Phytocoenologia	**33** (4)	801–818	Berlin–Stuttgart, November 26, 2003

Vegetation changes in a river oasis on the southern rim of the Taklamakan Desert in China between 1956 and 2000

by Helge Bruelheide, Ute Jandt, Dirk Gries, Frank M. Thomas, Andrea Foetzki, Göttingen, Andreas Buerkert, Kassel, Wang Gang, Lanzhou, Zhang Ximing, Urumqi, and Michael Runge, Göttingen

with 9 figures

Abstract. The indigenous vegetation surrounding the river oases on the southern rim of the Taklamakan Desert has drastically diminished due to overexploitation as a source of fodder, timber and fuel for the human population. The change in the spatial extent of landscape forms and vegetation types around the Qira oasis was analyzed by comparing SPOT satellite images from 1998 with aerial photographs from 1956. The analysis was supplemented by field surveys in 1999 and 2000. The study is part of a joint Chinese-European project with the aim of assessing the current state of the foreland vegetation, of gathering information on the regeneration potential and of suggesting procedures for a sustainable management.

With 33 mm of annual precipitation, plants can only grow if they have access to groundwater, lakes or rivers. Most of the available water comes into the desert via rivers in the form of seasonal flooding events resulting from snow melt in the Kun Lun Mountains. This water is captured in canal systems and used for irrigation of arable fields. Among the eight herbaceous and woody vegetation types and the type of open sand without any plant life that were mapped in 2000 in the oasis foreland, only the latter, the oasis border between cultivated land and open *Populus euphratica* forests and *Tamarix ramosissima-Phragmites australis* riverbed vegetation could be clearly identified on the photographs from 1956.

The comparison of the images revealed that the oasis increased in area between 1956 and 2000. Shifting sand was successfully combated near to the oasis borders but increased in extent at the outward border of the foreland vegetation. In contrast to expectations, the area covered with *Populus* trees was smaller in 1956 than today due to some new forests in the north of the oasis that have grown up since 1977. Subfossil wood and leaf remnants of *Populus euphratica* that were found in many places in the foreland must have originated from forests destroyed before 1956. In the last 50 years, the main Qira River has shifted its bed significantly northward and developed a new furcation with a large new bed in 1986. The natural river dynamics are not only an important factor in forming the oasis' landscape but also in providing the only possible regeneration sites for all occurring plant species.

The conclusion of the study is that the oasis landscape has changed considerably in the last 50 years due to natural floodings and to vegetation degradation by human overexploitation. The trend towards decreasing width of the indigenous vegetation belt resulting from the advancing desert and the expansion of arable land is particularly alarming because a decrease in its protective function against shifting sand can be expected in the future.

Keywords: aerial photographs, China, desertification, landscape ecology, oasis vegetation, remote sensing, SPOT, Xinjiang.

DOI: 10.1127/0340-269X/2003/0033-0801 0340-269X/03/0033-0801 $ 4.50

Introduction

Landscapes and their vegetation are shaped and changed by many different natural and anthropogenic factors (Farina 1998). In desert landscapes, the most important factors are wind and water erosion interacting with vegetation and land use (Forman 1995).

This is especially true of the Taklamakan Desert, the largest desert in China and one of the largest ergs on earth, covering over 337000 km² (Zhou 1993). Stretching 450 km from north to south and 1100 km from west to east, it is located in the Tarim Basin in the Xinjiang Uygur Autonomous Region (Fig. 1). The basin is surrounded by high mountain ranges with the Tien Shan (of which the highest peaks reach 7450 m a.s.l.) to the north, the Pamir to the west (8611 m) and the Kun Lun Mountains (7712 m) to the south. This leads to extremely arid conditions. The mean annual precipitation in the Tarim basin ranges between 20 and 70 mm; whereas the potential evapotranspiration is between 2100 and 3400 mm (Zhou 1993, Tian & Song 1997). The Taklamakan Desert came into existence in the early Pleistocene and has expanded continuously since then (Wu 1981). Due to northwesterly winds on the western side of the Tarim basin and

