346	Tetima (J)	J1	100		

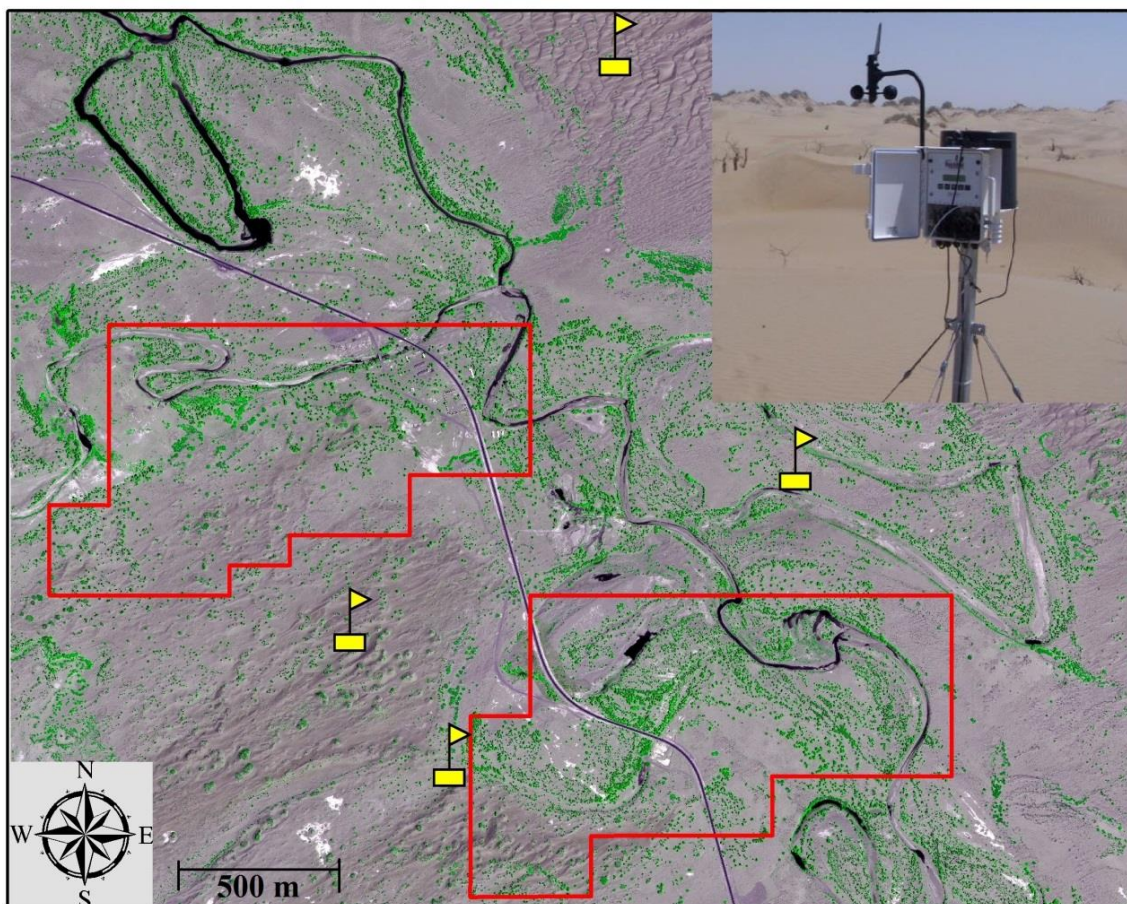
Source: data from TRAB

<sup>1</sup> TRAB has established these 9 monitoring transects at Akdun (A), Yakupmahan (B), Yingsu (C), Abdal (D), Karday (E), Tugmalla (F), Arghan (G), Yiganbujima (H), Korghan (I) and Tetima Lake (J). In this thesis, we only refer to data from Yingsu (C), Karday (E), Arghan (G), Korghan (I) and Tetima Lake (J). These transects are shown in Fig. 2.

Specifically, the groundwater depth data used for Yingsu, Karday and Arghan before the start of the water diversion were taken from Song et al. (2000). This work considers data from the five transects of Yingsu/C (60 km to the Daxihaizi Reservoir), Karday/E (110 km) and Arghan/G (190 km), Korghan/I (328 km) and Tetima Lake/J (346 km). For each of these three transects, groundwater data from different wells at 50-m, 150-m, 300-m, 500-m, 750-m, and 1050-m distances from the main river channel were provided. Due to unavailability of the latest groundwater data, only data from 2003 to 2011 were used for this thesis. The groundwater monitoring wells at the Tetima Lake were established in 2009. Therefore, we used the available data from 2009 to 2011 for the terminal lake Tetima.

#### 2.3.4 COLLECTION OF MICROCLIMATE DATA

Considering the distribution of vegetation and the differences of wind factors in space and time, four automatic weather stations (the WatchDog Spectrum 2000 series) were set up in Arghan in November 2011 as part of the SuMaRiO project (Fig. 2.10). The climatic parameters of wind speed, wind direction, soil surface temperature, solar radiation, precipitation and humidity (among others) were collected automatically on an hourly basis. The climate data used in this thesis were obtained from the four climate stations in the study area used in the SuMaRiO Project.



**Fig. 2-10** Location of the installed weather stations in the study area at Arghan. Map based on QuickBird image taken in 05. July 2005; Photo: Betz, 2013.

## 2.4 DATA PROCESSING

Hydrological data, meteorological data, terrestrial forest inventory data and QuickBird high resolution satellite data are used in this thesis. Data for volume and diverting time, as well as the duration of water releasing events and groundwater dynamics since the initiation of the project, have been supplied by the Tarim River Administration Bureau (TRAB). Groundwater variation before and after water diversion, as well as groundwater dynamics at the monitoring wells at different distances from the river, were processed with the Microsoft Excel 2010 software. Monthly and annual trend tests of groundwater depth variation were performed with the combination of packages “xts” and “Kendall” in the R programming language. The ArcGIS 10.0 software was used for buffer analysis, and the structure and distribution patterns of the main tree parameters, such as TH, DBH, CD, CH and CL, were plotted using R and the Origin Pro 8.5 software. Distribution maps of trees of different vitalities, young seedlings of different DBH, and of newly developed shoots and root suckers were obtained using ArcGIS in conjunction with a GIS database established by integrating QuickBird data with terrestrial field survey data. Fit statistics and model parameters for modelling the height-diameter relationship of *P. euphratica* trees were estimated using the R programming language (R Development Core Team 2013). The statistical differences of CD and CH data across the five random sampling plots and of temporal changes within these plots were tested using one-way ANOVA followed by Tukey`s post hoc test. Results were presented as mean values plus/minus the standard deviation. Box-whisker plots were constructed with the SPSS Statistics 19.0 software (IBM, Armonk, NY, USA) and R.

### 3 MONITORING THE HYDROLOGICAL RESPONSE TO RESTORATION MEASURES

As mentioned in the previous chapters, groundwater plays an important role in water supply for degraded riparian vegetation and the sustainable development of arid regions. The lower reaches of the Tarim River are extremely susceptible to water conflicts. Not only is groundwater the main source of floodplain agriculture, but it also maintains the regeneration of natural vegetation (Cui and Shao, 2005; Chen et al. 2010; Cao et al. 2012). Like other inland rivers worldwide, the lower reach of the Tarim River is a typical example of a highly degraded riparian ecosystem resulting from a long-term disconnection between hydrology and ecology. To counter the widespread eco-environmental consequences in the region, man-made restoration measures (i.e., water releases into the affected areas) have been implemented in recent years, starting in May 2000. One of the main goals of these attempts is to reconnect the riparian vegetation to its flood regime by replenishing and purifying the groundwater with the river runoff. In this chapter, an overview of the restoration measures implemented from 2000 to 2011 is given, and the corresponding spatial temporal groundwater responses as induced by these measures at the representative transect are discussed. Additionally, the contribution of these measures to the groundwater depth at our targeted research area at Arghan is examined in detail.

#### 3.1 OVERVIEW OF WATER RELEASES

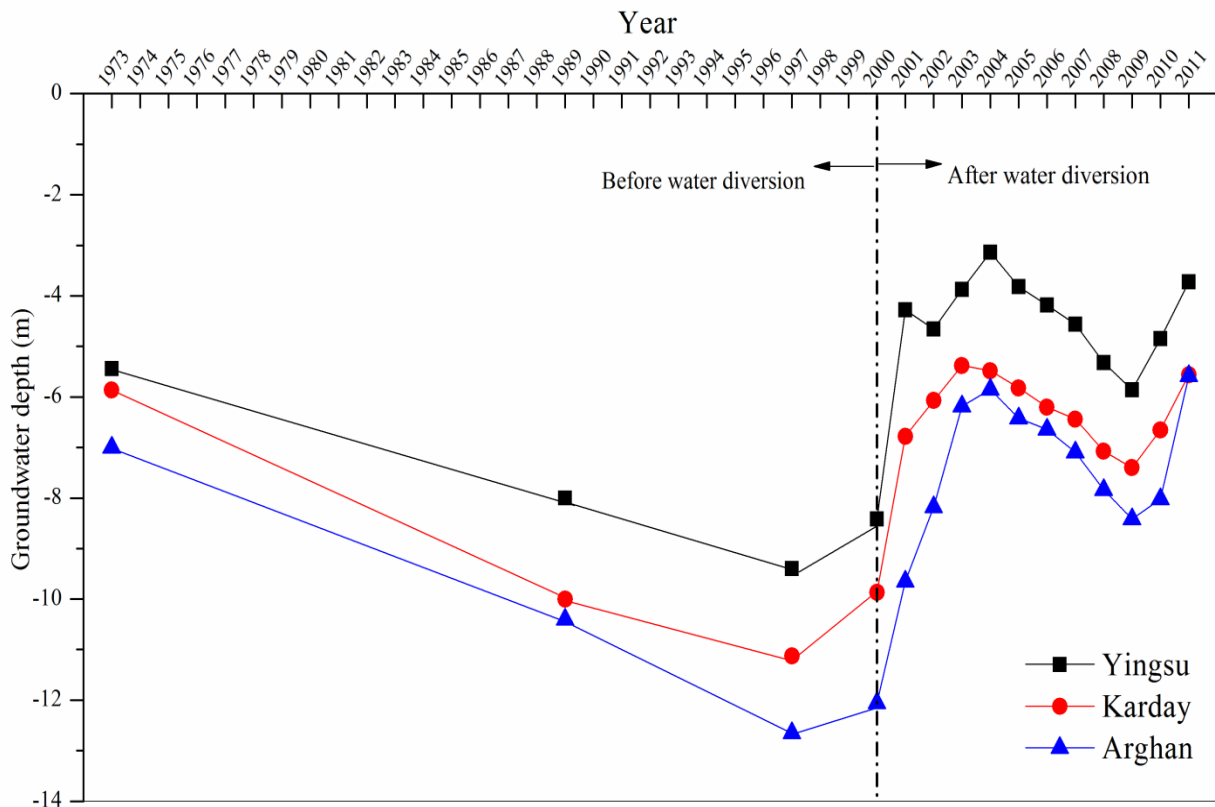
Water diversion to the Tarim's lower reaches is one of several large-scale ecological engineering projects in northwest China's (e.g., Integrated Management of the Tarim River Basin and the Heihe River Basin). The main objective of this project is to recharge the groundwater tables up to certain levels where natural vegetation can revitalize and severely damaged floodplain ecosystems under long-term water stress can be rehabilitated (Xu et al. 2008; Chen et al. 2011). Water is mainly diverted from the upper reaches of the Tarim River or from the Bagrash Lake and to the Daxihaizi reservoir, and continually delivered into Tetima Lake. The entire water flowing course is about 320 km long (Fig. 2.2). Until November 2011, water had been diverted twelve times at irregular intervals and over the course of 1289 days in eleven years, with a total volume of  $28.18 \times 10^8 \text{ m}^3$  diverted (Table 3.1). On seven occasions, water diversions reached Tetima Lake. As such, nearly 30 years of Tetima's desiccation, which had started in 1973, finally came to an end (Halik et al. 2006).

**Table 3-1** Ecological water diversions to the lower reaches of the Tarim River (data in this table provided by the TRAB).

Delivery	Starting time (d/m/y)	Ending time (d/m/y)	Duration (day)	Watering distance (km)	Water volume ( $\times 10^8 \text{ m}^3$ )	Section reached
1 <sup>st</sup>	14/05/2000	13/07/2000	61	106	0.99	Karday
2 <sup>nd</sup>	03/11/2000	14/02/2001	104	216	2.27	Arghan
3 <sup>rd</sup> (1 <sup>st</sup> period)	01/04/2001	06/07/2001	97	310	1.84	Korghan
3 <sup>rd</sup> (2 <sup>nd</sup> period)	12/09/2001	17/11/2001	67	357	1.98	Tetima
4 <sup>th</sup>	20/07/2002	10/11/2002	114	357	3.31	Tetima
5 <sup>th</sup> (1 <sup>st</sup> period)	03/03/2003	11/07/2003	131	357	3.40	Tetima
5 <sup>th</sup> (2 <sup>nd</sup> period)	04/08/2003	03/11/2003	90	357	2.85	Tetima
6 <sup>th</sup>	23/04/2004	22/06/2004	64	357	1.02	Tetima
7 <sup>th</sup> (1 <sup>st</sup> period)	18/04/2005	07/06/2005	49	230	0.52	Arghan
7 <sup>th</sup> (2 <sup>nd</sup> period)	30/08/2005	02/11/2005	65	350	2.30	Tetima
8 <sup>th</sup>	25/09/2006	26/11/2006	62	227	1.96	Korghan
9 <sup>th</sup>	10/10/2007	20/11/2007	41	60	0.14	Yingsu
10 <sup>th</sup>	25/11/2009	31/12/2009	37	105	0.11	Karday
11 <sup>th</sup>	20/06/2010	15/11/2010	145	357	3.76	Tetima
12 <sup>th</sup> (1 <sup>st</sup> period)	07/01/2011	25/01/2011	19	357	0.37	Tetima
12 <sup>th</sup> (2 <sup>nd</sup> period)	25/06/2011	23/11/2011	151	357	1.36	Tetima

### 3.2 DYNAMICS OF THE GROUNDWATER DEPTH BEFORE AND AFTER WATER DIVERSION

The water course downstream of the Daxihaizi Reservoir was desiccated before the implementation of the water diversion project in 2000, and so the groundwater in this region had not received any recharge from the river surface water for nearly 30 years. As a result, the groundwater table dropped and natural vegetation degraded accordingly. The groundwater depth at the Yingsu, Karday and Arghan transects declined to a minimum depth of 9-12 m, thus inhibiting any normal development of the floodplain forests. Since the water diversion in 2000, the groundwater depth close to the riverbed has started to rise again (Fig. 3.1). After a second water diversion in 2001, the groundwater depth at Yingsu has recovered significantly from 9.4 m in 1997 to 4.28 m in 2001. Karday and Arghan have also shown remarkable responses to water diversion practices (Fig. 3.1).



**Fig. 3-1** Groundwater depth before and after water diversion (annual average groundwater depth within a 300 m distance of the river channel). Source: data for the years 1973, 1989 and 1997 obtained from (Song et al. 2000), data for the period after water diversion (from May 2000) provided by TRAB.

### 3.3 SPATIAL AND TEMPORAL CHANGES IN GROUNDWATER DEPTH

Since 2000, when the first water diversion for floodplain restoration had been implemented, groundwater levels have responded with different degrees of recovery (Hou et al. 2007b). Groundwater variation analyses from 2003 to 2011 at the transects of Yingsu, Karday and Arghan, Korghan and the terminal lake Tetima showed that there were significant spatial and temporal differences between the impact intensity of water diversion on the groundwater recharge. Groundwater variation for Yingsu showed that the average groundwater depth at the monitoring well at 50 m from the river reached 0.58 m during the fifth water diversion (Fig. 3.2). Groundwater changes at different distances from the river showed various responses. Groundwater depth at the monitoring well at 150 m from the river had risen 3.30 m after the sixth (first period; Table 3.1) water diversion had been completed. During the sixth (water volume:  $3.32 \times 10^8 \text{ m}^3$ ; flooding time: 110 days) water diversion, the groundwater depths at all wells at 50-m, 150-m, 300-m, 500-m, 750-m and 1050-m distances from the river-flow channel had risen to their highest levels. This might be a result of extended releasing duration and water volume.

At the Karday transect (Fig. 3.3), the groundwater table also experienced an increase to various degrees during each water diversion period, but the change was less significant when compared to the Yingsu transect. This might be related to the distance of each transect from the Daxihaizi Reservoir, because transects close to the reservoir receive longer river runoff and a higher water volume. The groundwater depth at Well E1, at 50 m from the river,

fluctuated between 3.5 m and 5 m until the seventh water diversion. After the seventh water diversion, there was a declining trend in the groundwater table at all wells at 50 m, 150 m, 300 m, 500 m, 750 m, and 1050 m from the river.

At the Arghan transect (Fig. 3.4), the groundwater response to the water diversion was almost identical to that at the Karday transect. From Fig 3.4, the groundwater depth at the closest well to the river is below 5 m, a depth considered as a threshold for regeneration of the floodplain forests (Song et al. 2000). At the same time, there was a rise of the water table at the nearest well (50 m) from river channel for each transect. Along the Yingsu transect the groundwater depth at Karday and Arghan is well below 5 m. These are levels unlikely to support normal growth of floodplain forests. Floodplain forests growing farthest from the river course might still be suffering from water stress.

Clear variation patterns in groundwater depth at all wells in the Korghan transect were also observed (Fig. 3.5). During the third ecological flooding, the groundwater depth at the wells at 50 m (I1) and 150 m (I2) increased significantly compared to the groundwater depth at other wells. The groundwater depths of all wells had been under 5 m and had never reached the 5-m mark until the tenth water diversion, with the exception of the groundwater depth at a 50-m distance from the river during the third water diversion. A rise in groundwater can still be observed during the time of the water diversion in this transect, but is not very clear. During the tenth ecological water diversion, the groundwater depth at wells I1/50-m and I2/150-m reached 3.00 m.

For the terminal lake Tetima, hydrological data for the period from 2009 to 2011 was available. Fig. 3.6 shows that the groundwater depth was above 4.00 m until the start of the water diversion in 2010. With the implementation of the water diversion in 2010, the groundwater depth increased steadily and reached its highest levels (above the surface level) before the completion of twelfth water diversion in 2011.

Based on the data above, the high variability in the dynamics of groundwater depth appears to be highly correlated with the ecological diversion events. Apart from some time lag, the groundwater depths at all wells had fairly clear reactions to the water diversion practices, with higher or lower variations in the groundwater depth seemingly associated with the volume and duration of the diverted water. Therefore, achieving an advisable water diversion scheme that is able to stabilize groundwater depth is urgently needed.



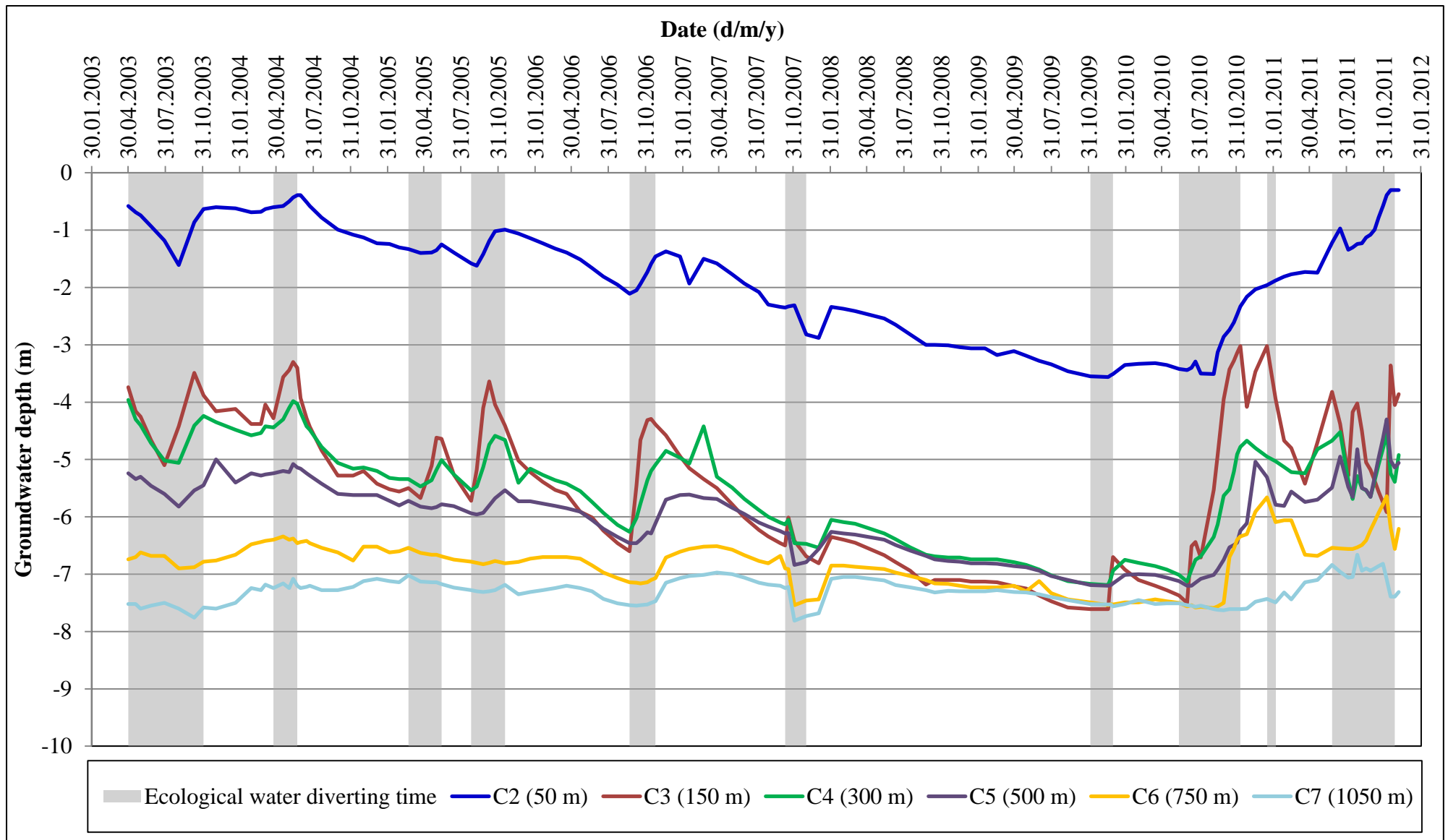


Fig. 3-2 Variations in groundwater depth at different distances to the river channel at the Yingsu transect (Source: TRAB).

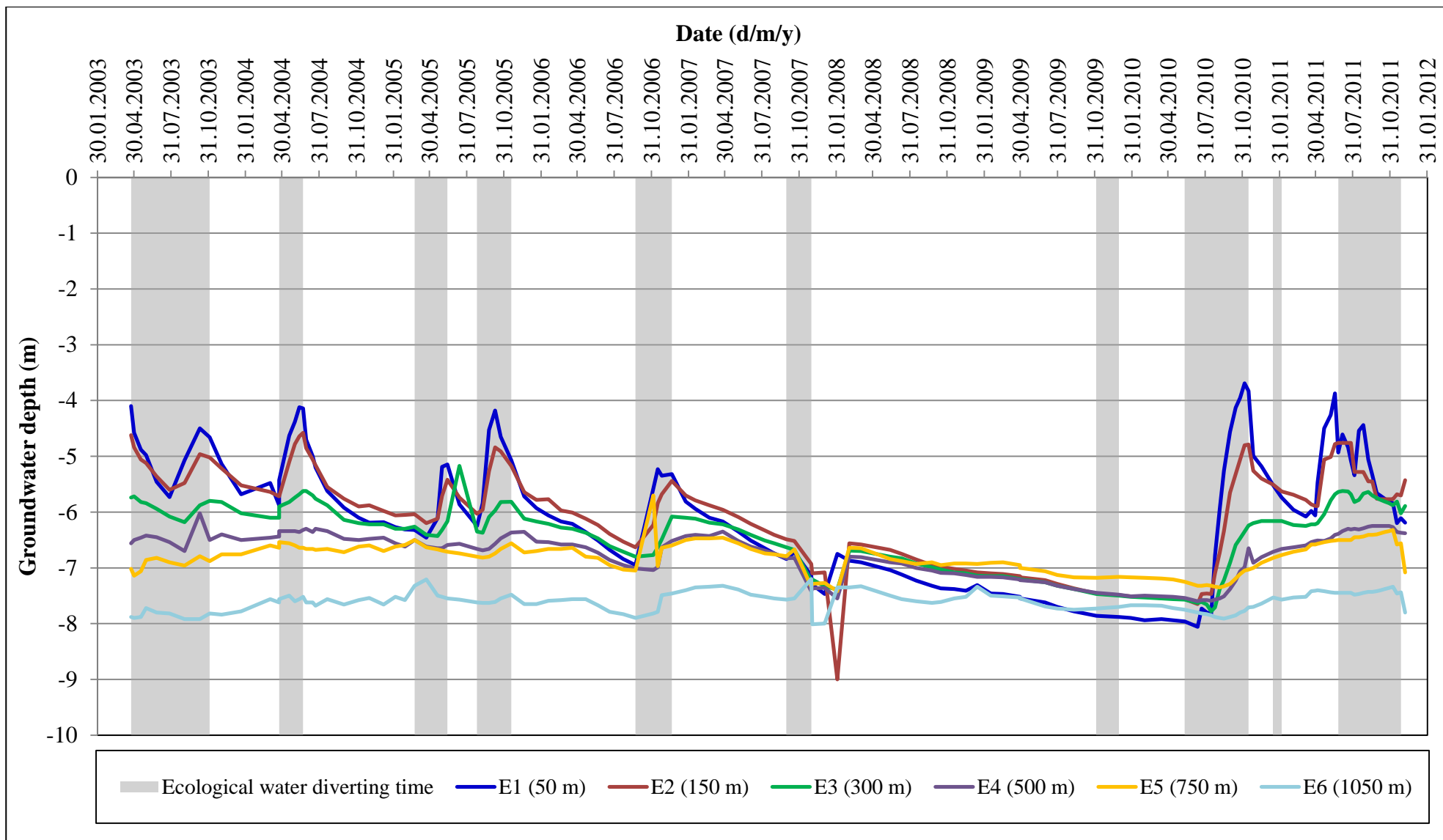


Fig. 3-3 Variations in groundwater depth at different distances to the river channel at the Karday transect (Source: TRAB).

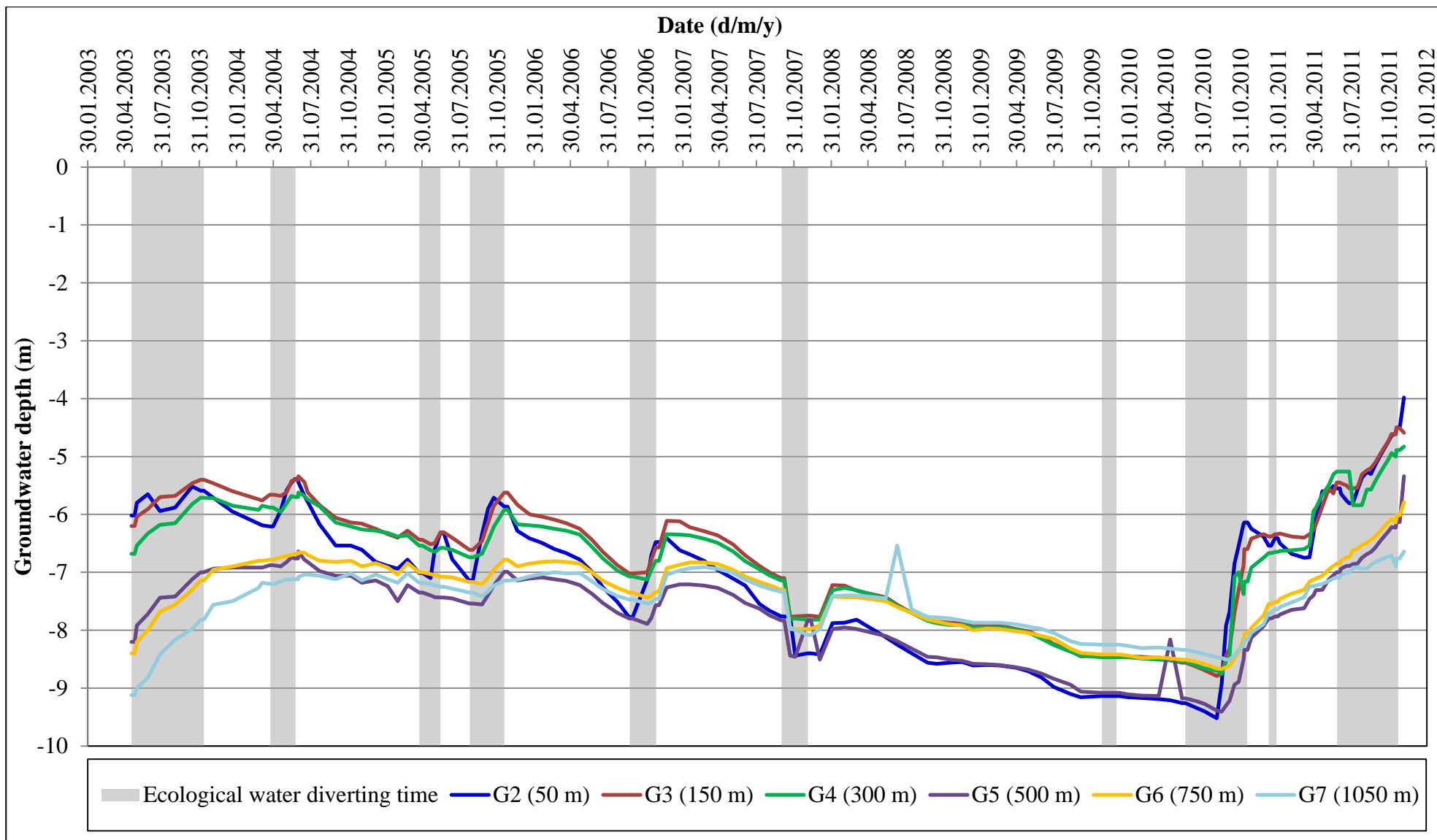


Fig. 3-4 Variations in groundwater depth at different distances to the river channel at the Arghan transect (Source: TRAB).

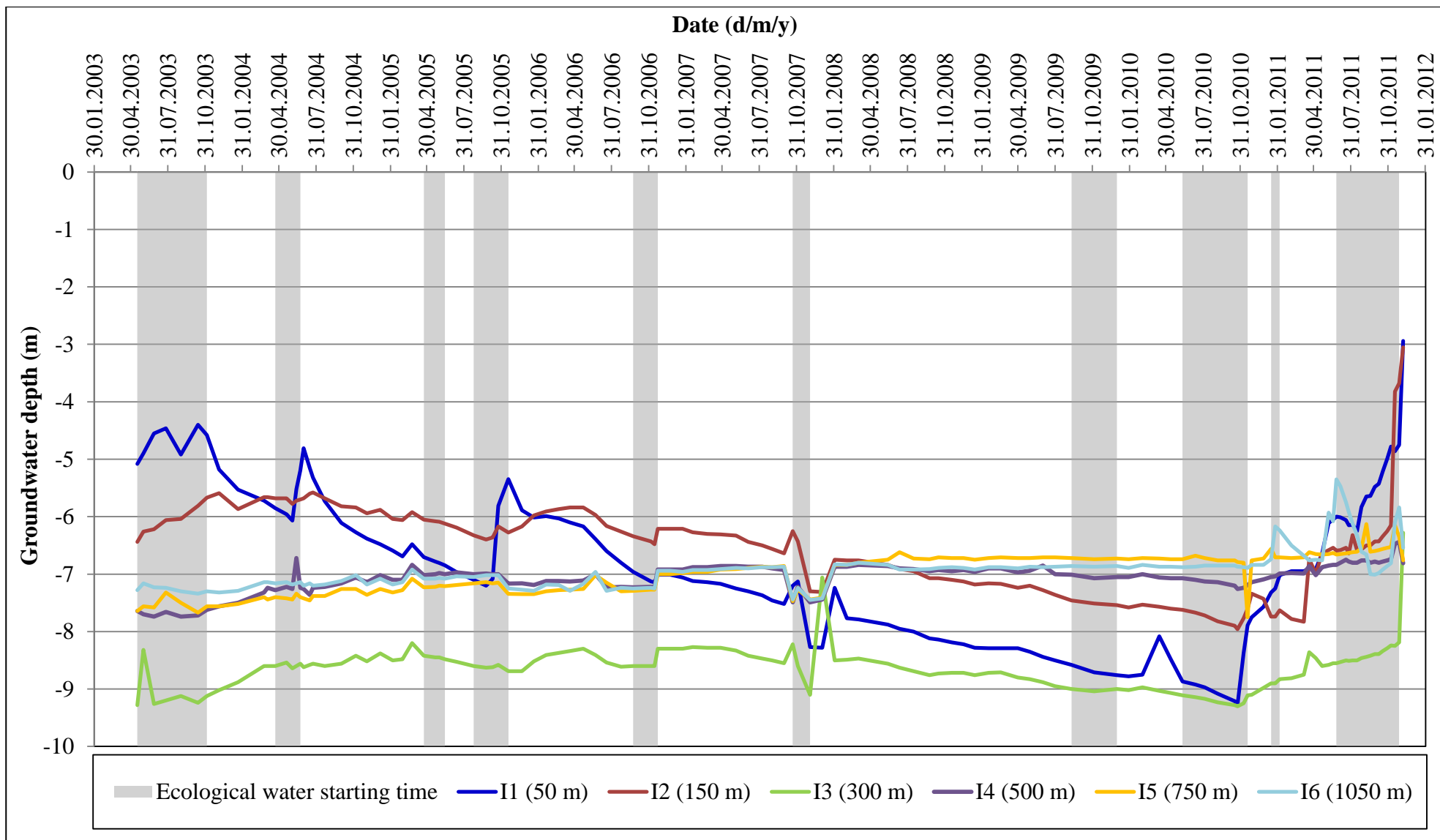
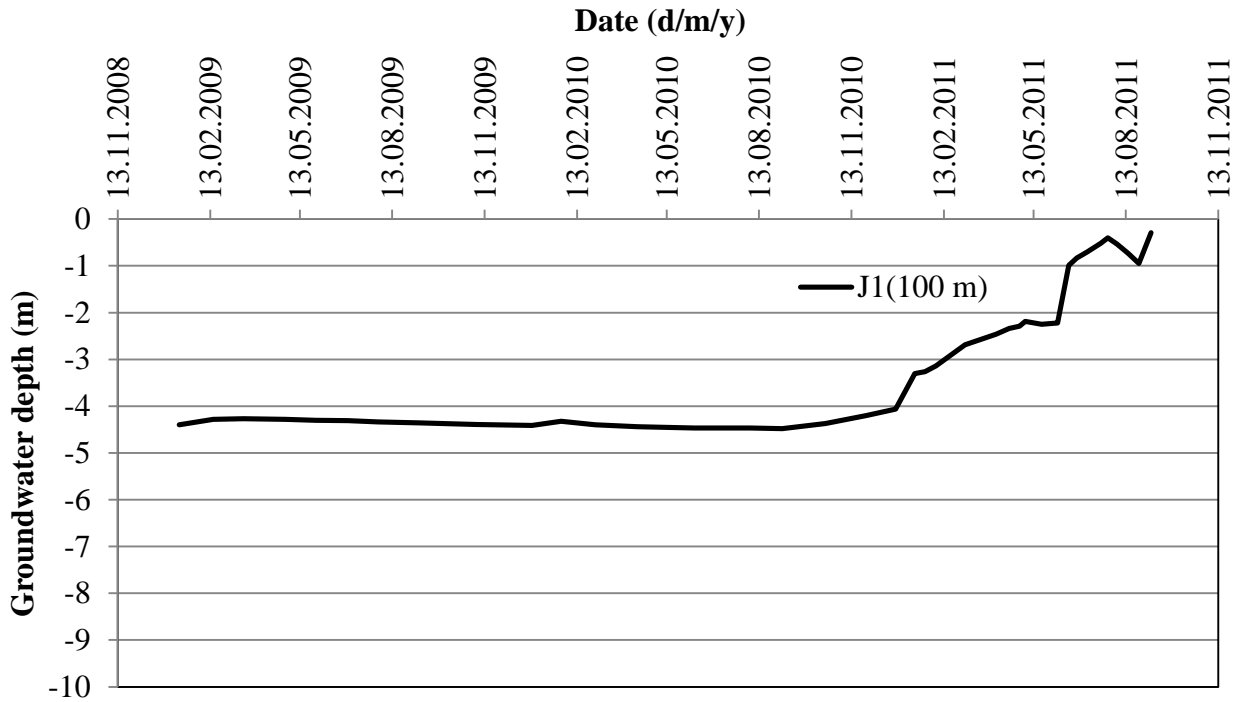


Fig. 3-5 Variations in groundwater depth at different distances to the river channel at the Korghan transect (Source: TRAB)



**Fig. 3-6** Variations in groundwater depth at 100 m distance to the river channel at the terminal lake Tetima. The groundwater depth has been measured since January 2009, with data from 2003 to 2009 not available (Source: TRAB).

### 3.4 MONTHLY AND ANNUAL TREND TESTS OF GROUNDWATER DEPTH VARIATION

The Mann-Kendall test is a non-parametric approach that has been widely used for the detection of trends in different fields of research, including hydrology and climatology (Ampitiyawatta and Guo, 2009). It is used for identifying trends in time series data, with each data value compared to all subsequent data values. The initial value,  $S$ , is assumed to be 0 (no trend). If a data value from a later time period is larger than a data value from an earlier time period,  $S$  is incremented by 1. If the data value from a later time period is lower than a data value from an earlier time period,  $S$  is decremented by 1. The net result of all such increments and decrements yield the final value of  $S$ .

The Mann-Kendall statistic ( $S$ ) is given by

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^n \text{sign}(x_j - x_k),$$

where

$$\text{sign}(\theta) = \begin{cases} 1, & \theta > 0 \\ 0, & \theta = 0 \\ -1, & \theta < 0. \end{cases}$$

The variance statistic is given as

$$Var(S) = \frac{n(n-1)(2n+5) - \sum_t^n t(t-1)(2t+5)}{18},$$

where  $t$  is the extent of any given time. Then, the test statistic,  $Z$ , is given below:

$$Z = \begin{cases} \frac{S-1}{\sqrt{Var(S)}} & S > 0 \\ 0 & S = 0 \\ \frac{S-1}{\sqrt{Var(S)}} & S < 0. \end{cases}$$

The presence of a statistically significant trend is evaluated using the  $Z$  value. A positive (resp., negative) value of  $Z$  indicates an upward (resp., downward) trend. The  $Z$  statistic has a normal distribution to test for either upward or downward trends at an  $\alpha$  level of significance (usually 5 % with  $Z_{0.025}=1.96$ ). The null hypothesis,  $H_0$ , is rejected if the absolute value of  $Z$  is greater than  $Z_{1-\alpha/2}$  (rejected  $H_0: |Z| > Z_{1-\alpha/2}$ ) where  $Z_{1-\alpha/2}$  is the standard normal deviate and  $\alpha$  is the significance level for the test. The probability value ( $p$ -value) from a two-tailed test using the  $Z$  value also can be used to test the significance of the trend. If the  $p$ -value is greater than  $\alpha$ , the null hypothesis ( $H_0$ : there is no trend in data series) is not rejected.

Table 3.1 shows that the annual average diverted water volume was  $2.34 \times 10^8 \text{ m}^3$ . The maximum water volume of  $6.25 \times 10^8 \text{ m}^3$  was diverted during the fifth ecological water diversion (the first and second diversion periods of 2003), with a duration of 221 days. The minimum was observed during the tenth water diversion, with a total volume of  $0.10 \times 10^8 \text{ m}^3$ , with a duration of only 37 days. The differences between the total volumes and the durations of the water diversions from 2000 to 2011 are very obvious. Fig. 3.4 indicates that the responses of all groundwater wells at different distances from the river during the fifth water diversion (2003) were very significant at Arghan. By contrast, during the tenth water diversion in 2009, the groundwater depths of all the wells at Arghan declined to their lowest levels (ranging from 8 m to 9 m). It is interesting to note that the magnitude of the decrease of the groundwater depth at the G2 well (at a 50-m distance from the river) was higher than at any other well. Clearly, variations in the groundwater depths are strongly correlated with the volume and the duration of the water diversions. There were also many ups and downs in fluctuation pattern. Therefore, to determine the trend in the available time series data of the groundwater depth for Arghan, the Mann-Kendall statistical trend test was applied to explore the tendency of groundwater depth changes at the long-term monitoring plots in the study area at Arghan over the course of 9 years from 2003 to 2011. Table 3.2 shows that value of  $Z$  for the different wells ranges from -2.07 to 5.99, with the fluctuation of groundwater depth at all wells exhibiting a statistically significant declining trend for the entire period of 2003-2011. In accordance with the data distribution, the entire data set was split into two categories - one for the period of 2003-2009, and another for 2010-2011. The Mann-Kendall test analyses for the first period (2003-2009) revealed that there was a significant declining trend (dropping of groundwater table,  $\downarrow$ ) in mean monthly and annually groundwater depths, which might be associated with insufficient volume and duration of the water diversion between the 5th and 10th diversions. This follows from the fact that during this time (from 2004 to 2009, 6 years),

only  $6.02 \times 10^8 \text{ m}^3$  of water was diverted into the lower reaches of Tarim River, accounting for about 20 % of the total volume over the 9 years (Tables 8 and 9). By contrast, the groundwater depths at all wells for the period from January 2010 to December 2011 showed a significantly increasing trend (rising of groundwater table,  $\uparrow$ ). This is likely because the amount of water ( $5.49 \times 10^8 \text{ m}^3$ ) diverted to the lower reaches of the Tarim River from 2010 to 2011 was the same as the total diverted in the years 2004-2009, thus suggesting that groundwater fluctuation is highly dependent on water volume and the duration of the diversion. Therefore, the minimal amount of ecological water sufficient to guarantee favorable groundwater levels for the normal growth of vegetation should be allocated and diverted into the affected region.

**Table 3-2** Mann-Kendall statistical trend test results for the mean monthly and annual groundwater depths at different distances from the river at the Arghan transect.

Well ID/Distance	Data set from January 2003 to December 2011					
	S	Var(S)	Z	P value	Trend	significance
G2/50 m	-1691	96735.66	-5.434	0.0000006	declining	significant
G3/150 m	-1865	96726.34	-5.993	0.00000002	declining	significant
G4/300 m	-1854	96728.00	-5.957	0.00000002	declining	significant
G5/500 m	-1746	96730.66	-5.611	0.0000002	declining	significant
G6/750 m	-1440	96720.00	-4.627	0.0000371	declining	significant
G7/1050 m	-647	96715.00	-2.077	0.037778	declining	significant
Well ID/Distance	Data set from January 2003 to December 2009					
	S	Var(S)	Z	P value	Trend	significance
G2/50 m	-2011	42311.00	-9,772	2.22e-16	declining	significant
G3/150 m	-1976	42305.33	-9,602	2.22e-16	declining	significant
G4/300 m	-963	42304.33	-4,677	2.22e-16	declining	significant
G5/500 m	-1721	42305.00	-8,362	2.22e-16	declining	significant
G6/750 m	-1295	42294.33	-6,292	3.1327e-10	declining	significant
G7/1050 m	-521	42293.00	-2,529	0.011454	declining	significant
Well ID/Distance	Data set from January 2010 to December 2011					
	S	Var(S)	Z	P value	Trend	significance
G2/50 m	179	1433.667	0,149	0.0000026	rising	significant
G3/150 m	187	1433.667	0,155	0.00000095	rising	significant
G4/300 m	187	1433.667	0,155	0.00000095	rising	significant
G5/500 m	199	1433.667	0,165	0.0000012	rising	significant
G6/750 m	193	1433.667	0,160	0.00000036	rising	significant
G7/1050 m	183	1433.667	0,152	0.0000015	rising	significant

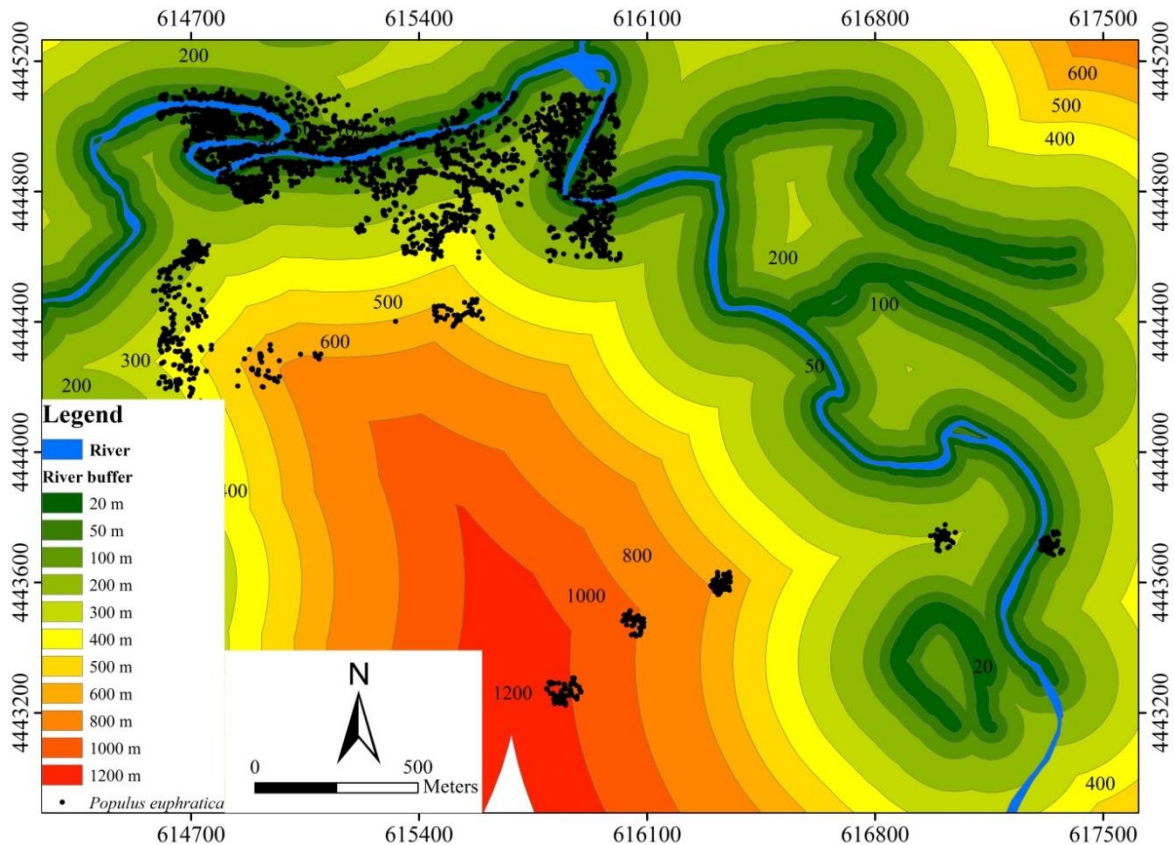
\*Note: declining: a dropping trend of groundwater table; rising: a rising trend of groundwater table.

## 4 STRUCTURE, DISTRIBUTION AND CURRENT STATUS OF *P. EUPHRATICA* RIPARIAN FORESTS

Quantifying the status quo of forest ecosystems and estimating their future development are primarily needed for sustainable forest management and forest policy decisions at different scales - i.e., at the national, regional and local levels. For the severely degraded Tugai riparian forest ecosystem in the lower reaches of the Tarim River, conservation and revitalization of the existing forests is a top priority and should be systematically monitored to provide a scientific support for forest managers and decision makers, as well as to improve environmental awareness of the importance of this ecosystem with regard to the long-term sustainability of the region. As mentioned in the previous chapters, the rising water consumption in the upper and middle reaches, together with massive hydro-technical interventions in the development of uncultivated land for cotton farming, especially during the last decades, have led to widespread destruction of the natural ecosystems. This is the case particularly in the lower reaches of the river, where 320 km of the floodplain forests are either highly degraded or dead. Since the year 2000, the Chinese government has made efforts to restore these ecosystems and has conducted man-made water diversion projects in the affected area. The initialization of these recovery measures triggered scientific interest among scholars and highlighted the need for an efficient and extensive long-term monitoring network for the affected ecosystem. In order to evaluate the effectiveness of the project scientifically, one permanent sampling site with a total area of 100 ha and one random sampling site with five 50-m radius circle plots at different hydrological conditions were established for the purpose of long-term monitoring (detailed information regarding both of the sampling sites and work being carried out is available in Chapter 2). In the present chapter, stand structure, size, vitality and spatial distribution of *P. euphratica* trees are analyzed using extensive ground truth forest inventory data obtained from the permanent sampling plots in the study area.

The investigation plots were buffered into 11 sub-transects (0-20 m, 20-50 m, 50-100 m, 100-200 m, 200-300 m, 300-400 m, 400-500 m, 500-600 m, 600-800 m, 800-1000 m, >1000 m) based on their distances from the river (Fig. 4.1). All transects extend towards both sides of the river, up until the border of the investigated plots where the *P. euphratica* trees were sampled. The furthest tree was found at a 1083.9-m distance from the river.





**Fig. 4-1** Map showing the different buffers from the river in the investigation plots at Arghan.

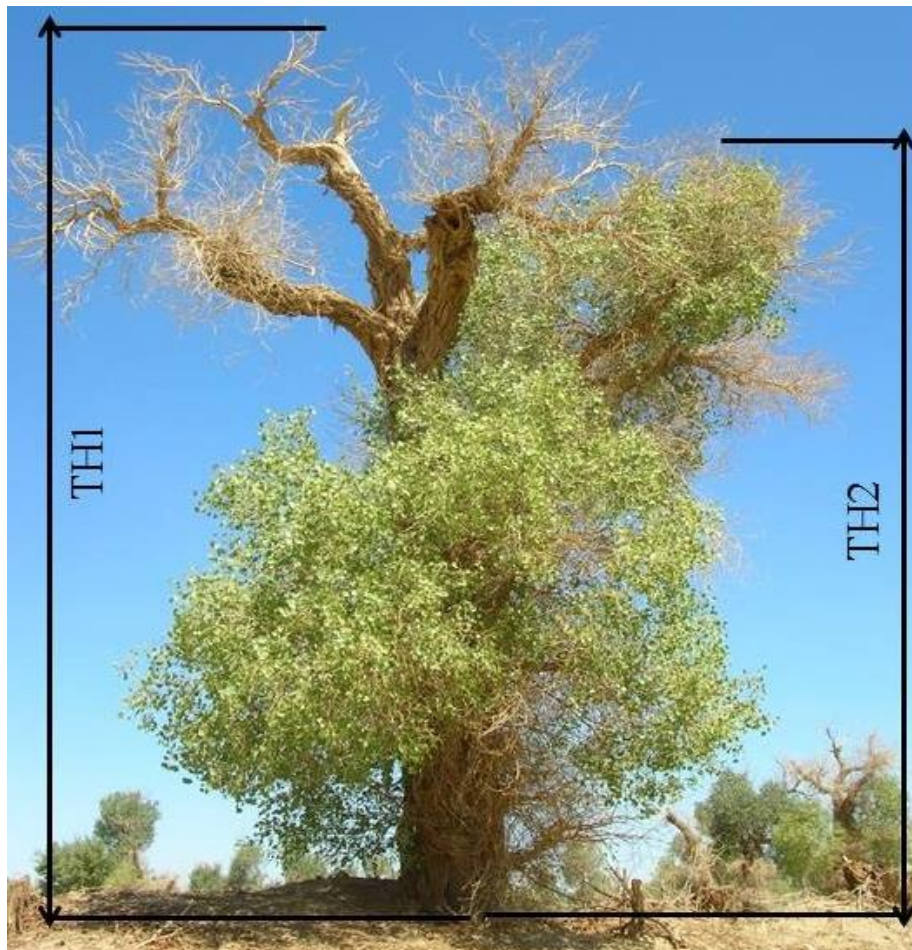
## 4.1 TREE PARAMETERS

### 4.1.1 TREE HEIGHT (TH)

Tree height (TH) is defined as the distance between the top and the base of the tree. In forestry science, the measurement of tree height provides an important parameter for calculating biomass production and for assessing the productivity capacity of the site. For example, based on the tree height distribution it is possible to estimate how rapidly the trees will grow at a certain site. Due to the severe water shortage in our study area, there is a dieback phenomenon within stands. The tops of the majority of the trees have died. To describe the individual differences in detail, two tree height parameters were measured - one being the total tree height (TH1), defined as the vertical distance from the base of tree to the (dead) tree top, and one being the green tree height (TH2), defined as the vertical distance between the base of the tree and the green point of the tree (Fig. 4.2).

Both TH1 and TH2 were analyzed for different distances from the river (P1-P11), with the results given in Figs. 4.3-4.6. The overall tree height ranged from 0.60 m to 19.00 m in the study area. A maximum TH1 value of 19.00 m was found on the P1 transect (within a 0-20-m distance from the river) and the P4 transect (within 100 m -200 m distance from the river). A maximum TH2 value of 19.00 m was found on the P4 transect (within a 100-200-m distance from the river). On average, the minimum and maximum values of both tree height parameters (TH1 and TH2) decreased with increasing distance from the river (from P1 to

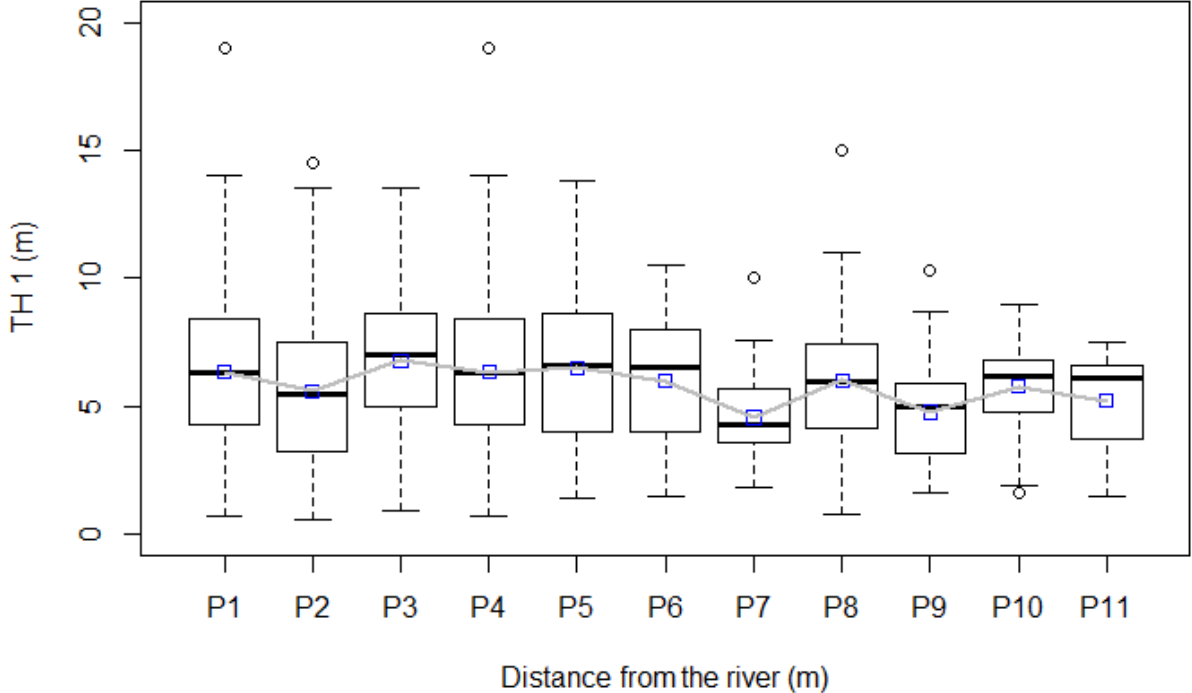
P11). Within a 0- 300m distance from the river, the minimum TH1 and TH2 values ranged from 0.60 m to 0.90 m, while the maximum TH1 and TH2 values ranged from 13.50 m to 19.00 m, suggesting that the trees distributed in this area are under development. There were many young trees distributed in these transects. At distances of 300 m or greater, the minimum values of TH1 and TH2 showed an increase (ranging from 0.80 m to 1.80 m), while the maximum values of TH1 and TH2 showed a decrease (ranging from 7.50 m to 13.80 m).



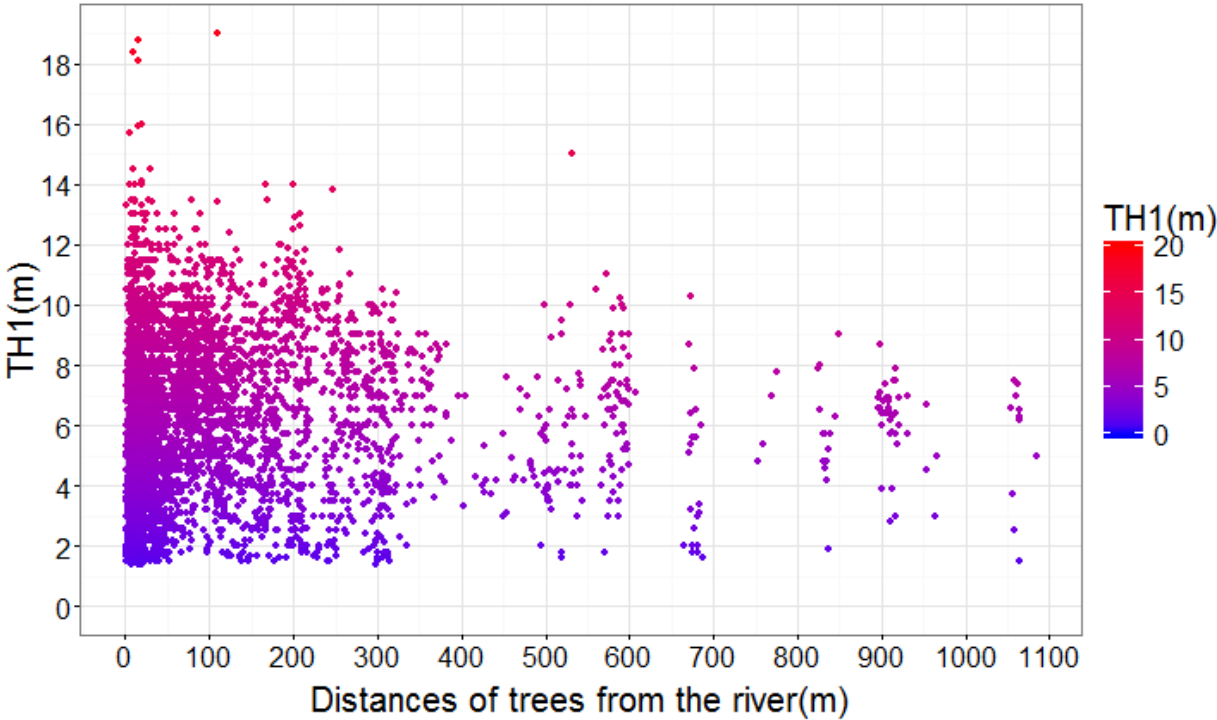
**Fig. 4-2** TH1 and TH2 parameters of a *P. euphratica* tree.

The green tree height parameter (TH2) was analyzed by grouping the data into seven classes (0 m, 0-1.5 m, 1.5-3.0 m, 3.0-6.0 m, 6.0 m-9.0 m, 9.0-12.0 m and greater than 12 m). The number of trees decreased as distance from the river increased, but trees belonging to different height classes displayed different spatial distribution characteristics. At the P1 transect, a total of 170 trees with a green height of 0 m were observed. Most of them had already lost their green branches or had become dead trees. The number of trees belonging to the height class of 0-1.5 m decreased as one went from P1 to P11, with the main concentration being on the P1 transect (59 trees). Trees with the height classes of 3.0-6.0 m and 6.0-9.0 m were distributed relatively uniformly all along the transect, when compared with the other height classes. A total number of 1607 trees belonging to this class were monitored, which accounted for nearly 60 % of total trees investigated in the study area, indicating that middle-aged trees were dominantly distributed in all transects. The number of trees in the height class of 9-12 m decreased sharply after the P5 transect. The majority of the tallest trees (above 12 m) were

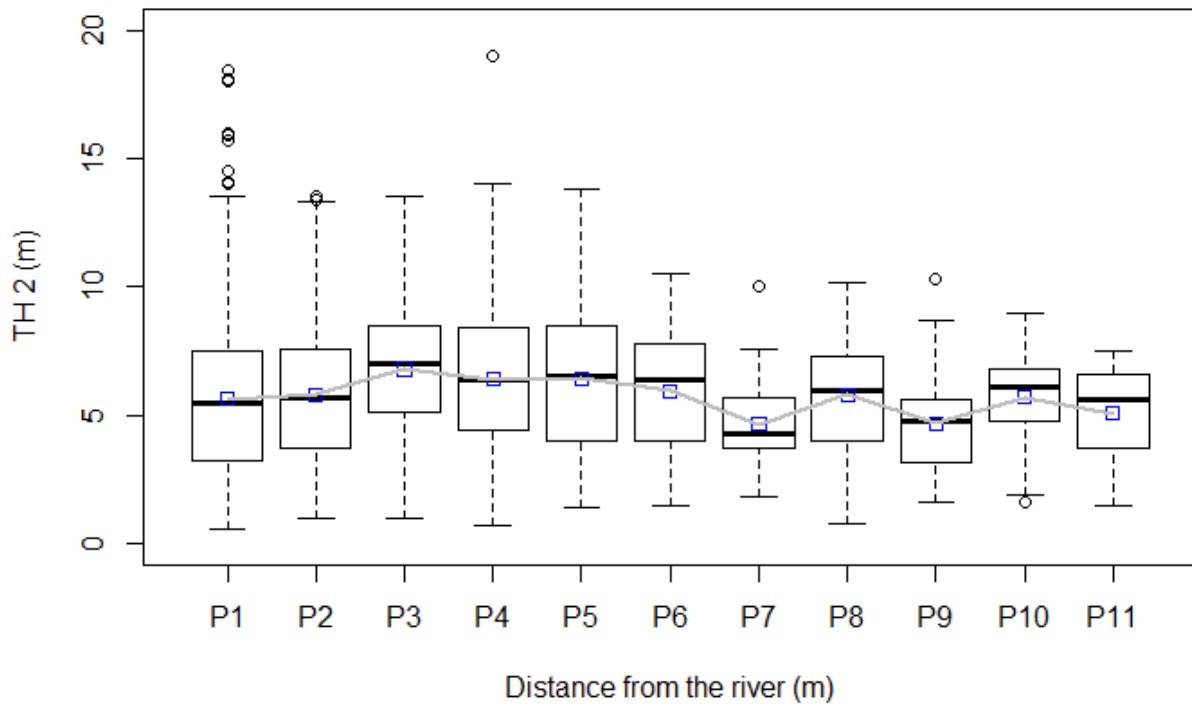
found on the P1 transect, and exhibited a clear decreasing trend as the distance from the river increased. A total of 61 trees with a height greater than 12 m were found in the study area, accounting for only 1.2 % of all investigated trees. All in all, the distributions of the height classes showed that the height in the P1, P2, P3 and P4 transects were close to normally distributed. Trees in the other transect demonstrated irregular distribution patterns (Fig. 4.7).



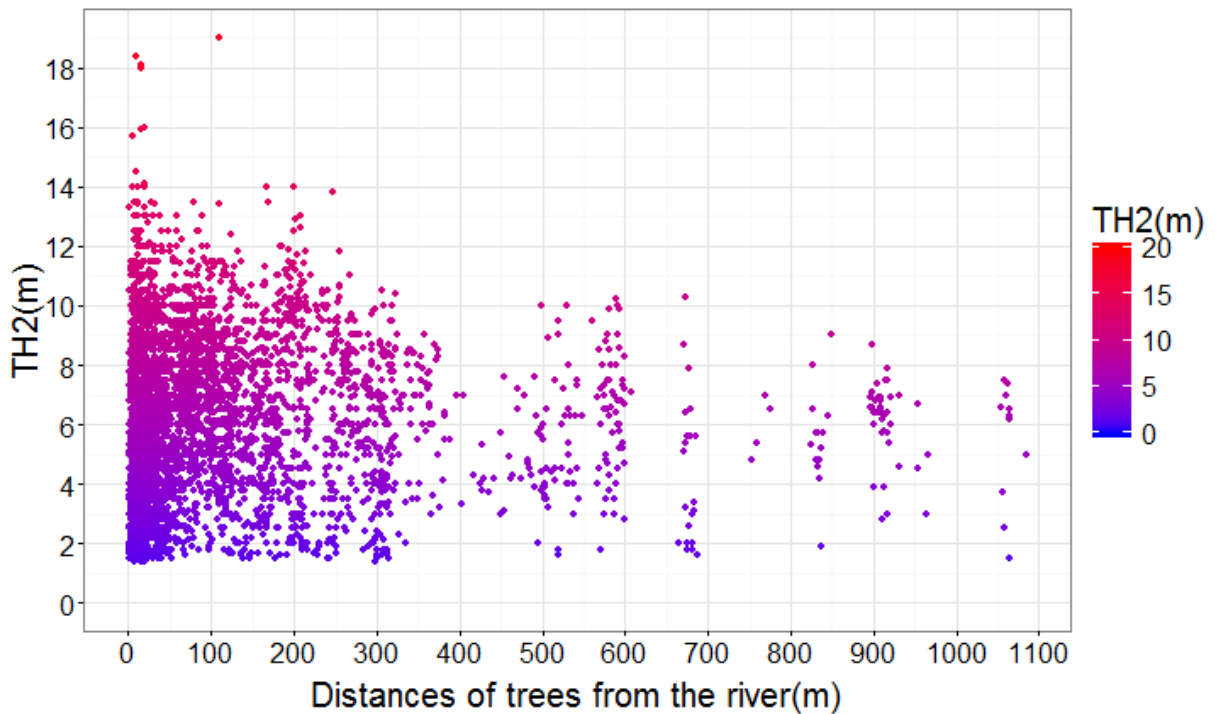
**Fig. 4-3** Boxplot showing the TH1 values of *P. euphratica* along the water gradient. Bold lines depict median values, the black boxes denote the 25–75 % quantile ranges, blue squares denote the mean value, circles represent outliers, and the whiskers are the maximum and minimum values.



**Fig. 4-4** Spatial distribution pattern of TH1 at different distances from the river course.



**Fig. 4-5** Boxplot showing the TH 2 values of *P. euphratica* along the water gradient. Bold lines depict median values, the black boxes denote the 25–75 % quantile ranges, blue squares denote the mean values, circles represent outliers, and the whiskers are the maximum and minimum values.



**Fig. 4-6** Spatial distribution pattern of TH2 at different distances from the river course.

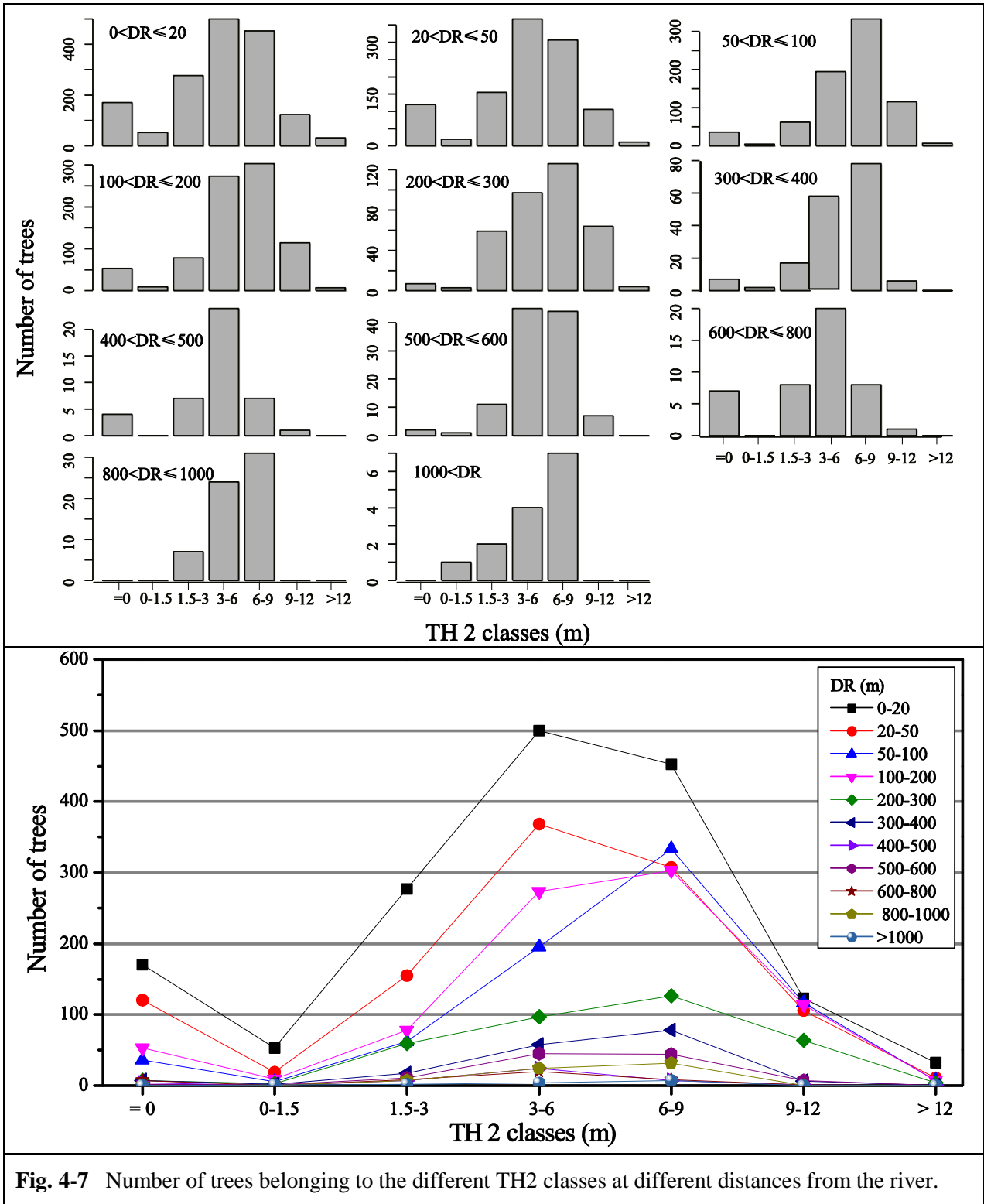


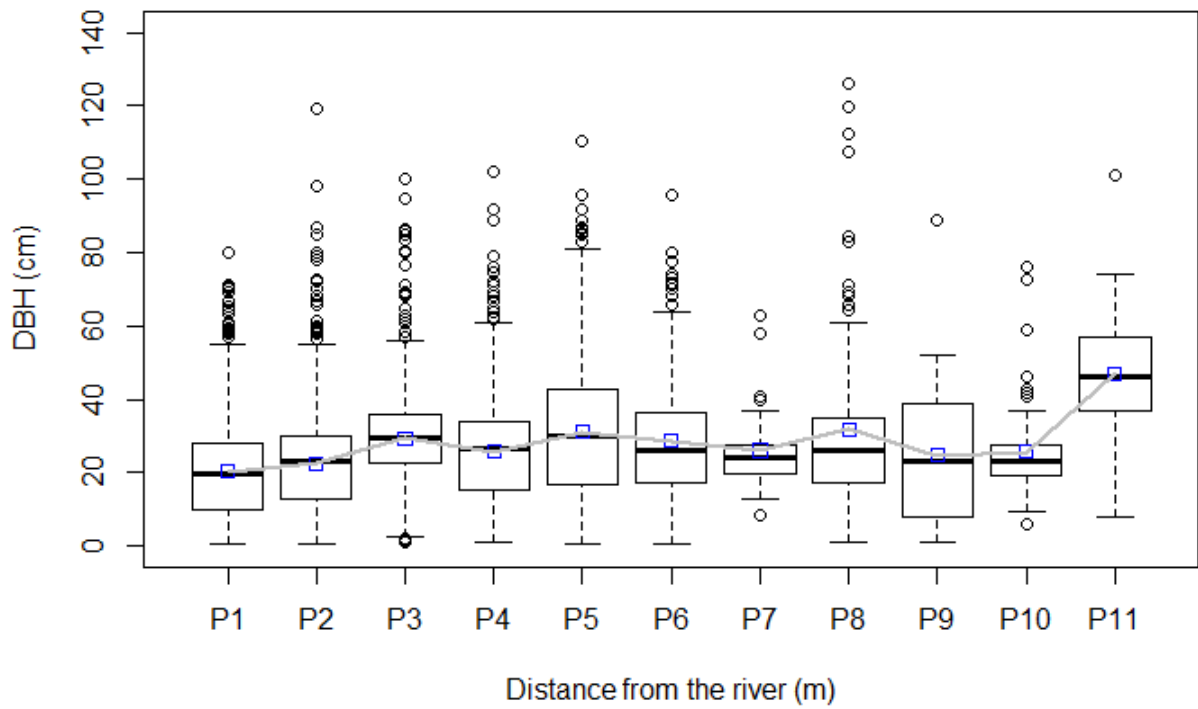
Fig. 4-7 Number of trees belonging to the different TH2 classes at different distances from the river.

#### 4.1.2 DIAMETER AT BREAST HEIGHT (DBH)

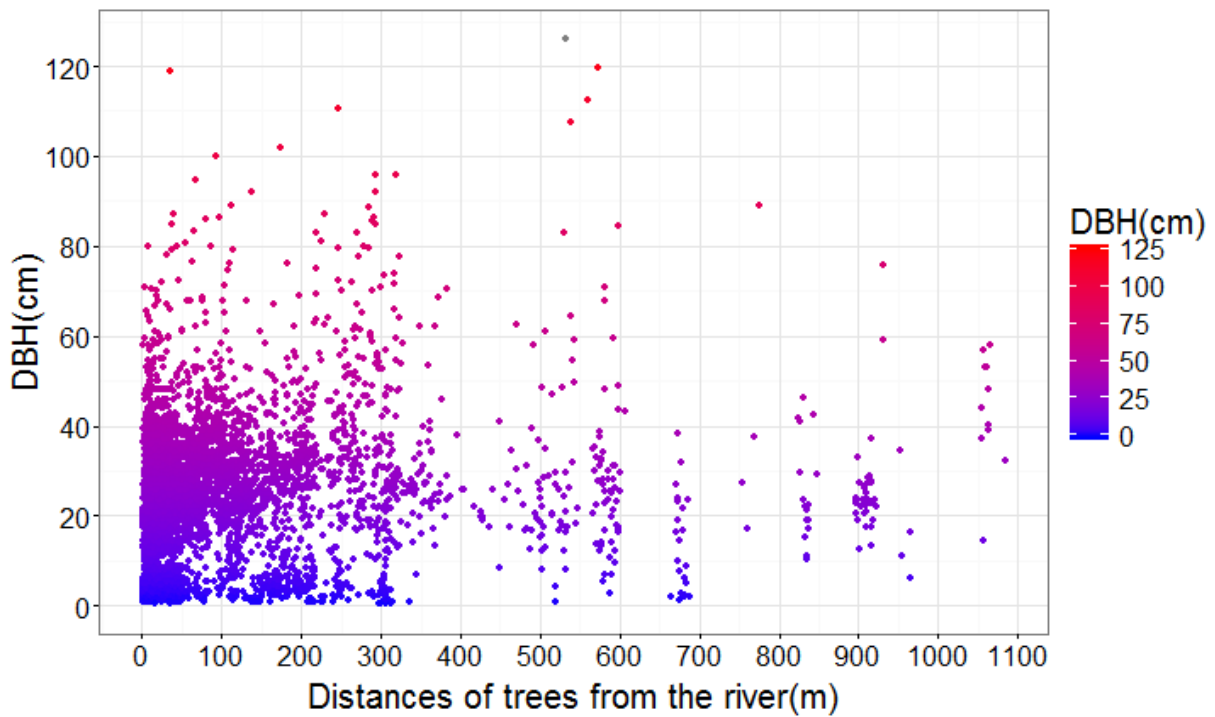
Diameter at breast height / DBH is measured at a height of 1.3 m from the ground. As the result of the restoration project, many of the young trees observed near to the river or around the water were logged lowland. Most of those trees have not grown enough to reach the breast height. Therefore, only the stem diameters were recorded for these trees. DBH is a key parameter that, like TH, correlates with many other forest attributes. For example, it is difficult to measure some attributes, like timber volume or the biomasses of the individual trees or stands. However, we can estimate those attributes by using DBH data together with allometric functions.

Figs. 4.8 and 4.9 show the DBH values of *P. euphratica* for different distance zones from the river. The overall DBH ranged between 0.50 cm and 126.00 cm. The maximum DBH value of 126.00 cm was recorded on the P8 transect (within a 500 -600-m distance from the river). A minimum DBH value of 0.50 cm was observed on the P1, P2, P5, and P6 transects. Relatively large minimum values of 6.00 cm, 8.00 cm and 8.30 cm were detected on the P10, P11 and P7 transects, respectively. These transects are mainly located where the groundwater depth is not favorable for the normal development of riparian forests in the study area. There was no clear trend of DBH along the water gradient, but the median and mean DBH values did tend to increase with increasing distance from the river (Figs. 4.8 4.9). Trees with diameters of above 30 cm were mainly concentrated within a 300-m distance of the river.

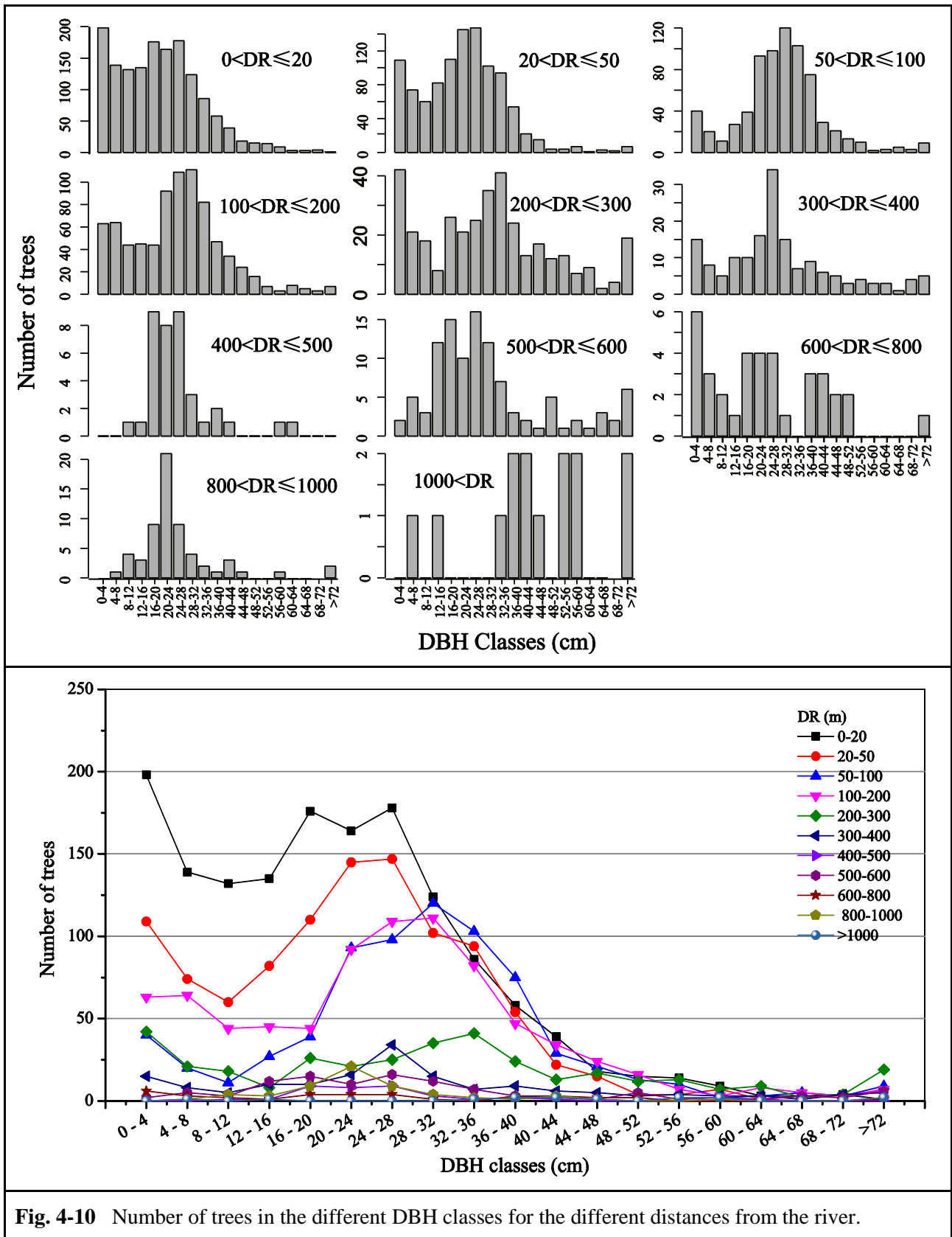
The number of trees in each DBH class (a total of 19 classes) for different distances from the river was analyzed (Fig. 4.10). DBH classes were divided into 18 groups of 4-cm intervals covering a range of 72 cm (0-4 cm, 4-8 cm, ..., 68-72 cm). Trees with DBH values above 72 cm were lumped into a single group. The largest number of young seedling trees with DBH values of 0-4 cm were found on the P1 transect (0-20 m from the river). This accounted for 13.24 % of the total trees investigated in the study area. In recent years, as the result of the ongoing restoration project, groundwater levels close to the river have risen significantly, thus creating favorable conditions for the establishment of newly generated young seedlings. On average, the proportion of young *P. euphratica* trees decreased accordingly with increasing distance from the river, and the range of DBH distributions became simpler (showing smaller variance). The proportion of trees with DBH values of 16-36 cm was higher than the proportion of trees in any other DBH class. In addition, the majority of mature and aging trees with DBH values of 48 cm or greater increased as one went from the P1 to the P11 transect. In general, trees with a DBH of less than 36 cm appeared more frequently as the distance from the river increased. Long-term forest monitoring in recent years has indicated that newly grown young trees (DBH < 4.00 cm) have mainly been spotted within a 400-m distance from the river. This result demonstrates that the *P. euphratica* population near the river is basically under steady development.



**Fig. 4-8** Boxplot showing the DBH values of *P. euphratica* trees along the water gradient. Bold lines denote median values, black boxes denote the 25–75 % quantile ranges, blue squares denote the mean values, circles represent outliers, and the whiskers are the maximum and minimum values.



**Fig. 4-9** Spatial distribution patterns of DBH values at different distances from the river course.



**Fig. 4-10** Number of trees in the different DBH classes for the different distances from the river.

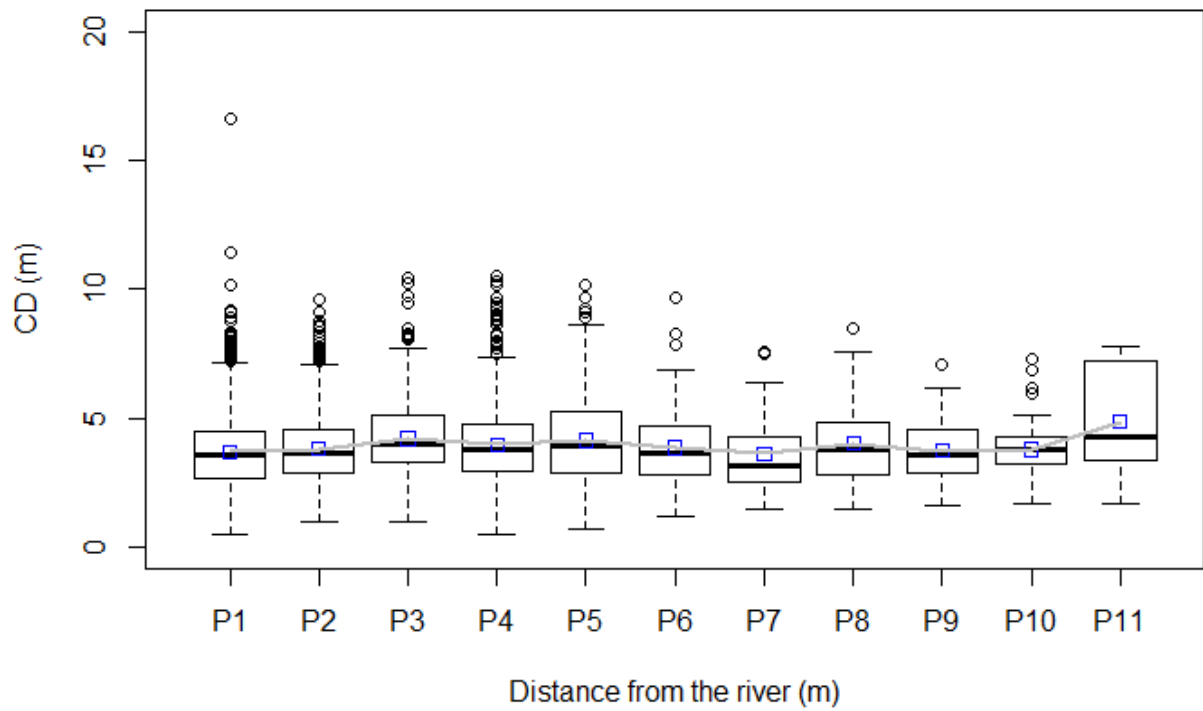


### 4.1.3 CROWN DIAMETER (CD)

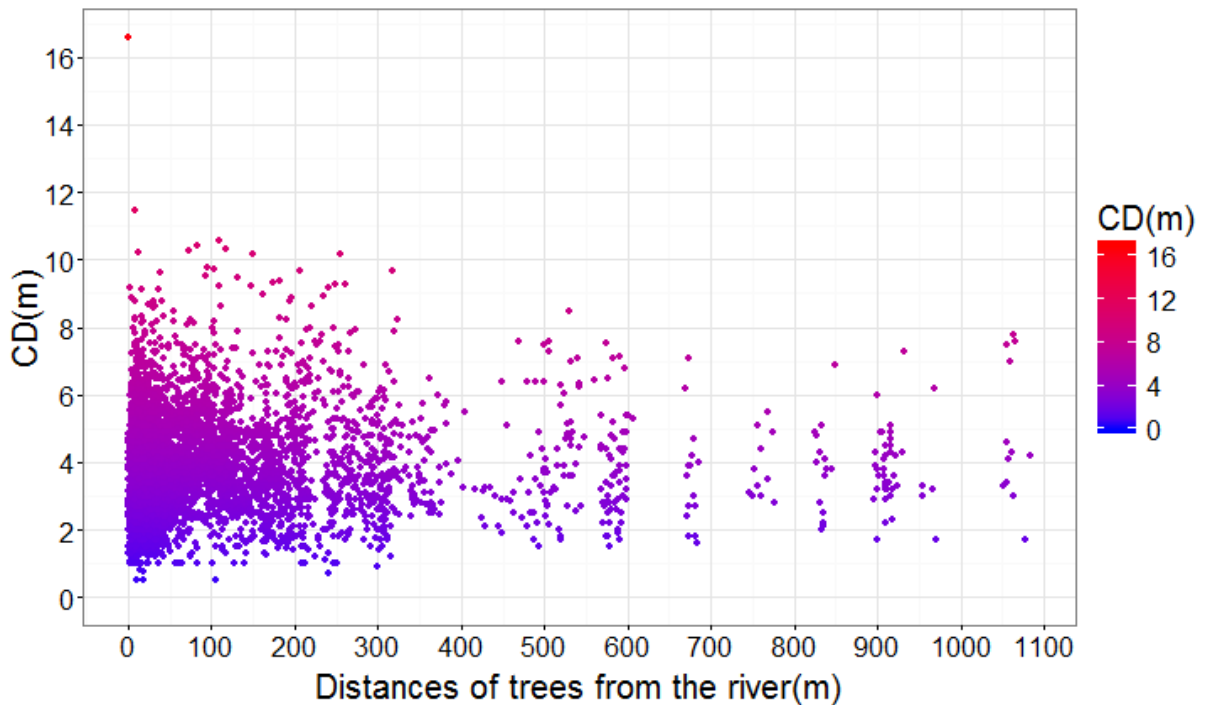
The crown diameter is defined as the average value of the maximum and minimum widths of the tree's outer canopy, and is one of the key ecological parameters of floodplain forests (Newton 2007; Halik et al. 2011; Aishan et al. 2015). Because of the long-term water stress, the majority of *P. euphratica* trees had lost their crown. For these, the crown diameter was recorded as 0 and excluded from the following analysis.

Figs. 4.11 and 4.12 show the CD values of *P. euphratica* for the different distance zones (ranging from P1 to P11). The overall CD ranged between 0.50 m and 16.58 m. The maximum CD value of 16.58 cm was found on the P1 transect (0-2 m from the river), and was located at a 1-m distance from the river. Minimum CD values of 0.50 m were observed on the P1 and P4 transects, with the minimum CD values on the P6, P7, P8, P9, P10 and P11 transects larger than on the others. With the exception of the P2 and P3 transects, there was clear increasing (resp., decreasing) trend of the minimum (resp., maximum) CD values along the water gradient.

The distribution of CD classes for different distances from the river reflects the CD response to the restoration measures to a certain extent. The number of trees in the 6 CD classes (0, 0-2, 2-4, 4-6, 6-8, >8) at different distances from the river was analyzed (Fig. 4.13). A considerable number of young trees in 0-2-m class were found close to the river (e.g., 147 on the P1 transect), with the number decreasing significantly as the distance from the river increased (there was a significant negative correlation between the CD distribution and the distance), suggesting that the restoration measures have had a positive impact on the recovery of the tree crowns. Within a 400-m distance from the river, a total number of 3841 trees in the 2-4-m and 4-6-m classes were found, accounting for 76 % of the total trees in the study area. The number of relatively vital and aging trees in the 6-8-m and >8-m classes made up 38 % of the total trees being investigated, indicating that there was a considerable number of aging trees in the study area, many having almost lost the ability to regenerate. Generally speaking, the CD values of healthy trees are positively correlated with their age, but it was found that the CD values of aging trees were generally less than the CD values of the young trees.



**Fig. 4-11** Boxplot showing the CD values of *P. euphratica* trees along the water gradient. Bold lines denote median values, black boxes denote the 25–75 % quantile ranges, blue squares denote the mean values, circles represent outliers, and the whiskers are the maximum and minimum values.



**Fig. 4-12** Spatial distribution patterns of the CD values at different distances from the river course.

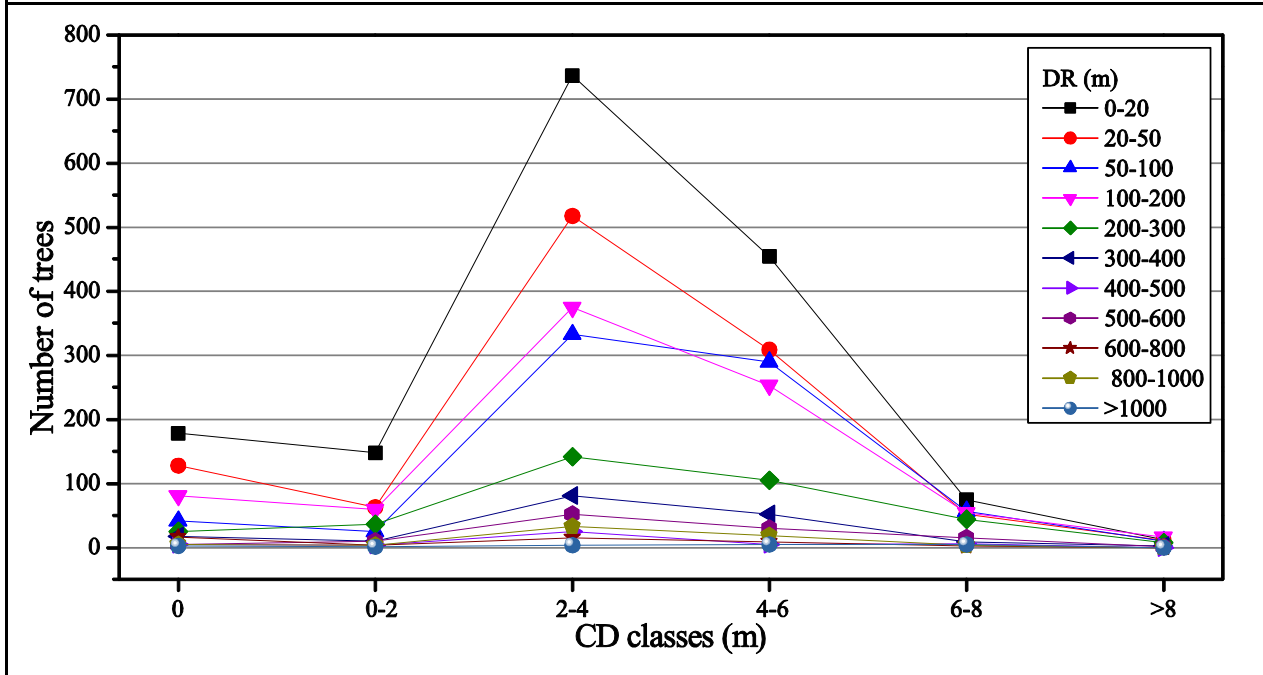
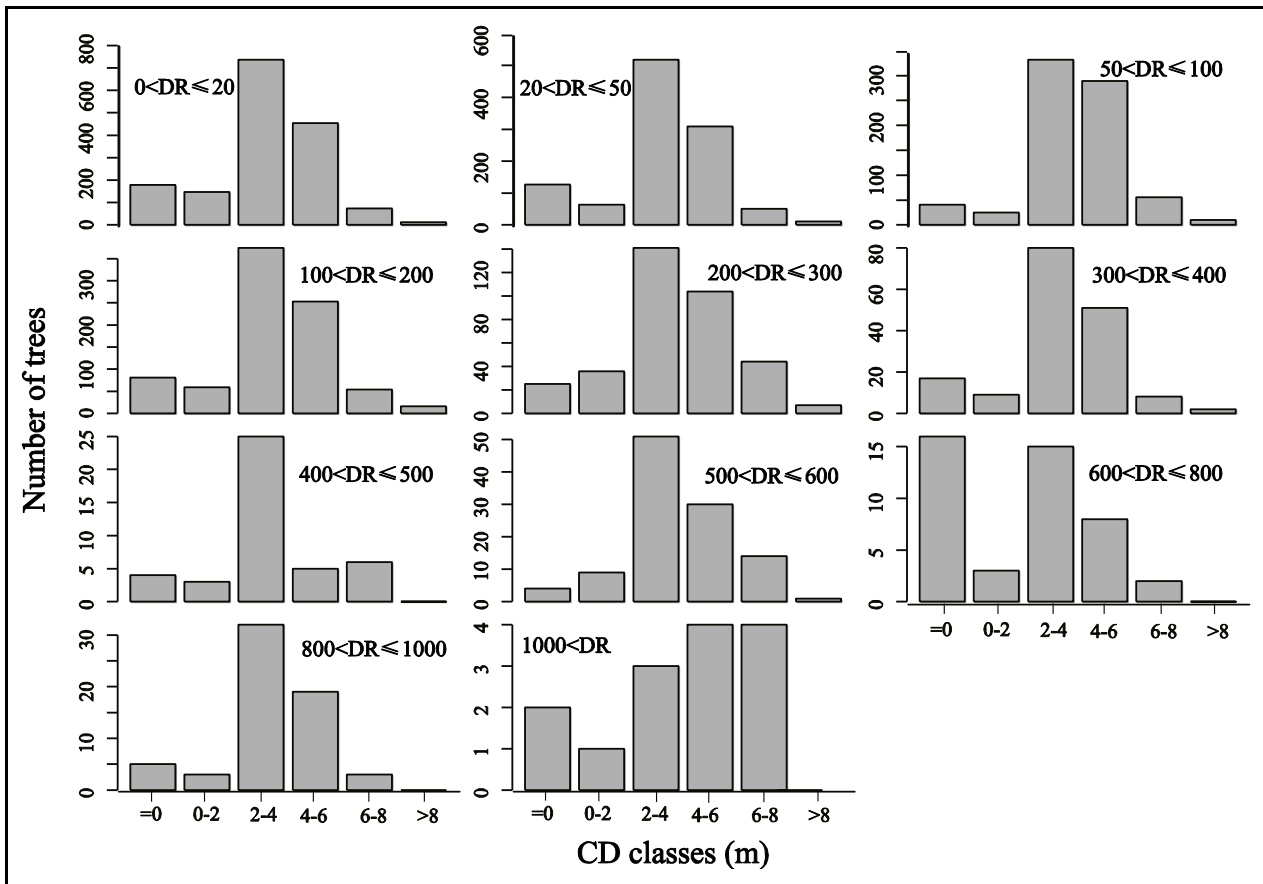


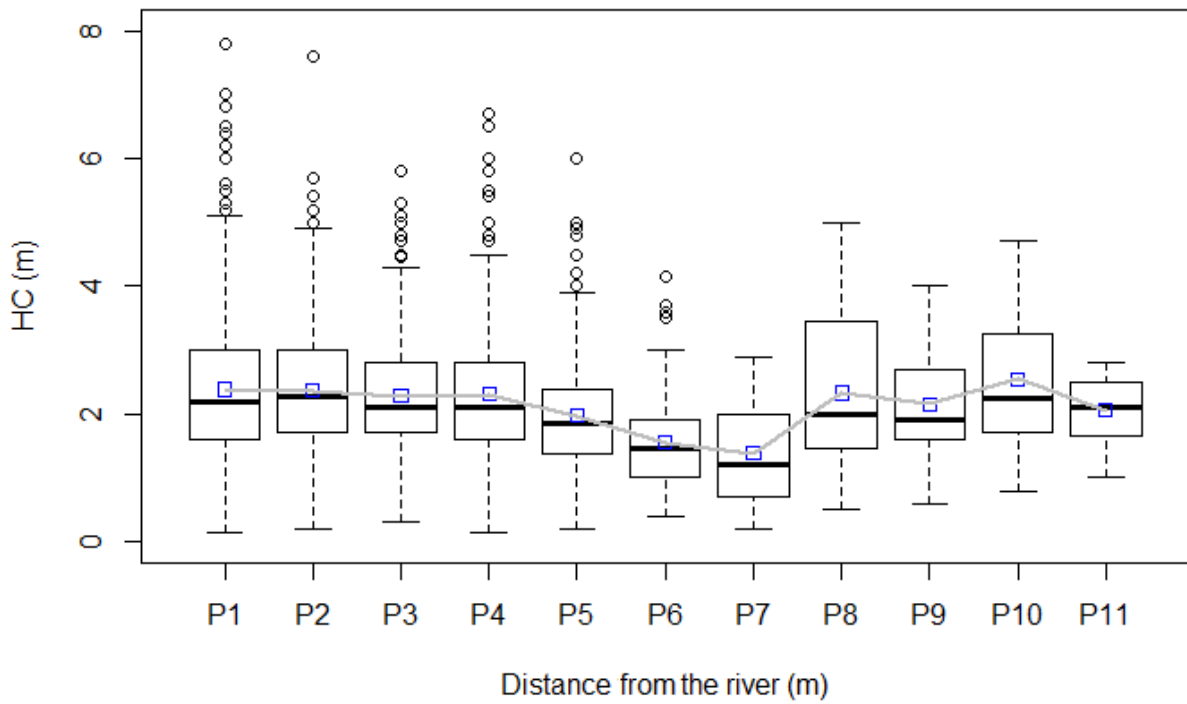
Fig. 4-13 Number of trees for the different CD classes for the different distances from the river.