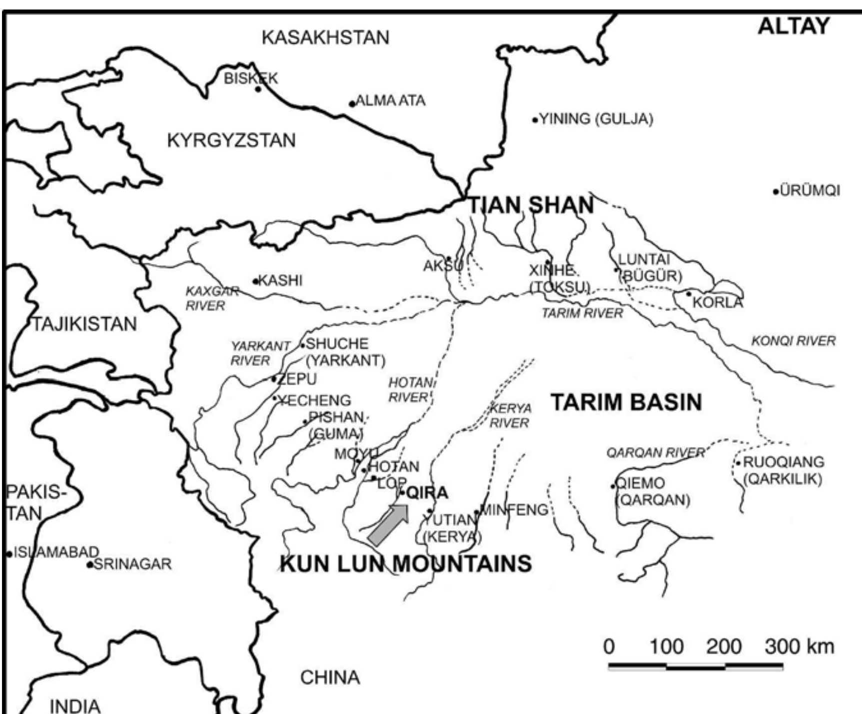
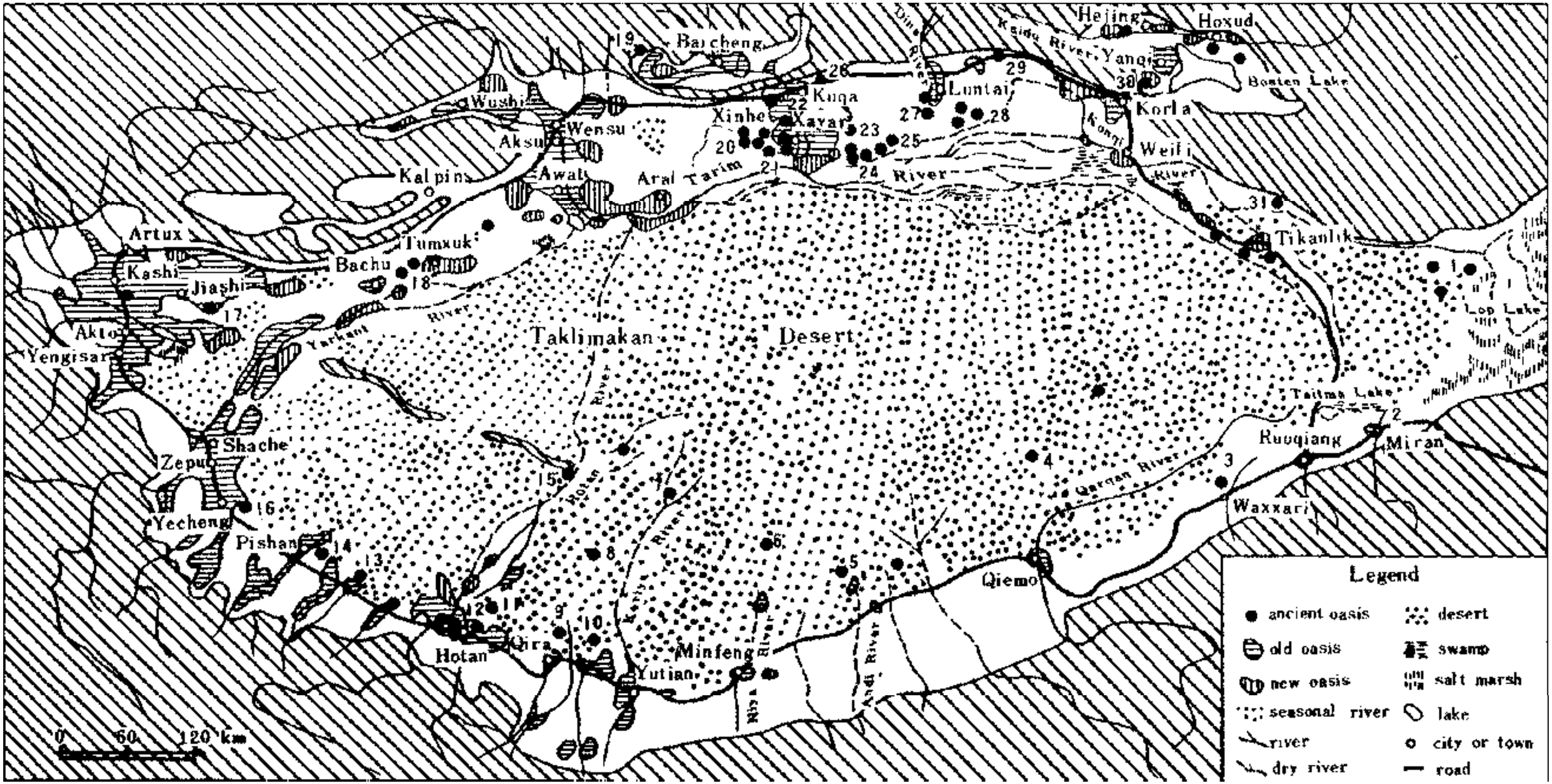