#### 4.1.4 HEIGHT TO CROWN (HC)

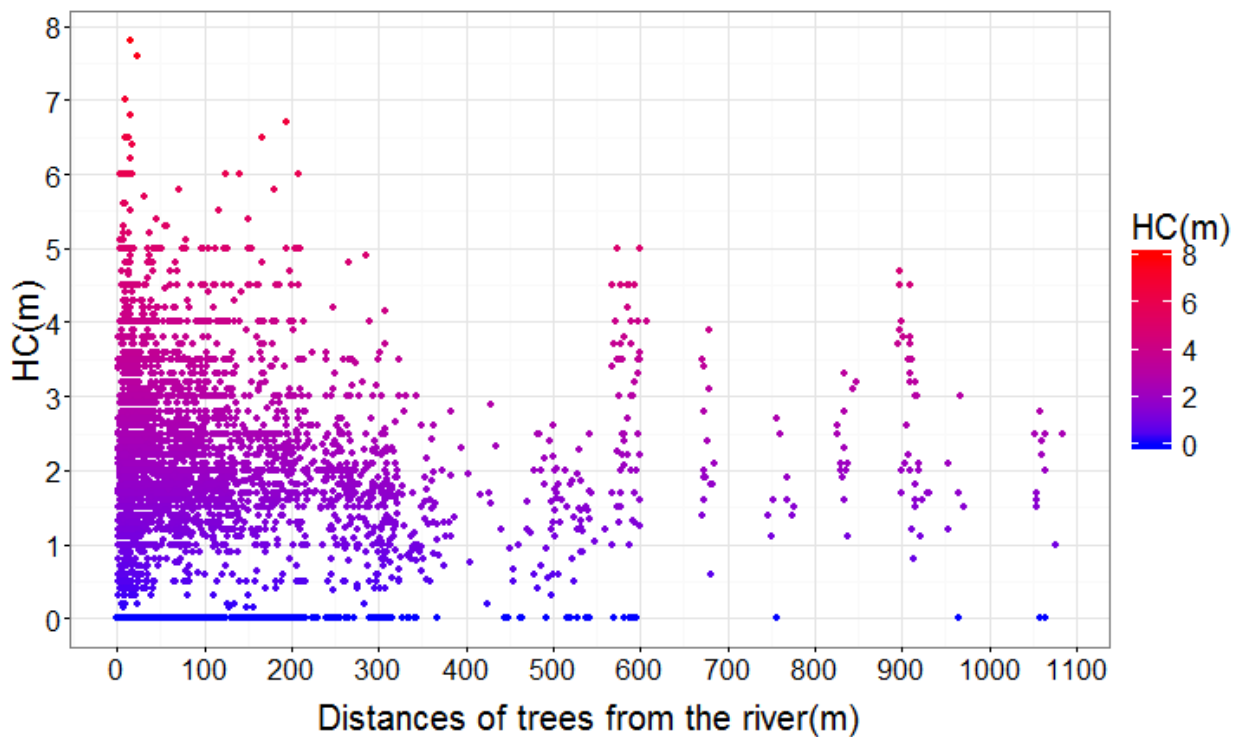
Height to crown (HC) is defined as the vertical distance (along the axis of the tree stem) from the ground level to either the lowest living branch of the crown or to the point where the branches supporting the foliage are attached to the trunk (Wang et al. 2008a,b). It is also known as the “Under Branch Height” (BH). For the degraded *P. euphratica* trees in the lower reaches of the Tarim River, it is one of the more meaningful ecological parameters for linking the effects of restoration measures to tree regrowth.

As seen in Figs. 4.14 and 4.15, the HC values in the study area ranged between 0.15 m and 7.80 m. A maximum HC value of 7.80 m was observed on the P1 transect. Minimum HC values of 0.15 m were found on the P1 and P4 transects. On average, the maximum HC value appeared to decrease with increasing distance from the river - this was mainly because many tall trees were distributed close to the river, where water availability was relatively sufficient. The minimum HC values tended to increase together with the distance from the river.

In order to discuss the distribution of HC values in the study area in more detail, the HC values were grouped into 6 classes (0.0 m, corresponding to young seedlings or dead trees, 0.0-1.5, 1.5-2.0, 2.0-3.0, 3.0-5.0, >5.0 m). From Fig. 4.16, it is seen that large numbers of trees in all HC classes were predominantly distributed in the P1, P2, P3 and P4 transects. As one went farther away from the river, the groundwater depth saw a gradual increase due to weaker effects of the restoration measures. A considerable number of young trees with HC values of 0 or of less than-1.5 m were detected on the P1 transect (n=371 and n=198, respectively). However, they appeared to decrease significantly as one progressed towards the P11 transect. This suggests that the restoration measures had a significant effect on young seedlings. In turn, this also reflects the importance and necessity of restoration measures on the regeneration of the degraded *P. euphratica* trees. The number of trees grouped into the 1.5-3.0-m HC classes was 2286, representing 50.8 % of the total number of trees in the study area. Additionally, they were distributed uniformly among the all transects, indicating that the fluctuation of groundwater depth due to restoration measures tended to meet the demands of tree regeneration. Trees with HC values greater than 5 m could only be found close to the river. Most of them were aging and were distributed sporadically.



**Fig. 4-14** Boxplot showing the HC values of *P. euphratica* along the water gradient. Bold lines denote the median values, black boxes denote the 25–75 % quantile ranges, blue squares denote the mean values, circles represent outliers, and the whiskers are the maximum and minimum values.



**Fig. 4-15** Spatial distribution pattern of the HC values at different distances from the river course.

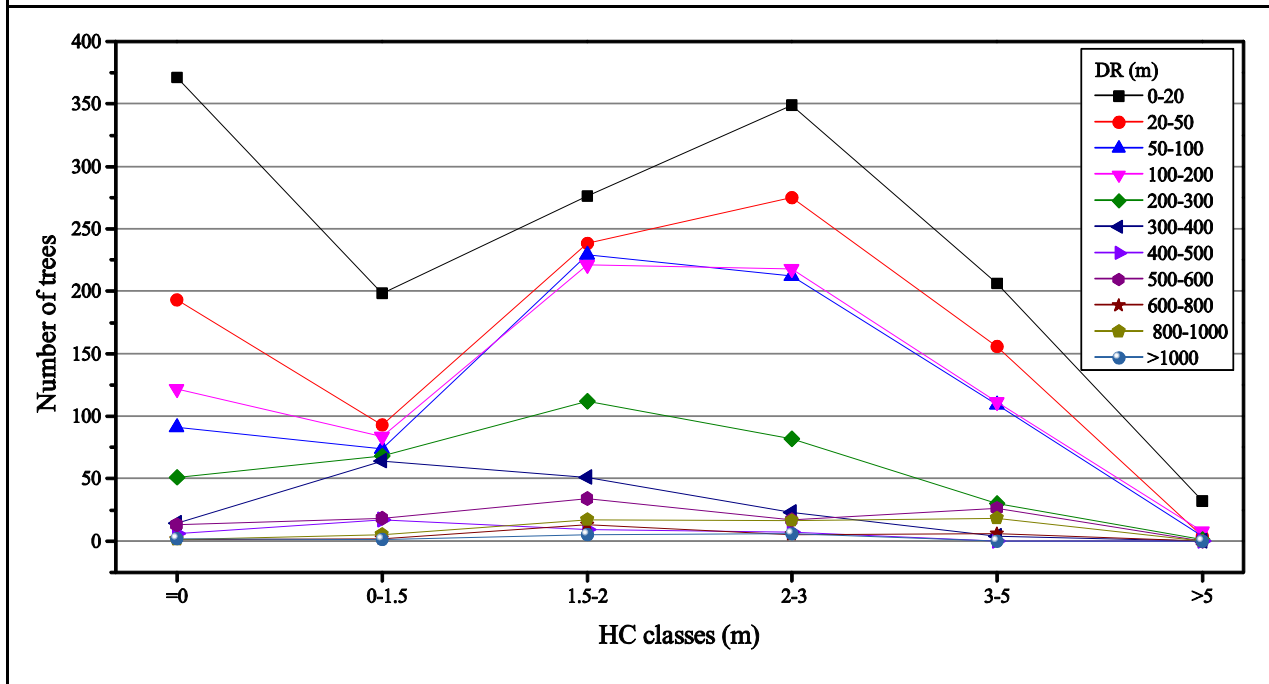
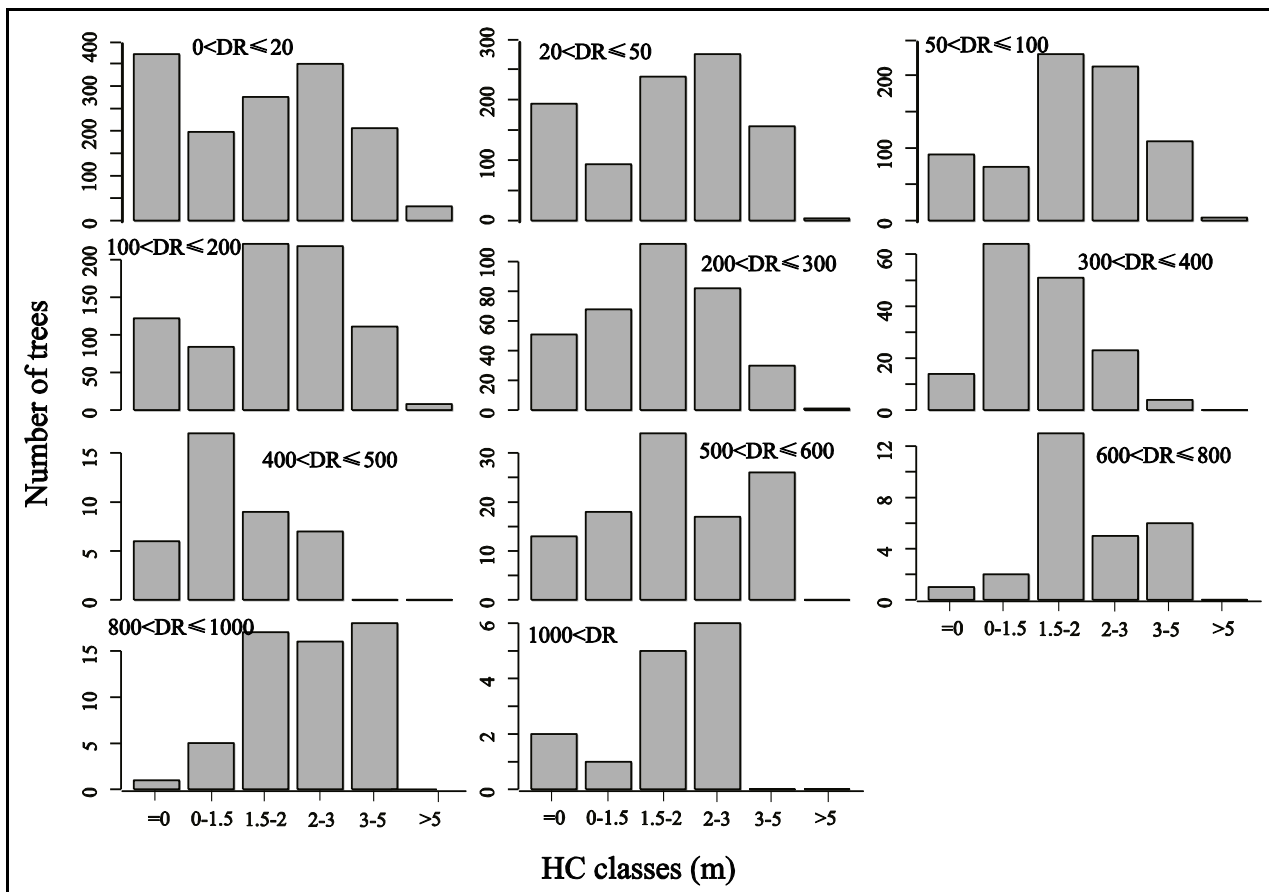
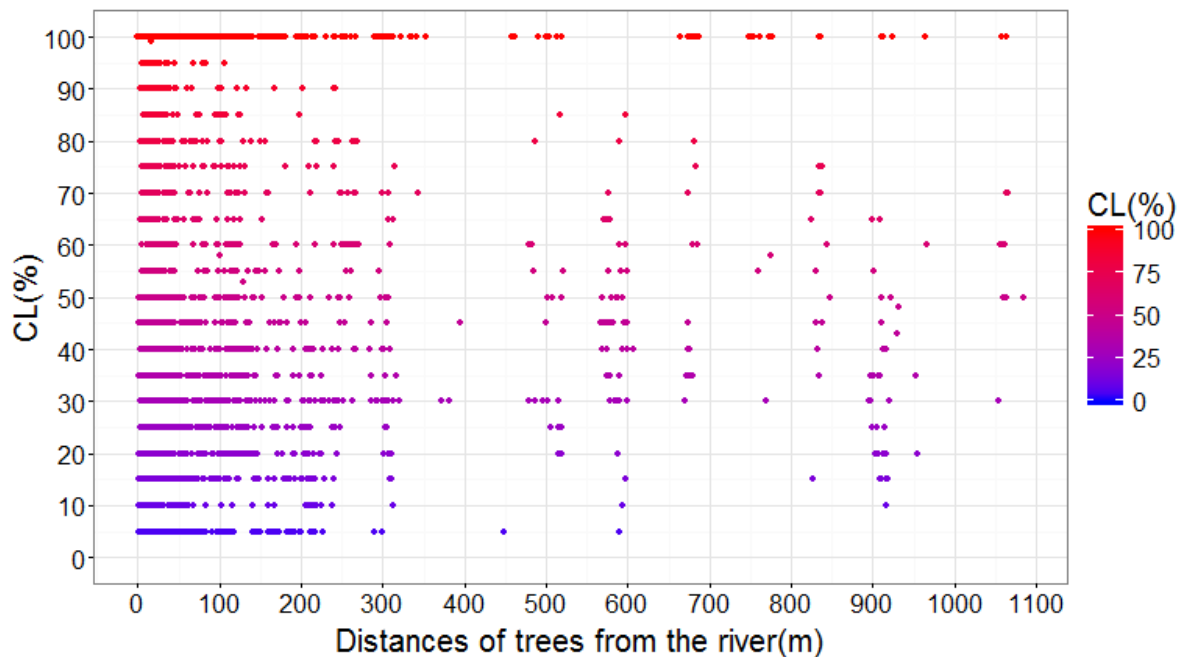


Fig. 4-16 Number of trees for the different HC classes for the different distances from the river.

#### 4.1.5 CROWN LOSS (CL)

Long-term drought stress in the study area caused widespread losses of leaves in the tree crowns. Crown loss is regarded as an important indicator to evaluate the vitality of the *P. euphratica* trees. Usually, tree crowns with smaller leaf density are considered to be low-vigor trees. In general, the crown loss of the ideal trees with a full crown is recorded as 0 %, and the crown loss of trees without any leaves (completely withered or dead) is recorded as 100 %. Due to the subjective nature of the crown loss assessment method, a group of two or more people should be involved in the field-work evaluation process so as to ensure accuracy.

The spatial distribution patterns of CL values for different distances from the river were analyzed (Fig. 4.17). The CL values covered the full range of 0-100 %. Within a 300-m corridor of the river course, there was great variation in CL values, with the full range of values observable. At distances of more than 300 m, the number of trees with CL values of 30 % or more tended to decrease. The majority of the CL values ranged between 30 % and 90 %, although trees without leaves (100 %) also accounted for a considerable number.



**Fig. 4-17** Spatial distribution pattern of the CL values at different distances from the river course.

The CL values were divided into 6 classes (0-10 %, 10-25 %, 25-50 %, 50-75 %, 75-100 % and =100 %). On the P1 and P2 transects (within a 50-m distance from the river), one mostly observed trees with CL values of 10 % or less. The number of these trees reached 264 (accounting for 69 % of the total vital trees in the study area), suggesting that the response to restoration measures of the trees close to the river was plausible. Within a 200-m corridor (P1, P2, P3 and P4), the number of trees went up to 2725 (89 % of the total number of trees investigated). Among them, the CL values of the majority of the trees were less than 50 % (n= 1856, 60.9 % of total trees). For distances greater than 200 m, the number and the vitality of the trees started to gradually reduce and deteriorate. At distances of 200-400 m, only 22 high-vitality trees with CL values of 10 % or less were observed - moreover, the number of

senesced and dying trees in the CL range of 50-100 % went up to 41, indicating that the number of low-vitality mature or aging trees had increased. In addition, the number of dead trees in these transects comprised 21.2 % of the total trees investigated within these transects. At distances of 400 m or greater, the density of the trees decreased sharply and the proportion of trees with regard to the total tree number went down to nearly 3 %, most of which was aging and dead trees (Fig. 4.18).

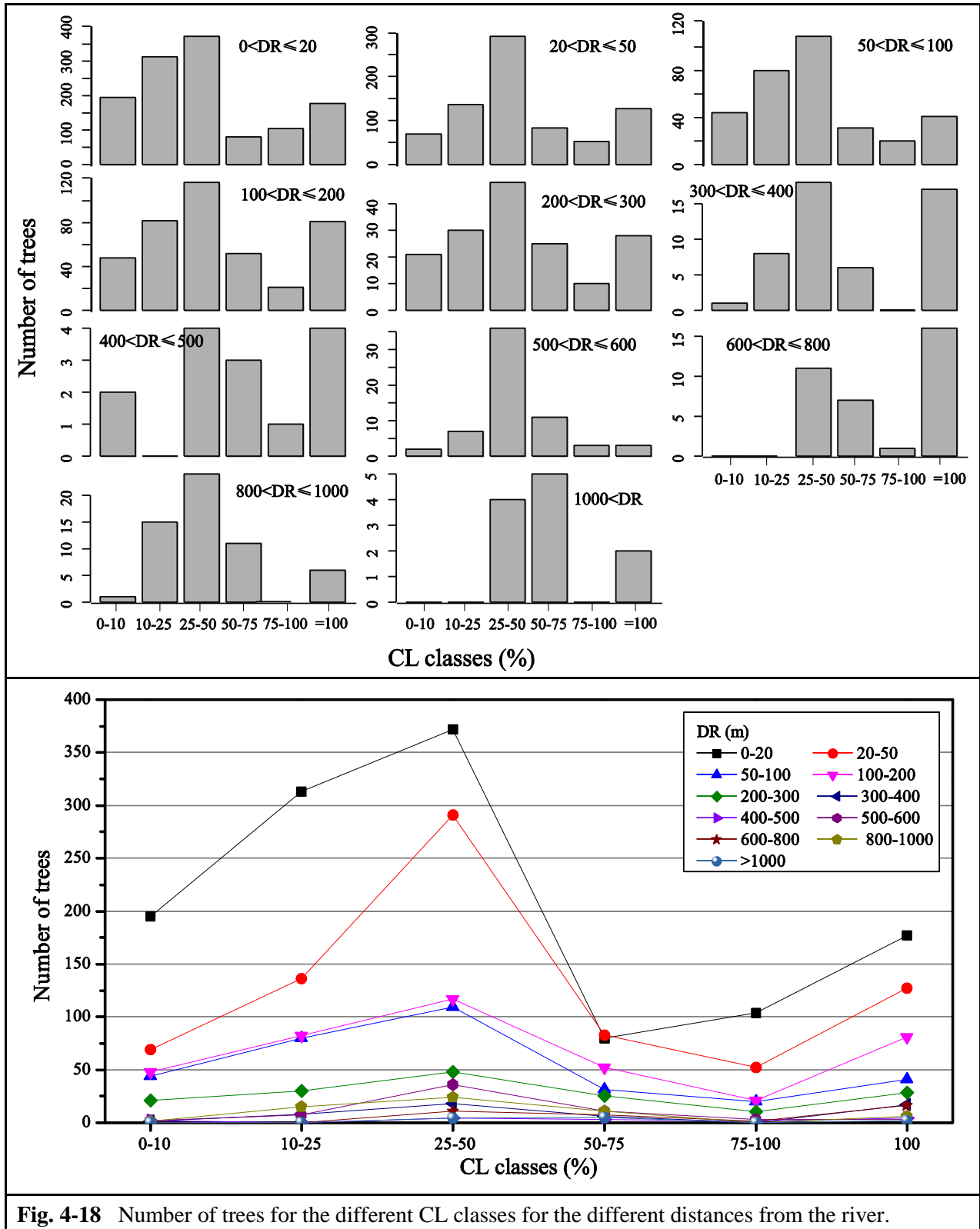


Fig. 4-18 Number of trees for the different CL classes for the different distances from the river.



## 4.2 TREE VITALITY

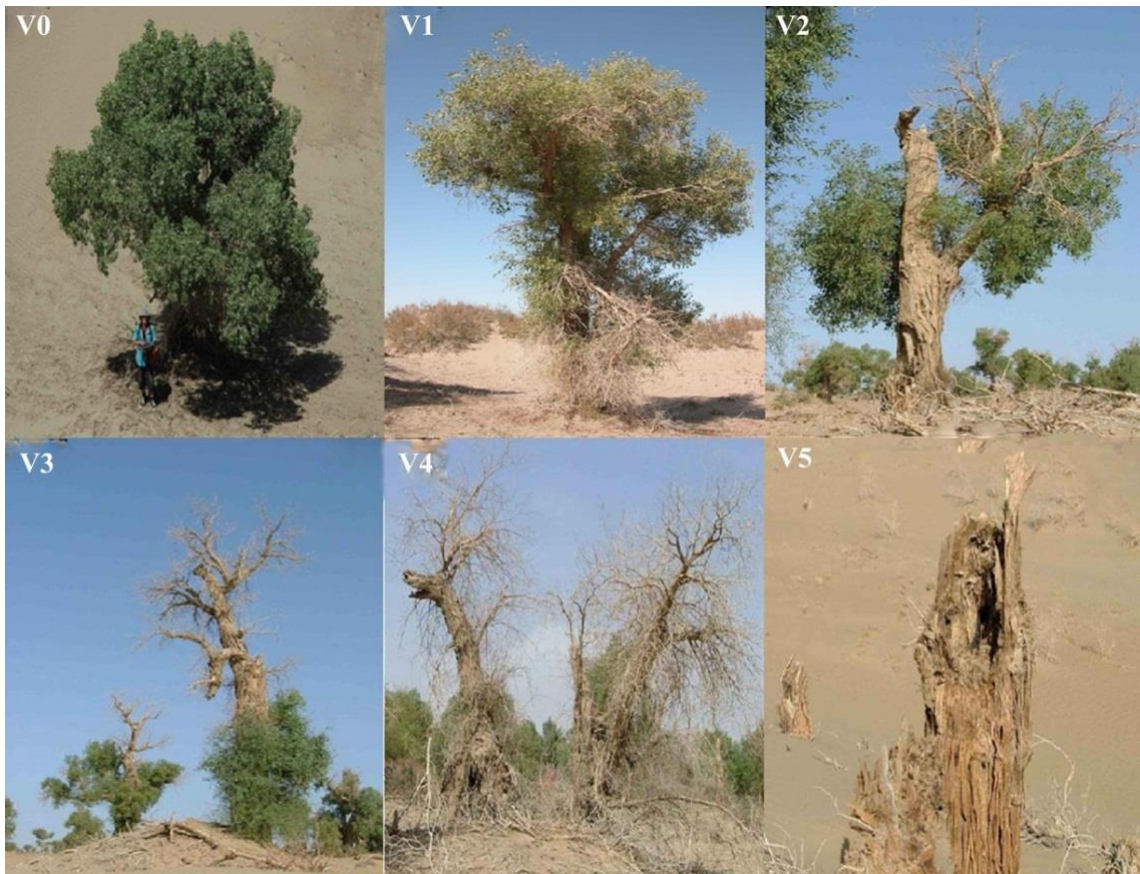
Tree vitality is an integrated concept associated with forest physiology, ecology and morphology, and refers to the growth status and trends of forests and shrubs (including crown, leaves, stems, and branches), as well as to the extension of canopy (Aishan et al. 2015). It can be a key indicator in assessing the overall situations of forests - e.g., their health conditions, integrity and resilience.

### 4.2.1 TREE VITALITY AND CLASSIFICATION

Based on the visual classification criteria for the vitality of *P. euphratica* trees (Table 4.1 and Fig. 4.19), tree vitality was grouped into seven classes (Table 4.1): Healthy tree (V0), Good (V1), Medium (V2), Senesced tree (V3), Dying tree (V4), Dead tree (V5) and Fallen tree (V6). Detailed ecological parameters of the fallen trees were not recorded, save for an explanation of their overall status during the field work. Therefore, further analysis for fallen trees has not been presented in this thesis.

Table 4-1 Classification criteria for the vitality of *P. euphratica* trees

Code	Vitality class	Leaf loss (%)	Overall status and crown features of <i>P. euphratica</i>
V0	Healthy tree	≤10	High-vitality tree that is (almost) without signs of damage; healthy full primary crown; leaves usually dark green
V1	Good tree	11-25	Crown slightly damaged, but still in good condition, less than 25 % loss of crown
V2	Medium tree	26-50	Crown moderately damaged, with some primary and secondary crown present; crown loss of 50 %
V3	Senesced tree	51-75	Crown heavily damaged; tendency towards deterioration (e.g. extant dried leaves); crown loss under 75 %
V4	Dying tree	76-99	Primary crown severely damaged; missing or secondary crown also damaged; evidence of residual vitality (for example, single green leaves); tree almost strays
V5	Dead tree	100	Standing dead wood; no evidence of (residual) vitality
V6	Fallen tree	100	Lying dead wood, stumps

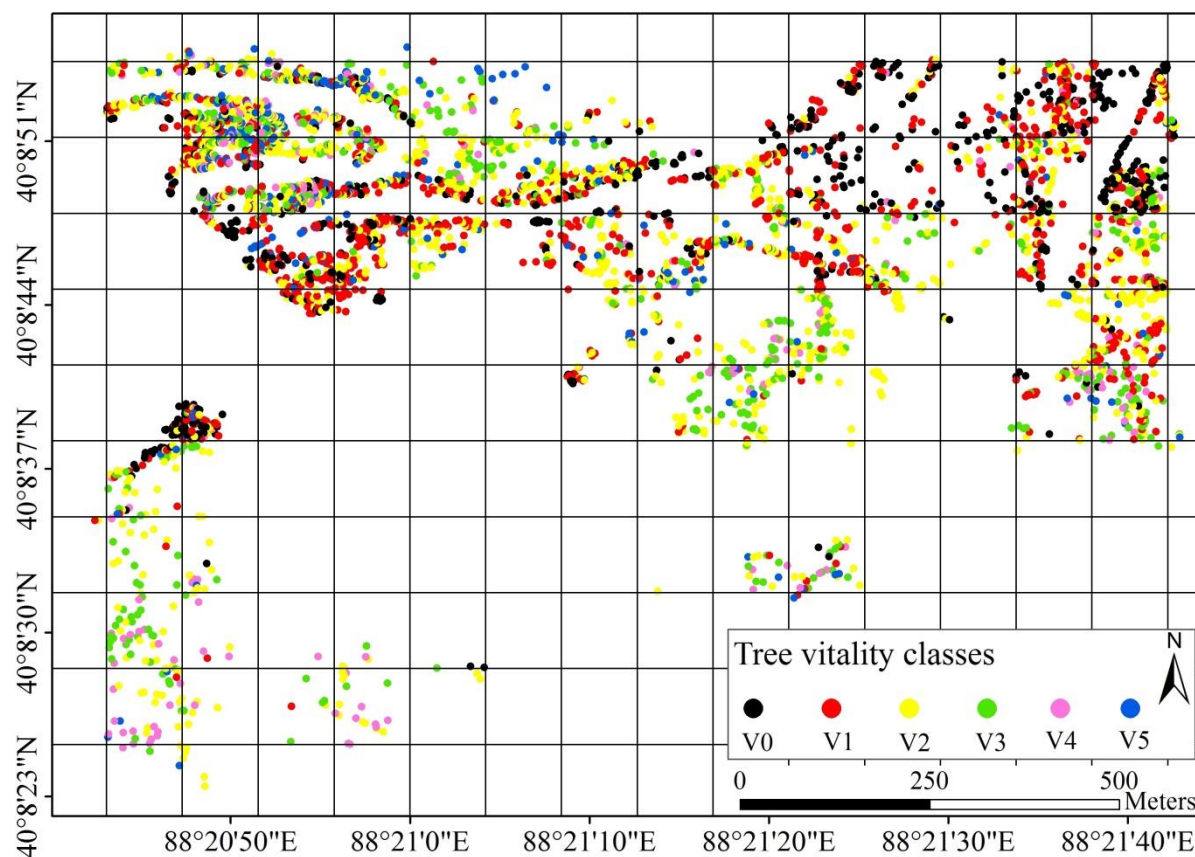


**Fig. 4-19** *P. euphratica* trees with different vitality classes. V0: healthy tree; V1: good tree; V2: medium tree; V3: senesced tree; V4: dying tree; V5: dead tree.

#### 4.2.2 DISTRIBUTION OF TREE VITALITY

During the nearly 30 years (1972–2000) of desiccation of the lower reaches of the Tarim River, the vitality of the *P. euphratica* trees declined sharply, with the majority of trees showing clear physical signs of deterioration. In order to assess the influence of the water diversion project on the revitalization of variously degraded *P. euphratica* trees, 5,097 (including trees in Sites a and b, see Fig. 2.9) individual trees in the study area at Arghan were investigated according to the vitality classification criteria given in Tables 4.1 and 4.2. Fig. 4.20 shows the relationship between the distribution of the *P. euphratica* trees in different vitality classes and their distances to the river. Large proportions of the *P. euphratica* trees (1,943 trees) in vital, good and medium classes were found near the riverbed. There were 459 vital (9.01 % of all trees in the study area), 650 good (12.75 %) and 834 medium trees (16.36 %) within a 50-m distance of the riverbed. Within the 200-m range from the riverbed, large numbers of trees (2,396 trees, 47 % of the total) were estimated as of good and medium vitality class. As depicted in Figs 3.1 and 3.4 in Chapter 3, the positive effect of the man-made water diversion on the replenishment of groundwater depth within the 150-m distance of the riverbed is obvious. The diversion has enabled *P. euphratica* trees to maintain contact with the groundwater and has allowed for the trees to maintain their normal growth. However, with increasing distance to the river, the number of trees in the senesced, dying and dead

vitality classed increased as well. Many of these trees were missing their tops or most of the branches. They accounted for approximately 50 % of all the trees in the 100-m × 100-m plots in the 600–800-m range. Groundwater depth at these distances is still at about 7 m, which is likely to lead to insufficient growth of the riparian vegetation (Song et al. 2000).



**Fig. 4-20** Spatial distribution of the *P. euphratica* trees for different vitality classes in the study area.

**Table 4-2** Distributions of the number of *P. euphratica* trees for the different vitality classes and the distances to the river.

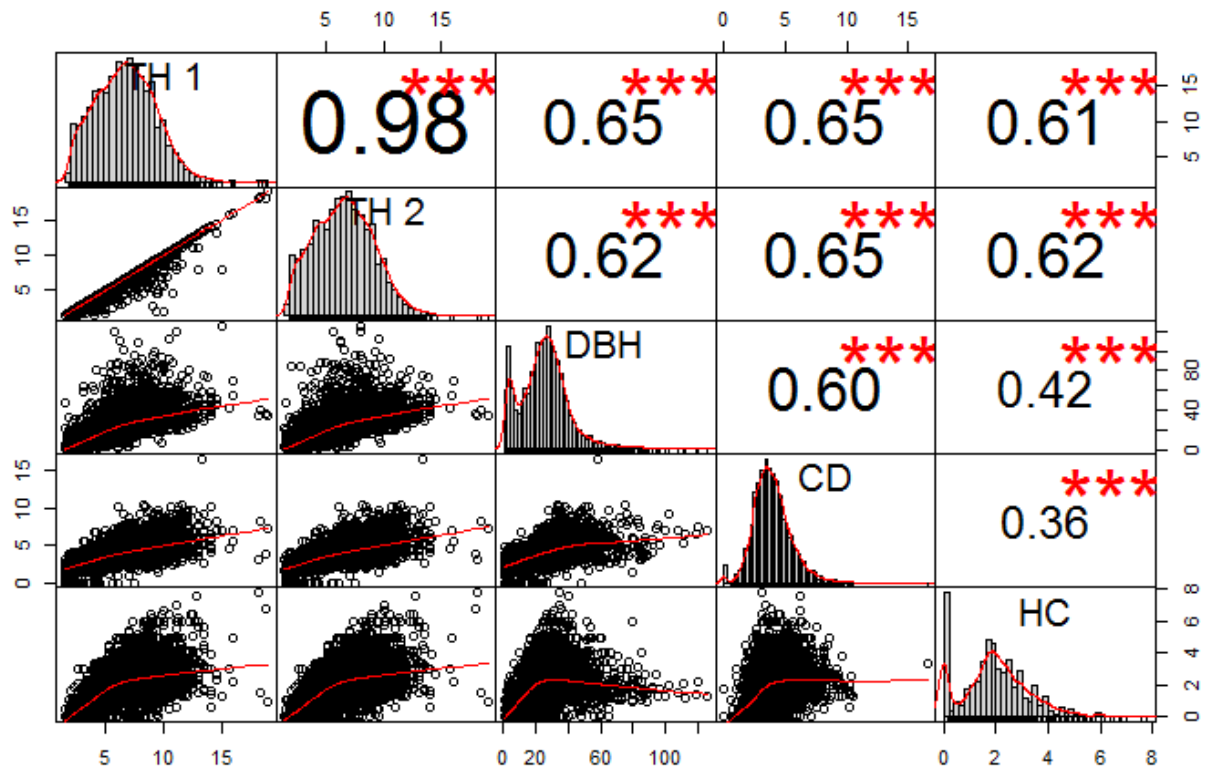
Vitality	Distance to the river (m)						
	$X \leq 50$	$50 < X \leq 200$	$200 < X \leq 400$	$400 < X \leq 600$	$600 < X \leq 800$	$800 < X \leq 1000$	$1000 < X$
V0	459	262	25	5	0	1	0
V1	650	467	59	13	0	15	0
V2	834	445	204	66	11	24	4
V3	311	223	132	35	7	11	5
V4	132	62	57	22	1	0	0
V5	281	110	42	6	9	6	2
V6	33	28	8	6	15	5	3
Total	2700	1597	527	153	44	62	14

## 4.3 RELATIONSHIPS BETWEEN THE TREE PARAMETERS ALONG THE TREE DEGRADATION GRADIENTS

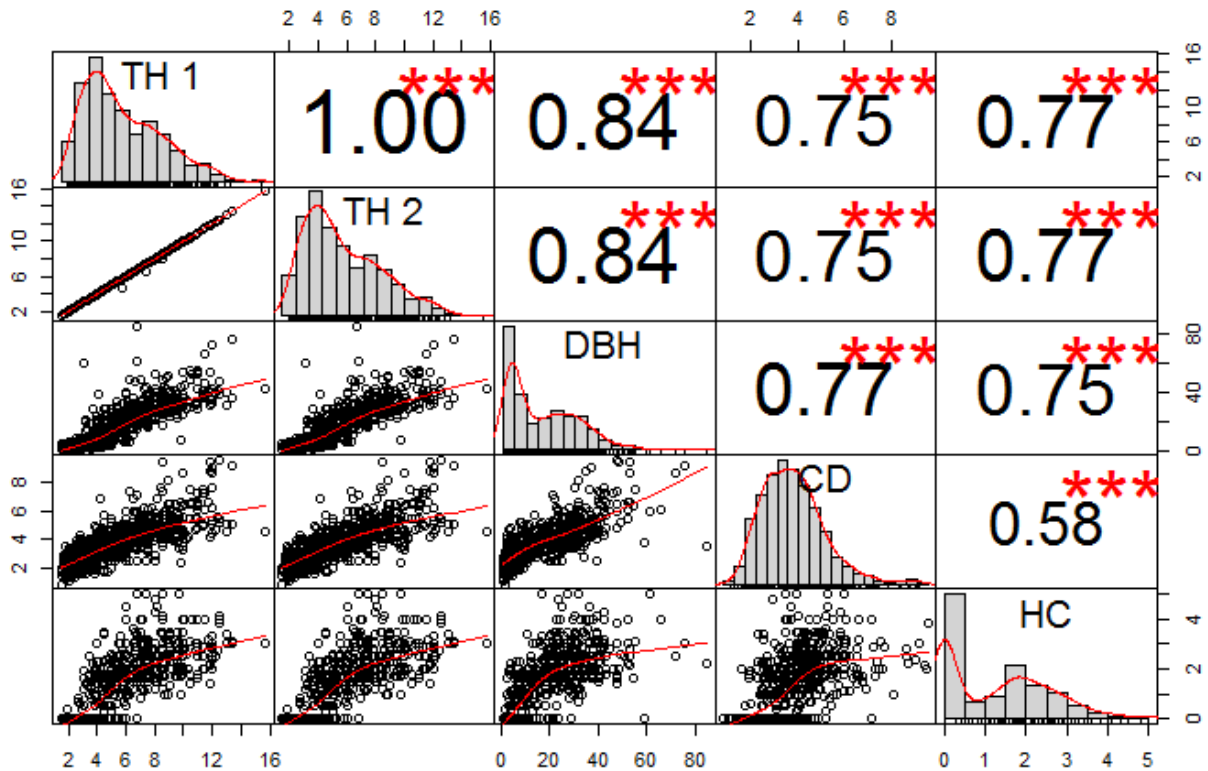
### 4.3.1 CORRELATION ANALYSES BETWEEN THE MAIN TREE PARAMETERS

Understanding the relationships between the different eco-morphological parameters of *P. euphratica* provides very useful information for establishing appropriate countermeasures and for the sustainable management of endangered forests. Under suitable site conditions, there is a strong biological relationship between the different ecological parameters of vegetation. *P. euphratica*, the dominant tree species in the study area, have experienced severe drought stress and have degraded enormously over the past 50 years. In turn, this long-term effect may have changed the internal growth mechanism of the trees, potentially destroying the relationships between the eco-morphological parameters.

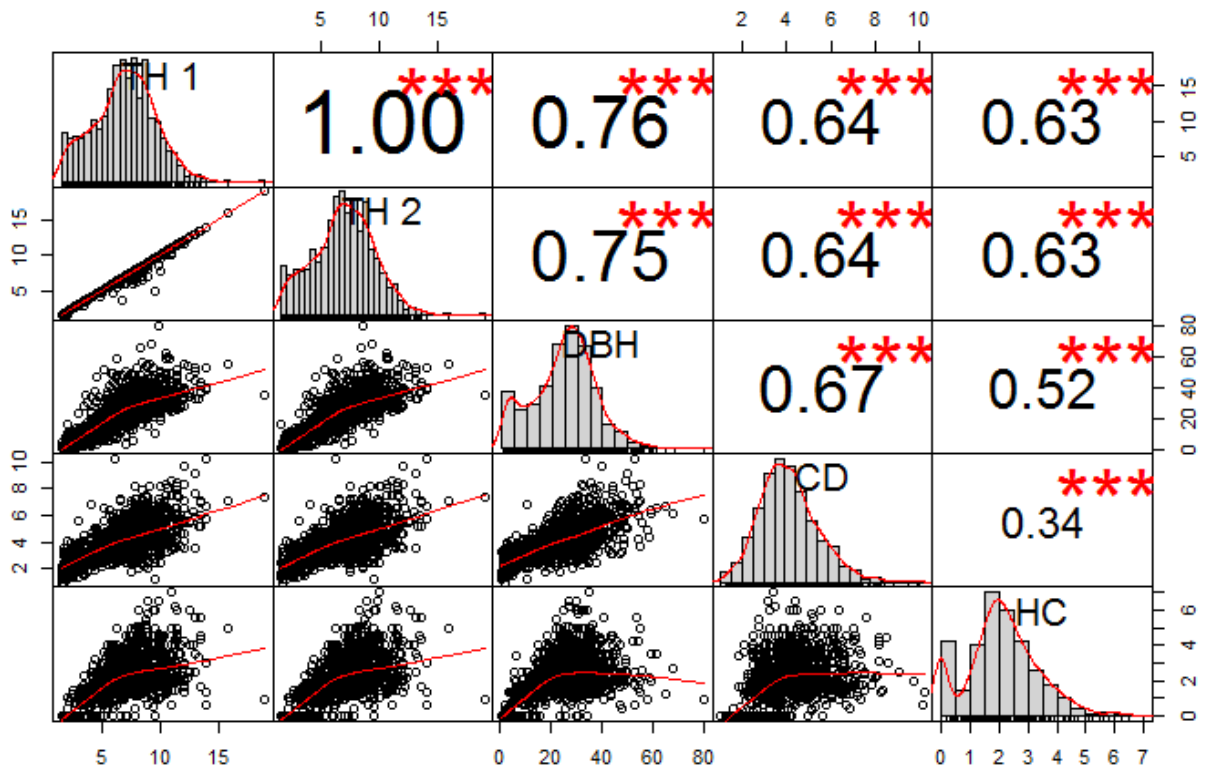
In order to understand the magnitude of the degradation effects on these relationships, Pearson correlations between the main parameters of *P. euphratica* were analyzed for all investigated trees (Fig. 4.21) and trees of different vitalities (Fig. 4.22-4.27). The correlation coefficient between TH2 and DBH for all investigated trees was 0.62 ( $P < 0.001$ ). The correlation coefficients between TH2 and DBH for the different tree vitalities from V0 to V5 were 0.84, 0.75, 0.64, 0.46, 0.47 and 0.31, respectively. From this result, we can see how the degree of degradation affects the strengths of the tree parameter relationships. Correlation analyses between other tree parameters for different vitalities produced similar results. For example, the correlation between DBH and CD of high-vitality trees was stronger ( $R = 0.77$ ,  $P < 0.001$ ) than that for other vitality classes, while the correlation between these two parameters in V5 was -0.21, which shows that the relationship between DBH and CD was damaged. Of course, most of the trees in V5 do not hold any leaves, and have a near absence of tree crowns. All in all, the correlation coefficients for healthy trees were higher than those for trees of other vitality classes. Additionally, the correlation coefficient decreased with the decline in tree vitality. Our results suggest that it might be possible to differentiate degraded *P. euphratica* trees from healthy trees by determining the correlation strength of the tree parameters, thus making these coefficients into a new parameter for detecting degradation and assessing forest conditions in arid regions.