Fig. 1. Location of the study area.

northeasterly winds on the eastern side, aeolic sediments are continuously accumulating at the southern margin, forming layers 200–500 m thick (Zhou 1993, Li et al. 1997). Since the particle size is comparably small with coarse silt to fine sand depending on region (Coque et al. 1991, Besler 1991, Chen et al. 1995, Bruelheide et al. unpubl.), the sediments are easily moved with moderate wind speeds of > 2 m s^{-1}. On the southern rim of the basin, winds blow with a velocity of > 6 m s^{-1} on 90–110 days a year, causing severe duststorms. The undulating topography of the Taklamakan Desert is due to shifting dunes that have heights of 20 m on average but can exceed 100 m in some places. Under these conditions the landscape is in a state of perpetual change.

Rivers are another landscape-forming force. In summer, during ice and snow melt in the mountains, immense amounts of water rush into the desert (Cheng 1997). Although the rivers carry only small amounts of water in winter (< 3 % from December to the end of February, Zhou 1993), they can flood large areas in summer, resulting in extensive water erosion (Fig. 2). Huge amounts of sediments are relocated with each flood, with transport capacities up to 193 kg m^{-3} (Gentelle 1992). Some rivers, like the Keriya River, carry so much water in summer that they penetrate more than 200 km into the desert before they drain away (Jäkel & Hövermann 1991). The Hotan River even cuts through the whole Taklamakan Desert over a distance of 400 km from the south and feeds into the Tarim River in the north. After the flooding in the summer the rivers leave large flood plains which may have a width of several kilometers. The whole river sys-

Fig. 2. Flooding incident of the Qira River in August 2000 with cliffs attaining heights of 15 m and causing lateral erosion of about 50 m in a period of one week.


Legend
ancient oasis
old oasis
new oasis
seasonal river
river
dry river
desert
swamp
salt marsh
lake
city or town
road
0 60 120 km
Taklimakan Desert
Hejing
Hoxud
Yanqi
Bosten Lake
Korla
Weili
Tikanlik
Lop Lake
Taitma Lake
Ruoqiang
Miran
Waxxari
Qiemo
Qarqan River
Andi River
Niya River
Minfeng
Yutian
Qira
Hotan
Pishan
Yecheng
Zepu
Shache
Yarkant River
Yengisar
Akto
Kashi
Artux
Jiashi
Bachu
Tumxuk
Kalpin
Wushi
Aksu
Awat
Wensu
Aral
Tarim River
Baicheng
Xinhe
Xayar
Kuqa
Luntai
Dina River
Kaidu River
Kongqi River
Hotan River
Keriya River

tem of the Taklamakan Desert is known to be continuously changing, with river diversions and shifting beds. These dynamics have been found both at a geological and historical time scale. For example, GIBERT et al. (1995) calculated that river discharges in the Quaternary reached their maximum at 10400 yr BP, when the Keriya River was connected to the Tarim River, and have been decreasing since then. Inside the Taklamakan Desert, old fluviatile sediments of former river systems have been found in many places (COQUE et al. 1991). Changes in the river systems are also seen at a historical scale. For example, the lower reaches of the Hotan River migrated steadily westward in the last 400 years (ZHOU 1993); whereas the lower reaches of the Keriya River have shifted eastward (ZHU & LU 1991).

Human life in this area has been linked to these river dynamics since prehistoric times. Settlements have been established along the entire perimeter of the Taklamakan Desert. All of them were founded as river oases with elaborate canal systems for irrigation (Fig. 3). Some of these settlements were very influential, like the ancient State of Loulan in the Northeast (first mentioned 176 BC and collapsed in 448 AD) or the State of Yutian in the south (founded about 250 BC and declined in the 13th century AD) (ZHOU 1993). As shown in Fig. 3 many of these oases have been deserted in the course of centuries. For example, along the Southern Silk Road over 20 ancient cities were abandoned and buried by the desert. The reasons for abandonment were the changing river beds with diversions in their lower reaches and periodically declining amounts of meltwater due to glacial fluctuations, in conjunction with shifting sand invading the cultivated land (COQUE et al. 1991, GENTELLE 1992). The inhabitants were repeatedly forced to give up their villages and to move with the rivers. For example, when the bed of the Yulongkarax River shifted westward, the ancient oasis of Akspil was left behind in the desert (ZHOU 1993).

Although sand drift and water erosion are natural processes that have continuously shaped and changed the desert landscape, these processes increased remarkably in intensity due to anthropogenic activities. In the late 1950s, the propagated "march into the desert" resulted in steadily increasing human populations living in the desert periphery. For example, the population in the Hotan Prefecture rose from 419000 in 1911 to 629000 in 1949 and to 1 172000 in 1983, which corresponds to a yearly growth rate of 1.83 % in the last 34 years (ZHANG 1993). This growth caused a rapid expansion of irrigated farmland. Since the early 1950s the water volume used for irrigation has doubled (CHENG 1997). Although the water

Fig. 3. Distribution of recent and ancient oases in the Tarim Basin (after ZHOU 1993). Deserted oases are 1. Loulan, 2. Miran, 3. Ancient Waxxari, 4. Ancient Qiemo, 5. Ancient Andir, 6. Niya, 7. Karadun, 8. Dandanwulik, 9. Uzongtati, 10. Damogou, 11. Bugaiwilik, 12. Yuetgan, 13. Zanggui, 14. Ancient Pishan, 15. Mazatag, 16. Kohancheng, 17. Damancheng, 18. Tohushalai, 19. Kerayulgun, 20. Dawangkumu, 21. Tongguzbashi, 22. Yangdakqin, 23. Yangdaksar, 24. Qiongsar, 25. Ganshigati, 26. Pijak, 27. Heitaiqin, 28. Zhaoguot, 29. Yeyoungou, 30. Ziniquanzi, 31. Yingpan.

discharge from the mountain tributaries was more or less constant in this period, the water discharge into the lower reaches has decreased drastically. For example, the annual water volume flowing into the lower reaches of the Tarim River was $10 \cdot 10^9$ m^3 in 1940 and $4 \cdot 10^9$ m^3 in the 1990s (Cheng 1997). The consequences are acute water shortages at the lower reaches.

Another effect of the growing human population is the increased exploitation of the indigenous vegetation. The increasing demand for fuel wood has reduced the forest to half its area over a period of 30 years in the Hotan Province (Zhang 1993). Apart from the native *Populus euphratica* trees, also the below-ground stocks of *Tamarix ramosissima* are used in large amounts for fire wood. Both species are also used for construction purposes. Herbaceous perennial plants are affected by intensive grazing by sheep, goat and camels or harvested for winter forage (e.g. *Alhagi sparsifolia, Karelinia caspica, Phragmites australis*). In particular, the vegetation belts around the oases have been overused in this manner. Although plant cover in the various vegetation types in this belt is at present generally lower than 10 % (Bruelheide et al. unpubl.) and biomass lower than 3 t ha^{-1} (Gries et al. unpubl.), this vegetation is vitally important as a shelter against sand drift. When this belt is degraded by overexploitation, its protective function is lost and the oases are threatened by desertification (Runge et al. 2001). The situation is particularly severe for oases along the southern border of the Taklamakan Desert. More details on this development are given in Xia et al. (1993) and some web sites (www.gwdg.de/~botanik/oekologie/china.html; www.unep.org/unep/program/natres/land/home.htm).

This paper is part of a broader project involving two European and three Chinese institutes. The project's objective was to investigate the ecological basis for a sustainable management of the shelter belt vegetation and the options for re-establishing this vegetation in desertified areas (Thomas et al. 2000, Runge et al. 2001). The project site was the Qira oasis, one of a chain of oases at the southern margin of the Taklamakan Desert (Fig. 1). One objective was the preparation of a vegetation map of the foreland vegetation of this oasis (Bruelheide et al. 2002), by means of remote sensing data and of a ground survey. With the access to historic aerial photographs of the Qira oasis, the possibility arose of documenting the landscape change in the last 42 years, which have been a period of particularly intensive human impact. It is the aim of this paper to focus on the alterations in the vegetation belt around the oasis, especially on the *Populus euphratica* forests, to quantify the change in the belt's spatial extent, to assess the expansion of land reclamation and to analyze the changes in the course of the Qira River.