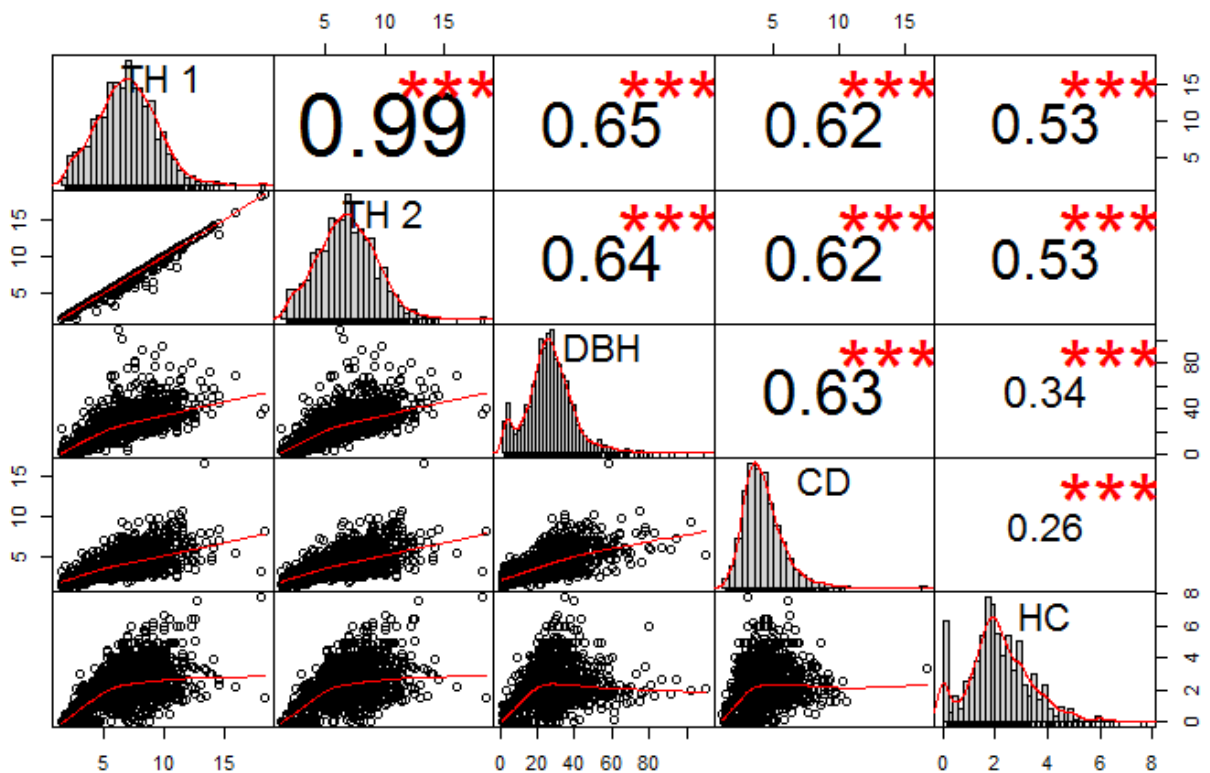
**Fig. 4-21** Correlation matrix between the ecological parameters of all investigated *P. euphratica* trees. The given values are the Pearson correlation coefficients, the histograms with kernel density overlays represent the distribution of each parameter, and asterisks are the statistical significance levels at 0.05, 0.01, 0.001.



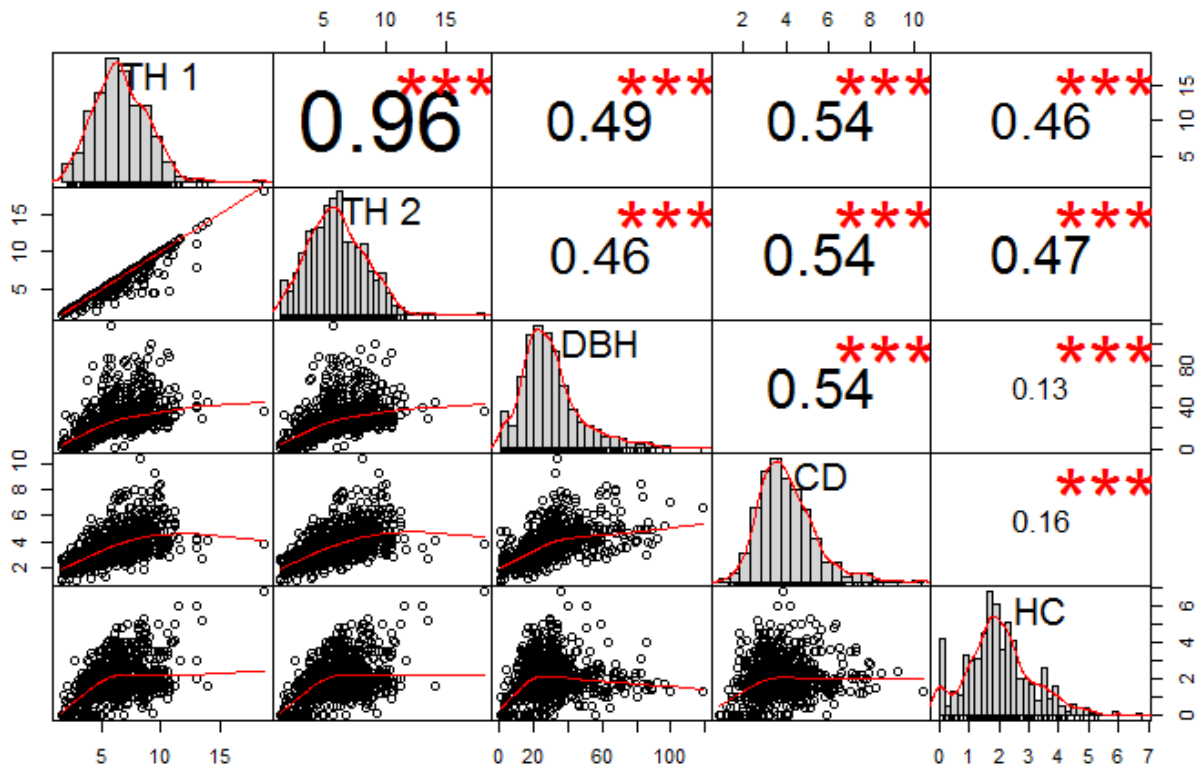
**Fig. 4-22** Correlation matrix between the ecological parameters of *P. euphratica* trees in the V0 vitality class.



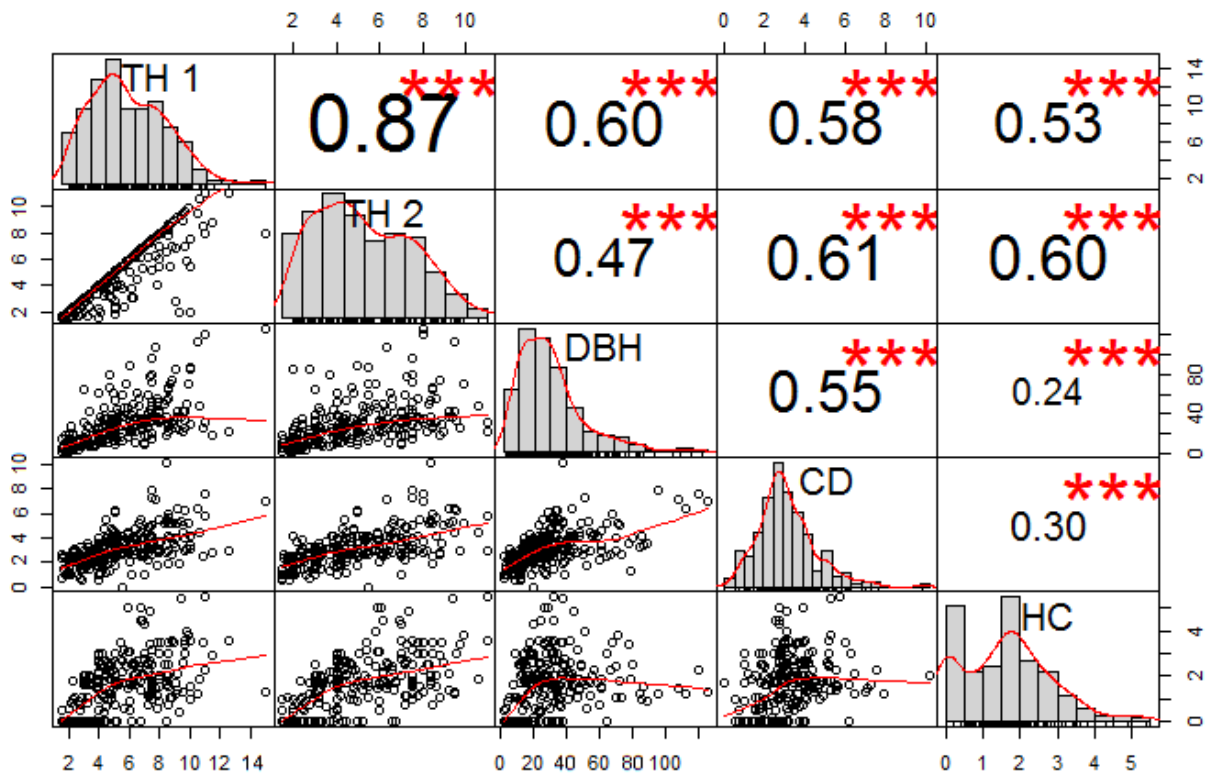
**Fig. 4-23** Correlation matrix between the ecological parameters of *P. euphratica* trees in the V1 vitality class.



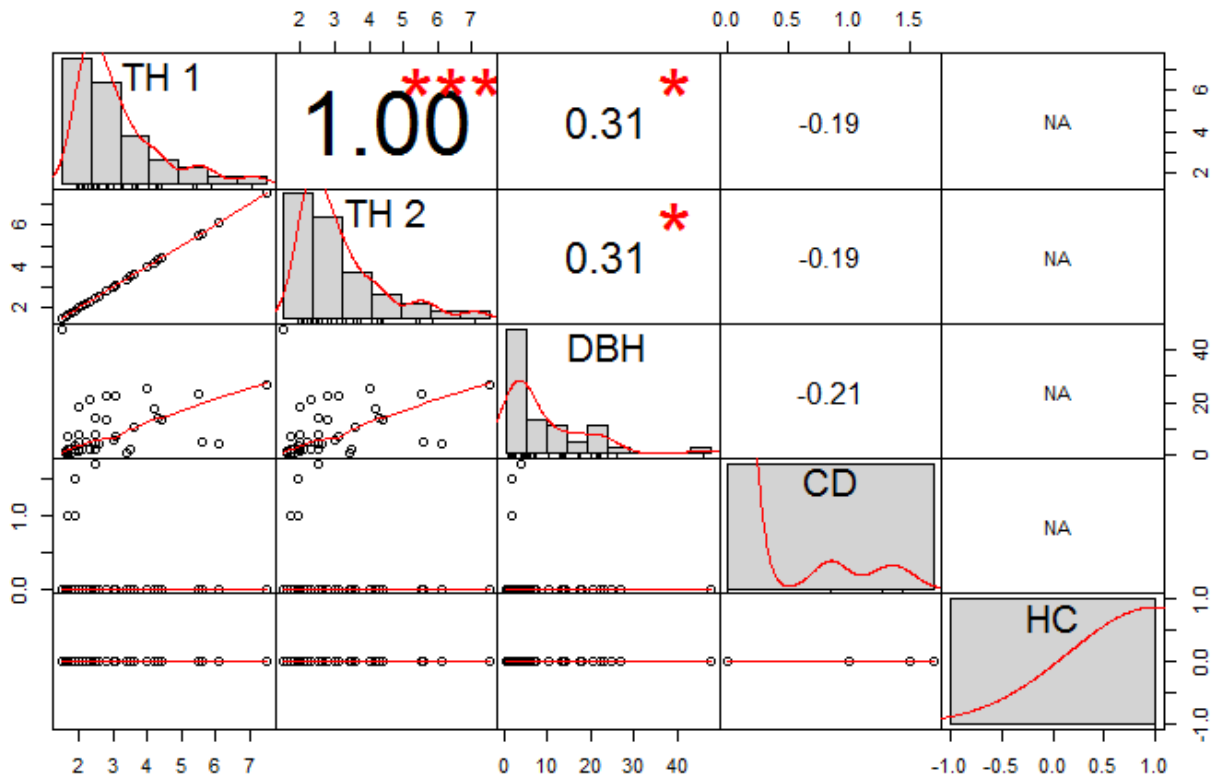
**Fig. 4-24** Correlation matrix between the ecological parameters of *P. euphratica* trees in the V2 vitality class.



**Fig. 4-25** Correlation matrix between the ecological parameters of *P. euphratica* trees in the V3 vitality class.



**Fig. 4-26** Correlation matrix between the ecological parameters of *P. euphratica* trees in the V4 vitality class.



**Fig. 4-27** Correlation matrix between the ecological parameters of *P. euphratica* trees in the V5 vitality class.

#### 4.3.2 HEIGHT-DIAMETER RELATIONSHIPS OF TREES FOR DIFFERENT DEGRADATION GRADIENTS

Special focus was given to exploring the height-diameter relationships, one of the most important relationships between tree parameters in forestry science, of *P. euphratica* trees in detail. The height-diameter distribution and the quality of linear regression between these two parameters for different vitality classes were reexamined. Table 4.3 shows that a large proportion of *P. euphratica* trees (1,761 trees) in high-vitality classes are found in our research area. Slightly degraded and highly degraded trees (e.g., medium, senesced, dying, dead and fallen tree classes) comprise nearly 60 % of the total trees (2556 trees). It is interesting to note that the mean DBH and TH values increased with the decrease in tree vitality, dead trees being the only exception. This indicates that there are more relatively younger trees among the healthy trees than there are among the degraded ones. It is clear that most of the dead trees are distributed farther away from the river, where they may have failed to receive sufficient water support for a long time. Therefore, the regrowth of dead trees is highly limited in that environment.

The TH and DBH parameters are closely associated with the forest environmental factors and other man-made and natural disturbances. The distribution of TH values demonstrates the vertical structure of forests and, most importantly, the growth conditions of riparian forests. The distribution of the number of trees in each DBH class directly reflects the regeneration patterns and morphological characteristics of the individual trees. It is not only an important



indicator of stand structure, but also displays the successional trend of forest stands (Wang and Rennolls, 2005). As such, it has been the focus of research in the field of forest ecology. The distribution patterns of the TH and DBH values of *P. euphratica* trees of different vitalities were analyzed (Fig. 4.28 and Fig. 4.29, respectively). The overall TH values ranged from 0 to 19 m, and the values of DBH were within a range of 0–125 cm. Trees with TH values of 15 m or greater and DBH values of 60 cm or greater appeared sporadically. There were irregular distribution patterns of TH values among all vitality classes (Fig. 4.28). The mean TH values ranged from 0.04 (V5) to 6.97 m (V2). The maximum observed TH value was 19 m (V1). There were no significant differences of TH values between the V2 and V3 vitality classes (18.00–18.40 m). The distributions of TH values in the V4 and V5 classes were flatter, with a smaller number of particularly large values.

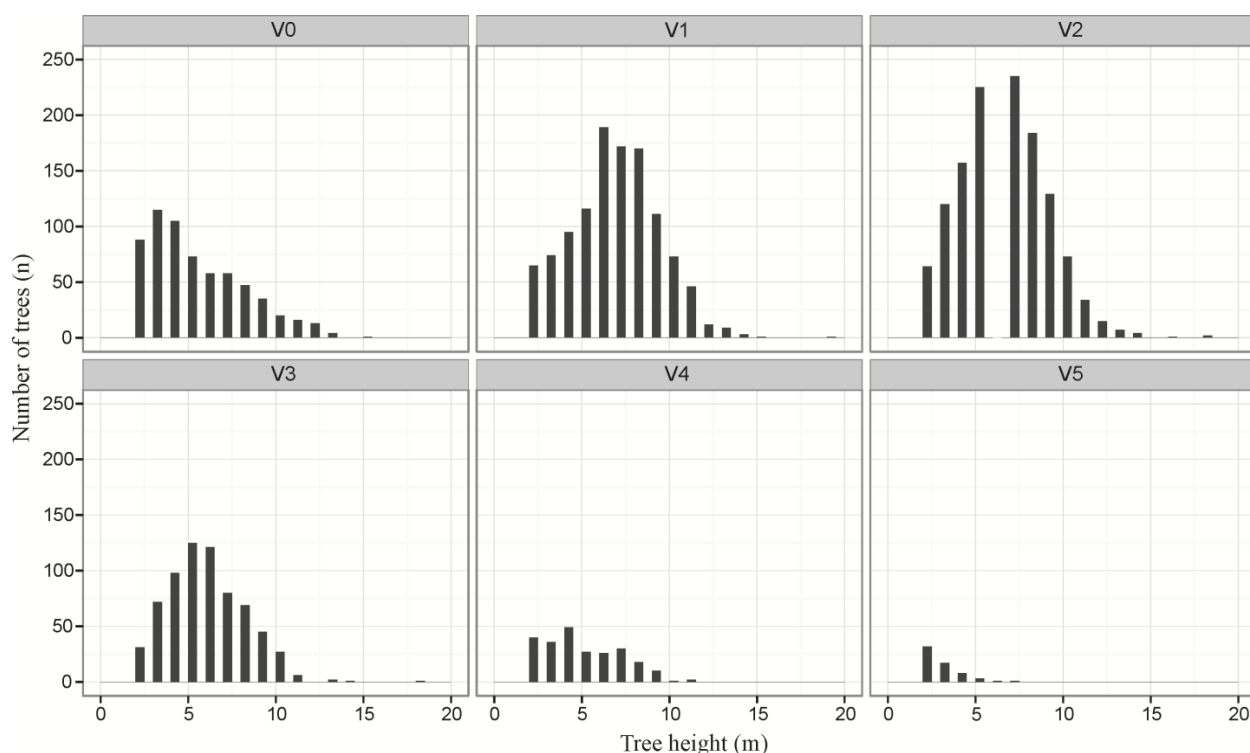
**Table 4-3** Summary statistics of the measured TH and DBH parameters of the *P. euphratica* trees of different vitality classes.

Vitality class	Number of trees (n)	DBH (cm)				TH (m)			
		Min.	Mean	Max.	SD	Min.	Mean	Max.	SD
V0	692	3.80	15.90	85.00	14.67	1.20	5.32	15.70	2.79
V1	1069	4.20	25.31	80.00	14.67	1.20	6.97	19.00	2.79
V2	1342	9.22	26.83	110.50	12.31	1.00	6.69	18.40	2.63
V3	617	14.20	30.22	119.00	13.66	0.80	6.12	18.00	2.51
V4	229	20.00	33.06	126.00	17.89	0.60	4.87	11.00	2.35
V5	368	34.00	17.43	92.00	15.58	0.00	0.04	3.90	0.36

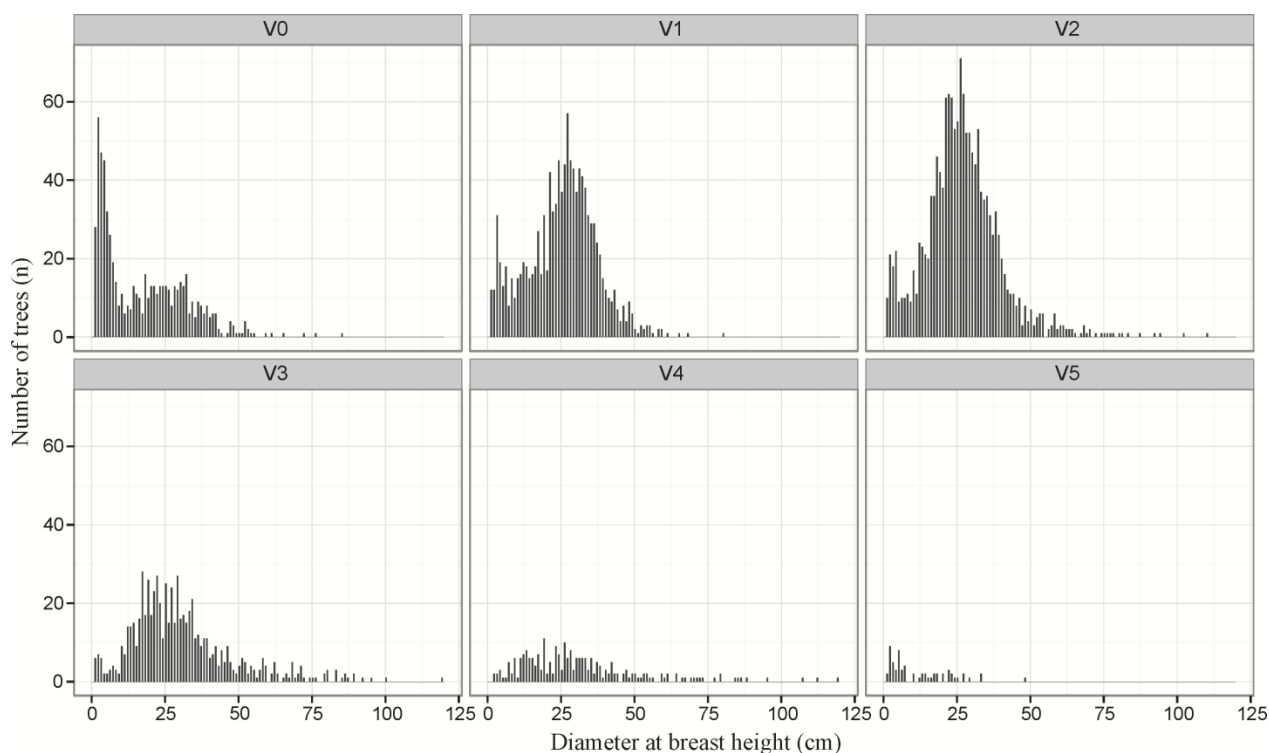
\* Min. = minimum, Max. = maximum, SD = standard deviation, DBH = diameter at breast height, TH = tree height

The DBH distributions of *P. euphratica* trees were characterized by an irregular shape in the different vitality classes (Fig. 4.29). The mean DBH values of *P. euphratica* trees increased from 15.90 to 33.06 cm as one went from the V0 to the V4 class, but exceptional values (17.43 cm) were noted for trees classified as V5 (Table 4.3). All trees with the exception of V5 were characterized by a greater variation in DBH. The largest trees had the maximum DBH values of 119 cm and 126 cm in the V3 and V4 classes, respectively. Using the method developed by Lu and Yan (1989) for determining the age of *P. euphratica* based on their TH and DBH values, it was found that a very large proportion of trees classified as having “healthy” and “good” vitalities were largely composed of relatively young trees. The DBH values in the V0, V1 and V2 classes were smaller (DBH ≤ 5 cm). In particular, the trees classified as V0 exhibited more young individuals, indicating that the regeneration process of the *P. euphratica* forests under current restoration practices in our study area tends to be ongoing. This shows that the *P. euphratica* trees have responded to water diversion significantly. It is also worth mentioning that there were great variations in DBH values for

different vitality classes, but that this was not the case for the TH values, suggesting that DBH (horizontal) growth of the *P. euphratica* trees in the lower reaches of the Tarim River seems to be faster than the TH (vertical) growth.



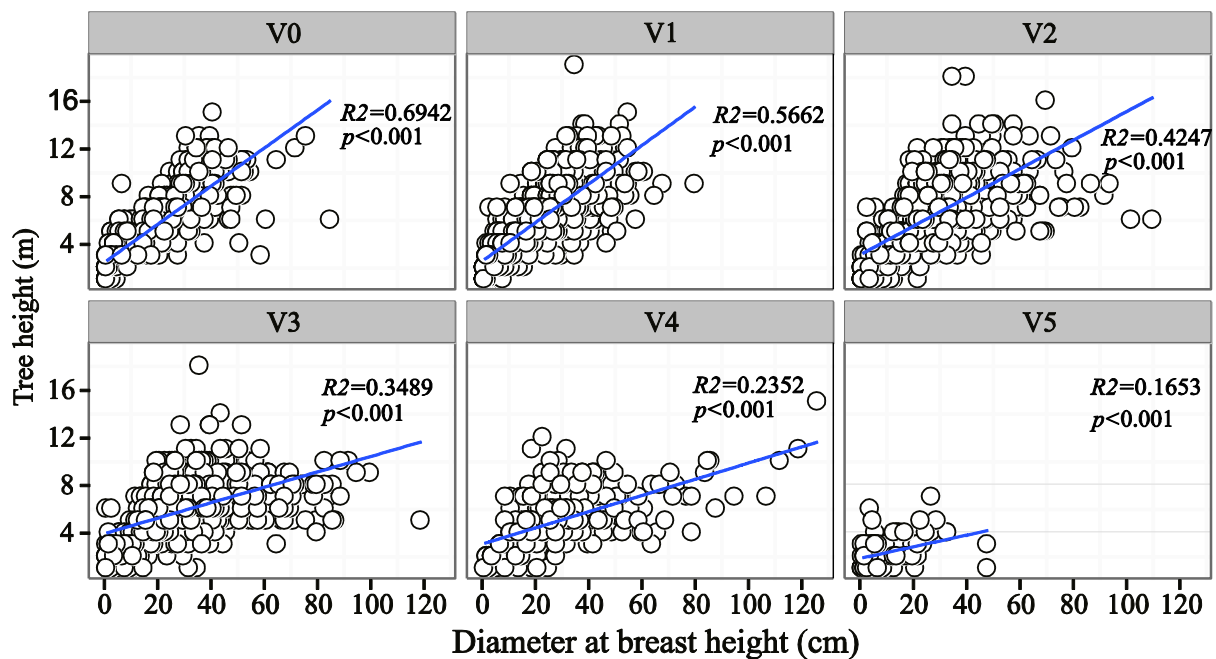
**Fig. 4-28** Distributions of tree height (TH) values of the *P. euphratica* trees of different vitality classes.



**Fig. 4-29** Distributions of diameter at breast height (DBH) values of the *P. euphratica* trees of different vitality classes.

### 4.3.3 INFLUENCE OF TREE VITALITY ON THE HEIGHT-DIAMETER RELATIONSHIP

The TH and DBH parameters are the most important variables with regard to forest structure, and are also essential variables in assessing forest condition and in modelling stand dynamics (Huang et al. 1992; Zhang, 1997; Maryamgul et al. 2013). Note, however, that the diameter of a tree is much easier to measure than its height, and that either one of these two parameters can be estimated by the height-diameter relationship model (Shawn et al. 2008). Under suitable site conditions, there is a strong biological relationship among the different ecological parameters of vegetation. The relationships between the TH and DBH parameters of *P. euphratica* trees of different vitality classes are shown in Fig. 4.30.



**Fig. 4-30** Correlations between TH and DBH for the *P. euphratica* trees of different vitalities.

In this relationship, the TH and DBH were taken as the independent and dependent variables, respectively. We estimated the  $R^2$  coefficient as obtained from the linear regression model for the TH and DBH values of the *P. euphratica* trees at a  $P < 0.001$  significance level. The relationship between TH and DBH in the V0 class appears to be stronger ( $R^2 = 0.6942$ ,  $P < 0.001$ ) than in the other vitality classes. Since the majority of the high-vitality trees grow close to the river watercourse, the *P. euphratica* trees have suffered less from limited water supply, given the favorable groundwater table (Aishan et al. 2013). The strength of the height-diameter relationship decreased significantly with decreasing tree vitality as one went from V2 to V5. The height-diameter relationships in medium, senesced, dying and dead trees were 0.4247, 0.3489, 0.2352 and 0.1653, respectively. The main reason for this result could be that the normal growth of trees in these vitality classes is highly limited by groundwater and soil moisture availability (Aishan et al. 2013; Grashey- Jansen et al. 2014).

## 5 ASSESSMENT OF THE REHABILITATION AND REGENERATION OF THE DEGRADED FORESTS

As mentioned before, one of the pressing environmental concerns in the Tarim Basin is further degradation of Tugai riparian forests along the both sides of the river, due mostly to the direct and indirect effects from anthropogenic activities. Restoring these forests for different degradation levels and the conservation of the existing forest resources are of critical importance with regard to enabling them to provide lasting ecosystem functions and ecosystem services. In the previous chapter, detailed analyses of the structures, distribution patterns and status quos of highly degraded *P.euphratica* forests under different hydrological regimes were introduced. The Tarim riparian forest ecosystems are highly depend on the particular flood regimes for their existence. With the construction of Daxihaizi Reservoir, the *P. euphratica* riparian forests in the lower reaches of the Tarim River have not been provided with a natural flow regime since 1972. Currently, a highly controlled and irregular man-made water diversion seems to be only one alternative. In this chapter, special focus is given to spatio-temporal dynamics and the response of degraded *P. euphratica* trees over recent years to restoration measures - i.e., to the water diversion project that has been regarded as the main driver for recharging the groundwater to the levels where the deteriorated vegetation could continue its life cycle and finally fulfill the rehabilitation of the ecosystem. The main reasons for establishing the permanent sampling site (a) and the random sampling site (b), the latter contained the 5 subplots (P1-P5), were addressed in Chapter 2. In such a harsh environment, the TH and DBH parameters are less responsive, but the other parameters, such as vitality, frequency of root suckers, crown reestablishment, the recruitment of young seedlings, the crown diameter and the height to crown, tend to be relatively sensitive to the environmental gradients (distance to the river, groundwater level, soil moisture, etc.). Therefore, it is mainly the responses of these parameters in different spatial and temporal scales that is assessed and discussed.

### 5.1 OVERVIEW OF THE FIVE RANDOM PLOTS

Five circular plots of 50-m radii were set up at different distances from the river channel (in the direction of the Taklamakan desert and perpendicular to the river) in order to assess the development of the forests under water stress. A detailed overview of the five plots (P1, P2, P3, P4, and P5) is given in Figs. 5.1-5.5, respectively. The tree parameters within each plot had been repeatedly measured during the growing seasons of vegetation (on July 2004, July 2007 and August 2011).

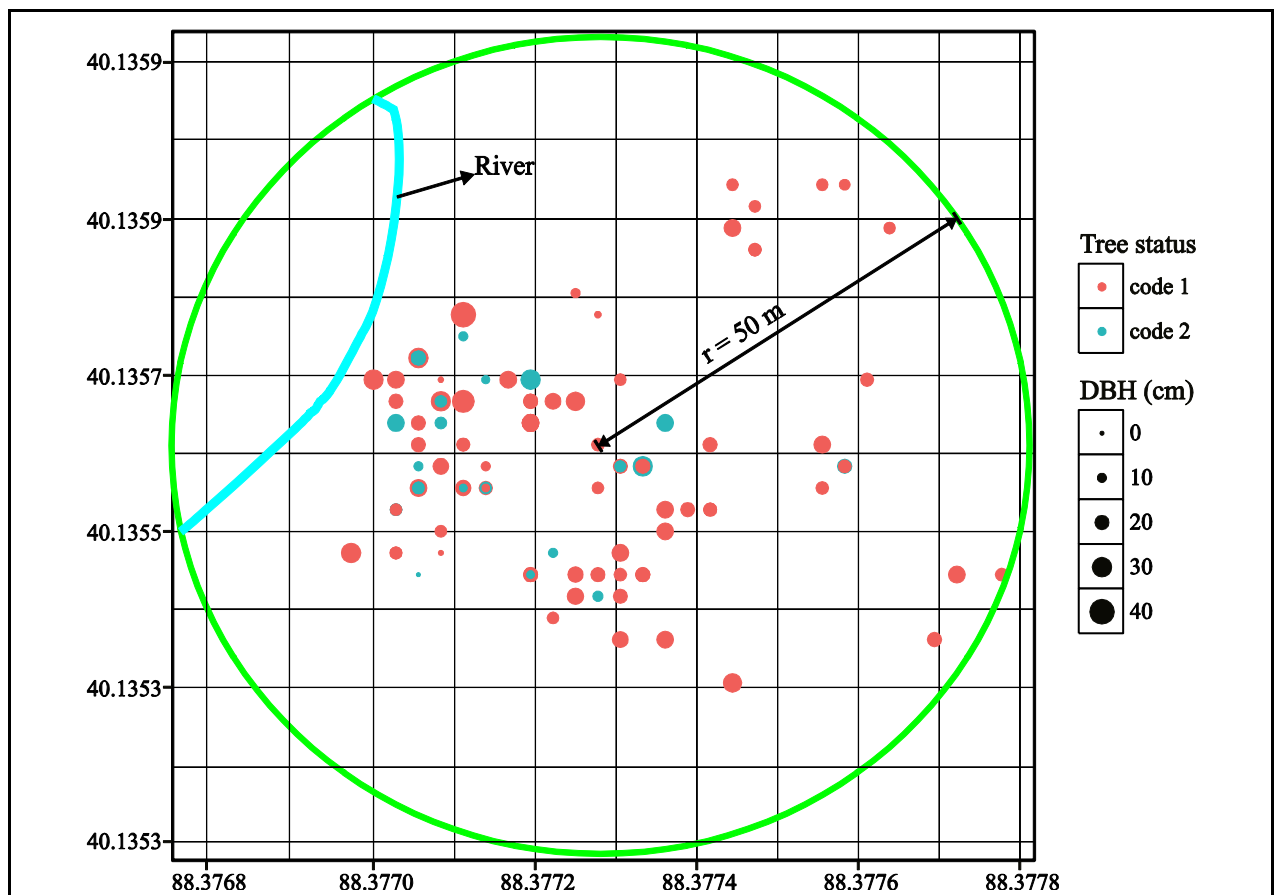
### 5.2 DESCRIPTIVE STATISTICS OF THE TREE PARAMETERS

As can be seen from Table 5.1, the structures of stands across the plots were different. A high tree density of 185,99 n/ha was observed for the P1 plot, located closest to the river. By

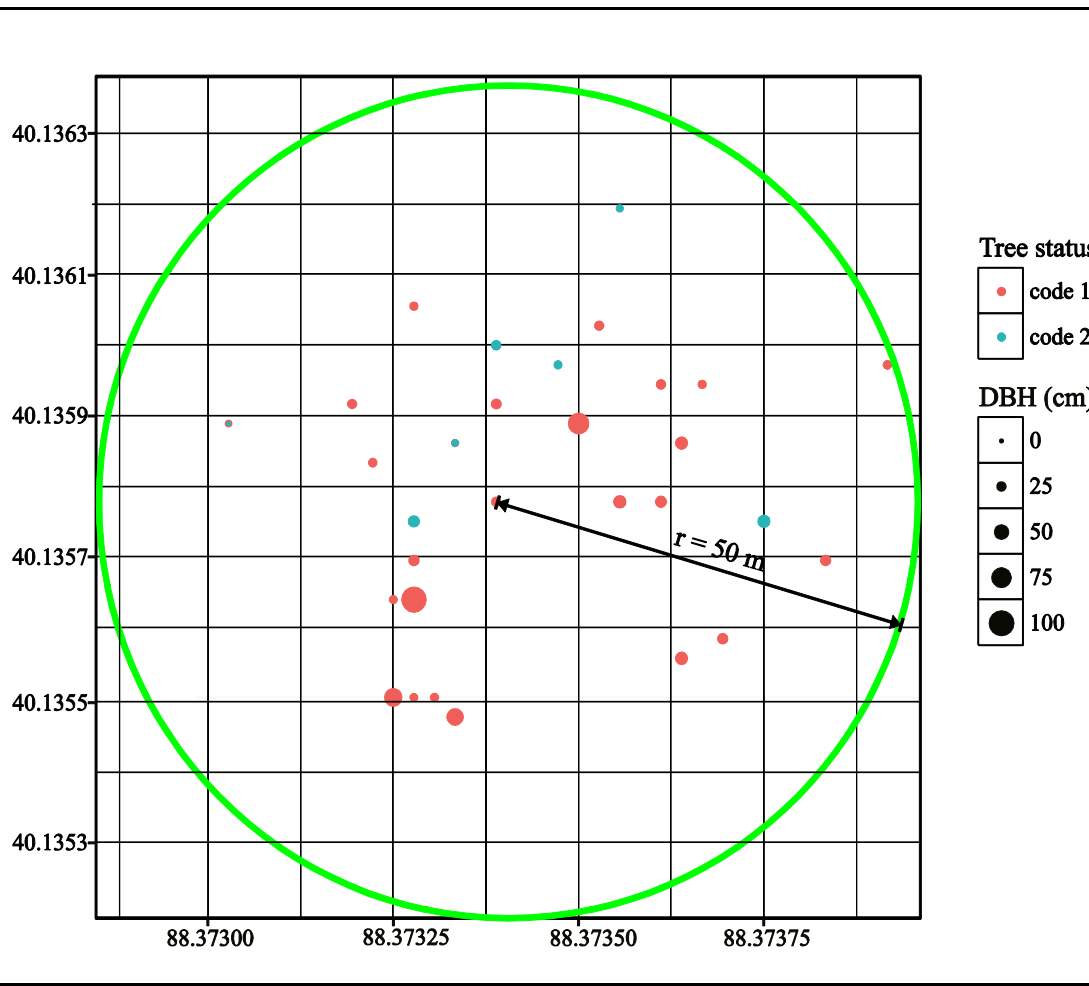
contrast, large numbers of dead or fallen trees were also observed, which was probably caused by the natural self-thinning of trees in the limited space. The trees in this plot tended to be distributed in clusters, which differed from the distributions in the other plots (Fig. 5.1). No apparent differences were found among the tree densities in the P3, P4, and P5 plots, and all of them had the same number of stands. However, with the exception of the P1 plot, there were considerable numbers of dead or fallen trees in the P4 ( $n = 28$ ) and P5 ( $n = 38$ ) plots. As such, the density of living stands tended to decrease as one went from P1 to P5. The mean DBH values ranged between  $17,49 \pm 6,61$  and  $47,59 \pm 19,17$  (Table 5.1). Stands in the P1 plot closest to the river had smaller DBH values, while stands in the P5 plot that was the farthest away had the largest. Additionally, there were significant differences between the DBH values of these two plots ( $P < 0.001$ , Fig. 5.6b). On average, the DBH value increased as one went from P1 to P5, suggesting that the age of trees distributed in the P1 plot was less than that at other plots. The TH value among plots also varied significantly - e.g., the TH values of trees in the P2 and P3 plots had maximum values of  $5,25 \pm 1,82$  and  $5,21 \pm 1,78$ , respectively, and there was no statistically significant difference ( $P < 0.999$ , Figure 5.5a). The lowest TH value was observed at the P3 plot, and was significantly different from the TH values at the other plots. Trees in the P5 and P3 plots had largest mean crowns ( $3,54 \pm 1,28$ ,  $3,26 \pm 1,30$ , respectively) when compared to trees in the other plots, but the difference was not significant ( $p < 0.771$ , Fig. 5.6c). It is worth mentioning that the majority of the trees in the P5 plot had already lost their living crown, and so the recorded values for these trees were recorded as non-values. This is one of reasons why trees in this plot had a relatively larger crown diameter. Another reason was that the morphological features of most trees in this plot had low TH, large DBH, and large CD values. The minimum HC value of  $1,76 \pm 1,27$  (Table 5.1) was observed in the P1 plot, and was significantly different from the HC values in the other plots (Fig. 5.6d), suggesting that the trees in this plot were the most likely to produce new branches and to develop new crowns.

**Table 5-1** Descriptive statistics for the main eco-morphological parameters of the *P. euphratica* trees for the five sampling plots.

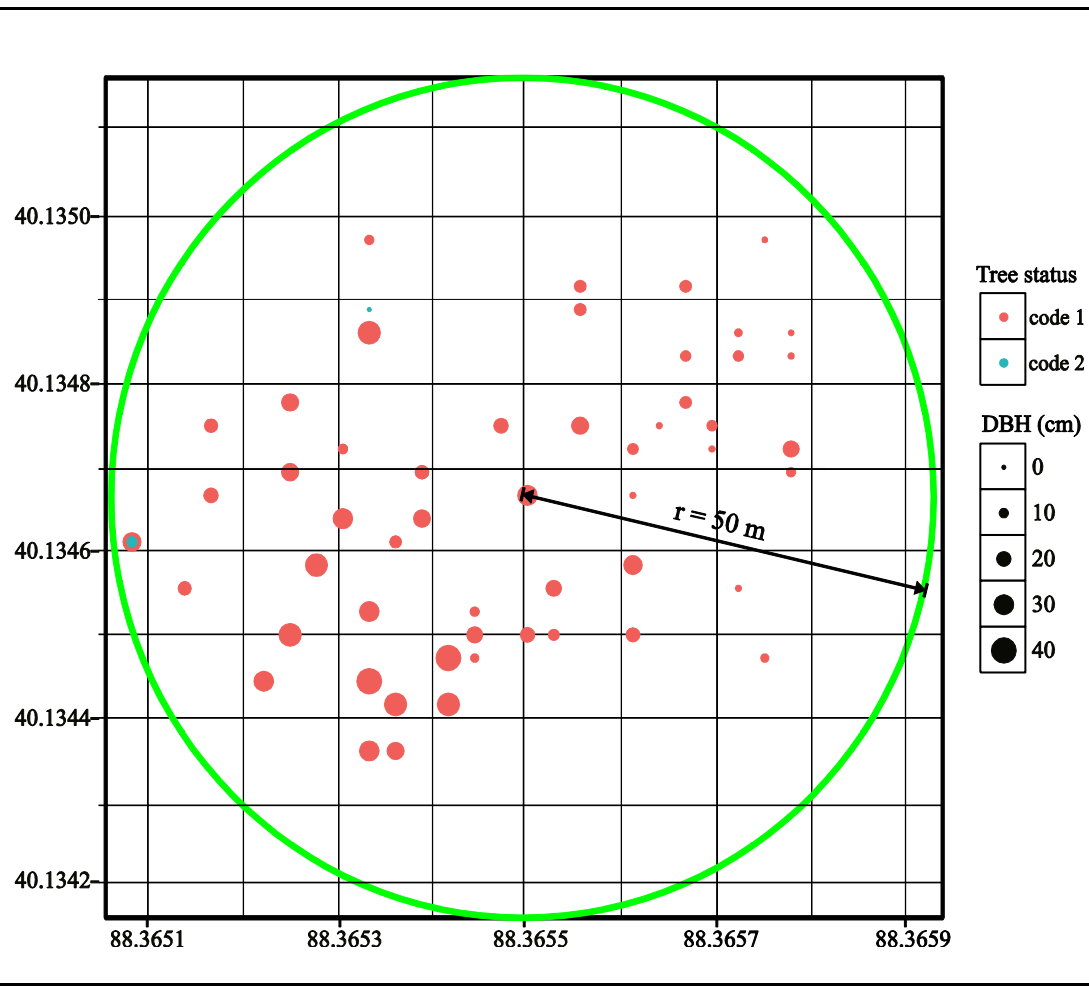
Parameters \ Plots	P1	P2	P3	P4	P5
Distance of central tree from the river	20 m ~	200 m ~	750 m ~	1000 m ~	> 1400 m
Number of trees (total)	146	51	90	80	90
Number of trees (V5-V6)	40	8	3	28	38
Density (n/ha)	185,99	64,97	114,65	101,91	114,65
Basel area (m <sup>2</sup> /ha)	5,04	5,24	3,62	6,55	16, 81
DBH (cm)	17,49 ± 6,61	27,74 ± 16,89	17,66 ± 9,69	25,73 ± 13,81	47,59 ± 19,17
TH (m)	4,75 ± 2,06	5,25 ± 1,82	5,21 ± 1,78	3,51 ± 2,70	4,37 ± 1,95
TH/DBH ratio (m/cm)	0,30 ± 0,14	0,23 ± 0,10	0,37 ± 0,17	0,20 ± 0,22	0,10 ± 0,05
CD (m)	2,15 ± 0,68	3,26 ± 1,30	2,60 ± 1,31	2,31 ± 0,74	3,54 ± 1,28
HC (m)	1,76 ± 1,27	2,71 ± 1,08	2,54 ± 1,18	2,19 ± 0,88	2,26 ± 0,86



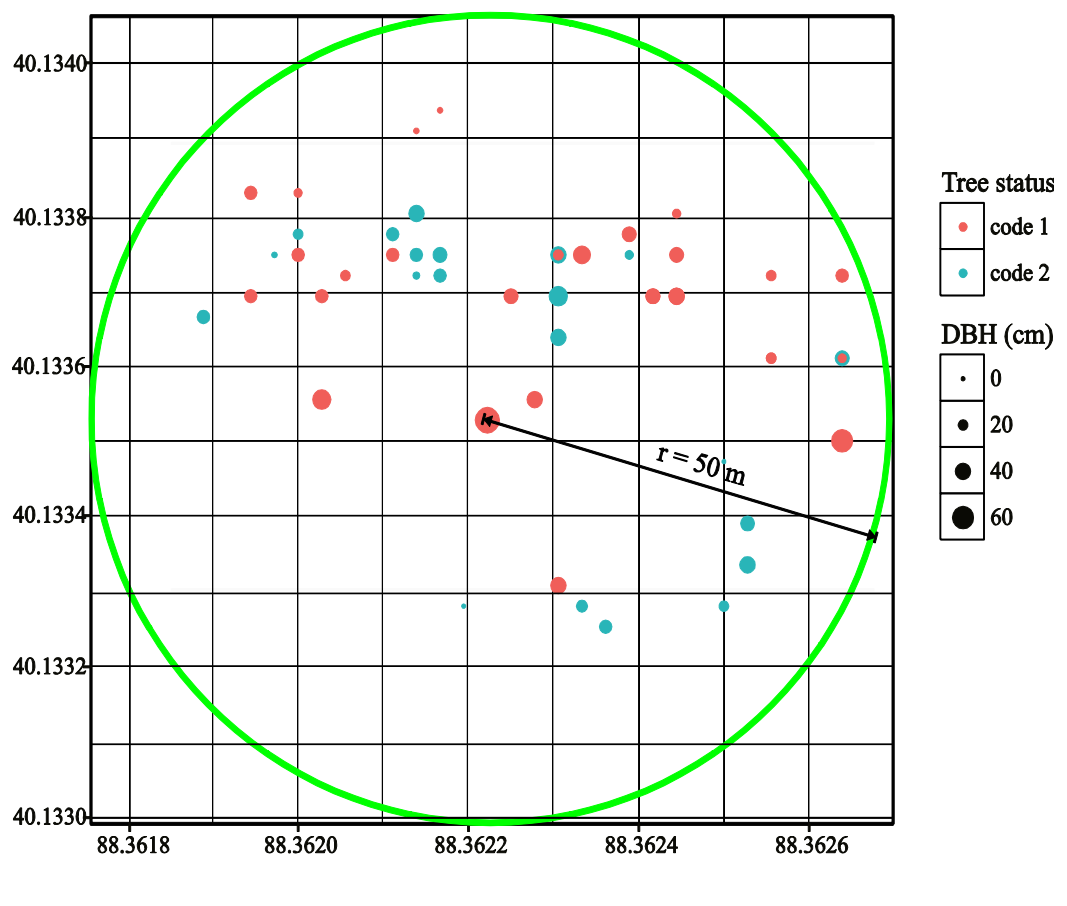
**Fig. 5-1** Map showing the distribution of trees on the P1 plot. The green circle represents the boundary of the plot, red dots (code 1) represent relatively healthy trees (with vitality ranges of V0-V4), and blue dots (code 2) represent highly degraded trees without living branches or dieback (with vitality ranges of V5-V6).