Study area

The Qira oasis, also known as Cele, is located at N 37°01′, E 080°48′ and at an elevation of 1365 m a.s.l. Between 1973 and 1988 the population increased from 87000 to 112000 (Zhang et al. 2001) and was estimated to be 130000 in 1998. In 1960, the course of the Qira River was influenced by a dam built across the channel, with the aim of directing water northward for irrigation. According to ZHANG (1993), the reduced flooding in the old river bed resulted in death of large *Populus euphratica* stands in the subsequent years. The authors make the degradation of the forests in particular and the shelter vegetation in general responsible for increased sand damages to fields and settlements. By 1980, sand dunes had approached to within only 1.5 km of the center of Qira and 25 % of arable land had been lost. One of the measures implemented against this trend was the establishment of a research station in Qira by the Chinese Academy of Science. Since then various countermeasures have been tested and successfully implemented (ZHANG et al. 2001). The most important action was a complete restructuring of farmland, canal and road system of the Qira oasis in the early 1980s, finished by the end of 1987, that included the construction of 40 km new canals with 153 sluice gates.

Methods

The analysis of the present state of the landscape in the oasis foreland was performed on the basis of a SPOT 4 satellite scene (Satellite Pour l'Observation de la Terre, No. 209-276 26/09/98, with center coordinates of N 36°51′30″N, E 080°44′28″E), one of the earth observation systems with the highest spatial and spectral resolution available at that time (HILL 2001). The image has a resolution of 20 m × 20 m and covers an area of 60 km × 60 km, of which only a section of 18 km × 15 km around the Qira oasis is considered here (compare to WANG et al. 2002). The SPOT scene was rectified using GPS (Global Positioning System) coordinates of distinctive bridges and road crossings in the Qira oasis and then projected into an UTM grid (44S) using EASI PACE 6.3. The four spectral channels were recombined to correspond to the human visual perception as far as possible. This was accomplished by combining red (SPOT channel 2), blue (SPOT channel 3) and green ([chan-nel 1 * 3 + channel 3]/4 + [(NDVI + 0.5) * 50 * 2]). For the printed version, the colour information of this image was transformed into a grey scale image using ADOBE PHOTOSHOP 5.0. This image was transferred into a GIS (Geographic Information System, ARC VIEW 3.1, ESRI) and outlines of landscape features were added manually based on ground surveys in 1999 and 2000. In the following, this situation is referred to as the state in 2000. Vegetation reference plots were established and vegetation type borders were mapped with GPS in the ground survey (BRUELHEIDE et al. unpubl.). In particular, all locations having remnants of *Populus euphratica* stands were noted. Such places can be unequivocally recognized by parts of trunks with bark and layers of dead leaves covered by sand.

The situation in 1956 was assessed using aerial B/W photographs, dated 18/10/1956 (series K-7-18X56). The photographs are of excellent quality and were taken at about 10:20 (UTC/GMT + 0800), which is about −2½ hrs local time and 1½ hrs after sunrise. Therefore, all tall objects cast distinct shadows, making it possible to recognize single trees. An exact georeferencing of the photographs turned out to be impossible because no feature that corresponded to objects present today could be detected. Buildings, canals and fields had been completely changed due to the oasis restructuring that occurred in the 1980s. Therefore, only road bends on some major traffic routes provided a rough georeference ±100 m. Six overlapping photographs were combined in ARC VIEW (K-7-18X56 no. 20, 22, 24 and 39, 41, 43). Using a stereoscopic microscope, trees, river courses and fields were delineated in the GIS map. For a comparison, the 2000 shapes are drawn together with the 1956 outlines on the 1956 photographs.

Results

The present landscape of the Qira oasis is shown in Fig. 4. The different types of land cover in the oasis' periphery appear in a variety of shades of light grey. In contrast, the agricultural areas within the oasis are displayed in dark grey or black. Inside the oasis, the village center is visible in the south. The main canal, which is fed by the Qira River in the south (outside the map section), runs across the whole oasis from south to north. It is the symmetry axis of the oasis from which the principal side canals divert in a fishbone-like manner. Between and along the side canals blackish areas indicate unharvested fields, still planted with mainly maize or cotton, and greyish areas are fields harvested shortly before the satellite image was taken.

In the oasis' foreland, the densest plant cover is found in the lower reaches of the Qira River flood plains and in the surrounding of the smaller periodical rivers coming out from the oasis' canals (Fig. 4). The vegetation around the oasis can be classified into nine types that are all characterized by dominant or codominant species or by a complete lack of plant growth (Bruelheide et al. unpubl.). Among these types only three types could be identified on the aerial photographs from 1956: open sand bare of plant life, open *Populus euphratica* forests (when consisting of trees more than 3 m high) and all other areas with plant growth.

In contrast to previous information that arable land had been lost in the 1980s (Zhou 1993, Zhang et al. 2001), Fig. 5 shows that the agricultural land increased in area, from 76 km^2 in 1956 to 90 km^2 in 2000. The expansion of farmland occurred mainly north of the oasis, in the area of sand dune intrusion west of the center and on the shoulder of the gravel plain in the east. There was also a loss of some area in the southwest due to water erosion by the Qira River. In addition, Fig. 5 shows the change of the agricultural structure of the oasis. In comparison to Fig. 4, there were no straight canals or roads, fields varying in size over several orders of magnitude and several smaller village cores scattered over the settled area.

The shifting dune west of the center covered almost 3.5 km^2 in 1956 but was almost completely fixed in 2000 (Fig. 6), most likely due to desert reclamation efforts in the 1980s (Zhang 1993). In contrast, the open sand approached closer to the northwestern outer foreland perimeter in 2000 by a distance of about 1 km. Since the oasis expanded by approximately

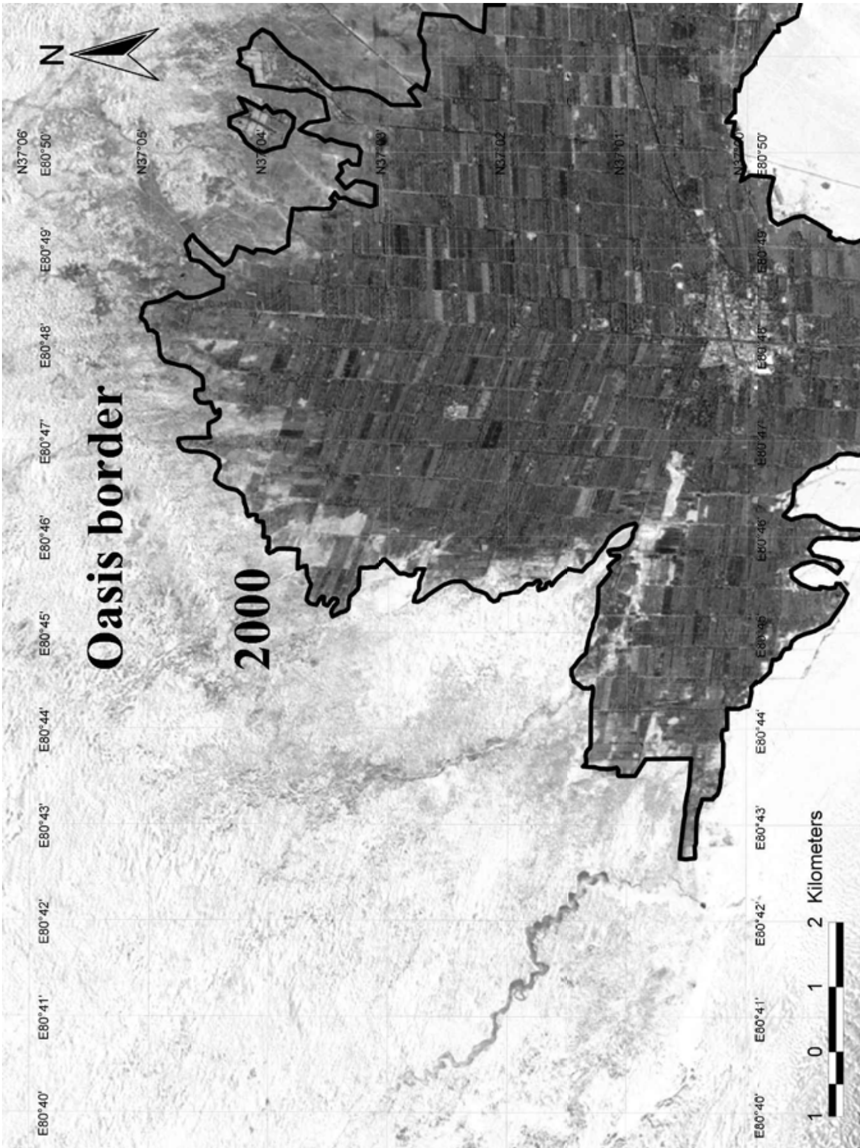


Fig. 4. SPOT satellite image from 1998 of the Qira oasis with the surrounding vegetation. The oasis border in 2000 is outlined in black.