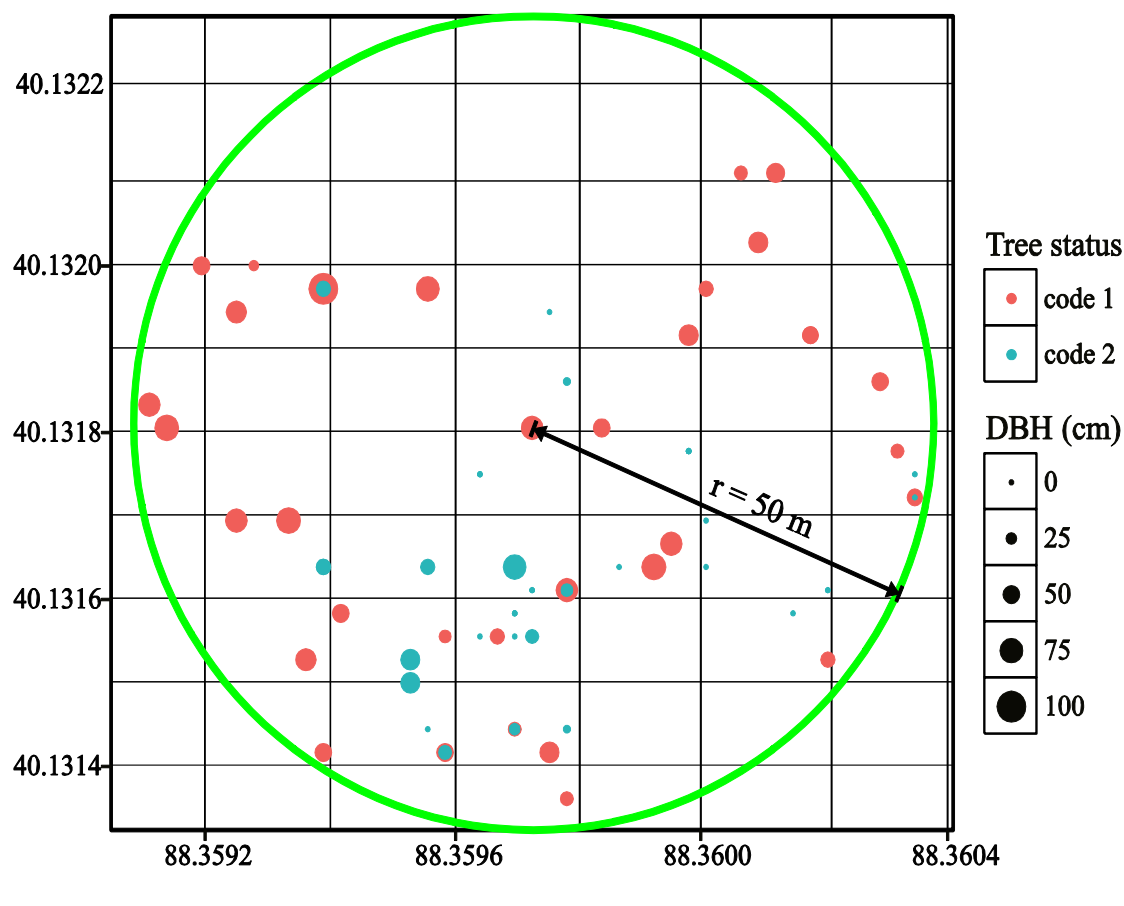
**Fig. 5-2** Map showing the distribution of trees on the P2 plot. The green circle represents the boundary of the plot, red dots (code 1) represent relatively healthy trees (with vitality ranges of V0-V4), and blue dots (code 2) represent highly degraded trees without living branches or dieback (with vitality ranges of V5-V6).



**Fig. 5-3** Map showing the distribution of trees on the P3 plot. The green circle represents the boundary of the plot, red dots (code 1) represent relatively healthy trees (with vitality ranges of V0-V4), and blue dots (code 2) represent highly degraded trees without living branches or dieback (with vitality ranges of V5-V6).

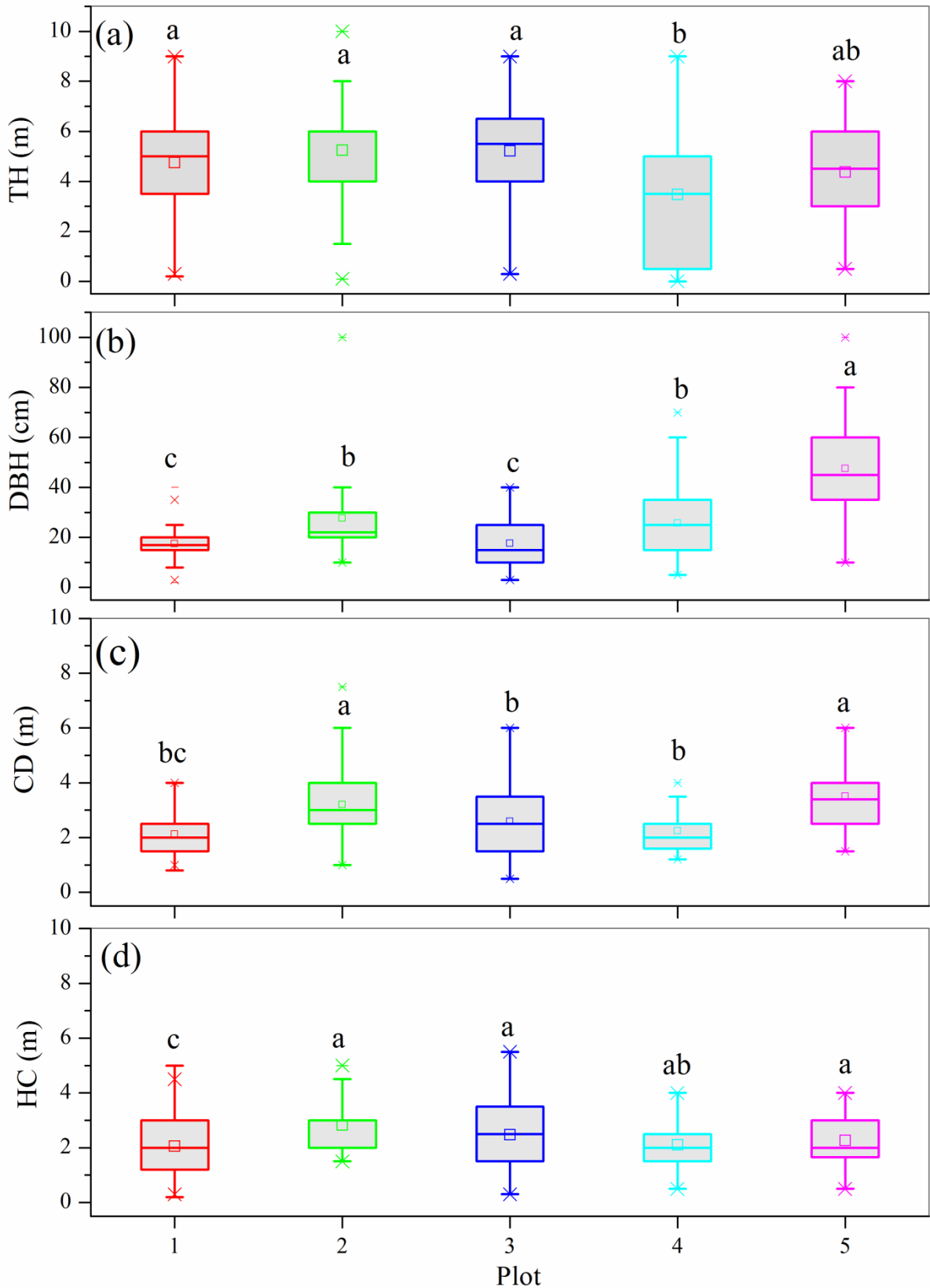


**Fig. 5-4** Map showing the distribution of trees on the P4 plot. The green circle represents the boundary of the plot, red dots (code 1) represent relatively healthy trees (with vitality ranges of V0-V4), and blue dots (code 2) represent highly degraded trees without living branches or dieback (with vitality ranges of V5-V6).



**Fig. 5-5** Map showing the distribution of trees on the P5 plot. The green circle represents the boundary of the plot, red dots (code 1) represent relatively healthy trees (with vitality ranges of V0-V4), blue dots (code 2) represent highly degraded trees without living branches or dieback (with vitality ranges of V5-V6).

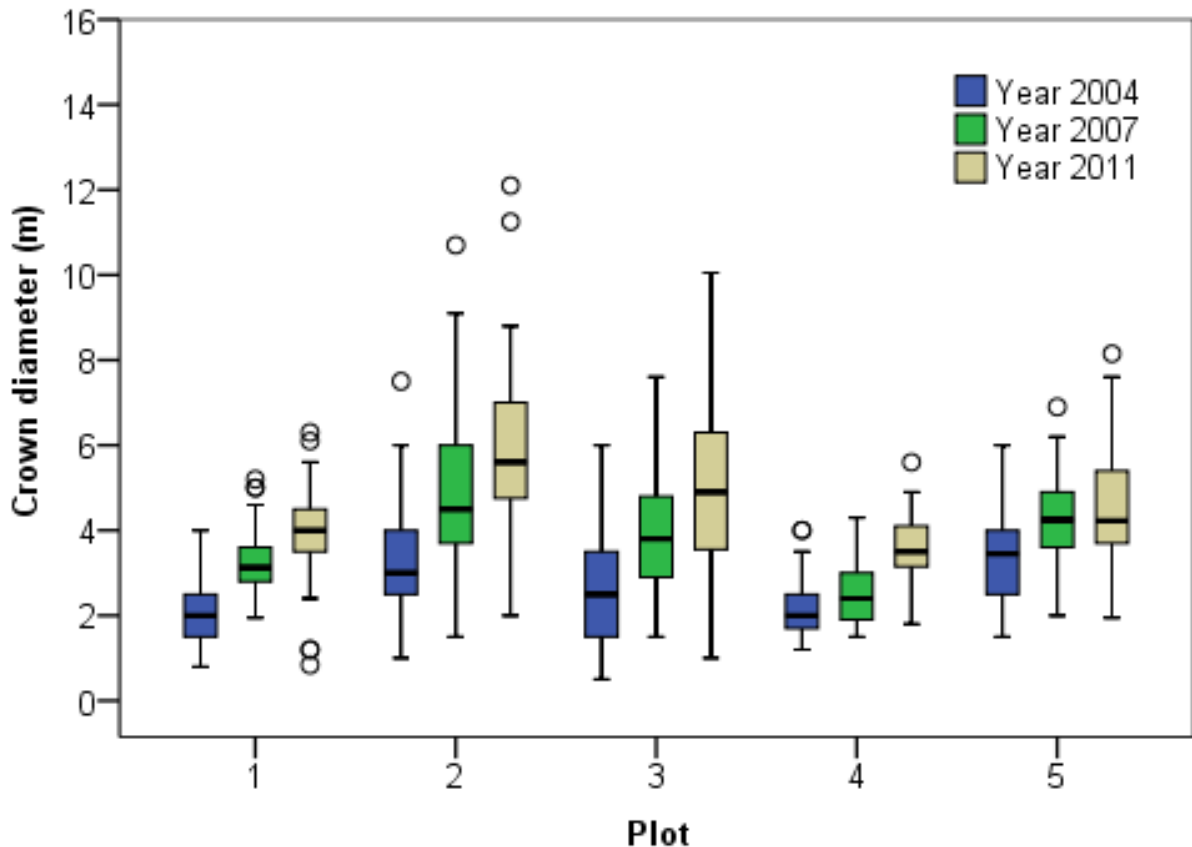




**Fig. 5-6** Box-whisker plots for the main eco-morphological parameters of *P. euphratica* trees at the five random plots (P1-P5). For each box plot, the box represents the 1st and 3rd quartiles, whiskers denote 1.5 times the interquartile range, the line inside the box indicates the median, unfilled squares indicate the means, and cross marks indicate outliers. The different letters denote significant differences at the 95 % level using a Tukey HSD test.

### 5.3 CHANGES IN CROWN DIAMETER

Crown diameter is one of the key ecological parameters of floodplain forests (Newton 2007; Halik et al. 2011). With regard to *P. euphratica* forests affected by the water diversion project, the variation of the CD value is one of the major indices for measuring the recovery effects. Fig. 5.7 shows the CD values of *P. euphratica* trees at the random sampling plot (b) at the Arghan transect for the years 2004, 2007 and 2011.



**Fig. 5-7** Crown diameter (CD) of *P. euphratica* trees in the years 2004, 2007 and 2011 for the random sampling plots at Arghan. The figure shows the median values (horizontal lines), the 25–75 % quartiles (boxes), the ranges (maximum and minimum) and the outliers (open points).

From this figure, one may conclude that the CD values of *P. euphratica* trees at the five plots, at different distances from the river, showed a variety of responses to the water diversion practices. The CD value of *P. euphratica* trees at the 50-m distance from the river (at the P1 plot) increased from 2.15 m in 2004 to 3.47 m in 2007, and to 3.96 m in 2011. Moreover, there are significant differences between the different years at the P1 plot (Table 5.2). This suggests that water diversion had a positive role in increasing the crown size of individual trees. Similar significant changes are observed in the CD values of the *P. euphratica* trees sampled at the P2 and P3 plots. Between 2004 and 2011, there were total increases of 2.62 m and 2.41 m at the P2 and P3 plots, respectively. Additionally, water diversion had positive effects on increasing foliage mass and the number of live branches of trees. The CD values for the P4 and P5 plots also showed some changes. However, the CD values at the P5 plot did not differ significantly from year to year, unlike what was found in the other plots. Notably, there was no significant increment in the CD value from 2007 to 2011 (Table 5.2). At the P4 plot,

the CD value increased from 2.30 m in 2004 to 2.53 m in 2007 and to 3.56 m in 2011. Even at the 1,000 m distance from the river (P5), the CD value of the *P. euphratica* trees still displayed a response to the water diversion and expanded by 4.23 m in 2007 and by 4.46 m in 2011. It is worth mentioning that the CD values increased more in the 3 years between 2004 and 2007 than in the 4 years between 2007 and 2011, regardless of the distance of the sampled trees from the riverbed. However, Table 5.2 shows that there are no clear significant trends among the plots (e.g., the differences in CD value increases at the P3 and P4 plots between different years are not significant). The groundwater levels at the different distances from the river at Arghan transect reached their highest levels after the sixth water diversion, after which they once more started to drop. As suggested above, this may be related to the water volume and the duration of flooding. To summarize, the variations in the CD values tend to decrease with increasing distance from the river, but there does not appear to be a clear trend.

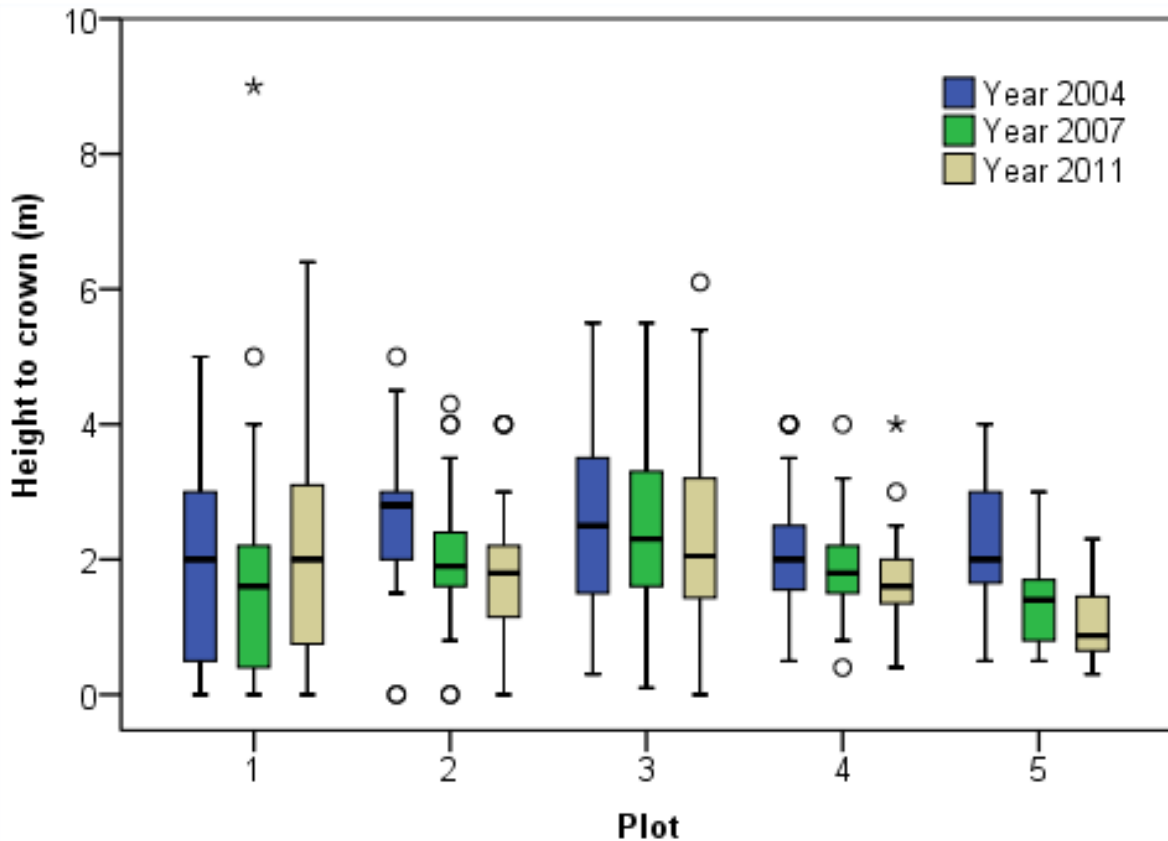
**Table 5-2** Statistical analyses of the CD variability between plots and for the temporal changes within plots.

Parameter	Year	Plot (P)				
		P1	P2	P3	P4	P5
CD	2004	2.15±0.68BCc	3.26±1.30Ac	2.60±1.31Bc	2.31±0.74Bc	3.54±1.28Ab
	2007	3.48±2.69Bb	4.91±1.94Ab	3.84±1.35Bb	3.67±1.26Bb	4.87±1.77Aa
	2011	3.96±0.92Ca	5.88±2.10Aa	5.01±1.94Ba	4.84±1.27Ba	4.46±1.51Ba

Values are given as mean ± SD; the different uppercase letters indicate statistically significant differences between the investigated plots, while the lowercase letters refer to statistically significant differences between measuring years, based on ANOVA ( $P < 0.05$ ). CD = crown diameter.

#### 5.4 CHANGES IN HEIGHT TO CROWN

As discussed in the previous chapter, HC values can indicate whether the water diversion project has had a positive impact on the tree growth or not. Fig. 5.8 depicts the development of the CH of *P. euphratica* trees at the Arghan transect for the years 2004, 2007 and 2011. The CH values at all five plots changed remarkably under a different regime of water availability. The HC values at the P1 plot decreased from 1.76 m in 2004 to 1.69 m in 2007, but increased again from 1.69 m in 2007 to 1.98 m in 2011. Due to plot P1's location being close the riverbed, the effects of water diversion on groundwater recharge were more significant here than those at the other plots. However, the temporal changes in HC values between years at the P1 plot are not statistically significant (Table 5.3).



**Fig. 5-8** Height to crown (HC) of *P. euphratica* trees in the years 2004, 2007 and 2011 for the random sampling plots at the Arghan transect. The figure shows the median values (horizontal lines), the 25–75 % quartiles (boxes), the ranges (maximum and minimum) and the outliers (asterisks and open points).

The water availability at the P1 plot is relatively suitable for vertical growth of the *P. euphratica* trees (mainly, the growth of tree height). It was at this plot that the majority of the taller trees were found during the field work. As a result, the growth of trees increased the HC values of the trees at this plot. At the P2 plot, the HC value has seen a significant decrease from 2.72 m in 2004 to 2.06 m in 2007, and to 1.7 m in 2011. However, as can be seen from the data in Table 5.3, there was no significant decline in the HC value from 2007 to 2011. Similar changes also occurred at the P3 and P4 plots, and even at the P5 plot — where the groundwater level does not support a normal development of riparian vegetation. There, the HC values also exhibited significant changes from 2004 to 2007, declining from 2.26 m in 2004 to 1.29 m in 2007 and to 1.02 m in 2011. The decreasing HC values at the P5 plot showed the greatest decreases among the five plots in the study area. The HC value differences between plots are also significant, with the differences the P2 and P3 plots being the only exception. The decreases were mainly caused by new branches sprouting from the stem and base. It can thus be concluded that *P. euphratica* trees under water stress may tend to develop their tree structure horizontally rather than vertically.

**Table 5-3** Statistical analyses of the HC variability between plots and for the temporal changes within plots.

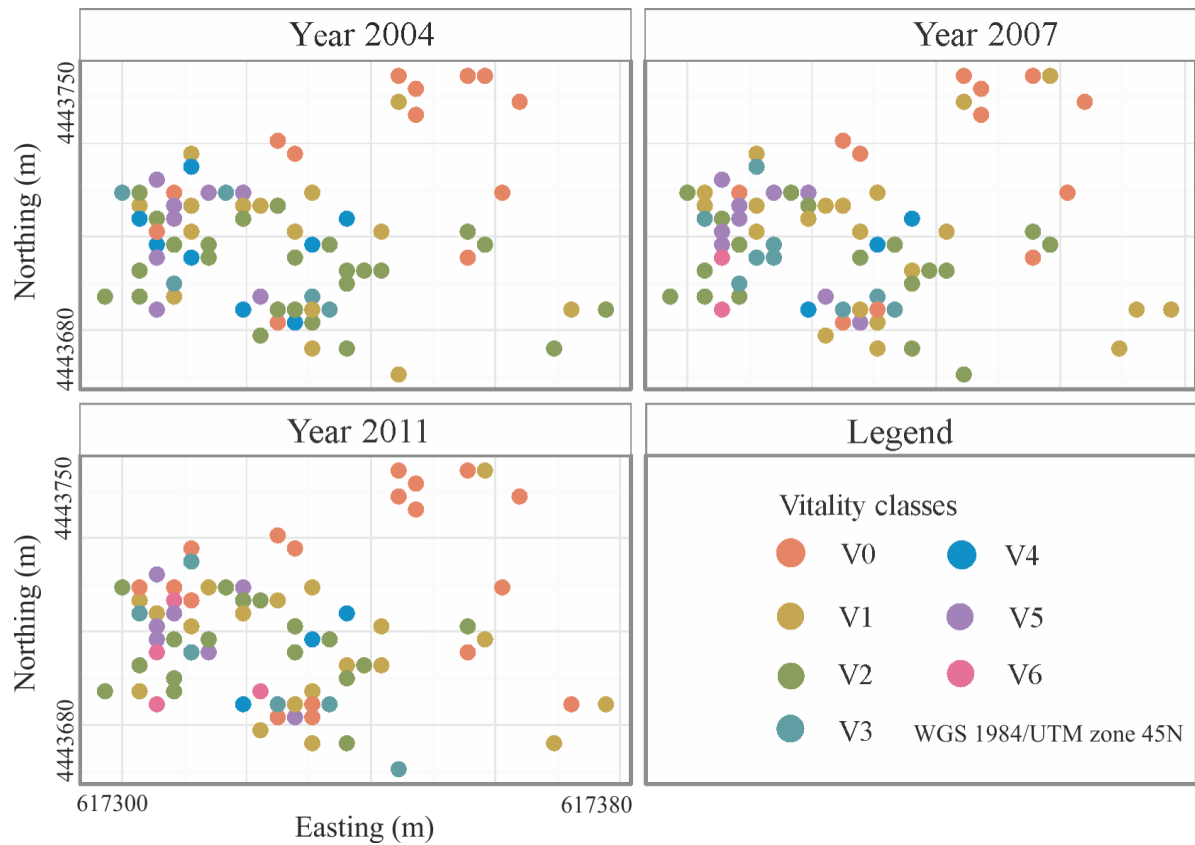
Parameter	Year	Plot (P)				
		P1	P2	P3	P4	P5
HC	2004	1.76±1.27Ca	2.71±1.08Aa	2.54±1.18Aa	2.19±0.88ABa	2.26±0.86Aa
	2007	1.69±1.96ABa	2.06±0.95Ab	2.40±1.22Aa	1.87±0.95ABa	1.87±0.95ABb
	2011	1.98±1.48Ba	1.70±1.05Bb	2.36±1.34Aa	1.68±0.65Bb	1.03±0.50Cb

Values are given as mean ± SD; the different uppercase letters indicate statistically significant differences between investigated plots, while the lowercase letters refer to statistically significant differences between measuring years, based on ANOVA ( $P < 0.05$ ). HC: Height to Crown.

## 5.5 DYNAMICS OF TREE VITALITY

As mentioned in the previous chapter, the vitality of trees can be a key indicator in assessing the overall situation of a forest - e.g., its health conditions, integrity and resilience. Based on the visual classification criteria for the vitality of *P. euphratica* trees, the tree vitalities at the five plots were grouped into seven classes: Healthy tree (V0), Good (V1), Medium (V2), Senesced tree (V3), Dying tree (V4), Dead tree (V5) and Fallen tree (V6). Each of the classes was then analyzed for the years 2004, 2007 and 2011 so as to assess the health conditions of the trees in those plots (Figs. 5.9-5.13 and Tables 5.4-5.8).

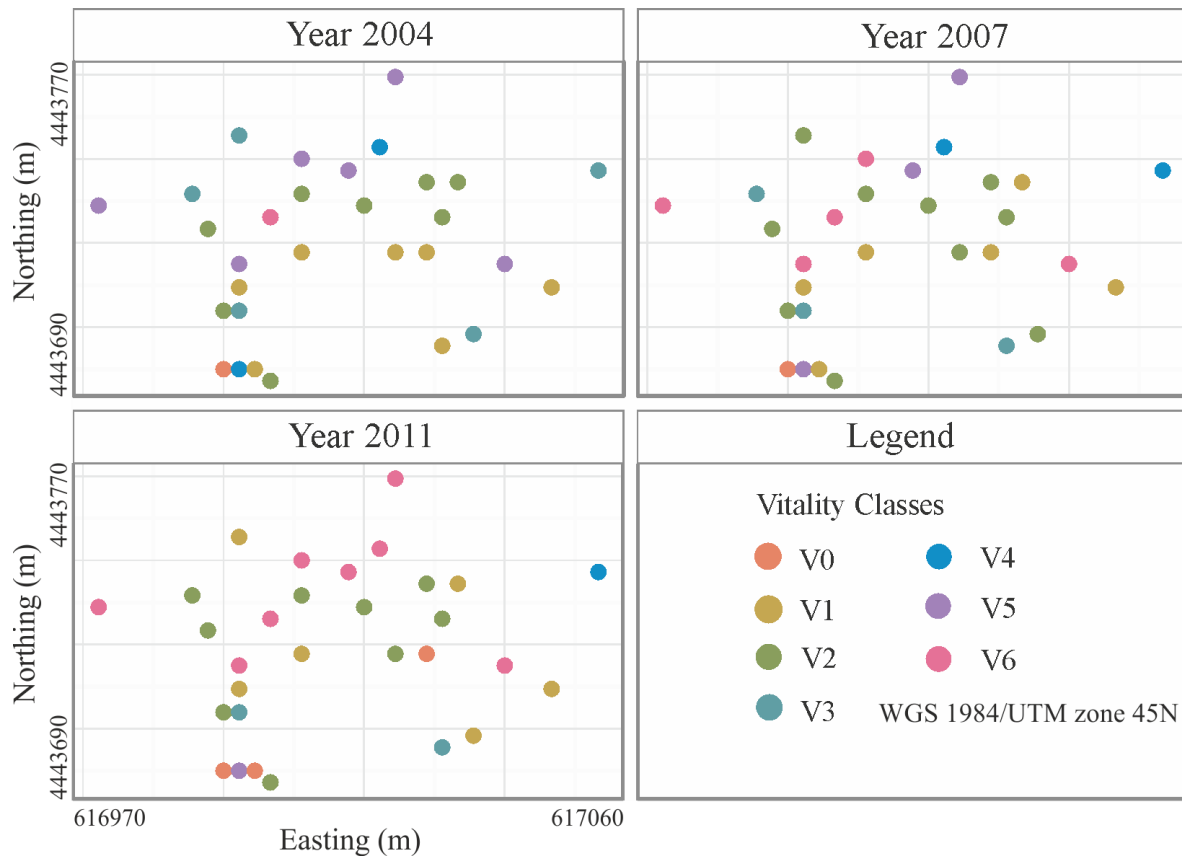
On average, the proportion of trees belong to the vital, good and medium classes seemed to decline in the vertical direction from the river to the Taklamakan desert (i.e., from the P1 plot to the P5 plot). Large portions of the trees in the P1, P2, and P3 plots were mainly composed of trees from the V0, V1 and V2 vitality classes. For example, at the P1 plot, trees belonging to the V0-V2 classes accounted for 61 % in 2004, 63 % in 2007 and 65 % in 2011 (Table 5.4). At the P2 plot, they accounted for 55 %, 62 % and 69 % for the year 2004, 2007 and 2011, respectively (Table 5.5). Considerable numbers of trees in the P4 and P5 plots, however, were dying, dead or fallen (on average, 50 % at the P4 plot and 65 % at the P5 plot - see Tables 5.7 and 5.8). The P5 plot had the largest number of dead trees. Specifically, 6 fallen trees were observed in 2007 and 13 in 2011, with only a single high-vitality tree observed in 2011 (Table 5.8). This result indicated that trees in this plot are still suffering from water stress and are in the process of degradation. Over the seven years from 2004 to 2011, the number of trees in the different vitality classes at the 5 plots has shown different change patterns, with fluctuations mainly taking place between trees in the V0, V1, V2 and V4 classes. At the plots closer to the river (V0 and V1), the number of trees exhibited an increasing trend. Most of the trees belonging to the V3 class in 2004 shifted to the V2 and V1 classes as an effect of relatively favorable groundwater availability, suggesting that restoration measures took effect in halting further degradation of these trees. However, the proportion of trees in the V4, V5 and V6 classes did reach high levels. All in all, the trees at all plot demonstrated different degrees of recovery, but examples of maximum recovery seemed to be restricted to the P1 and P2 plots. Trees at the other plots showed lesser degree of recovery and even some degradation trends.



**Fig. 5-9** Distribution of trees in the different vitality classes in the plot 1 for the investigated years. Map section is identical for the investigated years 2004, 2007 and 2011.

**Table 5-4** Variation of the number of trees in different vitality classes in the plot 1 for the investigated years

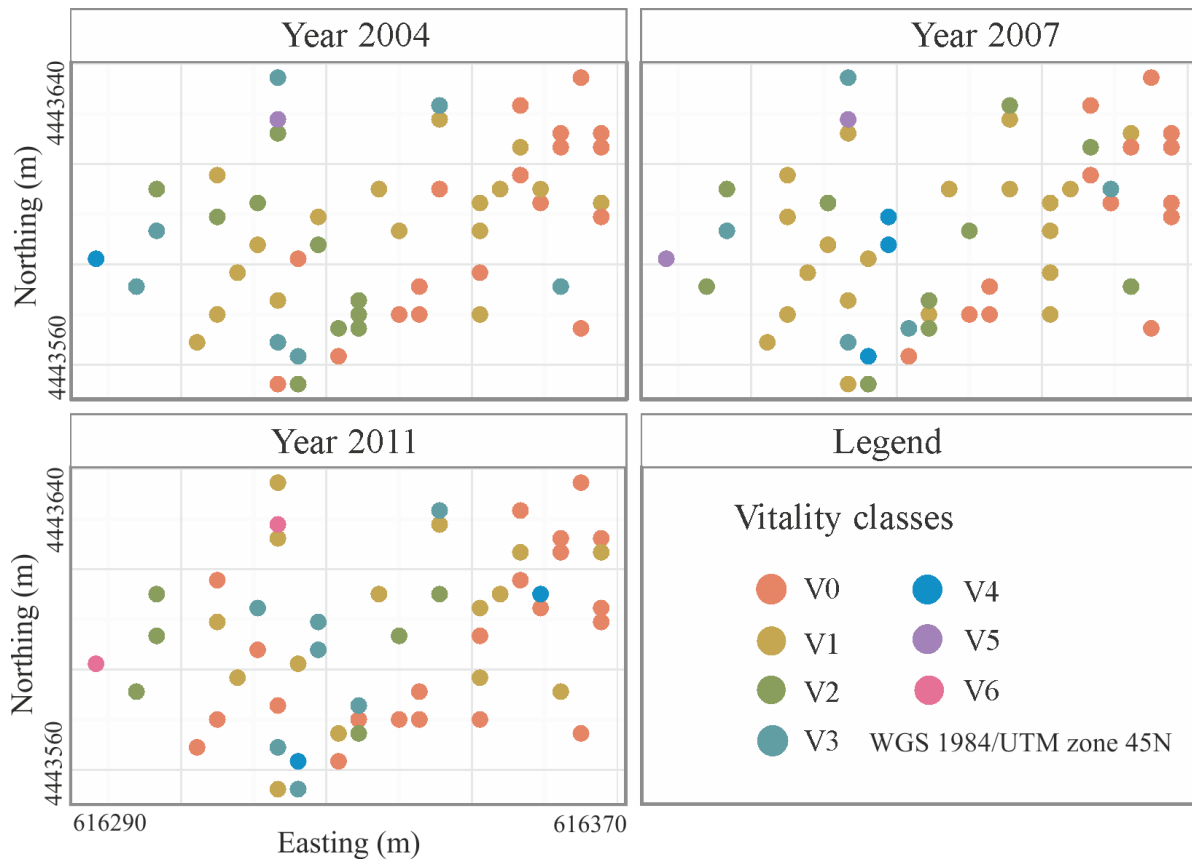
Plot	Year	Number (n) & proportion (%)	Vitality classes						
			V0	V1	V2	V3	V4	V5	V6
Plot 1	2004	n	18	25	46	17	23	17	0
		%	12,33	17,12	31,51	11,64	15,75	11,64	0
	2007	n	17	33	42	24	8	19	3
		%	11,64	22,60	28,77	16,44	5,48	13,01	2,05
	2011	n	25	33	38	19	6	18	6
		%	17,12	22,60	26,03	13,01	4,11	12,33	4,11



**Fig. 5-10** Distribution of trees in the different vitality classes in the plot 2 for the investigated years. Map section is identical for the investigated years 2004, 2007 and 2011.

**Table 5-5** Variation of the number of trees in different vitality classes in the plot 2 for the investigated years.

Plot	Year	Number (n) & proportion (%)	Vitality classes						
			V0	V1	V2	V3	V4	V5	V6
Plot 2	2004	n	1	13	15	9	5	8	0
		%	1,96	25,49	29,41	17,65	9,8	15,69	0
	2007	n	1	15	16	8	2	3	6
		%	1,96	29,41	31,37	15,69	3,92	5,88	11,76
	2011	n	7	12	16	4	1	2	9
		%	13,73	23,53	31,37	7,84	1,96	3,92	17,65

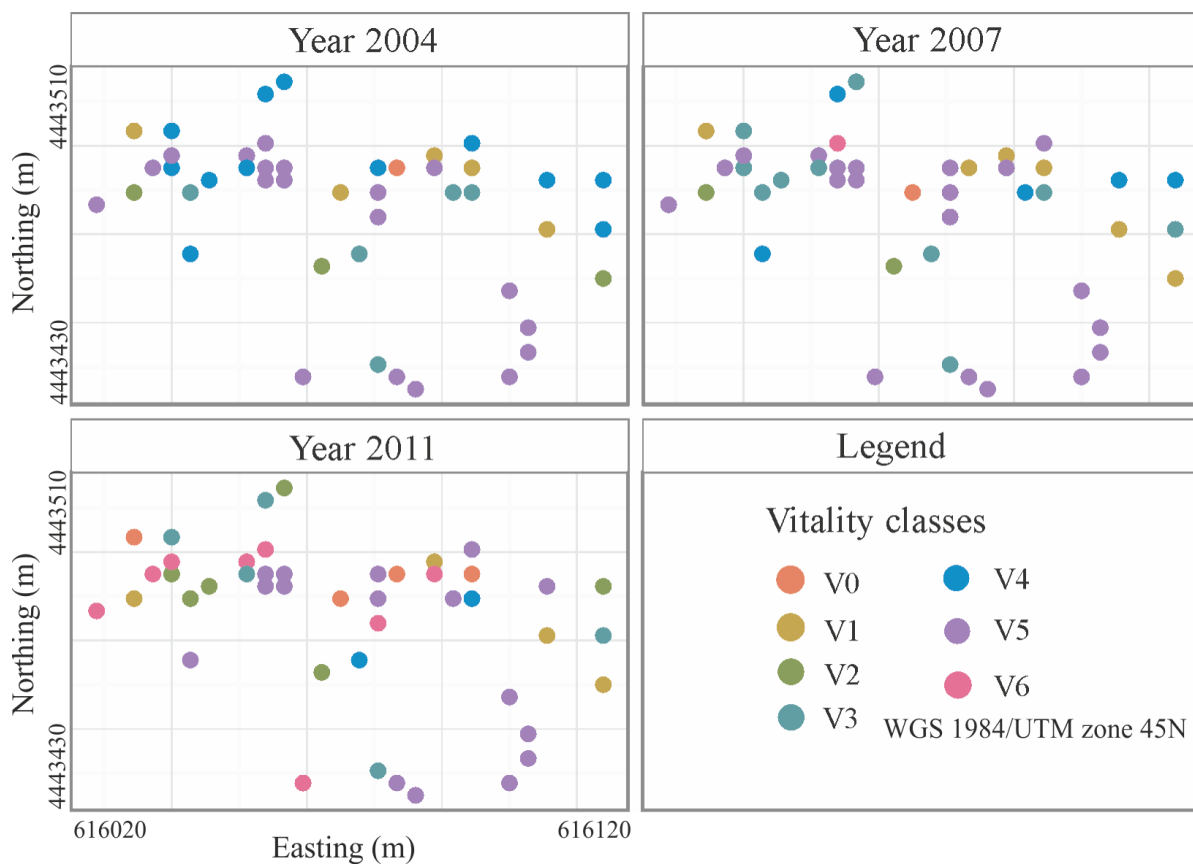


**Fig. 5-11** Distribution of trees in the different vitality classes in the plot 3 for investigated years. Map section is identical for the investigated years 2004, 2007 and 2011.

**Table 5-6** Variation of the number of trees in different vitality classes in the plot 3 for the investigated years

Plot	Year	Number (n) & proportion (%)	Vitality classes						
			V0	V1	V2	V3	V4	V5	V6
Plot 3	2004	n	21	26	24	16	2	1	0
		%	23,33	27,78	26,67	17,78	2,22	1,11	0
	2007	n	17	29	26	12	3	3	0
		%	18,89	32,22	27,78	13,33	3,33	3,33	0
	2011	n	29	25	14	14	5	0	3
		%	32,22	27,78	15,56	15,56	5,56	0	3,33

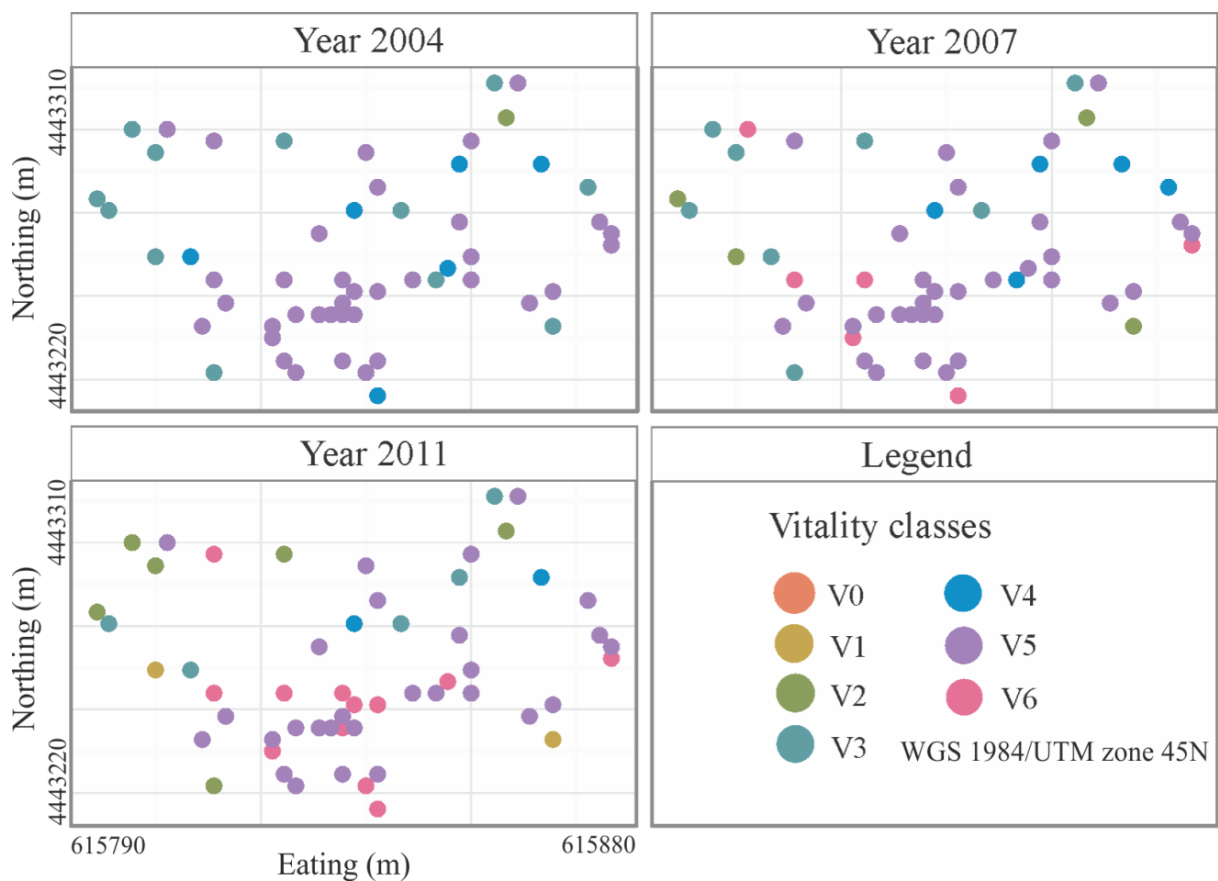




**Fig. 5-12** Distribution of trees in the different vitality classes in the plot 4 for the investigated years. Map section is identical for the investigated years 2004, 2007 and 2011.

**Table 5-7** Variation of the number of trees in different vitality classes in the plot 4 for the investigated years.

Plot	Year	Number (n) & proportion (%)	Vitality classes						
			V0	V1	V2	V3	V4	V5	V6
Plot 4	2004	n	3	12	7	8	22	28	0
		%	3,75	15	8,75	10	27,5	35	0
	2007	n	3	11	7	15	10	31	3
		%	3,75	13,75	8,75	17,5	12,5	38,75	3,75
	2011	n	6	10	11	7	7	27	12
		%	7,5	12,5	13,75	8,75	8,75	26,25	15



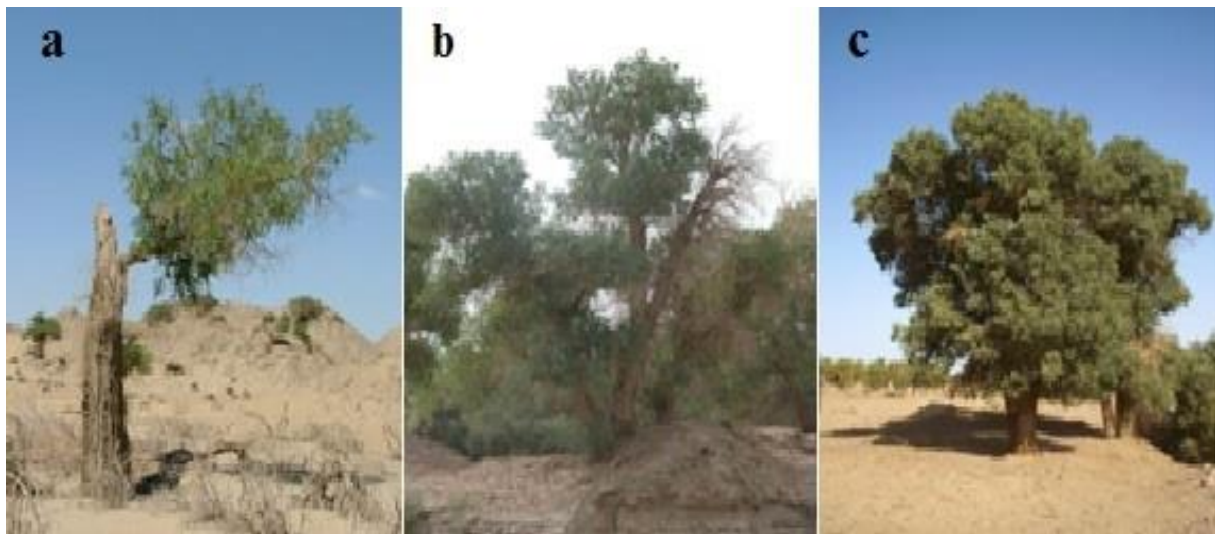
**Fig. 5-13** Distribution of trees in the different vitality classes in the plot 5 for the investigated years.

**Table 5-8** Variation of the number of trees in different vitality classes in the plot 5 for the investigated years.

Plot	Year	Number (n) & proportion (%)	Vitality classes						
			V0	V1	V2	V3	V4	V5	V6
Plot 5	2004	n	0	0	4	18	10	58	0
		%	0	0	4,44	20	10	64,44	0
	2007	n	0	1	4	17	8	54	6
		%	0	1,11	4,44	18,89	7,78	60	6,67
	2011	n	1	2	10	11	3	50	13
		%	1,11	2,22	11,11	12,22	3,33	55,56	14,44

## 5.6 RE-ESTABLISHMENT OF THE TREE CROWN

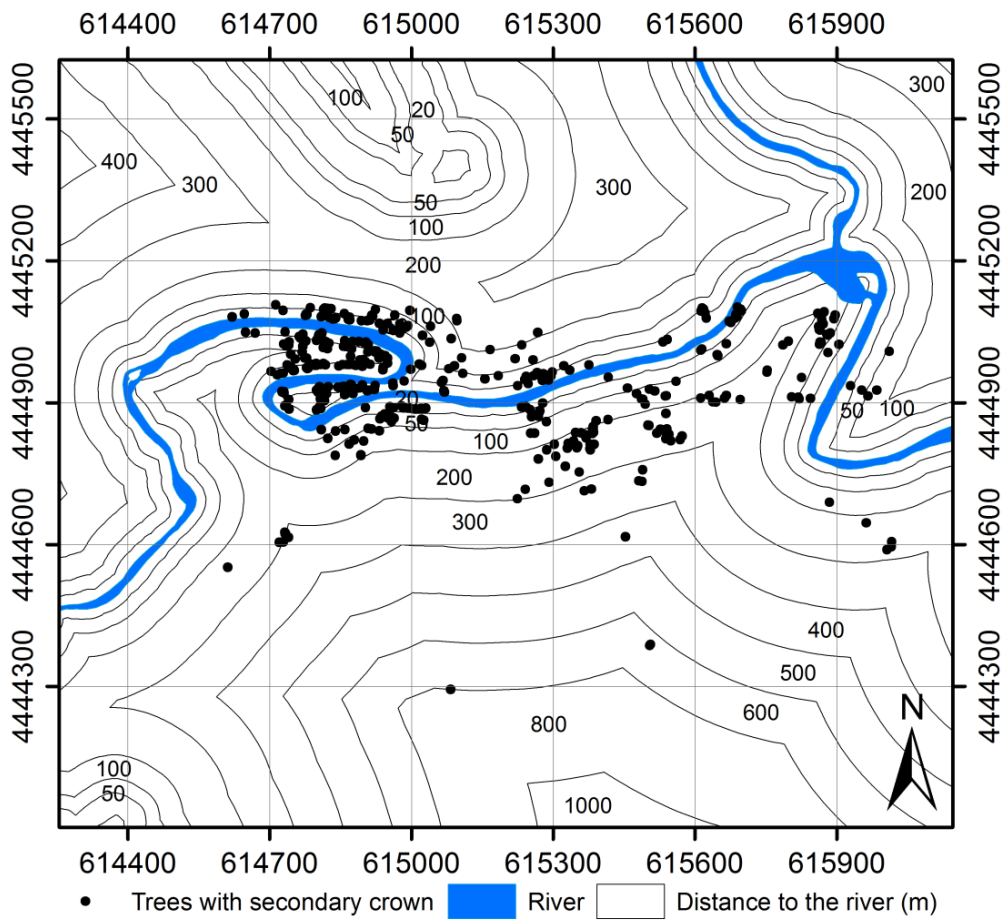
In order to assess the influence of the water diversion project on the recovery of the tree crown of degraded riparian vegetation along the lower reaches of the Tarim River, 4,499 individual *P. euphratica* trees were reinvestigated during the growing season of vegetation in 2011 at the permanent sampling plot (a). Three different tree crown types were found in this study area: the primary tree crown (Fig. 5.14c), the secondary tree crown (Fig. 5.14a) and the composite tree crown (a mix of both primary and secondary) (Fig. 5.14b). The primary tree crown is a tree crown that was developed before the water diversion project. The secondary crown refers to new crowns that were developed following water diversion by trees with dead and broken tops. This can be clearly seen from the left-hand picture in Fig. 5.14.