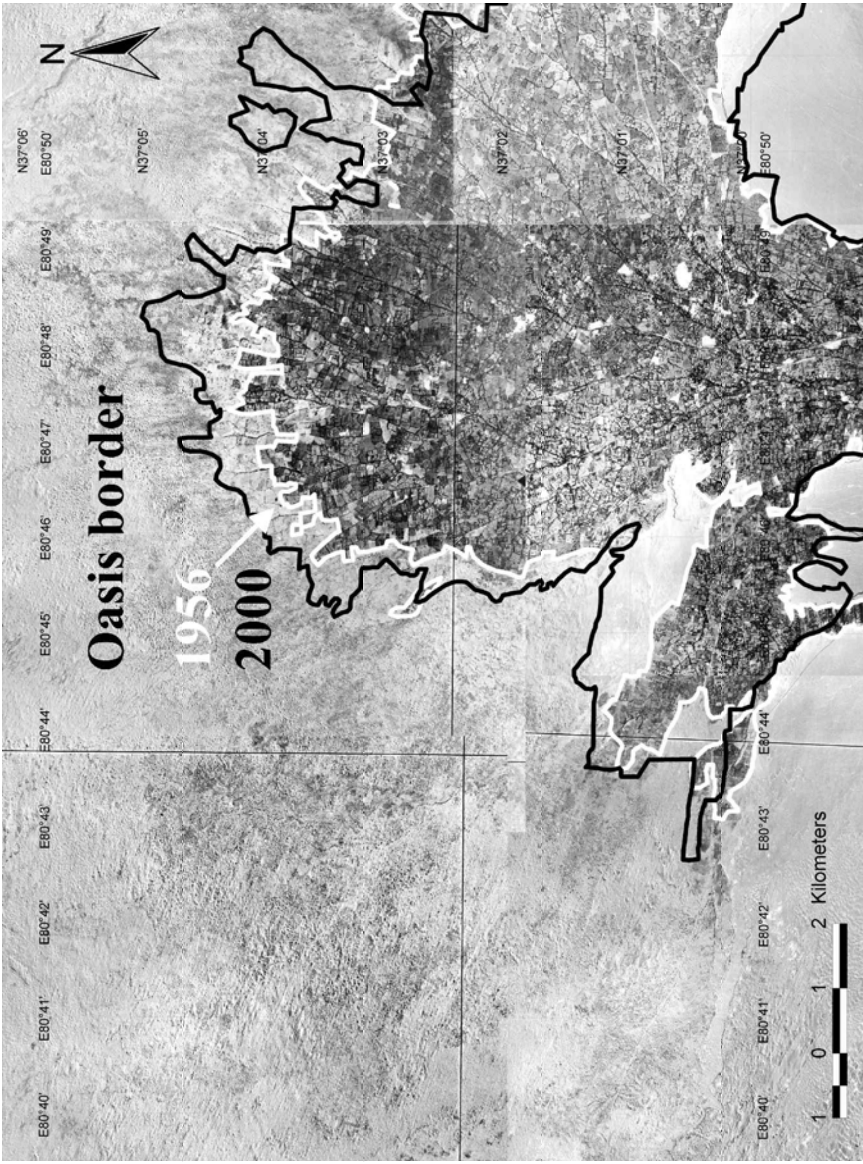


Fig. 5. Aerial photographs from 1956 with the oasis border in 1956 in white and in 2000 in black.