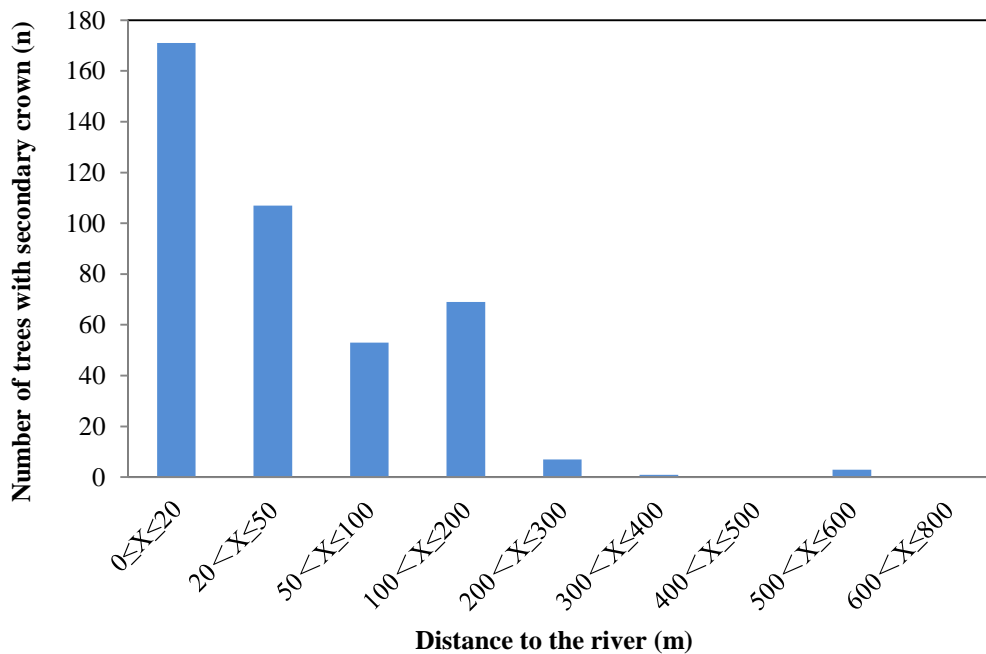
**Fig. 5-14** Crown types of *P. euphratica* trees at Arghan in the lower reaches of the Tarim River (Photo: Halik, 2005). a: dead stem of a *P. euphratica* tree with a newly developed secondary crown after water diversion; b: *P. euphratica* tree with both a primary and secondary crown; c: *P. euphratica* tree with a primary crown.

The composite crown can be defined as a tree crown composed of both a primary crown and a secondary crown. Figs. 5.15 and 5.17 depict the spatial distribution of trees with secondary crowns and composite crowns, respectively, at the permanent sampling plot (a). Trees with secondary crowns and trees with composite crowns are primarily distributed within a 200-m distance from the river channel. Within a 100-m distance, in particular, one sees that the density of trees with secondary and composite tree crowns is remarkably higher. This demonstrates that the formation of secondary tree crowns is closely correlated with distance to the river, groundwater depth and water diversion practices. Figs. 5.16 and 5.18 show the number of trees with secondary and composite crowns for different distances from the riverbed. 408 *P. euphratica* trees with secondary crowns were investigated; 170 trees were located within a 20-m distance from the riverbed, 107 were sampled within a 20–50-m distance, 53 trees within 50–100 m and 69 trees within 100–200 m. The same trend was obtained from the analysis of trees with composite crowns (Fig. 5.18). The number of trees with secondary crowns accounted for approximately 8 % of all trees and the number of trees with composite crowns made up about 3.6 % of all trees at the permanent sampling plot

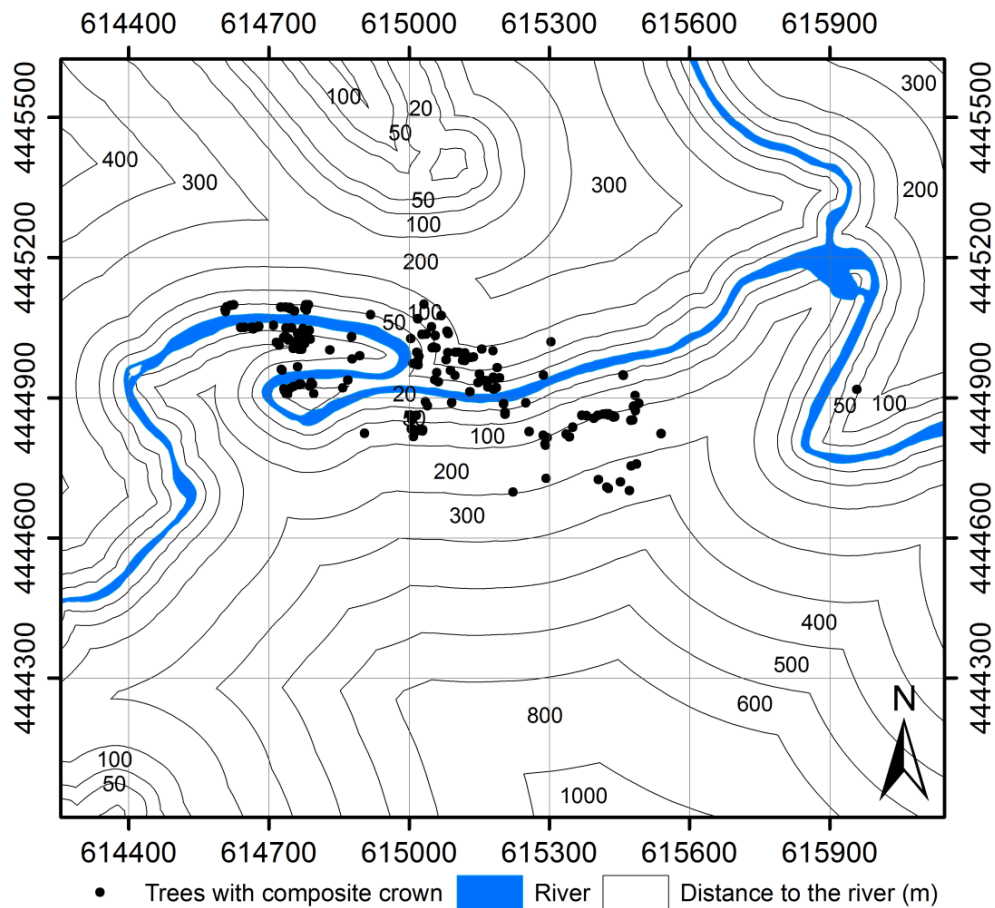
(a).The results show that there is a high correlation between the number of trees with newly developed crowns and their distance to the riverbed where water diversion provided sufficient groundwater resources.



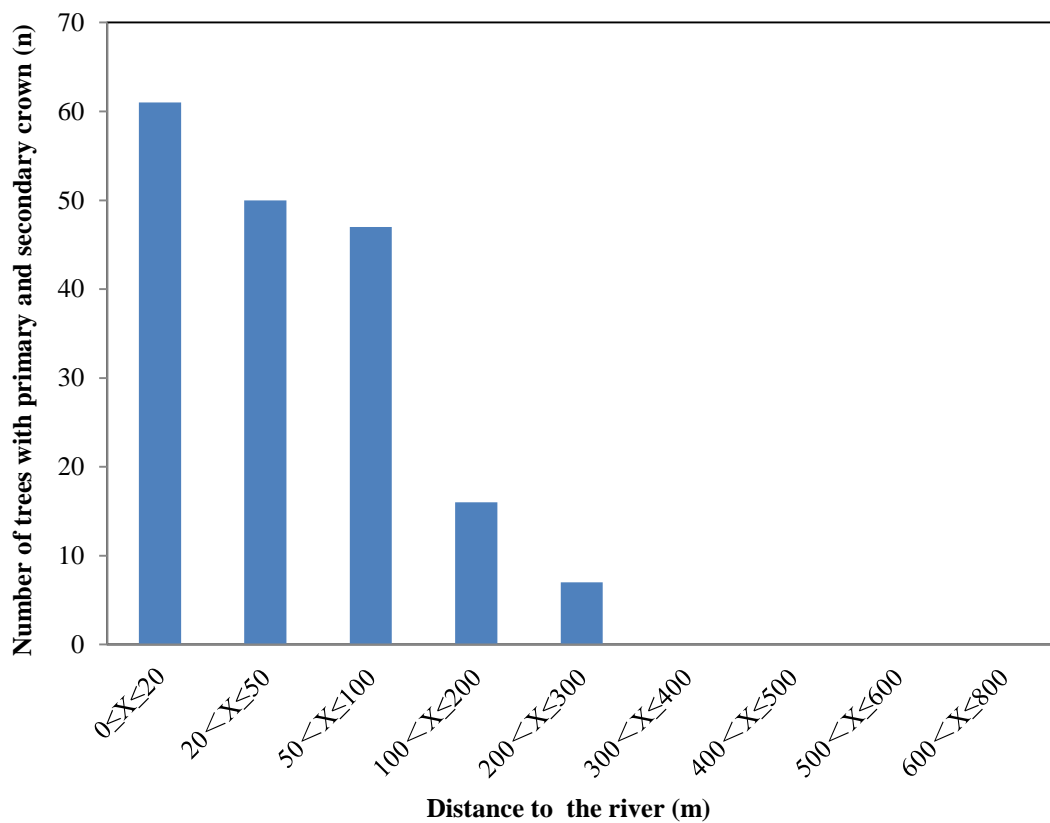
**Fig. 5-15** Spatial distribution pattern of *P. euphratica* trees with secondary crowns at Arghan in 2011.



**Fig. 5-16** Number of dieback trees with redeveloped secondary crowns at Arghan in 2011.



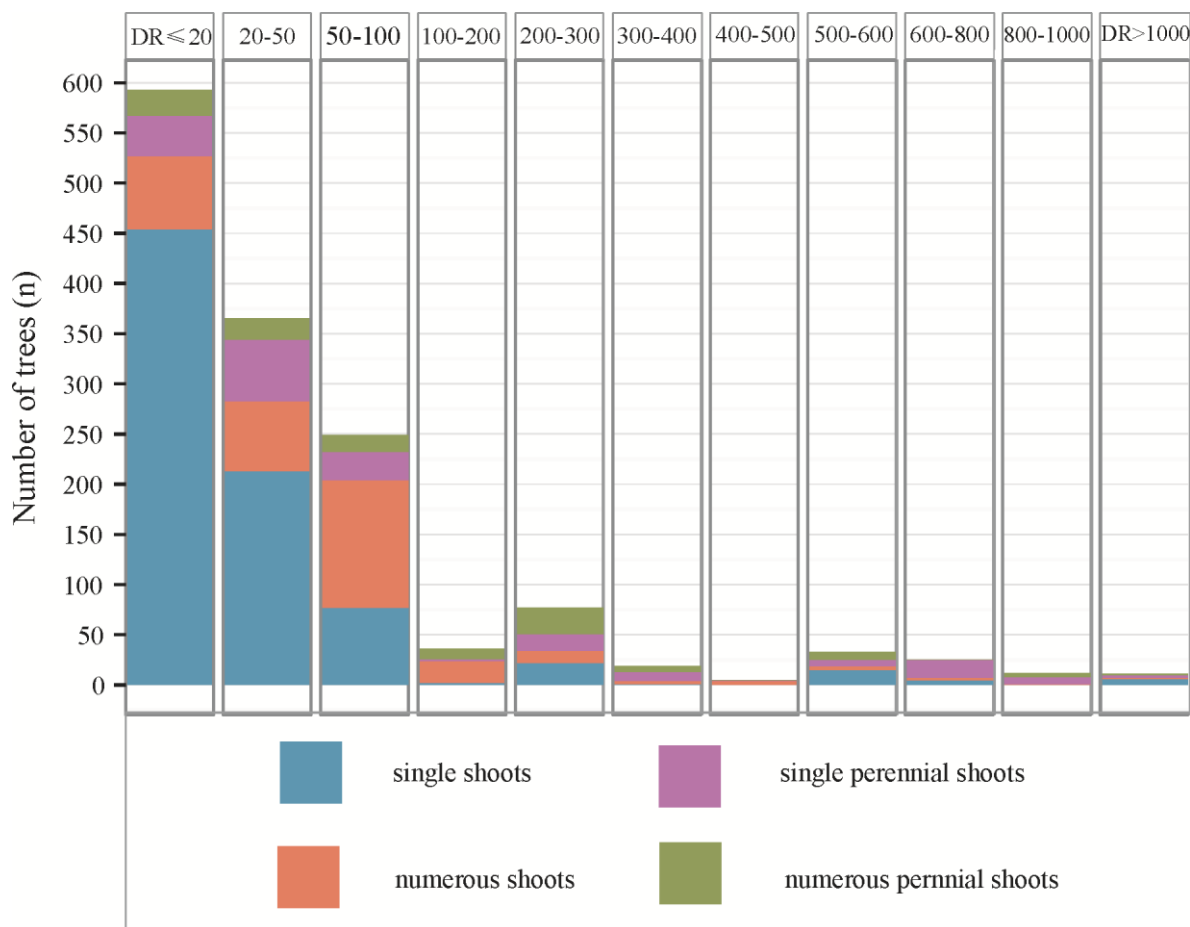
**Fig. 5-17** Spatial distribution pattern of *P. euphratica* trees with composite crowns at Arghan in 2011.



**Fig. 5-18** Number of dieback trees with composite crowns at Arghan in 2011.

## 5.7 DEVELOPMENT OF NEW SHOOTS

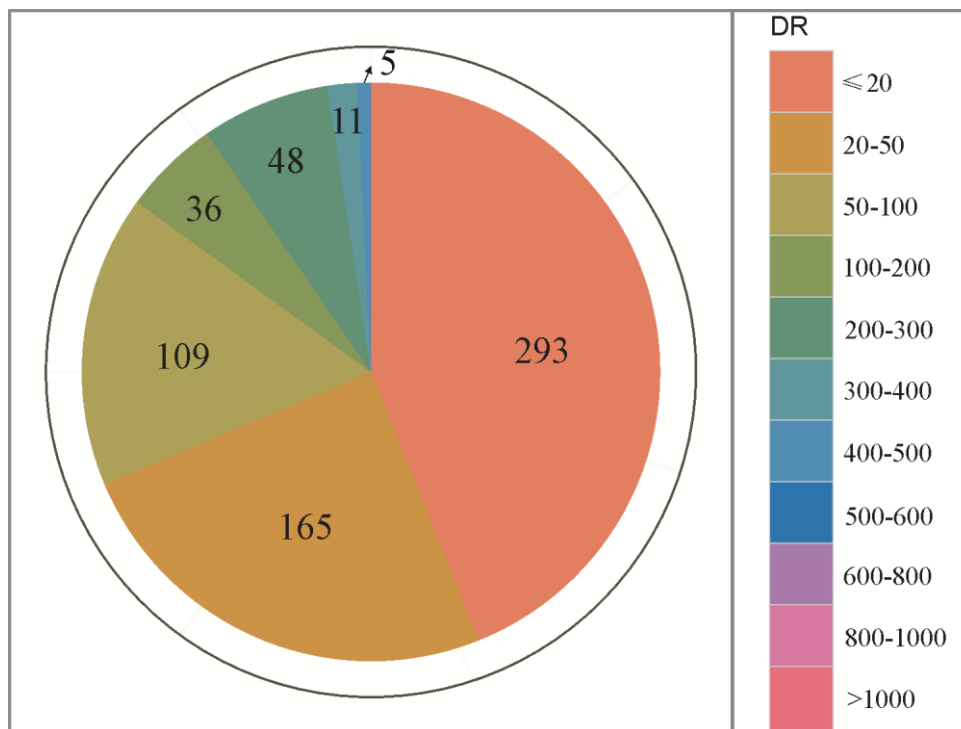
As explained by Takenaka (1997), vegetation shoots have several functions, including exploiting available space, capturing light for photosynthesis, bearing flowers and fruit for reproduction and supporting other shoots. In addition, the development of shoots contributes to the overall structure of tree crowns. Thus, the crown size and crown diameter (CD) of trees are closely related to the extension of new shoots. As such, the frequency of occurrence of trees with new shoots is a major indicator of the contribution of water diversion to the morphological development of *P. euphratica*. From Fig. 5.19, one sees that a large number of trees (n = 596) with various numbers of new shoots are mainly distributed within a 20-m distance from the river. With increased distance, the frequency of new shoots of *P. euphratica* appeared to decline. At distances of 500 m or above from the river channel, trees with new shoots become extremely rare due to unfavorable groundwater supply. *P. euphratica* is the dominant tree species in the floodplain ecosystems of arid Central Asia (Thevs 2011), and large scale recruitment of new seedlings of floodplain forests is essential to their long term sustainable development (Hughes and Rood, 2003; Rood et al. 2003, 2005). It is also a key parameter for assessing the output and success of water diversion in the lower reaches of the Tarim River.



**Fig. 5-19** Effects of restoration measures on the development of new shoots of *P. euphratica* (DR stands for “distance from the river”).

## 5.8 ESTABLISHMENT OF ROOT SUCKERS AND YOUNG SEEDLINGS

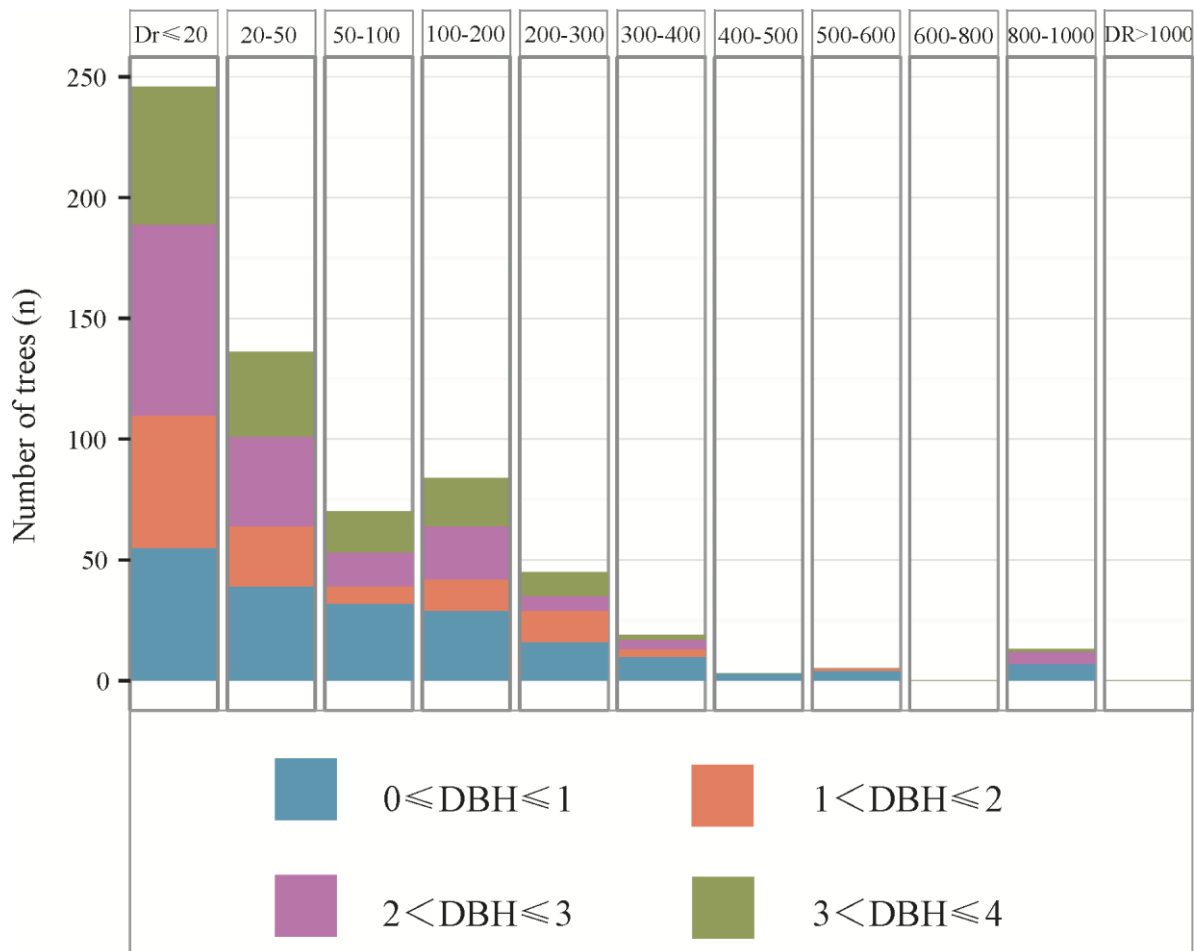
Previous studies found that *P. euphratica* has the ability to regenerate by both seeds/seedlings and root suckers (Hukin et al. 2005; Wiehle et al. 2009, Xu et al. 2007). An attempt was made to examine the contribution of water diversion to the development of root suckering of *P. euphratica* trees (Fig. 5.20). The number of root suckers decreased significantly with increasing distance from the river course. Young and middle age trees, which have shorter roots than adult trees, have a very strong tendency to produce root suckers if the habitat conditions are suitable (mainly, with respect to soil moisture).



**Fig. 5-20** Occurrences of root suckers of *P. euphratica* at the different distances from the river.

Extensive surveys of the permanent monitoring plots at the Arghan forestry station have been conducted since 2005, and all the trees in this permanent monitoring plot were reinvestigated in 2011, so as to more accurately interpret the response of the *P. euphratica* seedlings ( $0 \leq \text{DBH} \leq 2$ ) and saplings ( $2 < \text{DBH} \leq 4$ ) to the environmental alternations. The frequency of young seedlings is a sensitive ecological parameter as it is closely related to soil water content, soil salt content, and groundwater depth, which are significantly influenced by water diversion (Ma et al. 2011). Figs. 5.21 and 5.22 show the numbers of young *P. euphratica* seedlings of different DBH values, along with their spatial distribution at different distances to the river channel. Within a 20-m distance from the river course, the frequency of young tree seedlings in  $\text{DBH} \leq 4$  cm was relatively high. As the distance from the main river course increased, the number of young tree seedlings decreased dramatically. Large numbers of young seedlings were mainly distributed within 200 m of the main river channel. At distances further than 200 m, the distribution of seedlings of different diameters is simpler and sparser. At more than 400 m from the river, no seedlings formed. As soil moisture is a key factor for

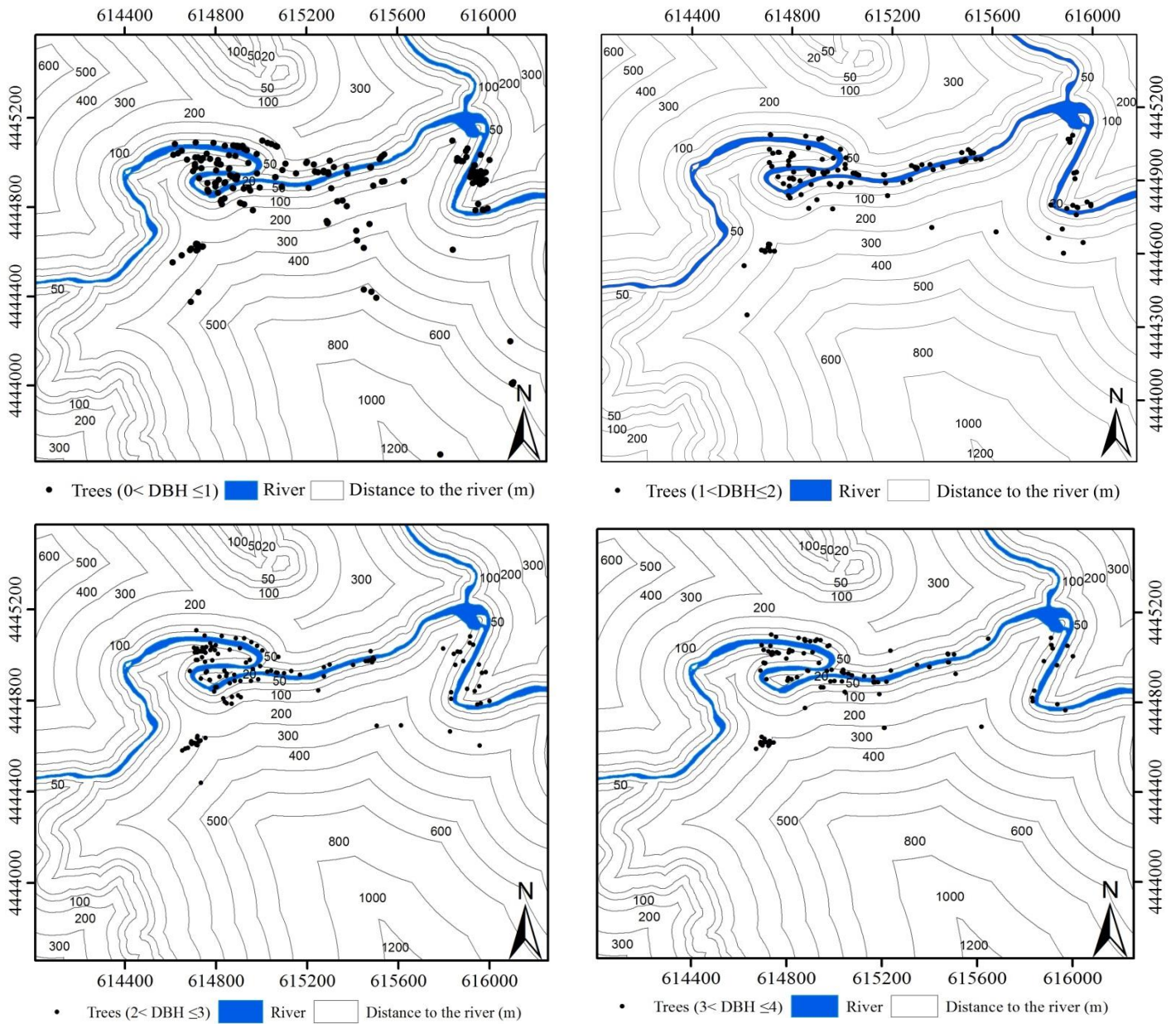
the establishment of *P. euphratica* seedlings and their survival (Cao et al. 2012), high densities of *P. euphratica* seedlings along the Arghan transect can only occur in the vicinity of the flooding zones affected by water diversion. However, the zone far away from the river is unable to provide favorable habitat requirements for seedling recruitment, and subsequently the few remaining successful seedlings would not be able to maintain contact with adequate soil moisture due to their shallow root system.



**Fig. 5-21** Effect of restoration measures on seedlings and young saplings of *P. euphratica* (DR stands for “distance from the river”).

*P. euphratica* stands have limitations in renewing their forest structure by seeds in large areas under current conditions. All onsite investigations confirmed that high densities of seedlings occur near the riverbank every year, and they are likely to germinate rapidly if they land on suitable moist site conditions. However, many will not survive due to drought stress. Therefore, additional research should be conducted to determine the flow regime that affects soil moisture content and seedling success, and to develop a model identifying suitable site conditions for the establishment of *P. euphratica* seedlings successfully, and for further evaluating the contribution of water diversion to forest recovery and maintenance.





**Fig. 5-22** Spatial distribution patterns of *P. euphratica* seedlings for different diameters (DBH).

## 6 MODELING OF RIPARIAN FOREST STRUCTURES

Modeling height-diameter relationships is important for estimating and predicting forest development under different forest management scenarios. In this chapter, ten widely used candidate height-diameter models were fitted to tree height (TH) and diameter at breast height (DBH) data of *P. euphratica* within a 100 ha permanent plot at the Arghan village. Data from a total number of 4781 trees was used and split randomly into two sets: 75 % of the data was used to estimate model parameters (model calibration), and the remaining data (25 %) were reserved for model validation. All model performances were evaluated and compared by means of multiple model performance criteria such as asymptotic *t*-statistics of model parameters, standardized residuals against predicted height, the root mean square error (RMSE), Akaike's information criterion (AIC), mean prediction error (ME) and mean absolute error (MAE).

The results showed that the estimated parameter *a* for Model (6) was not statistically significant at the  $\alpha = 0.05$  level. RMSE and AIC test results for all models showed that the exponential models (1), (2), (3) and (4) performed significantly better than the others. The ME and MAE tests revealed that all ten models had very small ME and MAE values. Nearly all models underestimated the tree heights with the exception of Model (6). Comparing the MEs and MAEs of the models, Model (1) produced relatively smaller MEs (0.0059) and MAEs (1.3754) than other models. Additionally, in order to assess the predictive performance of the models, the MEs were also calculated by splitting the model validation data set into 10-cm DBH classes, which suggested that all models were likely to create higher mean prediction errors for trees with DBH values above 20 cm. No clear trend was found among the models for trees with DBH values greater than 20 cm. An interesting point is that Model (6) generated significantly smaller mean prediction errors across all tree DBH classes. Considering all of the aforementioned criteria, Model (1):  $TH = 1.3 + a/(1 + b \times e^{-c \times DBH})$  and Model (6):  $TH = 1.3 + DBH^2/(a + b \times DBH + c \times DBH^2)$  are recommended as the suitable models for describing the height-diameter relationship of *P. euphratica*. The limitations of the other models in predicting tree height accurately are also discussed. Potential explanations for these shortcomings are also formulated.

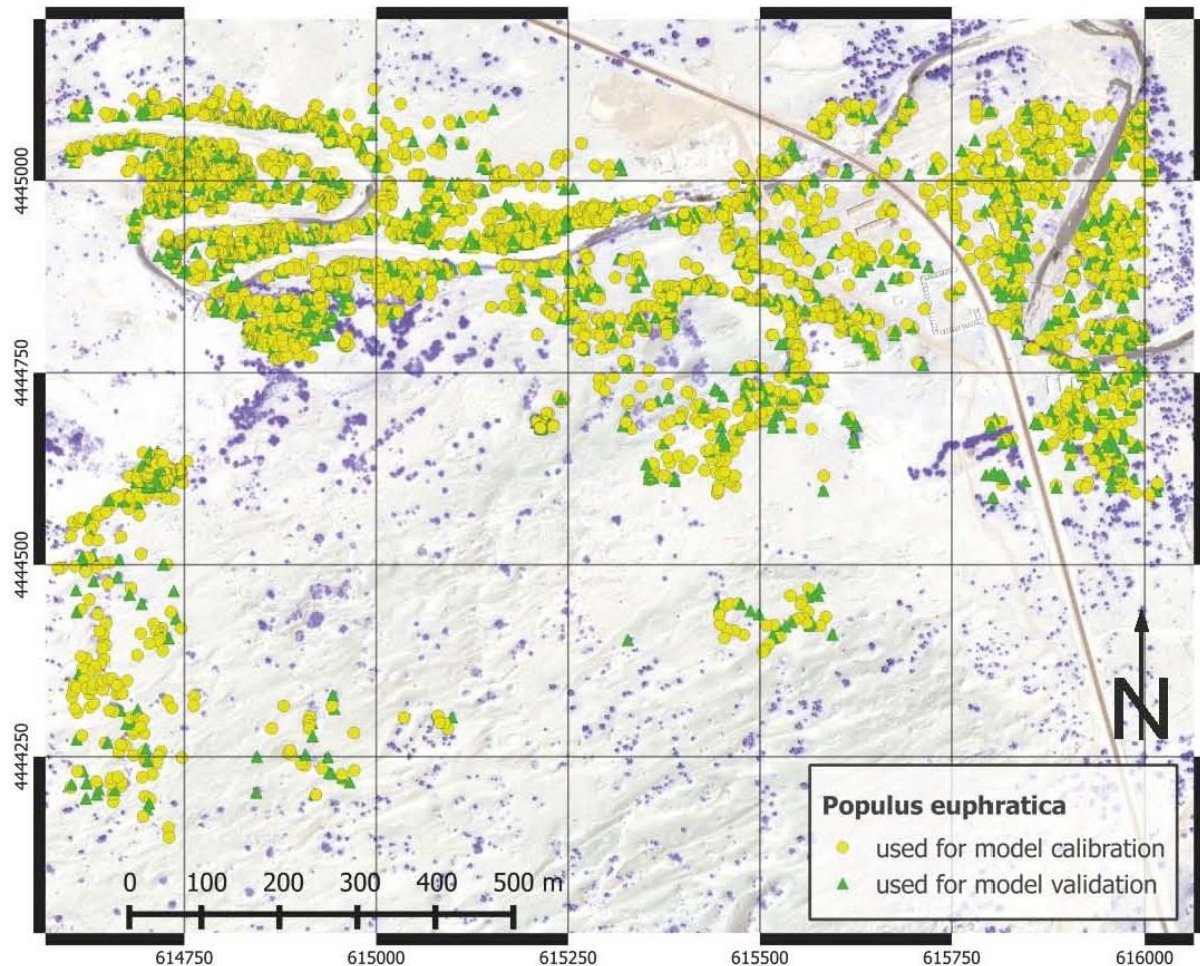
The tree height (TH) and diameter at breast height (DBH) are the most important variables of forest structure, and are also essential parameters in forest condition assessment and modelling stand dynamics (Huang et al. 1992; Zhang 1997). DBH, as a key parameter of forest inventories, can be measured *in situ* more easily and accurately with lower labor intensity and cost than tree height (Fang and Baily, 1998; Sharma and Parton 2007). Height-diameter models are very useful in predicting the heights of the unmeasured trees in the field site, thus reducing the cost and time of data collection (Schmidt et al. 2011). Additionally, developing a suitable height-diameter model is very important for estimating tree growth, biomass production, and carbon storage capacity as well as for modeling forest development over time (Molto et al. 2014; Temersgen et al. 2014).

Euphrates poplar (*Populus euphratica* Oliv.) is the dominant species of Tugai forests in the Central Asian deserts and plays an irreplaceable role in maintaining the sustainable development of these regions (Huang 2002; Halik et al. 2006; Xu et al. 2007; Thevs et al. 2012, Eusemann et al. 2013). More than 90 % of the existing floodplain forests along the Tarim River are of this species (Song et al. 2000; Huang 2002). These riparian forests provide a wide range of ecosystem services (ESS). They protect biodiversity, reduce the impact of sandstorms, moderate desertification, regulate oasis climate, and fertilize forest soils as well as maintain ecosystem balance (Huang et al. 2010; Cyffka et al. 2013; Aishan et al. 2013; Kuba et al. 2013). However, the natural flood regime and habitat conditions of riparian forests along the lower reaches of the Tarim River have been altered due to the human interventions and climate change. The multiple effects of these two processes have affected spatial and temporal patterns of the distribution of natural water resources in the upper and middle reaches of the river. In 2000, an integrative water management project was launched and comprehensive management of riparian forest resources along the lower reaches of the Tarim River was implemented (Halik et al. 2011). Following the launch of this project, many eco-hydrological studies were conducted in order to assess the efficacy of the applied countermeasures and to assess the dynamics of riparian forests under the current forest management strategy. Nevertheless, systematic forestry studies focusing on the further development of a height-diameter model for *P. euphratica* are hardly found either in the Chinese and international scientific literatures. However, here it is argued that a height-diameter model is crucial for designing forest development models in regions under changing hydrological conditions and forest management schemes.

The main objectives of this chapter are: a) to explore the regression performance of our TH and DBH data of *P. euphratica* for commonly employed nonlinear height-diameter models, b) select the most suitable and best performing model for predicting TH as a function of DBH in *P. euphratica* forest stands in the research area, c) provide a useful foundation for extracting the vegetation input parameters for producing a large-scale GIS-based model for ecosystem service assessment of forest stands in the Tarim Basin and in other similar regions.

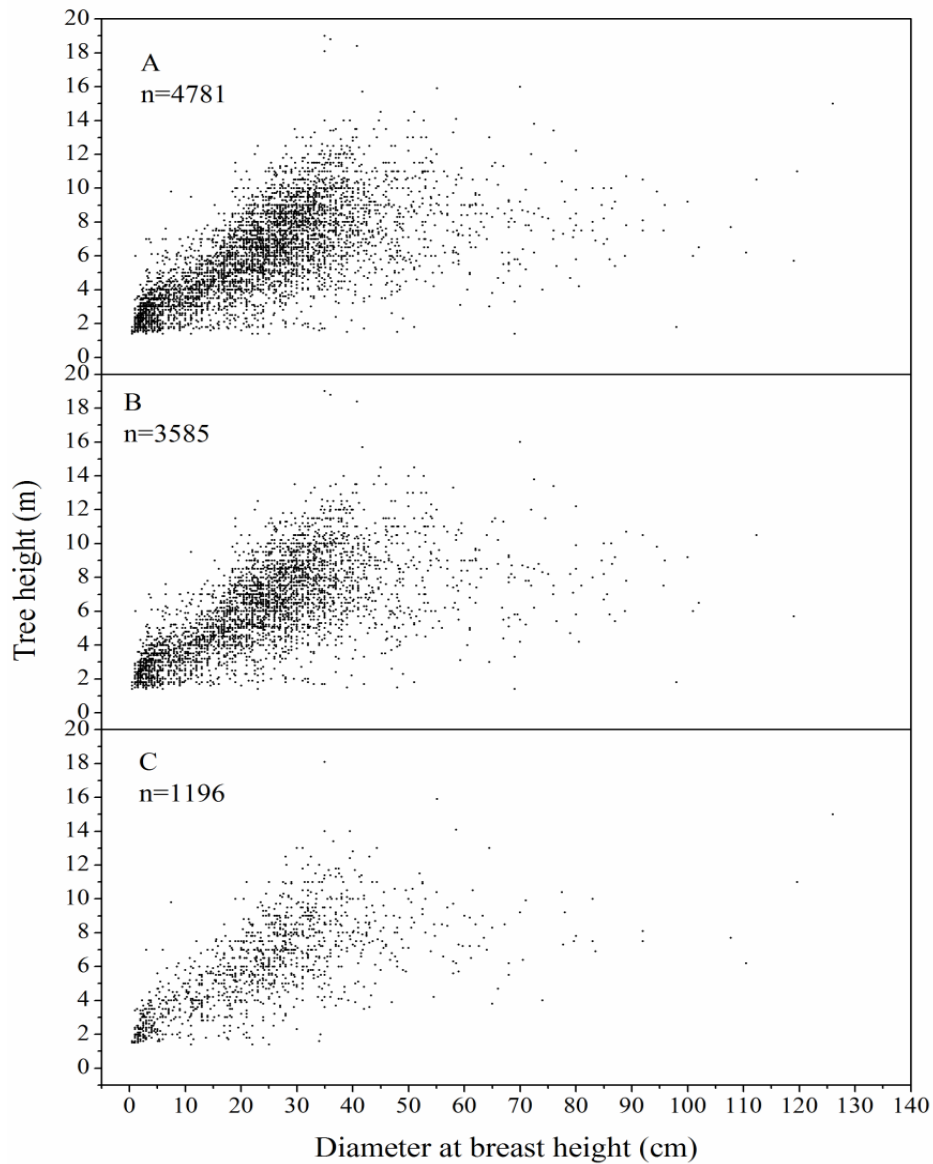
## 6.1 DATA PROCESSING FOR CALIBRATION AND VALIDATION

Forest inventory data for more than 5000 *P. euphratica* trees collected from a 100-ha permanent sampling plot (100 square plots each with a size of 100 m × 100 m) in the study area are used in this chapter (Fig. 6.1).



**Fig. 6-1** Distribution map of the individual trees used for model calibration and model validation. Base map is false color QuickBird image

The detailed quantitative variables (tree height, DBH, crown diameter, crown loss, vitality, root suckers, height under branch, geographical coordinates, etc.) were systematically investigated during the vegetation season in 2011 for individual trees, together with the categorical/qualitative variables of their surrounding environment (slope, micro-topography, crown types, pest infection, etc.). Dead trees, trees below 1.3 m in height, and trees without corresponding data records were excluded from further analysis. Tree height and diameter at breast height values for 4781 trees were obtained and used for model calibration ( $n = 3585$ ) and for model validation ( $n = 1196$ ) (Fig. 6.2). Data for model calibration and validation were split randomly using R (R Development Core Team 2013). Summary statistics for TH and DBH are given in Table 6.1.



**Fig. 6-2** Plots of tree height (TH) against diameter at breast height (DBH). (A) Total data set. (B) Data set for model calibration. (C) Data set for model validation. (n) Number of trees.

**Table 6-1** Summary statistics of all sampled trees, trees for model calibration and model validation.

Data class	Number of trees	DBH (cm)				Tree height (m)			
		Mean	Min.	Max.	SD	Mean	Min.	Max.	SD
Sampled tree data	4781	24.66	0.50	126.00	15.489	6.14	1.40	19.00	2.659
Model calibration	3585	24.59	0.50	119.00	15.339	6.16	1.40	19.00	2.663
Model validation	1196	24.88	0.50	126.00	15.949	6.11	1.40	18.10	2.648

**Note:** Min. = minimum, Max. = maximum, SD = standard deviation, DBH = diameter at breast height

## 6.2 NON-LINEAR CANDIDATE MODELS FOR DATA FITTING

Due to the lack of previous studies regarding height-diameter relationships for our research object *P. euphratica* Oliv, a total of 10 candidate height-diameter non-linear models were chosen to fit our model calibration dataset based on what has been proposed in the literature (Huang et al. 1992; Huang et al. 2000; Peng et al. 2001). Model details are provided in Table 6.2.

**Table 6-2** Nonlinear height diameter models selected for this study.

Model No. & equation	References
(1) $TH = 1.3 + a/(1 + b \times e^{-c \times DBH})$	Pearl and Reed 1920
(2) $TH = 1.3 + a(1 - e^{-b \times DBH})^c$	Chapman 1961; Richards 1959
(3) $TH = 1.3 + a(1 - e^{-b \times DBH^c})$	Yang et al. 1978
(4) $TH = 1.3 + a \times e^{-b \times e^{-c \times DBH}}$	Winsor 1932
(5) $TH = 1.3 + a \times e^{-b \times DBH^{-c}}$	Stage 1963; Zeide 1989
(6) $TH = 1.3 + DBH^2 / (a + b \times DBH + c \times DBH^2)$	Curtis 1967
(7) $TH = 1.3 + a \times DBH^{b \times DBH^{-c}}$	Sibbesen 1981
(8) $TH = 1.3 + a \times e^{b/(DBH+c)}$	Ratkowsky 1990
(9) $TH = 1.3 + a/(1 + b^{-1} \times DBH^{-c})$	Ratkowsky and Reedy 1986; Huang et al. 1992
(10) $TH = 1.3 + a(1 - e^{-b \times DBH})$	Farr et al. 1989; Moffat et al. 1991

**Notes:** *TH* = Tree height (m); *DBH* = Diameter at breast height (cm); *a*, *b*, *c*, *d* = parameters to be estimated; *e* = base of the natural logarithm ( $\approx 2.71828$ ); 1.3 = a constant used to account for *DBH* being measured at 1.3 m above the ground.

Fit statistics and model parameters were estimated using the R programming language (R development core team 2013). In an attempt to find a global minimum, the starting value of each parameter for the chosen models was decided before running the model and several runs were performed until satisfactory estimations were obtained. To approach variance homogeneity of the residuals, weighted nonlinear regression was performed using  $1/\widehat{H}_1^{2/3}$  as weighting factor, where  $\widehat{H}_1$  are the fitted values of the model run (Huang et al. 2000). This procedure was performed in an iterative way until variance heterogeneity was minimized.

## 6.3 MODEL PERFORMANCE CRITERIA

It is crucial that appropriate criteria be considered to assess model performance. There are many criteria for comparing model performance (Burnham and Anderson 2002). Because each criterion has its strengths and weaknesses, using multiple measurements of performance

instead of single measurements appears as the most suitable and effective approach (Aersten et al. 2010). In this work, several criteria such as the asymptotic  $t$ -statistics of parameters, residuals against predicted values, root mean square error (RMSE), and Akaike's information criterion (AIC), were examined to evaluate the fitting performance of the models. As the coefficient of determination ( $R^2$ ) is not advisable for assessing nonlinear regression models (Cameron and Windmeijer 1997), we did not apply it for assessing model performance in this study. In the following expressions,  $H_i, \widehat{H}_i$  are the observed and predicted values, respectively,  $n$  is the number of observations used for fitting and validating the model, and  $p$  is the number of model parameters to be estimated. In addition, the mean prediction error and the mean absolute prediction error were determined from the differences between the observed and predicted tree heights. To verify the model prediction performance more precisely, the mean prediction errors across different DBH classes in 10-cm intervals were calculated using a model validation data set.

The RMSE is a widely used goodness-of-fit criterion that measures the differences between the values predicted by a model or an estimator and the values actually observed (Burnham and Anderson 2002). A smaller value generally indicates better model performance. The RMSE is defined as given in Expression (1) below (Castaño-Santamaría et al. 2013):

$$RMSE = \sqrt{\frac{\sum_{i=1}^n (H_i - \widehat{H}_i)^2}{n-p}} \quad (1)$$

The Akaike Information Criterion (AIC) is among the most reliable ways of selecting a model from a set of models. The chosen model is the one that minimizes the Kullback-Leibler distance between the model and the truth (Burnham and Anderson 2004). It is calculated through the following expression:

$$AIC = n \ln(RMSE) + 2p \quad (2)$$

The mean prediction error (ME) and mean absolute prediction error (MAPE) are calculated via Expressions (3) and (4), respectively, to verify the difference of model predictions. Average underestimation and overestimation can be indicated by positive and negative values, respectively.

$$ME = \frac{\sum_{i=1}^n (H_i - \widehat{H}_i)}{n} \quad (3)$$

$$MAE = \frac{\sum_{i=1}^n |H_i - \widehat{H}_i|}{n} \quad (4)$$

## 6.4 MODEL CALIBRATION

Nonlinear least squares techniques were applied to estimate model fitting parameters for the model calibration dataset. The fitting results of all candidate models for *P. euphratica* are presented in Table 6.3. All models were examined and evaluated based on the multiple model performance criteria. Table 6.3 reveals that nearly all models performed equally well and that the parameter estimates (coefficients) for all 10 models were statistically significant at the 0.05 level, except for the estimation of the parameter *a* for Models (6) and (7). This indicates that the best model for *P. euphratica* cannot be determined based solely on the *t*-statistics assessment.

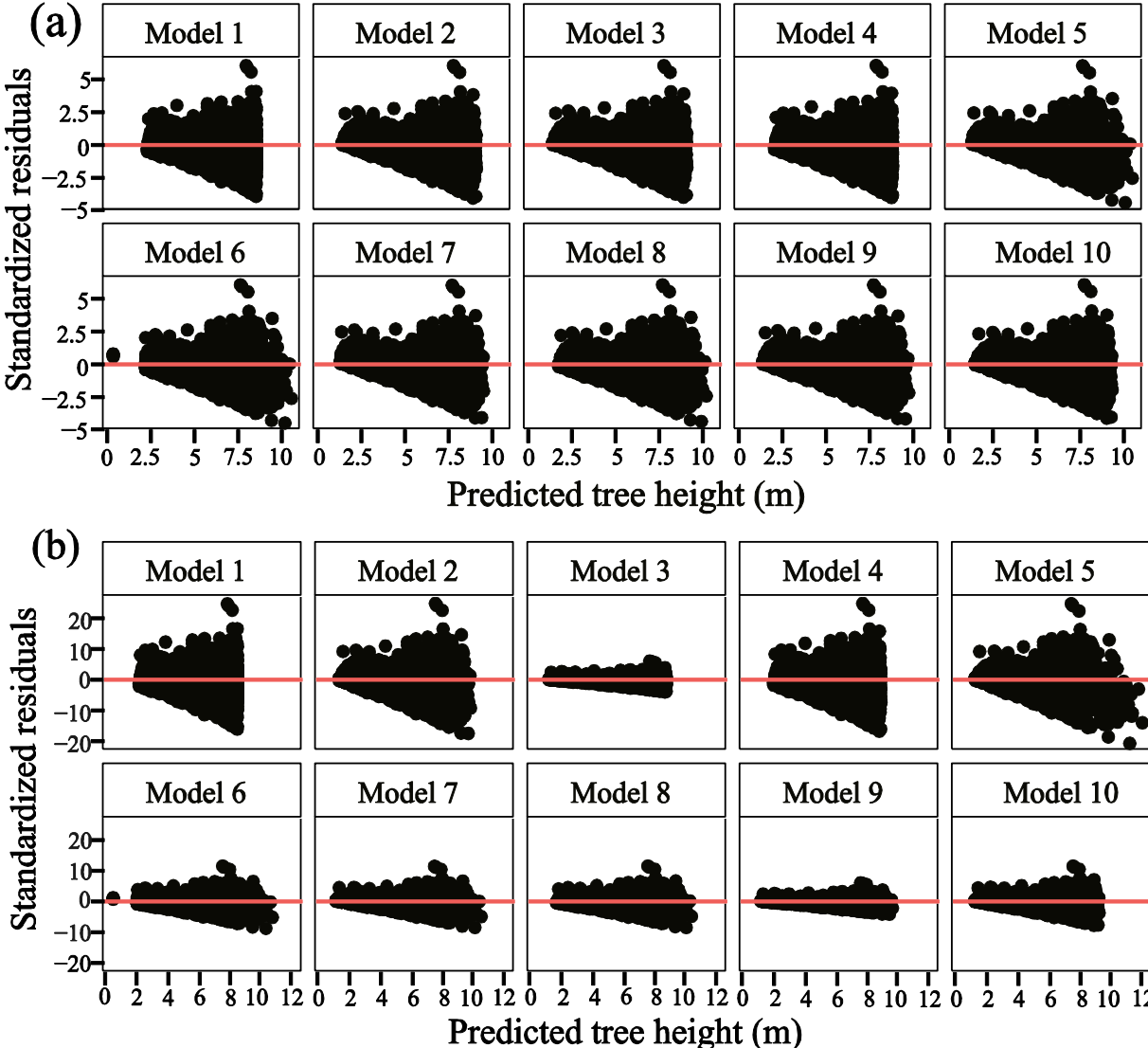
**Table 6-3** Parameter estimates for the candidate non-linear height-diameter models and the comparison of the goodness of model fit for model calibration data set of *P. euphratica*.

Model	Parameter	Estimate	SE	<i>t</i> -value	<i>p</i> >  <i>t</i>	RMSE	AIC
(1)	<i>a</i>	7.2587	0.0870	83.43	<0.0001	1.8232	2159.109
	<i>b</i>	6.5474	0.4025	16.27	<0.0001		
	<i>c</i>	0.1233	0.0043	28.48	<0.0001		
(2)	<i>a</i>	7.8178	0.1650	47.38	<0.0001	1.8529	2216.980
	<i>b</i>	0.0547	0.0042	13.15	<0.0001		
	<i>c</i>	1.1785	0.0702	16.80	<0.0001		
(3)	<i>a</i>	7.5789	0.1515	50.04	<0.0001	1.8499	2211.216
	<i>b</i>	0.0290	0.0031	9.277	<0.0001		
	<i>c</i>	1.1865	0.0429	27.63	<0.0001		
(4)	<i>a</i>	7.5219	0.1092	68.87	<0.0001	1.8326	2177.606
	<i>b</i>	2.3873	0.0836	28.56	<0.0001		
	<i>c</i>	0.0823	0.0032	25.60	<0.0001		
(5)	<i>a</i>	13.855	1.3071	10.60	<0.0001	1.8815	2271.929
	<i>b</i>	5.0476	0.2789	18.09	<0.0001		
	<i>c</i>	0.5249	0.0469	11.20	<0.0001		
(6)	<i>a</i>	0.9587	0.9273	1.034	0.301	1.8714	2252.707
	<i>b</i>	2.2626	0.1216	18.60	<0.0001		
	<i>c</i>	0.0917	0.0031	29.68	<0.0001		
(7)	<i>a</i>	0.0601	0.0163	3.686	0.00023	1.8722	2254.262
	<i>b</i>	2.6676	0.2169	12.29	<0.0001		
	<i>c</i>	0.1993	0.0069	28.64	<0.0001		
(8)	<i>a</i>	10.476	0.2871	36.49	<0.0001	1.8637	2237.922
	<i>b</i>	-20.1511	1.3605	-14.81	<0.0001		
	<i>c</i>	5.8828	0.7116	8.267	<0.0001		
(9)	<i>a</i>	9.1762	0.3382	27.13	<0.0001	1.8644	2239.174
	<i>b</i>	0.0219	0.0028	7.742	<0.0001		
	<i>c</i>	1.3138	0.0650	20.21	<0.0001		
(10)	<i>a</i>	8.0723	0.1474	54.77	<0.0001	1.8551	2219.364
	<i>b</i>	0.0456	0.0017	26.23	<0.0001		



Figure 6.3 shows the graphical display of the standardized residuals against predicted tree heights from the 10 candidate non-linear height-diameter equations before and after applying weighted regression. The result indicates that weighted, rather than unweighted, ordinary nonlinear regression can enhance the model performance to some degree by avoiding the assumption of variance homogeneity. Nevertheless, a careful evaluation is necessary - e.g., Models (3), (6) and (9) perform better with weights than without. As all models have been treated with the same procedure, two scenarios seem to be possible: 1) the complex structure of the models does not perform well with weighting, 2) the large amount of data points causes problems for the software. A mixture of both is also possible.

Furthermore, we calculated the RMSE and AIC values for each model based on the model calibration data set (Table 6.3). It can be seen that Model (1) performed significantly better than the rest. Models (3), (6) and (9) also showed relatively good performance. However, the exact differences among them are not clear.



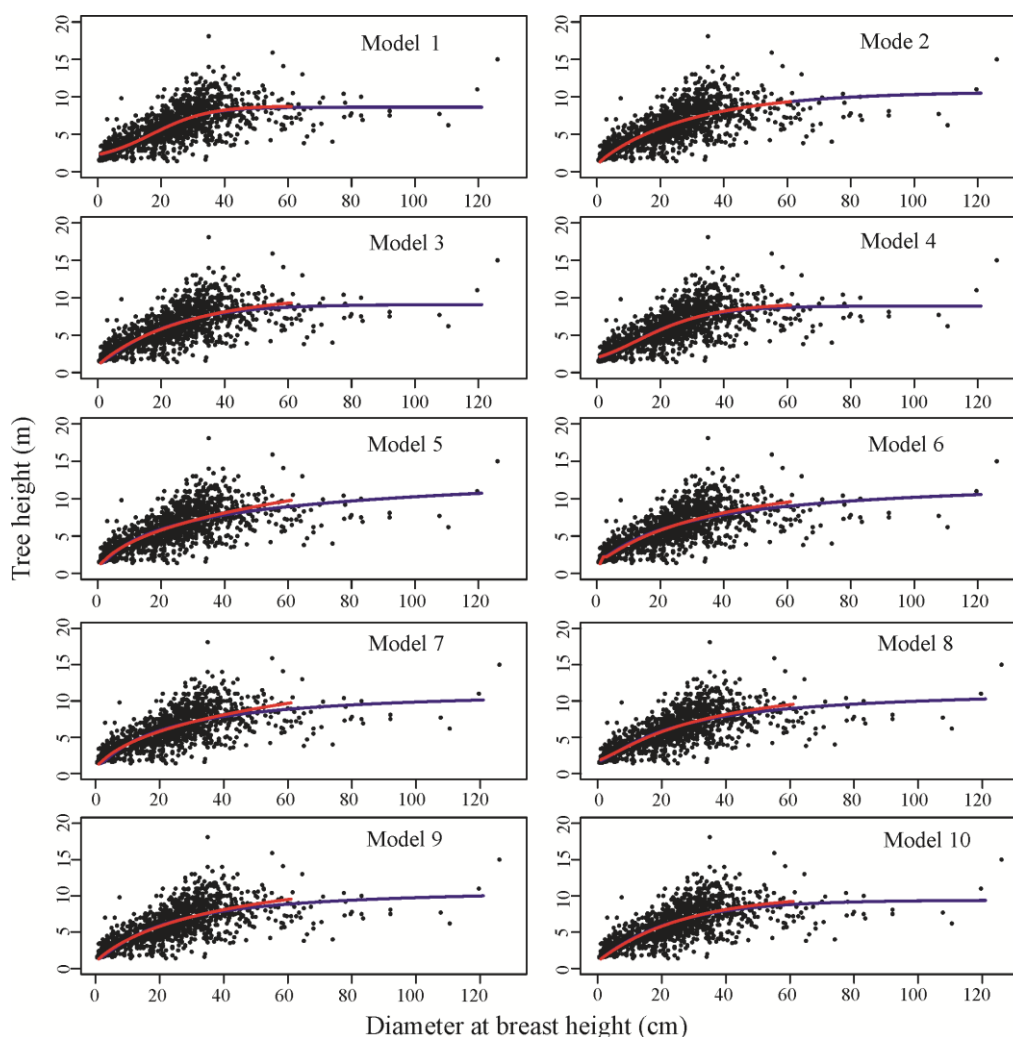
**Fig. 6-3** Plots of standardized residuals against predicted tree heights from the 10 candidate non-linear height-diameter equations before (a) and after (b) applying weighted regression.

## 6.5 MODEL VALIDATION

Huang et al. (2000) suggested that the quality of fit based on model calibration data does not represent the quality of predictions. Therefore, it is necessary to carry out an assessment of the selected height-diameter model (1) on a model validation dataset before applying it. If a significant difference between the fit statistics derived from the model calibration data and the prediction statistics from the model validation data is detected, the model should not be selected as a best potential model for future applications. As we mentioned above, the total data set ( $n = 4781$ ) in this thesis was randomly split into two parts, the model calibration ( $n = 3585$ ) set and the model validation ( $n = 1196$ ) set, as shown in Fig. 6.2. Plots of TH against DBH from the model calibration dataset, the model validation dataset and the combined dataset showed a similar distribution pattern. However, cross validation analysis was conducted once more based on the model performance criteria. The aim was to examine the difference between the fitting statistics for the model calibration data set and the prediction statistics for the model validation dataset using the selected model (1). Fig. 6.4 displays an example of the simulation plot of observed TH against DBH for the models (1)-(10) fitted to the model validation dataset of *P. euphratica*. The models (1)-(10) were refitted by deleting trees with  $DBH > 60$  cm so as to compare the model fitting performance against current models. However, no obvious difference in the fitting was found. Prediction statistics of Models (1)-(10) for the model validation dataset of *P. euphratica* are shown in Table 6.5. It is seen that the estimated parameters, standard errors and RMSE for Model (1) based on the model validation data set were almost identical to the indicators obtained from the fitting of Model (1) based on the model calibration dataset. This suggests that there was no significant difference between the statistical characteristics derived from Model (1) for both the model calibration and validation data sets (Tables 6.3 and 6.4). Fig. 6.5 shows a plot of the observed height value against predicted height value for Models (11)-(16). The intercept and slope for the diagonal line in Fig. 5 are 0 and 1, respectively. All the predicted and observed values on the line were equal. The mean prediction error (ME) and mean absolute prediction error (MAE) of all candidate models for the model validation data set are shown in Table 6.4. In general, all ten models had very small MEs and MAEs. The mean prediction errors ranged from -0.0114 to 0.0426 while the mean absolute prediction errors ranged from 1.3754 to 1.4181. Almost all models underestimated the tree heights except for Model (6). Comparing the MEs and MAEs of the models, Model (1) produced relatively smaller ME (0.0059) and MAE (1.3754) than the other models.

The performance of Model (1) for *P. euphratica* was also satisfactory when applied to the model validation data (Table 6.5). Furthermore, to verify the difference of model prediction performance from Models (1) to (10), the mean prediction errors across all validation data sets with DBH classes in 10-cm intervals were calculated. Due to an insufficient number of trees with DBH values of 60 cm or greater, the average prediction errors for them could not be calculated. The results are shown in Figs. 6.6 and 6.7. The overall mean prediction errors ranged from 0.97776 to 1.685711, depending on the model. Generally, all of the models produced small and similar mean prediction errors for the different tree DBH classes, with the exception of the highest positive mean prediction errors of Model (2) for trees in the 40-50 cm DBH class. For trees in the 0-10-cm and 10-20-cm classes, all of the models seemed to

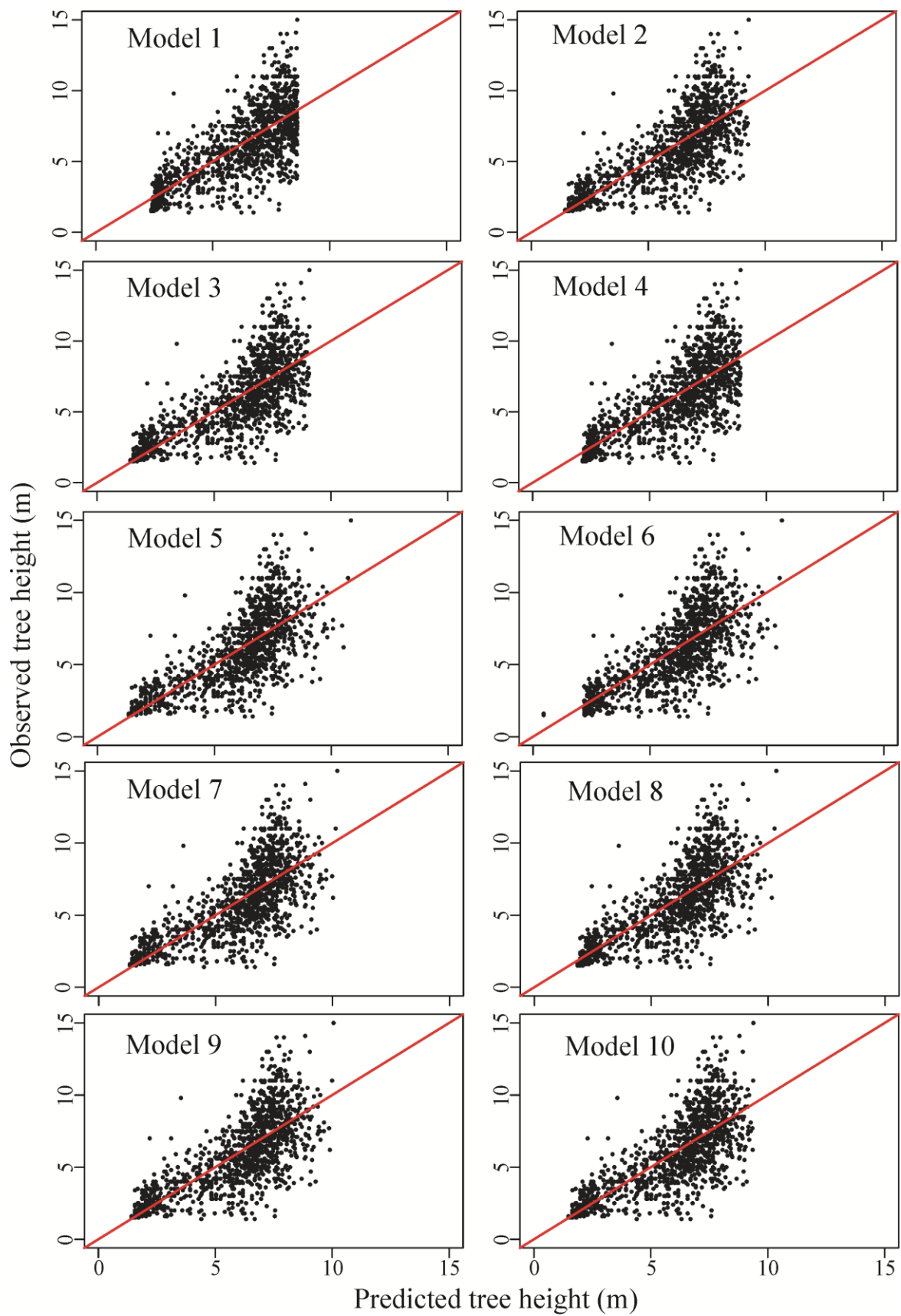
produce similar mean prediction errors. More specifically, Models (2), (5), (8), (9) and (10) yielded relatively higher positive mean prediction errors for classes with DBH values above 30 cm, whereas the highest negative mean prediction errors were observed for Models (1), (2), (3) and (4) for classes with DBH values above 40 cm. It is clear that all models were likely to create higher mean prediction errors for classes with DBH values above 20 cm. However, no significant trends were found. It is interesting to note that Model (6) generated significantly smaller mean prediction errors across all DBH classes. Considering all the aforementioned criteria and analyses, Models (1) and (6) are recommended for predicting the tree height of *P. euphratica* species in the region.



**Fig. 6-4** Simulation of the height–diameter models (1)-(10) for the model validation data set of *P. euphratica*. The blue and red lines represent the model fitting for the entire validation data set and for the data subset with  $DBH \leq 60$  cm, respectively.

**Table 6-4** Mean prediction error (ME) and mean absolute prediction error (MAE) of all candidate models for the model validation data set.

Model	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
ME	0.0059	0.0289	0.0426	0.0078	0.0233	-0.0114	0.0357	0.0054	0.0344	0.0196
MAE	1.3754	1.3976	1.3982	1.3817	1.4181	1.4097	1.4158	1.4006	1.4059	1.3972



**Fig. 6-5** Observed and predicted tree heights for the model validation data set of *P. euphratica*. The predicted tree height was determined by the height-diameter models (1) - (10).

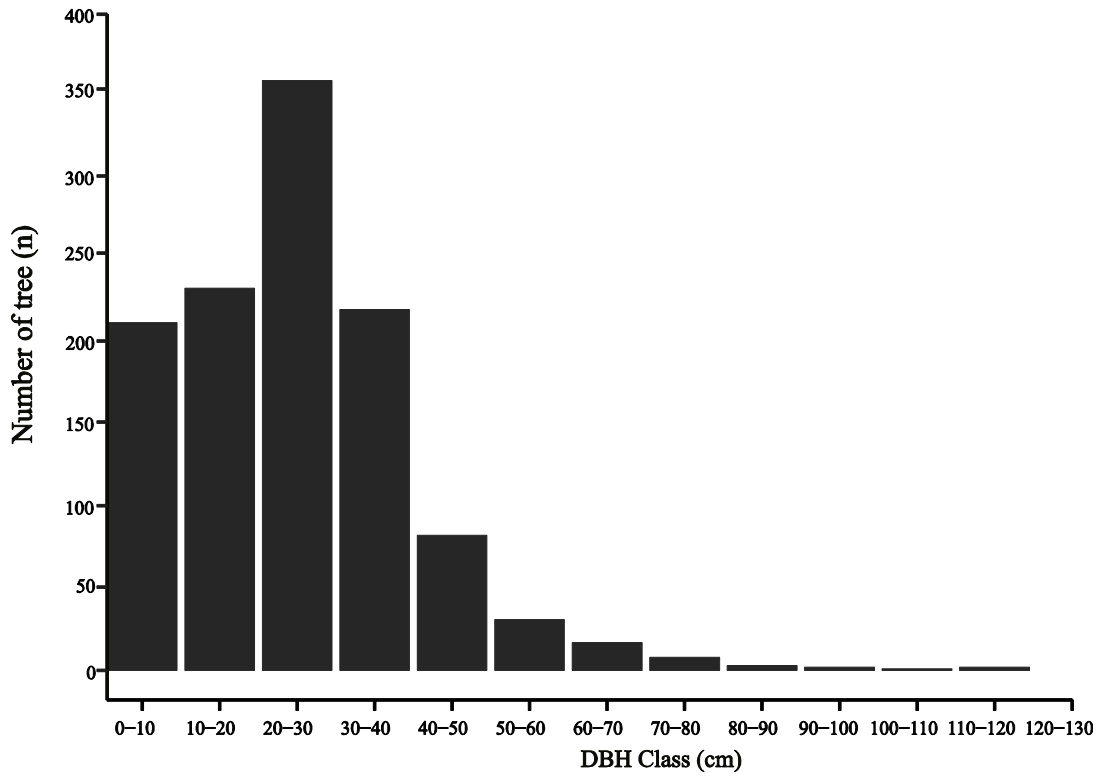


Fig. 6-6 Number of trees across DBH classes from the model validation dataset.

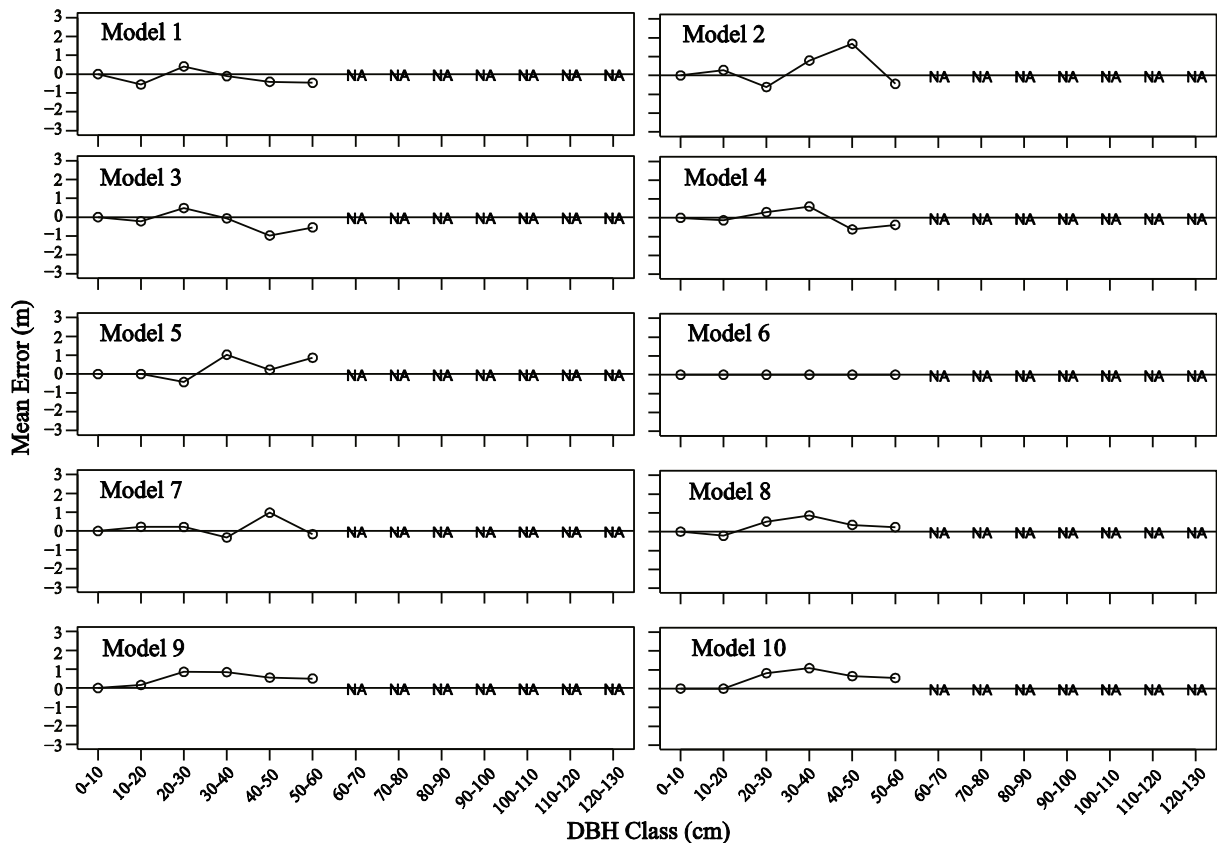


Fig. 6-7 Mean prediction errors across tree DBH classes (in 10-cm intervals) for the model validation data set of *P. euphratica* (the mean errors for Model (6) for the different DBH classes (0-60cm) are 0.0028, 0.000152, 0.00005, 0.00018, 0.00015 and 0.0005).

**Table 6-5** Prediction statistics of the selected height-diameter models (1)–(10) for the model validation data set of *P. euphratica*.

Model	Parameter	Estimate	SE	t-value	p> t	RMSE	AIC
(1)	<i>a</i>	7.3217	0.1609	45.493	<2e-16***	1.8239	708.382
	<i>b</i>	6.1095	0.6256	9.766	<2e-16***		
	<i>c</i>	0.1146	0.0071	16.258	<2e-16***		
(2)	<i>a</i>	8.0165	0.3352	23.919	<2e-16 ***	1.8539	726.373
	<i>b</i>	0.0468	0.0069	6.817	1.49e-11***		
	<i>c</i>	1.0595	0.1089	9.732	<2e-16 ***		
(3)	<i>a</i>	7.7876	0.3174	24.539	<2e-16 ***	1.8527	725.619
	<i>b</i>	-0.0341	0.0061	-5.596	2.74e-08 ***		
	<i>c</i>	1.1053	0.0729	15.165	<2e-16 ***		
(4)	<i>a</i>	7.5944	0.2029	37.420	<2e-16 ***	1.8345	714.106
	<i>b</i>	2.2963	0.1367	16.800	<2e-16 ***		
	<i>c</i>	0.0767	0.0053	14.380	<2e-16 ***		
(5)	<i>a</i>	17.1333	3.9015	4.391	1.23e-05***	1.8761	740.298
	<i>b</i>	4.5962	0.3095	14.850	<2e-16***		
	<i>c</i>	0.4261	0.0767	5.558	3.39e-08***		
(6)	<i>a</i>	-1.6211	0.3536	-4.584	5.04e-06***	1.8660	734.000
	<i>b</i>	2.6103	0.1387	18.826	< 2e-16 ***		
	<i>c</i>	0.0864	0.0043	20.188	<2e-16 ***		
(7)	<i>a</i>	0.1394	0.0557	2.503	0.0124 *	1.8713	737.292
	<i>b</i>	1.9723	0.3097	6.369	2.73e-10 ***		
	<i>c</i>	0.1718	0.0154	11.185	<2e-16 ***		
(8)	<i>a</i>	10.6952	0.5302	20.172	<2e-16 ***	1.8591	729.672
	<i>b</i>	-22.1570	2.6224	-8.449	<2e-16 ***		
	<i>c</i>	6.9681	1.3625	5.114	3.68e-07 ***		
(9)	<i>a</i>	9.8420	0.7751	12.698	<2e-16 ***	1.8631	732.184
	<i>b</i>	0.0275	0.0055	5.039	5.42e-07 ***		
	<i>c</i>	1.1756	0.1071	10.972	<2e-16 ***		
(10)	<i>a</i>	8.1210	0.2662	30.510	<2e-16 ***	1.8541	724.531
	<i>b</i>	0.0437	0.0029	14.920	<2e-16 ***		

**Note:** Significance codes ‘\*\*\*’ 0.001, ‘\*\*’ 0.01, ‘\*’ 0.05

## 7 DISCUSSIONS AND CONCLUSIONS

This study investigated the hydrological conditions, status quo and stands development of the remaining Tugai riparian forest (i.e., *Populus euphratica* Oliv.). It has also modeled the crucial relationship between two of the most important parameters (TH as a function of DBH) of this tree species based mainly on the terrestrial tree parameter data collected over the years (2004-2011) from two investigated sites (permanent and random) in Arghan village. In this chapter, the results will be discussed in detail and some conclusions will be drawn.

### 7.1 DISCUSSION

#### 7.1.1 EFFECTS OF WATER AVAILABILITY ON STAND STRUCTURE AND TREE VITALITY

The structure and distribution of tree parameters such as TH, DBH, CD, HC and CL showed great variation within a 300-m distance from the river course. The overall tree height ranged from 0.60 m to 19.00 m in the sampling plots. The maximum TH value was found on the P1 (within a 0–20-m distance of the river) and P4 (within a 100-200-m distance of the river) transects, respectively. On average, the minimum and maximum values of the tree height decreased as one got farther from the river (as one went from the P1 to the P11 transect). Within a 0-300-m distance from the river, the minimum values of TH ranged from 0,60 to 0,90 m, while the maximum TH1 and TH2 values ranged from 13,50 m to 19,00 m, suggesting that the trees at this location were still under development. By contrast, the overall DBH values ranged between 0.50 cm and 126.00 cm. The maximum DBH value of 126 cm was found at a distance of 500 -600 m from the river. Trees with TH values greater than 15 m and with DBH values greater than 60 cm appeared sporadically. There was no clear trend in DBH values along the water gradient, but the median and mean DBH values tended to increase with increasing distance from the river, since favorable groundwater depth was limited and closely related to the distance from the river course. As *P. euphratica* trees got closer to the river course and were supplied by relatively sufficient water (groundwater and soil moisture), their TH and DBH values were much more diverse than those of the other *P. euphratica* trees far away from the river course. A large number of degraded and stump stands could be found at distances of 750 and 1,050 m away from the river course (close to the desert border), respectively, indicating that the growth of *P. euphratica* trees is severely limited by water availability. Within a 300-m distance from the river course, the values of the tree parameters were relatively diverse. Large variation in the TH, DBH, CD, CH and CL values occurred in this corridor, indicating that the effects of water diversion on vegetation recovery were significant in this area. At distance of 300 m or greater from the river course, the variations of these tree parameters became smaller. In accordance with the age defining method (Table 7.1) of *P. euphratica* given by Lu and Yan (1989), and considering the ecological conditions of the highly degraded *P. euphratica* in the study area, the ages of the investigated poplar trees were broken up into five groups, based on their DBH values (i.e., juvenile,  $DBH \leq 8$ ; middle-aged,  $8 < DBH \leq 16$ ; near-mature stand,  $16 < DBH \leq 28$ ; mature stand,  $28 < DBH \leq 48$ ; over-mature stand,  $DBH > 48$ ). Fig. 7.1 shows that the largest number ( $n = 1645$ ) of observed trees was in the near-mature class, accounting for nearly 34 % of the

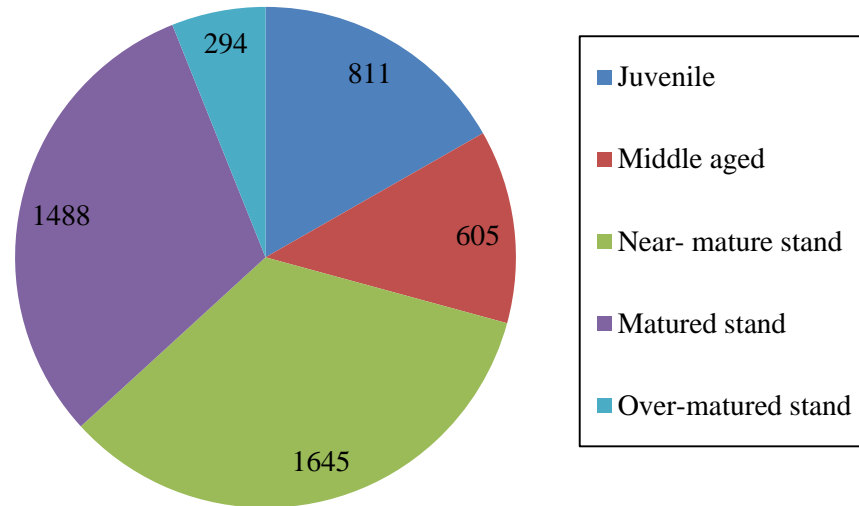
total trees in the sampling plots. There was also a considerable number of mature trees (n = 1448, almost 30 % of the total). Juvenile and middle-aged trees made up 16,74 % and 12,49 % of the total, respectively. All in all, more than 60 % of the trees in the sampling plots were grouped as near-mature or mature, suggesting that *P. euphratica* under the current rehabilitation measures exhibited a clear aging trend. However, the largest portions of these trees were distributed within 200 m of the river, which was preliminary estimated as a high potential area effected by the current restoration measures (Fig. 7.2). By contrast, the largest portion of the juvenile trees was found close to the river where seedling-friendly water conditions were available. Lu and Yan (1989) suggested that some individual trees can reach up to 120 cm in DBH value if the water regime is favorable. Three *P. euphratica* trees of about 120 cm in DBH were observed - two of them with DBH values of 119 cm (one 34 m from the river and another at 573 m), and one of them with a DBH value of 126 cm (532 m from the river). This clearly implies that the area with a distance of above 500 m had experienced favorable water conditions for riparian forest development before river desiccation.

**Table 7-1** Different stages of the *P. euphratica* growth process.

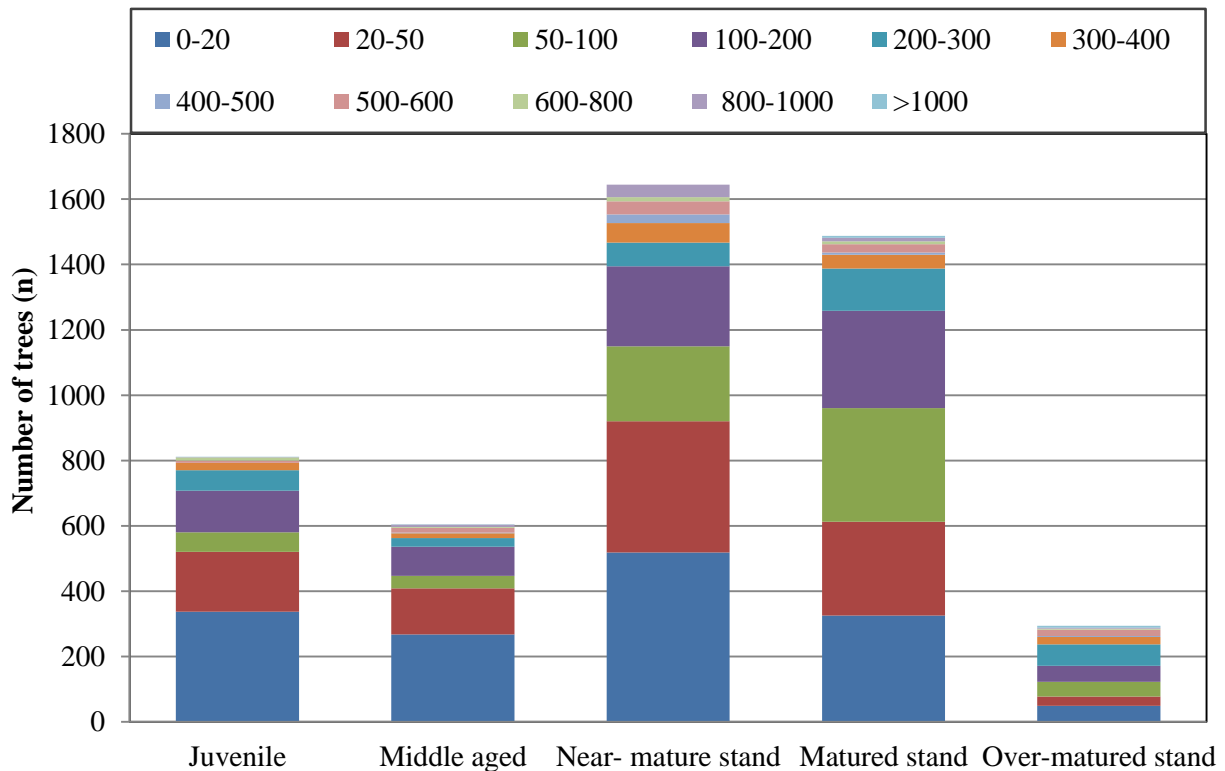
Growth stages	Characteristics of eco-morphological parameters
Juvenile	Age: 1~10; in the juvenile stage, the above-ground part grows slowly while its main root develops quickly and deeply. Under favorable site conditions, the height of one-year-old seedling is 6-8 cm while the depth of its root reaches 20 cm. At 2-year-old seedling height is 20-30 cm while the depth of root reaches 30-40 cm. in general, TH: ≤ 3.00 m or higher, DBH: around 4 cm; Leaves: mostly lanceolate form.
Middle aged	Age: 11~20, peak period of TH growth, TH: 4~8 m; DBH: 6~10 cm. Tree crown: Narrowly ovate; leaves: wide lanceolate and sparsely serrated.
Near- mature stand	Age: 21~30, peak period of DBH growth, TH: 10~14 m, DBH: 11~16 cm, with some individual up to 25 cm. Leaves: diversifolia type.
Matured stand	Age: 31~50, TH: 14~18 m, DBH: 30~50 cm. The stem is coarse, bark is thicker. Leaves: near kidney oval.
Over-matured stand	Age: 61~80, stand can reach age of 100 if ware regime is favorable. TH: ≥ 20 m, DBH:50~70 cm, some individuals even reach up to 120 cm, in this stage, bark is very coarse and thick, up to 5-10 cm, and drop off naturally. Crown becomes smaller, inclined and asymmetrical, often with dieback and heart wood rot.
Withered stand	Age: 80-100, the tree continues to live if it is supplied by sufficient water availability, although it is with nearly 100 % of leave defoliation rate and rarely live branches. In most cases, desertification already penetrates inside of this kind of stand.

Source: Chen et al. 1996





**Fig. 7-1** Number of observed trees in the different age classes.



**Fig. 7-2** Number of trees in the different age classes for different distances from the river.

It is clear that tree vitality is highly correlated with various environmental factors. Therefore, assessing tree vitality is important for identifying the ways in which forest health is influenced by external or internal stress. *P. euphratica* trees in the lower reaches of the Tarim River are frequently subject to various stresses resulting from environmental factors (Ma et al. 2011). These include groundwater quantity and quality, as well as soil conditions (soil moisture, soil organic matter and soil salinity). Here, the relationships between the distributions of *P. euphratica* trees were examined, their vitality and the distance to the river, which had a significant impact on groundwater levels. The main parameter selected for determining tree

vitality was defoliation rate. Defoliation harms plants by eliminating their food-production capability. The refoliation process, which frequently occurs right after defoliation, requires energy for budbreak and leaf expansion, which cause further depletion of stored food reserves (Schulz and Hartling 2003; Halik et al. 2009; Trinidad et al. 2010). During the collection of data in the recent years, we found that most of the trees have been damaged by insects, which caused the decline of the floodplain ecosystem health and inhibited recovery, with some trees having lost their vitality due to the damage. Therefore, insect infections affect to some extent the assessment of trees' vitality. Since tree vitality is related to a number of complex processes, as well as to the visual determination criteria introduced in this study, other environmental factors for determining the vitality of *P. euphratica* trees must be also taken into account in future research.

### 7.1.2 UNFAVORABLE HYDROLOGICAL CONDITIONS FOR STAND GROWTH

With the implementation of ecological water diversion in the lower reaches of the Tarim River in recent years, the groundwater has obtained a certain degree of supply both quantitatively and qualitatively, and has played a positive role in the recovery of *P. euphratica* and other natural plant species (Chen et al. 2006; Xu et al. 2007; Halik et al. 2009). Due to the increasing conflicts between agricultural irrigation and ecological water demand, the man-made ecological water conveyance could not be ensured in terms of its flooding time and amount. Therefore, in the vertical direction of the watercourses, the river conveyance has been influenced by space constraints to some extent. With increasing distance from the river course, the degree of influence of water conveyance on groundwater recharge decreases accordingly - namely, the farther away from the river course one is, the deeper the groundwater depth (Chen et al. 2006). The groundwater depth variation analyses of this study suggested that groundwater depth at the well closest to the river is below 5 m, a depth considered as a threshold for the regeneration of floodplain forests (Table 7.2). However, there was a rise of the water-table at the nearest well (50 m) from the river channel of each transect. Along the Yingsu transect, the groundwater depths at Karday and Arghan are well below 5 m. These are levels unlikely to support the normal growth of floodplain forests (Table 7.2). Floodplain forests growing the farthest from the river course might be still be suffering from water stress.

**Table 7-2** Plant species and their corresponding groundwater depths measured at the lower reaches of the Tarim River.

Plant Species	Depth of main root (m)	Groundwater depth favorable to growth (m)	Groundwater depth causing insufficient growth (m)	Groundwater depth resulting in partial or total
<i>Populus euphratica</i>	< 7.0	1.0-4.0	5.0-6.0	Generally>8.0
<i>Tamarix</i> sp.	< 5.0	1.0-6.0	> 7.0	> 10.0
<i>Phragmites australis</i>	0.5-1.0	1.0-3.0	> 3.0	> 3.5
<i>Glycyrrhiza inflata</i>	1.0- 2.0	1.0-3.0	> 3.0	> 4.0
<i>Alhagi sparsifolia</i>	> 4.0	1.0-4.0	> 4.0	> 5.0
<i>Halostachys caspica</i>	< 1.6	1.0-2.5	> 3.0	> 3.5
<i>Halimodendron halodendron</i>	1.0-3.0	2.0-4.0	> 4.0	> 5.0
<i>Apocynum venetum</i>	2.0-3.0	1.5-4.0	> 4.0	> 5.0
<i>Karelinia caspica</i>	> 3.0	1.0-3.0	> 4.0	> 5.0
<i>Elaeagnus angustifolia</i>	0.5-2.5	1.0-4.0	> 5.0	> 6.0
<i>Halocnemum strobilaceum</i>	1.02-2.0	1.0-2.5	> 3.0	> 4.0

Source: Song et al. 2000

### 7.1.3 CHALLENGES OF RESTORATION MEASURES FOR FOREST REGENERATION

Eco-morphological parameters of *P. euphratica* trees sampled at the main study area in Arghan responded to water stress relief measures, which aimed at improving groundwater conditions through man-made water diversions in the lower reaches of the Tarim River. It is clear that the groundwater level has recovered to about 5.50–8.50 m for the entire study area in Arghan and has played a positive role in motivating tree growth (even of dieback trees) and other natural vegetation. The effects of water diversion on the degraded desert riparian forests in the lower reaches of the Tarim River have been analyzed based on groundwater levels and the measurements of physical and eco-morphological parameters of the affected trees (Chen et al. 2008, 2010; Wang et al. 2008a, b; Xu et al. 2007, 2009). Chen et al. (2008, 2010) analyzed the impact of the environmental factors (groundwater table, salt concentration in groundwater) on the physio-morphological parameters of *P. euphratica* before and after water diversion. Their investigation suggests that in the aftermath of water diversion, the groundwater table was raised, thereby reducing the physiological stress on *P. euphratica*. Within a 250-m distance from the river, groundwater levels were very sensitive to water recharge and hence riparian vegetation recovered remarkably. Within 250–450 m of the river, groundwater recharge was less significant and vegetation showed a medium level of response. Beyond distances of 750 m, groundwater levels and vegetation responded weakly. In their study about the relationship between the changes in groundwater level and the response of vegetation, Xu et al. (2007, 2009) demonstrated that the groundwater depths along the Tarim River channel have a significant spatial–temporal pattern. Groundwater levels closest to the river channel show the most immediate and pronounced changes in response to water

diversion while those further away tend to respond slowly. With rising groundwater levels, natural vegetation responded with higher growth rates, biomass and biodiversity. Our results support the idea that groundwater levels and soil conditions within the 0–200-m distance of the river are more suitable for stimulating regular the eco-morphological developments of riparian vegetation (Table 7.3). This study demonstrates that in the vertical direction to the river bed, replenishment of groundwater is greatly influenced by distance to the river. With an increasing distance from the river course, the effect of water diversion practices on groundwater recharging declines: the farther away from the river course one is, the deeper the groundwater levels sink. The majority of trees in vital, good and medium classes were found near the riverbed, accounting for 38.12 % of the sampled trees. This shows that water diversion had a significant effect on the revitalization of degraded trees. Nevertheless, the degraded riparian vegetation located at farther from the riverbed is still suffering from water stress. Cases of crown re-establishments by dieback trees in the aftermath of the water diversion project were also mainly found within the 200-m distance of the riverbed. However, it has to be mentioned that the eco-morphological responses of *P. euphratica* to environmental changes in the lower reaches of the Tarim River may be less evident when compared to their physiological responses.

**Table 7-3** Effect of water diversion on the overall recovery of *P. euphratica* forests.

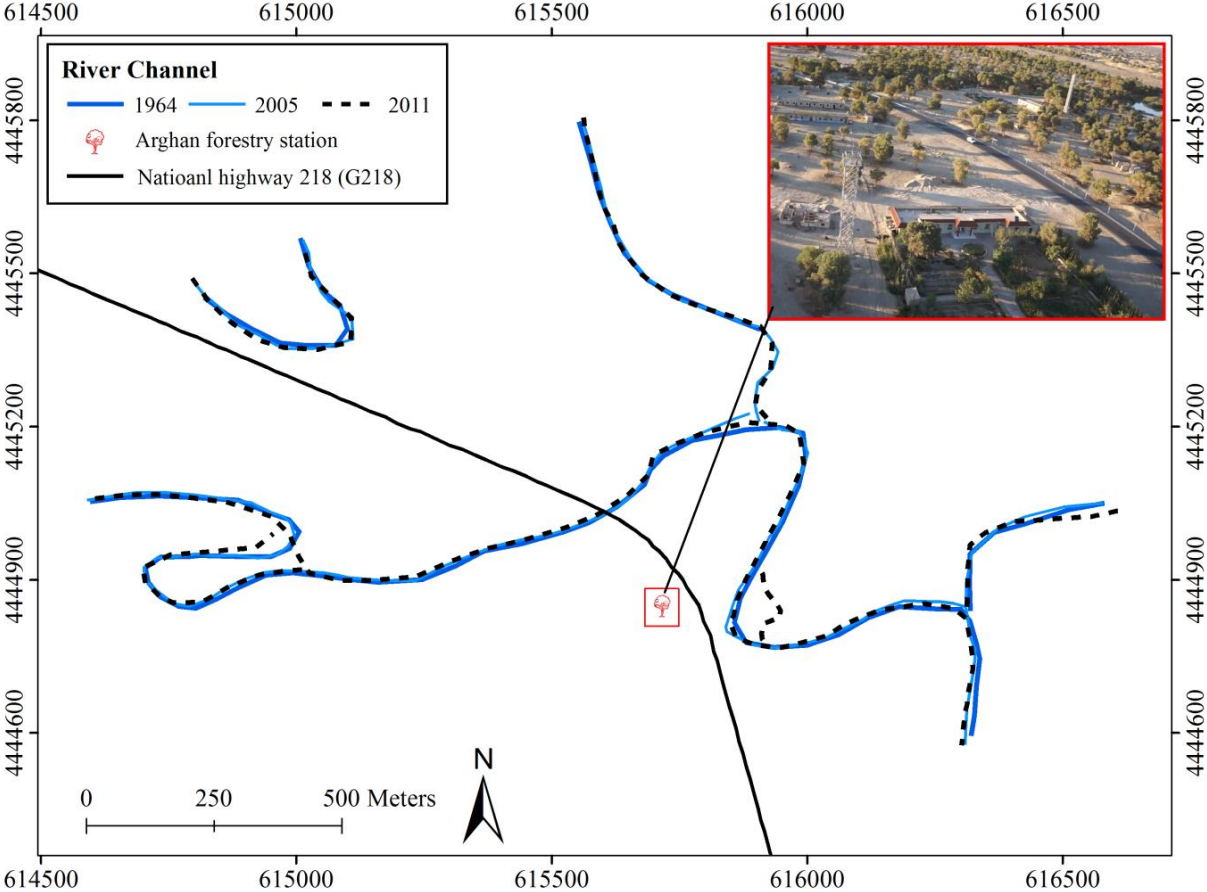
Response of Eco-morphological parameters	Responding area (m)	Groundwater depth / m	Overall Recovery of <i>P. euphratica</i>
Responded obviously	0-200	5.5-6.5	Some root sucker and seedlings occurred, canopy density reach over 50 %,tree vitality improved, most of the trees lost less than 25 % leaves
Medium response	200-800	6.5-8.0	Less root sucker occurred, canopy density is between 15-40 %, most of the trees are in middle vitality class and lost 25-75 % leaves
Less sign of recovery	>800	>8.0	No root sucker and seedlings occurred, most trees were highly degraded or dead, almost no sign of regeneration, less vitality, trees lost more than 75 % leaves

All in all, the response of groundwater levels to water diversions weakened with increasing distance from the river, which restrained the process of revitalization due to unfavorable groundwater supply. Therefore, because of the high dependency of riparian vegetation in the lower reaches of river on man-made water diversion practices, the time, frequency, and volume of water diversion must be not only guaranteed but also flexibly adjusted to changing demands of natural forests with respect to bio-physiological requirements (Wang et al. 2007; Fu et al. 2011; Aishan et al. 2013). Table 7.4 shows the water diversion times and the biological life cycle of the riparian vegetation in the restoration area. Several water diversion practices took place outside the scope of the vegetation season. There was a frequent temporal mismatch between the water diverting time and the seed dispersal season of *P. euphratica* trees.

**Table 7-4** Water diversion times and the biological life cycle of riparian vegetation in the restoration area (the temporal match between the water diversion times and the seed dispersal season of *P. euphratica* trees is indicated by the red frame).

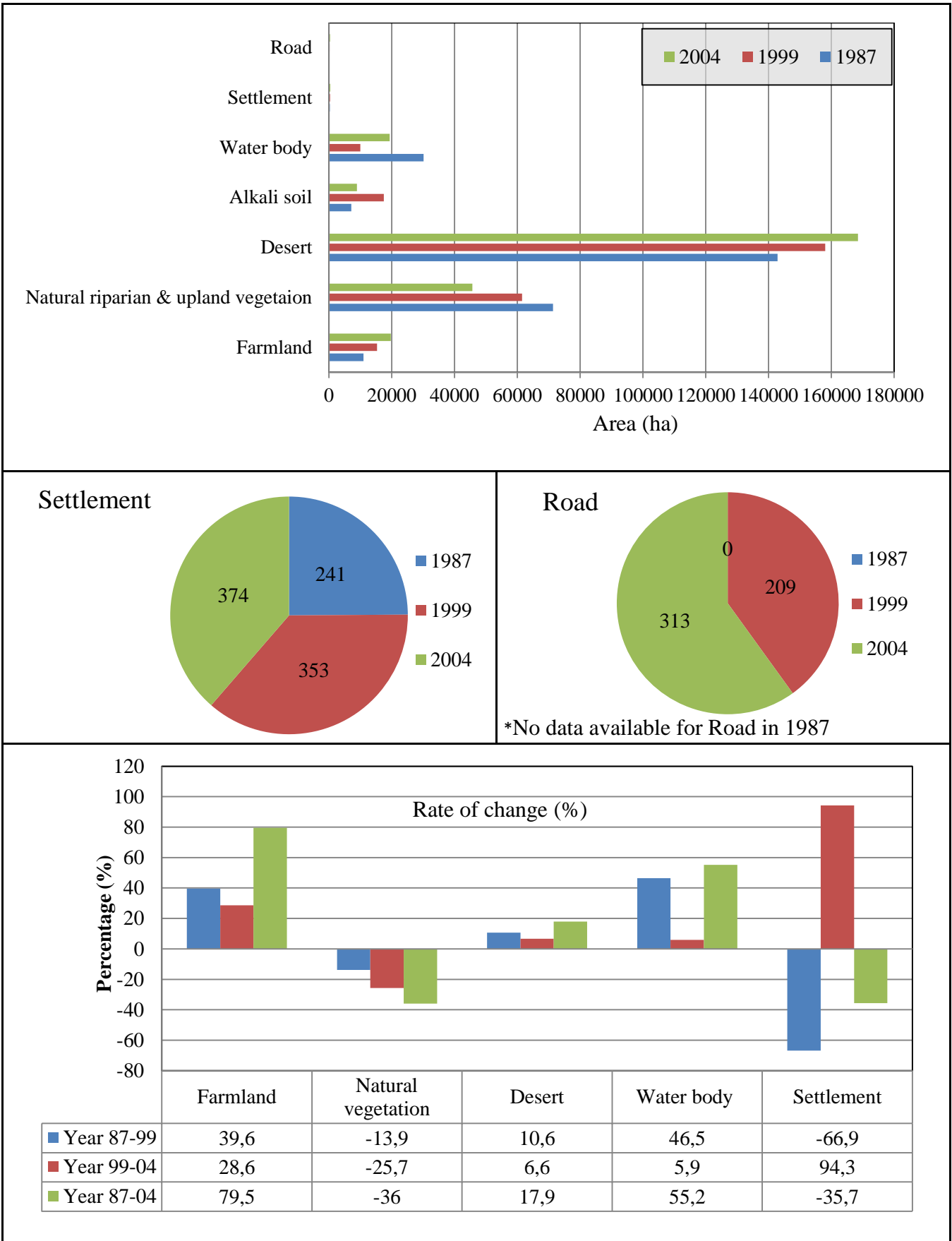
Month Diversion	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
1 <sup>st</sup>					from 14/05	√	till 13/07					
2 <sup>nd</sup>	√	till 14/02									from 03/11	√
3 <sup>rd</sup> (1 <sup>st</sup> period)				√	√	√	till 06/07					
3 <sup>rd</sup> (2 <sup>nd</sup> period)									from 12/09	√	till 17/11	
4 <sup>th</sup>							from 20/07	√	√	√	till 10/11	
5 <sup>th</sup> (1 <sup>st</sup> period)			√	√	√	√	till 11/07					
5 <sup>th</sup> (2 <sup>nd</sup> period)									from 12/09	√	till 07/11	
6 <sup>th</sup> (1 <sup>st</sup> period)				From 22/04	√	till 25/06						
6 <sup>th</sup> (2 <sup>nd</sup> period)								√	till 15/09			
7 <sup>th</sup> (1 <sup>st</sup> period)				From 18/04	√	till 07/06						
7 <sup>th</sup> (2 <sup>nd</sup> period)									√	√	till 02/11	
8 <sup>th</sup>									from 25/09	√	√	
9 <sup>th</sup>										from 15/10	till 21/11	
10 <sup>th</sup>					from 12/05	till 20/06						
11 <sup>th</sup>						from 25/06	√	√	√	√	till 11/11	
12 <sup>th</sup> (1 <sup>st</sup> period)	07-25/01											
12 <sup>th</sup> (2 <sup>nd</sup> )						from 25/06	√	√	√	√	till 23/11	
<b>Legend</b>		Vegetation growing season						Water diverting time				
		Seed rain season for <i>P. euphratica</i>					√	Diverting time throughout the month				

In addition, riparian forest development is inherently dependent on high fluvial dynamics, which cause channel movement and sediment deposition. Accordingly, these provide potential regeneration sites. However, channel movement did not take place in the study area (Fig. 7.3). Therefore, it appears that regulated rivers can no longer sustain the natural development of forests, since the streamflow cannot be managed to mimic pre-restoration conditions.



**Fig. 7-3** Channel movement of the Tarim River in Arghan for the time period of 1964-2011 (Source: Betz 2014).

Kong et al. (2004) found that 26 % of the land experienced cover changes during the 1987-2004 period in the lower Tarim River drainage area (from the Qira reservoir to the Daxihaizi reservoir). Much of the LUCC (Land Use & Land Cover Change) were changed from the natural riparian and upland vegetation to other land covers (Keilholz 2014). The natural and riparian and upland vegetation were transformed mostly to desert and to farmlands, indicating that the land reclamation process is still going on in the area (Figs. 7.4 and 7.5).



**Fig. 7-4** Land use and land cover change along the lower reaches of the Tarim River for 1987, 1999 and 2004, together with the rate of change between assessment years. (Source: Kong et al. 2010)



**Fig. 7-5** Reclamation of agricultural land inside of the *P. euphratica* forest stand in the upper reaches of the Tarim River (Source: <http://news.sina.com.cn/c/2011-07-12/001022795500.shtml>).

During their study period (1987-2004), the natural riparian and upland vegetation decreased by 36 % in a part of the lower reaches of the Tarim River (from Qira reservoir to Daxihaizi reservoir), with deserts and farmlands increasing by 18 % and 80 %, respectively (Fig. 7.4). Most critically, the farmlands have kept increasing in the restoration area even while the water diversion project was being implemented - e.g., the natural riparian and upland vegetation decreased by 25,7 %, with deserts and farmlands increasing by 5,6 % and 28,6 % (Fig. 7.4). This means that the current land and water resource management along the lower reaches of the Tarim River is not effective and that it should be improved. At the same time, holistic countermeasures to save as much water as possible for the rehabilitation of degraded forests should be taken in order to avoid further degradation (Fig. 7.4).

As mentioned in Chapters 2 and 3, the lower reaches of the Tarim River were cut off from its water supply for nearly 30 years, which has correspondingly resulted in the majority of riparian forests on both sides of the riverbed completely losing their vitality. Current restoration measures are facing great challenges both in improving the ecological statues of the existing vegetation as an effect of the rising water table, and in establishing a rejuvenation of stocks and the colonization of new vegetation with the creation of moist and sediment sites. Because restoring these highly degraded desert riparian forest ecosystems is an arduous process, politically, socially and economically practical long-term solutions are needed to assure the sustainable future of this region.



#### 7.1.4 EFFECTS OF TREE VITALITY ON THE RELATIONSHIP BETWEEN TH AND DBH

The TH and DBH values of *P. euphratica* trees showed different distribution patterns. The relationship of height-diameter in *P. euphratica* trees varied remarkably among the different vitality classes. Water supply is generally suggested as the reason for these results. Because of the long-term desiccation of the river watercourse and the continued falling of groundwater depth (to levels failing to meet the needs of riverside vegetation), a majority of the riparian forests with weak vitalities have lost the ability to renew and regenerate (Westermann et al. 2008; Chen et al. 2010, Aishan et al. 2013; Si et al. 2014). The values of the DBH of trees in different vitalities varied significantly, while the distribution patterns of the TH values were simpler. This result indicated that the growth of TH was highly limited when compared to the growth of DBH in the lower reaches of the Tarim River. The vitality of *P. euphratica* forests weakens gradually along the two sides of the river course.

By analyzing the relationships between the TH and DBH values of *P. euphratica* for different vitality classes and for different distances from the river, it was found that the TH values of trees in the “senesced” and “dying” vitality classes were significantly positively correlated with the distance of trees from the river course (Table 7.5). However, the TH values of trees belonging to the other vitality classes did not display significant correlation with distance from the river. In addition to the TH values of the *P. euphratica* in the “dead” vitality class, the correlation between TH and distance from the river increased correspondingly with the decrease in tree vitality. This showed that the distance of the trees from the river course was a major factor in determining the vitality of *P. euphratica* trees. The majority of healthy trees were located close to the river course where the moisture conditions were sufficient. Therefore, the distance of trees from the river course does play a key role in determining the tree vitality. Likewise, there were significant positive correlations between the DBH values of *P. euphratica* with distance of trees from the river course for the V1, V2, V3, and V4 vitality classes, while the DBH values of healthy and dead trees were not correlated with distance from the river. A possible explanation for this phenomenon is that most of the healthy trees are predominantly distributed close to the river course (Aishan et al. 2015). The majority of highly degraded trees may have already lost contact with the groundwater, and so cannot be revitalized under the current restoration measures.

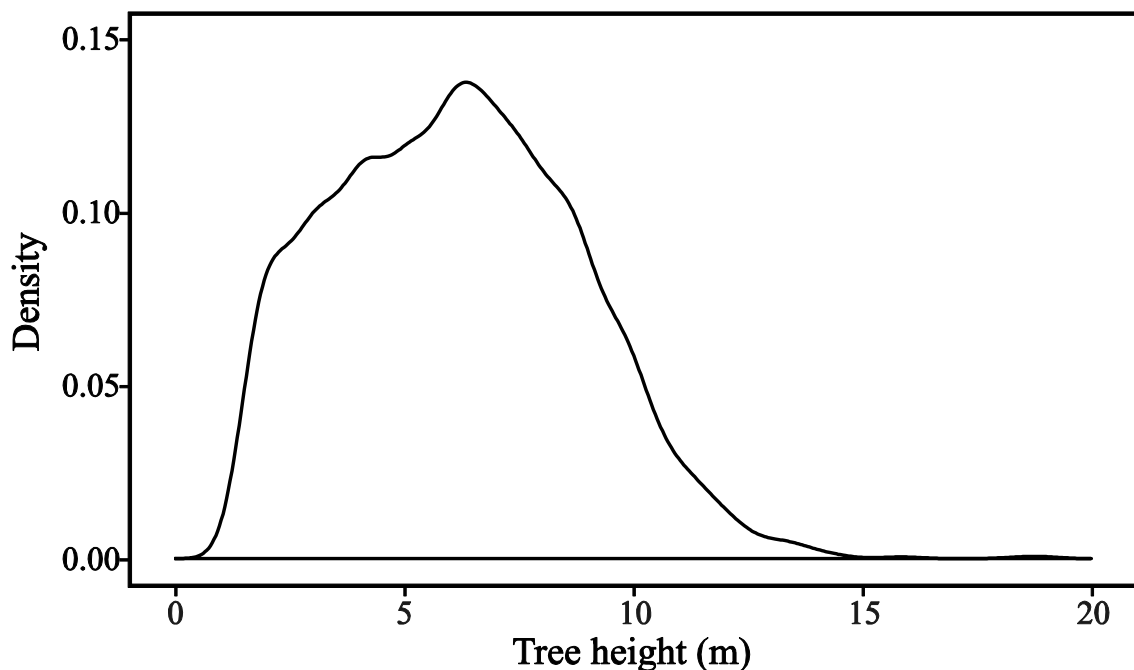
**Table 7-5** Relationships between the TH and DBH values of *P. euphratica* trees in the different vitality classes for different distances from the river course.

Parameter	Statistic	Vitality class					
		V0	V1	V2	V3	V4	V5
TH	<i>r</i>	0.014	0.027	0.025	0.730*	0.209**	0.024
	<i>P</i>	0.692	0.346	0.317	0.048	0.001	0.609
DBH	<i>r</i>	0.046	1.000**	0.091**	0.141**	0.539**	0.049
	<i>P</i>	0.240	0.000	0.000	0.000	0.000	0.318

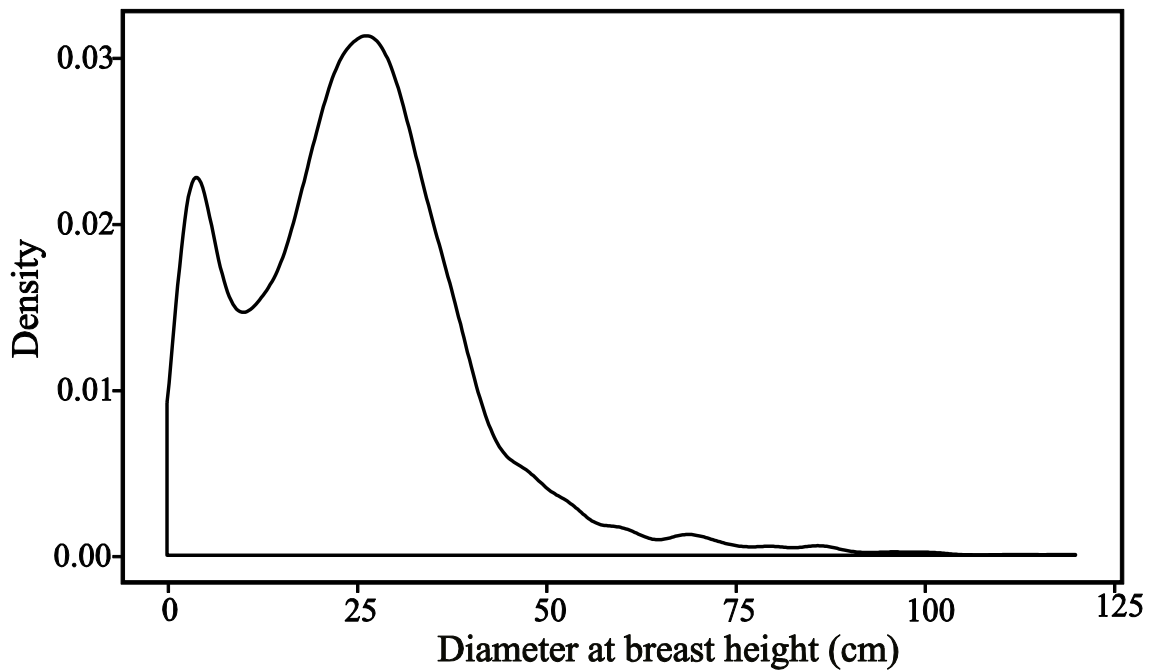
Note: *r* is correlation coefficient; *P* is significance level. \* and \*\* mean significance at  $P < 0.05$  and  $P < 0.01$  (two-tailed), respectively.

### 7.1.5 MODEL LIMITATIONS FOR PREDICTING TREE HEIGHT

The fitting results of the extensively collected TH and DBH data to ten candidate height-diameter nonlinear models were presented in this study. Most of the candidate models performed quite well in delineating the TH and DBH relationship. Based on the analysis of the multi-model performance criteria, it was found that Models (1), (2), (3) and (4) proved more effective in predicting the tree heights of *P. euphratica* than the other candidate models. Among them, Model (1) provided the most satisfactory tree height estimates. With all of the model performance criteria considered, Model (6) was selected as a potential best model due to the fact that it performed the best across various DBH classes. Nonetheless, nearly all of the models had limitations when predicting tree heights above 9 m. specifically, the models tended to fail when it came to predicting the tree heights of trees with large diameters (above 50 cm). This is mainly because trees thinner than 50 cm in DBH are usually less than 9 m high. Variations of tree height beyond DBH values of 50 cm were insignificant. In order to determine how representative the selected model for *P. euphratica* was, the density of the height-diameter distribution was plotted (Figs. 7.6 and 7.7). 263 trees with DBH values exceeding 50 cm were found in the combined dataset, accounting for 5.23 % of the total data set used in this study. Clearly, trees larger than 50 cm in DBH are not very common in the study area. For this reason, the selected model (1) should not be applied in stands with dominant height values of above 9 m and DBH values of more than 50 cm.



**Fig. 7-6** Density plot for TH distribution of *P. euphratica* within the model calibration dataset



**Fig. 7-7** Density plot for DBH distribution of *P. euphratica* within the model calibration dataset.

Huang et al. (2000) developed tree height-diameter models for white spruce trees growing in different ecoregions and concluded that the condition of the habitat of tree species also affects the model performance and the prediction accuracy to some degree. Height-diameter relationships vary between ecoregions, because of the differences in bioclimatic conditions (Meng et al. 2008). Because groundwater availability is the main driving factor determining the functioning of the riparian forest ecosystem along the Tarim River and its sustainable development (Aishan et al. 2013, 2015), additional research is necessary to evaluate the height-diameter model performance of *P. euphratica* under different levels of water stress, as this could provide more satisfactory models for the height prediction of *P. euphratica* trees. Recent literature suggests that mixed-effect models may be most appropriate for predicting tree height in heterogeneous environments (Trincado et al. 2007; Temesgen et al. 2008; Esteban et al. 2014). For this reason, it is suggested that on the one hand careful validation be done for the selection of a suitable model, while on the other hand the inclusion of factors like tree vitality and water availability as parameters in the original height-diameter model be taken into consideration so as to minimize the model limitations and to determine the tree heights of *P. euphratica* more precisely in future work.

## 7.2 CONCLUSIONS

The results of this thesis can be summarized as follows:

- The research findings indicate that the 12 water diversion events in the lower reaches of the Tarim River have played a significant role in raising groundwater tables near the main river course and in recovering floodplain forests to a certain degree. However, the amount by which the groundwater table rose decreases with increasing distance from the river. The responses of the ecological indices (average crown diameter, average crown loss) of trees within a short distance of the river were striking. The contributions of water

diversions to the recovery of vegetation growing relatively far from the main riverbed were not obvious. Young seedlings, new shoots, and root suckers of *P. euphratica* mainly appeared close to the river. The distribution of floodplain forests is also influenced by topographic conditions, soil moisture and soil salinity. All these factors need to be further investigated. Current water diversion practices have achieved the preliminary step of making site conditions favorable for forest recovery within a 200-m distance of the main river. To date, such expensive efforts fall short of fully restoring the hundreds of kilometers of the highly degraded floodplain ecosystem in the near future. Intensified and excessive upstream exploitation of water resources should be effectively controlled to allocate regular and sufficient water for the successful restoration of the degraded floodplain.

- The TH and DBH values of *P. euphratica* forests had irregular distribution patterns across different vitality classes. The values of DBH for different vitalities varied greatly while the distribution patterns of the TH values were simpler, indicating that the DBH (horizontal) growth of *P. euphratica* in the lower reaches of the Tarim River seemed to be faster than the TH (vertical) growth. Trees classified as “healthy”, “good” and “medium” consisted of large numbers of juvenile trees (DBH  $\leq$  5 cm). In particular, “healthy” trees were composed of relatively young individuals, which suggest that the regeneration process of degraded *P. euphratica* forests by current water diversion projects is still ongoing. Height-diameter relationships of the *P. euphratica* trees showed significant variations across different vitality classes. There was a clear trend with regard to the coefficients of the height-diameter correlation decreasing with decreasing tree vitality. All in all, differentiating the degraded *P. euphratica* trees from the healthy trees might be possible by determining the height-diameter correlation coefficient, and then using this coefficient as a new parameter for detecting the degradation level of riparian forests in arid regions.
- There is a close link between eco-morphological parameters - such as CD, under BH, tree crown types and tree vitality - and the environmental drivers (water diversion practices, distance to the river, groundwater depth). Twelve irregular man-made water diversions to the lower reaches of the Tarim River resulted in the elevating of groundwater levels and provided suitable conditions for normal tree growth and for the reestablishment of secondary crowns on dieback trees. The vitality of *P. euphratica* trees at the study area in general saw a significant improvement. However, while the growth increment in CD and under BH of trees near the river was high, trees that were sampled farther away from the river reacted weakly. Thus, the positive effect of the water diversions on restoring the highly degraded *P. euphratica* trees was restricted to within 200 m of the riverbed. As for the dominant species, such as *P. euphratica* and *Tamarix spp.*, the suitable groundwater depth is about 5–6 m, and the extension of the flooding time and an increase in frequency can positively affect the opportunities for successful restoration of floodplain forests (even in locations beyond 200 m from the river, where the groundwater levels are still well below 6 m). Hence, such intensified and excessive upstream exploitation of the water resources should be effectively controlled to allocate regular and sufficient water for the

successful restoration of the degraded floodplain ecosystem in the lower reaches. By this means, the volume and duration of water diversion can be ensured and, consequently, an enhanced eco-morphological development and regrowth of degraded trees may be possible.

- The fitting results of all 10 models to tree height and diameter data showed varying performances. A comparative analysis for evaluating the goodness of each model performance indicated that Model (1):  $TH = 1.3 + a/(1 + b \times e^{-c \times DBH})$  and Model (6):  $TH = 1.3 + DBH^2/(a + b \times DBH + c \times DBH^2)$  provided the best prediction capability for *P. euphratica* tree heights. Because of model limitations, however, as well as other eco-environmental factors influencing the predictions, the selected model (1) should not be applied in stands with dominant height values above 9 m or with DBH values above 50 cm. As *P. euphratica* is a key tree species in the Tarim riparian forest ecosystem, understanding its height-diameter relationship is essential for developing growth, biomass production and carbon storage prediction models to be applied in the current forest management projects. This would be the very first step to understanding the riparian forest dynamics over time and with respect to the forest restoration measures conducted in the region since 2000. After all, Models (1) and (6), which were selected as the most effective for predicting the tree height of *P. euphratica* along the lower reaches of the Tarim River, may well provide a basic scientific foundation for a sustainable forest management program in China and in other similar regions of the world.

### 7.3 OUTLOOK

Restoration and sustainable management of riparian forest in arid ecosystems require combined scientific knowledge from different disciplines and practical guidelines for forest managers and decision makers. This thesis summarized current hydrological and ecological conditions of *P. euphratica* stands at the Arghan long-term forest-condition monitoring sites in the lower reaches of the Tarim River. The rehabilitation and regeneration of degraded forests under different water limitation gradients were assessed using extensively re-measured tree data. In addition, considering the high costs and the labor intensity of tree height measurement in the field, height-diameter models suitable for *P. euphratica* trees were successfully developed. The results will provide a scientific basis for how restoration efforts in the arid regions can contribute to highly degraded ecosystems. At the same time, they may also serve as a supplement of information for forest managers and other practitioners. In this research, the main focus was given to monitoring and assessing *P. euphratica* riparian forests over long-term time periods so as to determine the effectiveness of ecological restoration. Since water is a crucial determining factor for both natural and unnatural ecosystems, addressing how limited water resources are allocated and managed effectively is of key importance to sustaining ecological and socio-economic development in the region. Lessons, experience and scientific knowledge from the past and current restoration activities regarding its difficulties of restoring degraded natural ecosystems in the region should be learned and applied to future efforts associated with the objectives of ecological restoration projects.

As mentioned by many scientists both inside and outside of China, the vitality of the degraded forests along the Tarim River riparian ecosystems depends highly on how the limited water is managed in the present and future. Specifically:

- Due to the significant differences among the water use strategies of individual *P. euphratica* stands, methods for estimating the optimum water requirements of *P. euphratica* stands for different degradation gradients and hydrological conditions should be developed not only at field scale but also at landscape scale.
- Tree ring analyses are also needed to link the natural growth of trees to the impact of water diversion. The reproductive strategy of *P. euphratica* in the long-term investigation area should be systematically studied.
- As mentioned earlier, establishing a large number of young seedlings and ensuring their survival until they become self-sustaining trees is very difficult under the current forest restoration and management practices - most of the renewed trees are root sucker. Therefore, it is very important to study the reproductive pattern and development tendency of *P. euphratica* forests under different hydrological conditions, and their positive/negative effects on the sustainable development of the forests in the region.
- During the recent years of doing PhD work and reviewing the relevant literature, I have concluded that there is a big research gap with regard to the below-ground structure of *P. euphratica*. For example, what is happening in the below-ground ecosystem of the riparian forests under different water regimes is still unclear. Given the long-term extreme water scarcity, *P. euphratica* might have developed more adaptive underbodies (roots) to survive (in comparison to its upper body). Systematic research on this scientific issue is highly suggested.
- Finally, water for eco-environmental needs should be secured by reducing human water consumption (land reclamation and agricultural irrigation), reforming the water allocation policy, replacing high-level water-consuming crops with possible farming alternatives, improving irrigation technologies, and implementing soil and water management laws tightly and effectively.

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## **APPENDIX**

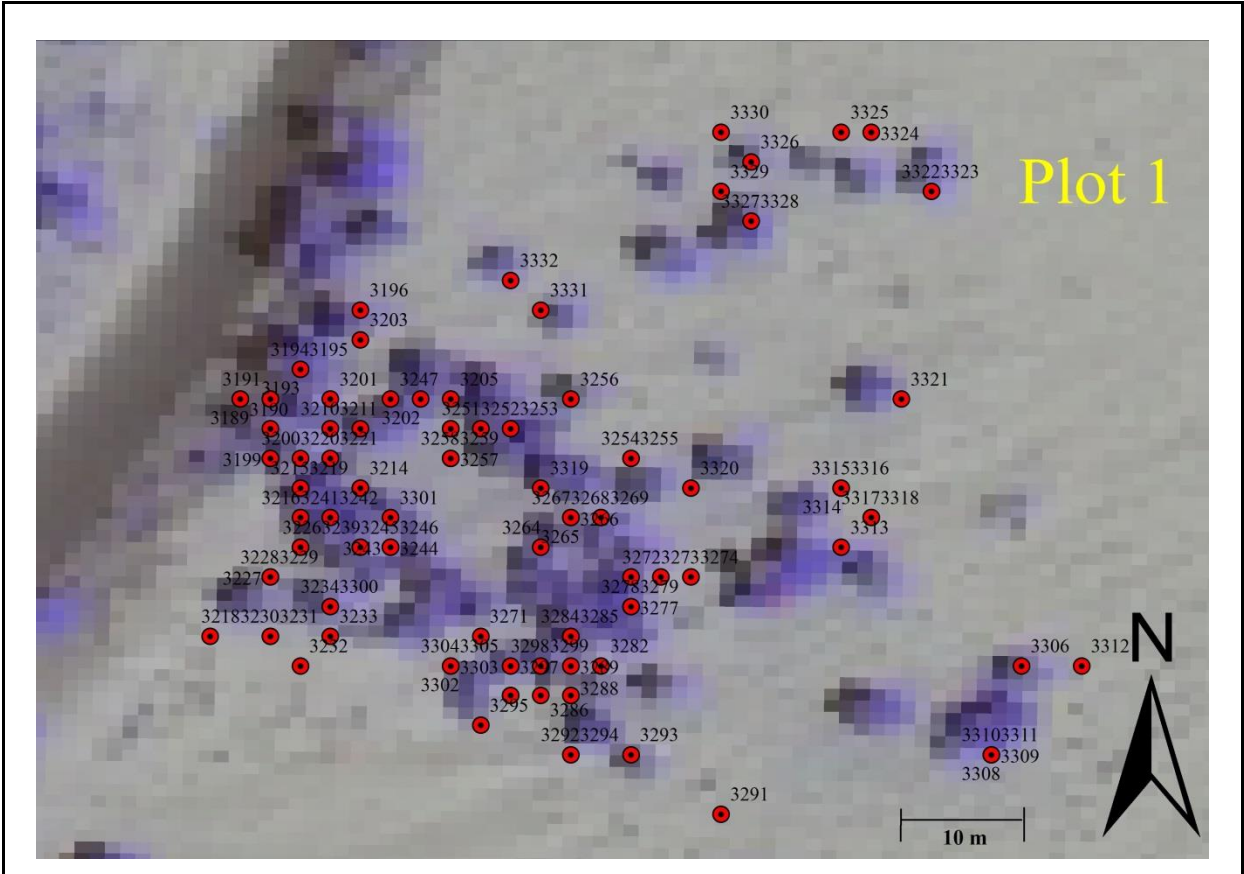
Fig. A-1 Overview of the P1 random sampling plot. Background is QuickBird image.

Fig. A-2 Overview of the P2 random sampling plot. Background is QuickBird image.

Fig. A-3 Overview of the P3 random sampling plot. Background is QuickBird image.

Fig. A-4 Overview of the P4 random sampling plot. Background is QuickBird image.

Fig. A-5 Overview of the P5 random sampling plot. Background is QuickBird image.



**Central tree in the Plot 1**

Tree-Nr.3319

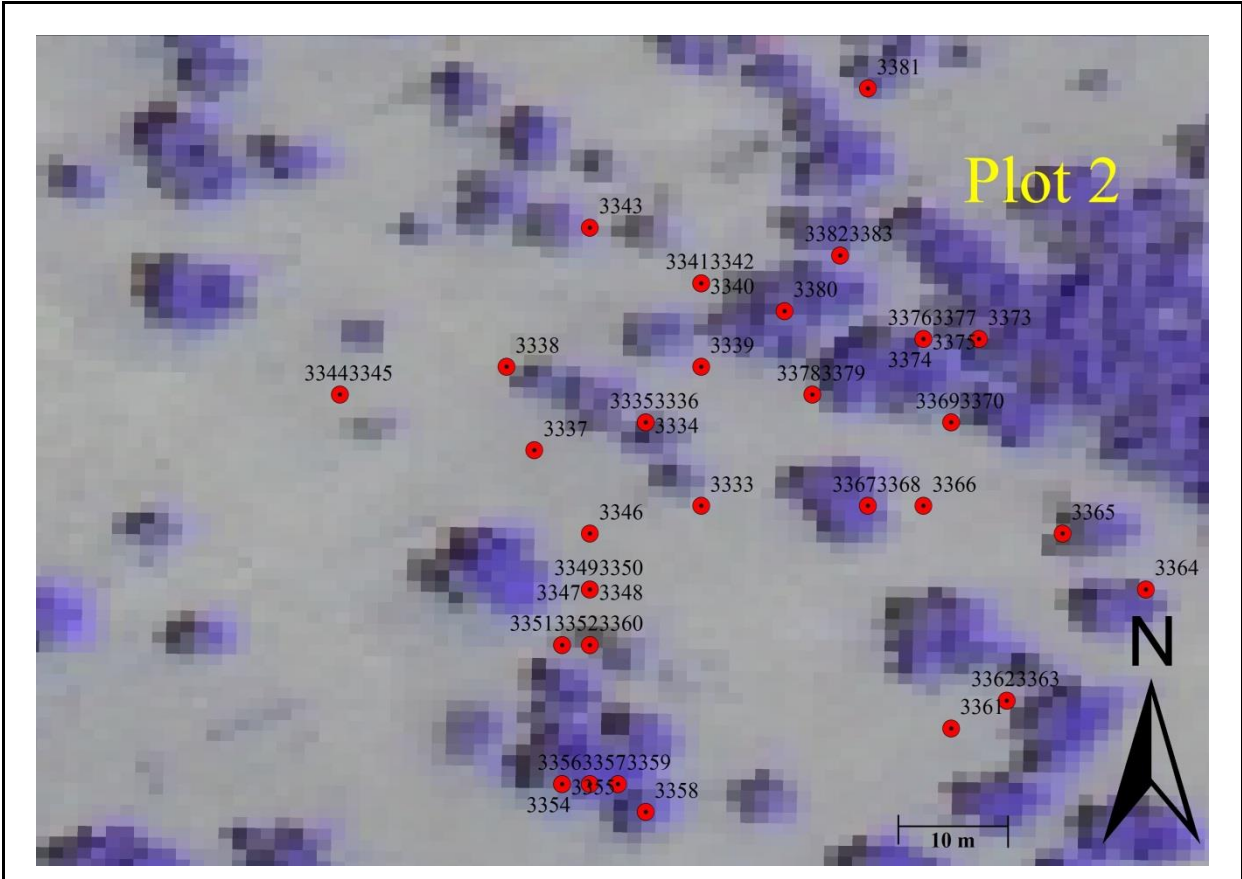
GPS Coordinates:

N40 °08 08.2" E88 °22 38.2"

TH= 6.0 m,

DBH= 17 cm

Fig. A-1 Overview of the P1 random sampling plot. Background is QuickBird image.



**Central tree in the Plot 2**

Tree-Nr.3333

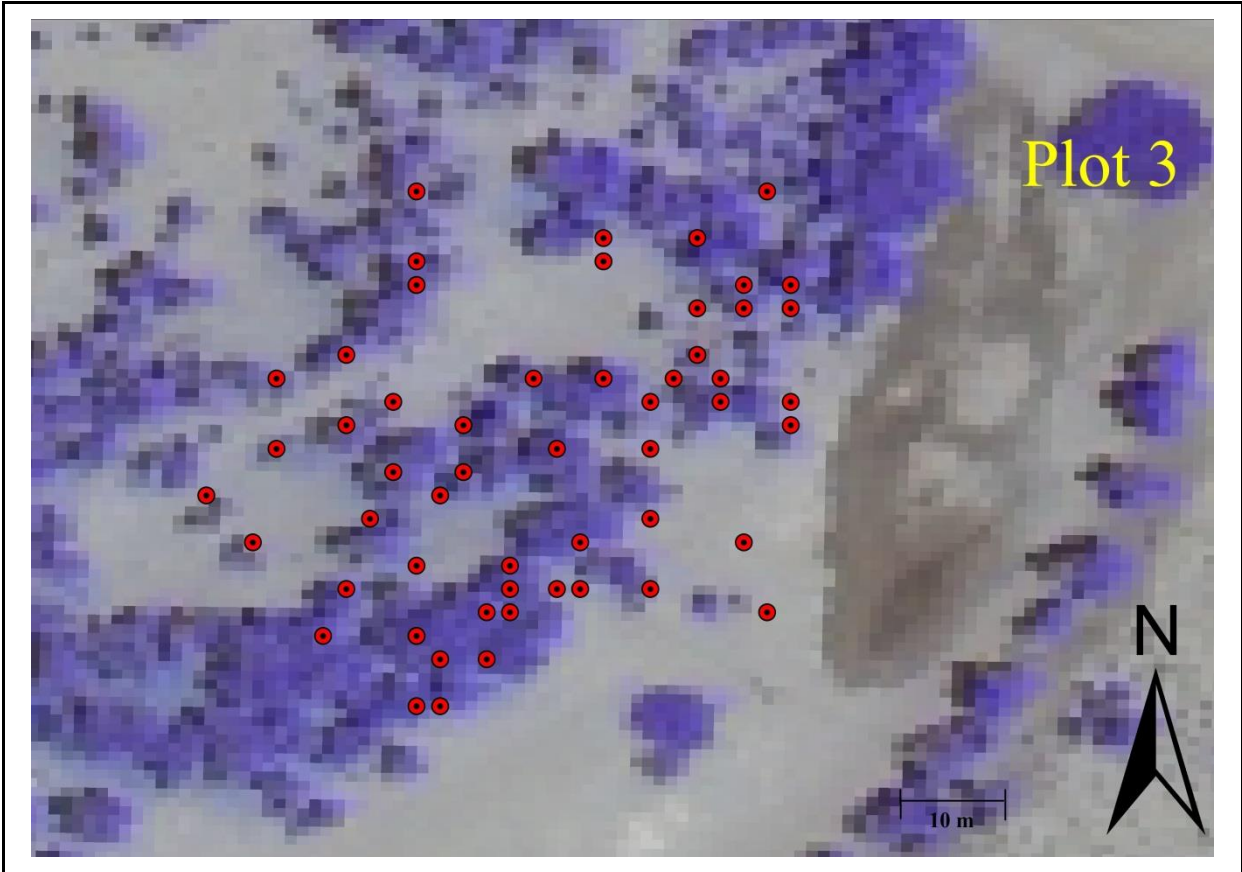
GPS Coordinates:

N40 °08 08.8" E88 °22 24.2"

TH= 5.0 m,

DBH= 25 cm

Fig. A-2 Overview of the P2 random sampling plot. Background is QuickBird image.



**Central tree in the Plot 3**

Tree-Nr.3384

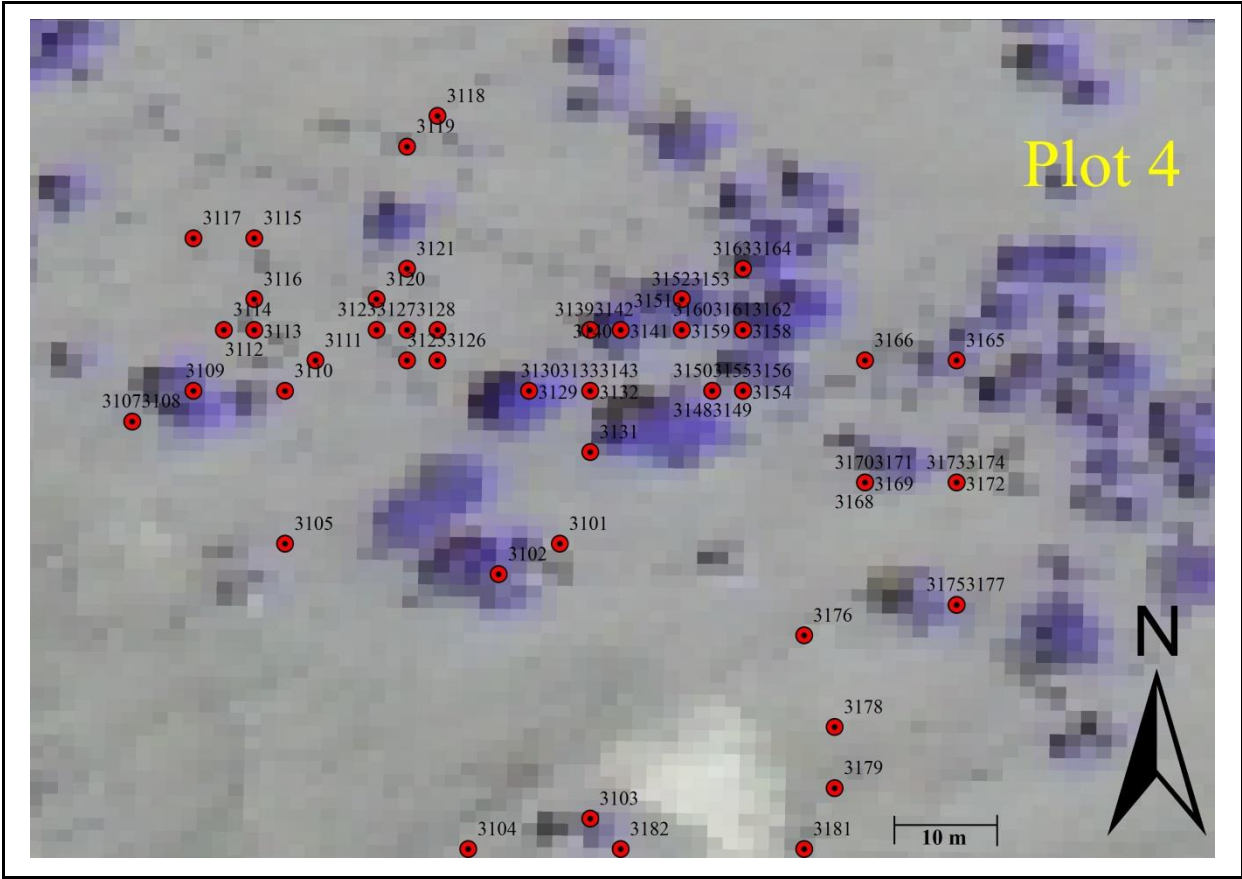
GPS Coordinates:

N40°08'04.8" E88°21'55.8"

TH= 9.0 m,

DBH= 30 cm

Fig. A-3 Overview of the P3 random sampling plot 3. Background is QuickBird image.



**Central tree in the Plot 4**

Tree-Nr.3101

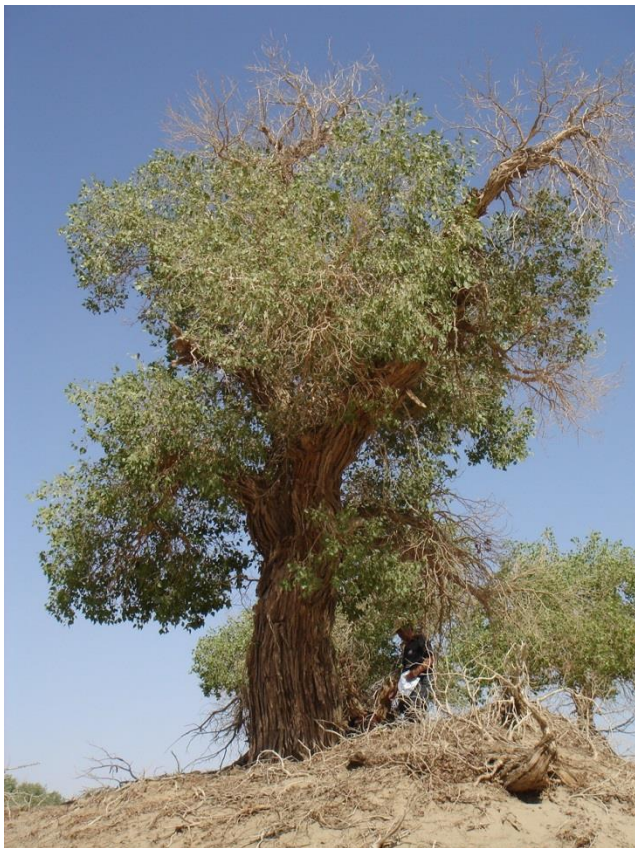
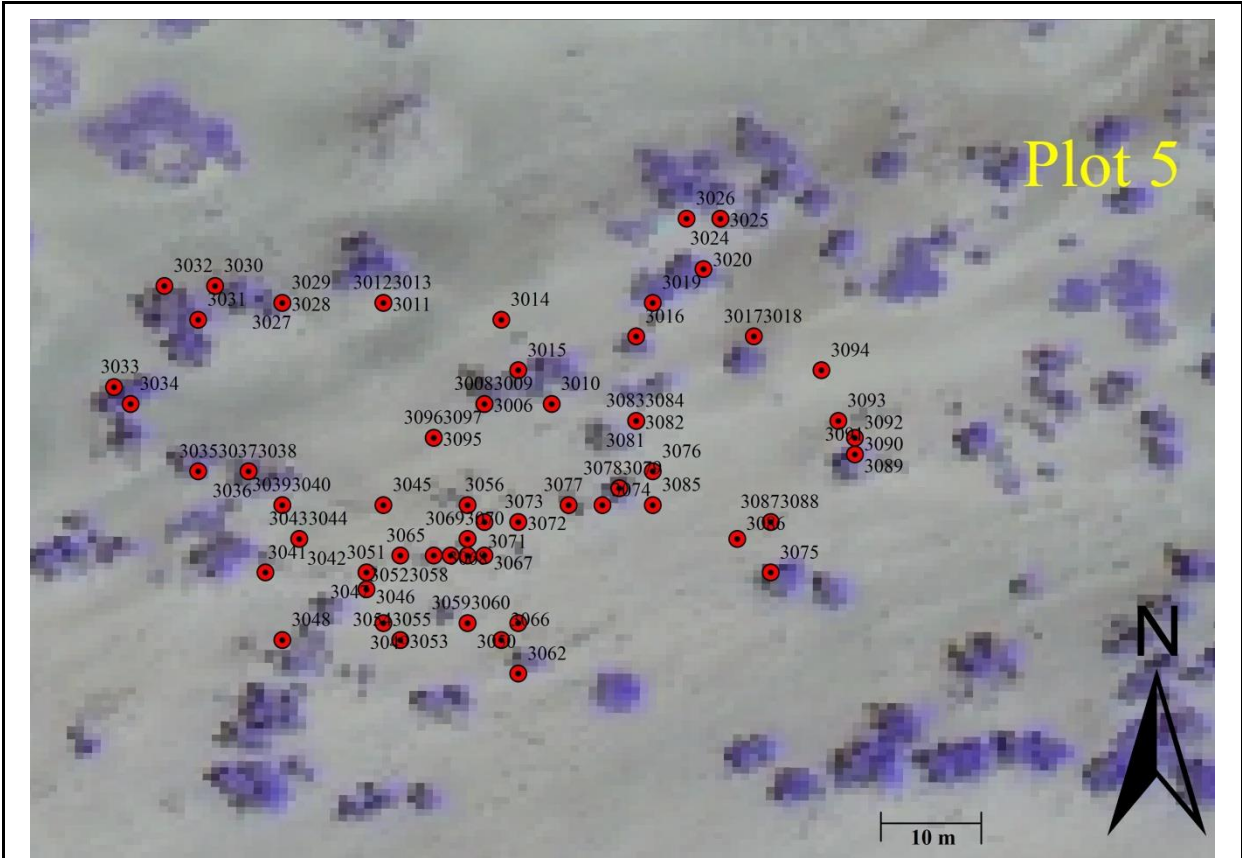
GPS Coordinates:

N40 °08 00.8" E88 °21 44.2"

TH= 6.0 m,

DBH= 40 cm

Fig. A-4 Overview of the P4 random sampling plot. Background is QuickBird image.



**Central tree in the Plot 5**

Tree-Nr.3006

GPS Coordinates:

N40 °07 54.5"    E88 °21 35.1"

TH= 8.0 m,

DBH= 70 cm

Fig. A-5 Overview of the P5 random sampling plot. Background is QuickBird image.

## Thesis Declaration

I hereby declare that this Ph.D. thesis entitled “*Degraded Tugai Forests under Rehabilitation in the Tarim Riparian Ecosystem, Northwest China: Monitoring, Assessing and Modelling*” was carried out by me for the degree of Doctor of Philosophy under the guidance and supervision of Prof. Dr. Ümüt Halik and Prof. Dr. Bernd Cyffka, Faculty of Mathematics and Geography at the Catholic University of Eichstaett-Ingolstadt, Germany.

I hereby confirm that I independently carried out the research for this thesis and wrote it without any other aids that those referenced. In each individual case, I have clearly identified the source that are taken word for word or paraphrased from other works.

I certify that this work contains no material which has been accepted for the award of any other degree or diploma in my name, in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text. In addition, I certify that no part of this work will, in the future, be used in a submission in my name, for any other degree or diploma in any university or other tertiary institution without the prior approval of the University of Catholic University of Eichstaett-Ingolstadt.

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Eichstätt, den 08.02.2016

Aishan Tayierjiang