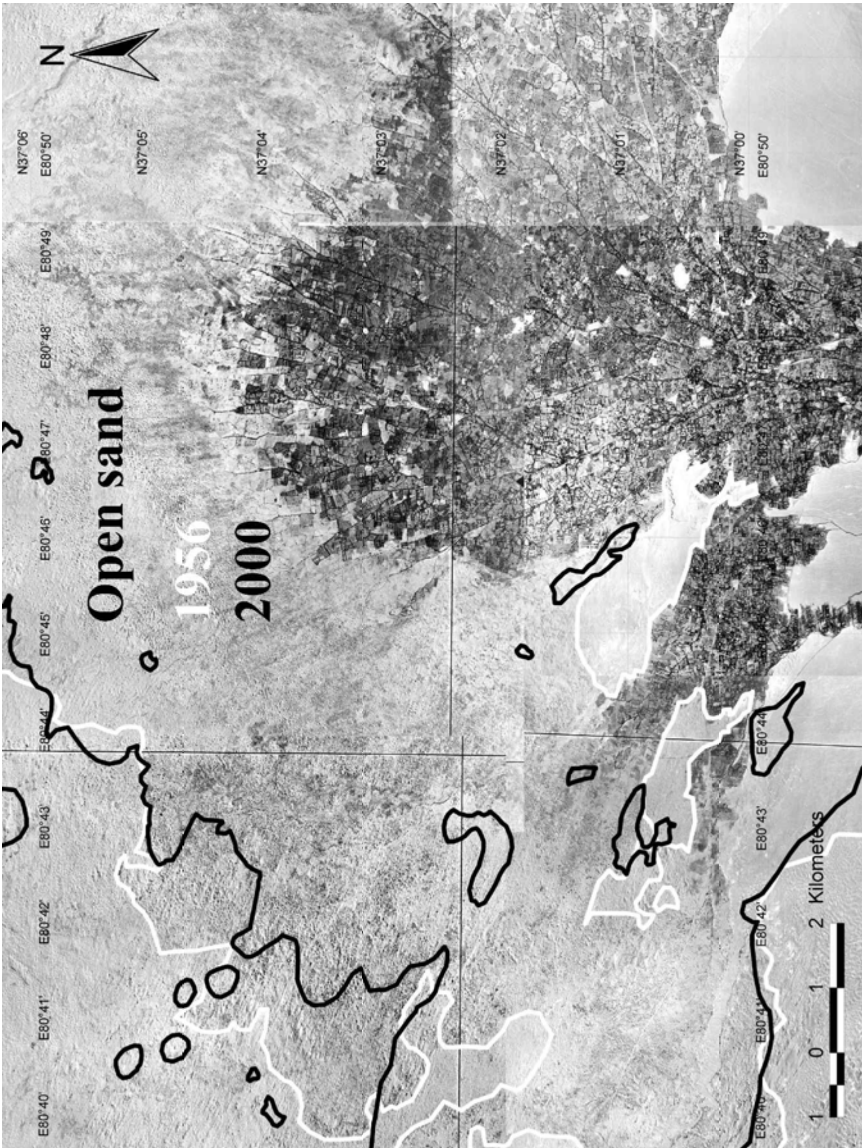


Fig. 6. Aerial photographs from 1956 with areas covered by open sand in 1956 outlined in white and in 2000 in black.

0.5 km, the width of the foreland belt in the northwest decreased from 7.5 in 1956 to 6 km in 2000.

In contrast to expectations, the forest area covered by *Populus euphratica* was not larger 44 years ago than today (Fig. 7). Even when stands of trees adjacent to the outer border of the oasis, which could not be distinguished from planted poplars (*P. nigra*, *P. alba* and hybrids) in the aerial photograph, are taken into account, the area was smaller in 1956 (1.5 km^2) than in 2000 (5.5 km^2). However, these figures have to be considered with some reservation because delimiting the area with tree growth was arbitrary to a certain degree both on the aerial photographs and in the field. Nevertheless, in the main area of *Populus euphratica* stands in the north (between E 080°44′ and E 080°45′) no tree could be found in 1956. Today this area is covered with a large *Populus euphratica* forest (Fig. 8). There is much information available about this stand because it was one of the project areas (Thomas et al. 2000). According to tree ring analysis the forest grew up in 1977 (Gries et al. unpubl.). Inhabitants of that part of the oasis said that the trees grew up after an occurrence of exceptional intensive flooding (Zhang Henian pers. comm.). Interestingly, the trees show clear signs of clonal growth by forming clusters of two to five stems. DNA fingerprinting with AFLP technique confirmed that all (but one) trees within a sampling area of 4 ha belonged to one genet (Bruelheide unpubl.). A clone of this size must have developed over centuries. This large time span corresponds to radiocarbon data of dune development (Jäkel 1991). Therefore, it can be concluded that some time in the past, i.e. before 1956, a large forest area had been cleared and that at this site the present forest grew up since 1956. The fact that no tree was present in this area in 1956 can be explained if one recalls that only trees above a certain height could be identified on the aerial photograph. Resprouting trunks of limited size would not be distinguishable from other shrubs in the photograph. Such shrub-like *Populus euphratica* are a common feature of areas that are heavily grazed (Zhang 1992).

In contrast to the forest reestablishment in the north, many scattered patches in the west that were probably covered with trees in 1956 are treeless today. These patches partly correspond to places where remnants of former *Populus euphratica* stands were found (Fig. 7). At least three of these sites had already been deforested in 1956, in particular the locations near to the oasis border. The wood remnants discovered showed clear signs of chopping indicating that trees had been felled. However, it is possible that the trees had withered away due to water deficit and were collected when dead.

Fig. 9 shows that the main Qira River changed its channel considerably. In 1986, a furcation occurred at N 37°00′30″, E 080°42′10″ and part of the river flowed northward. The photograph in Fig. 2 was taken near to the point of the furcation and demonstrates the force of water erosion. This event was also responsible for the interruption of the old desert path between Qira and the neighbor oasis Lop. The old river bed moved northward by a distance of about 400 m. This northward shift was also responsible for the loss of farmland in the southwestern part of the oasis (Fig. 5).

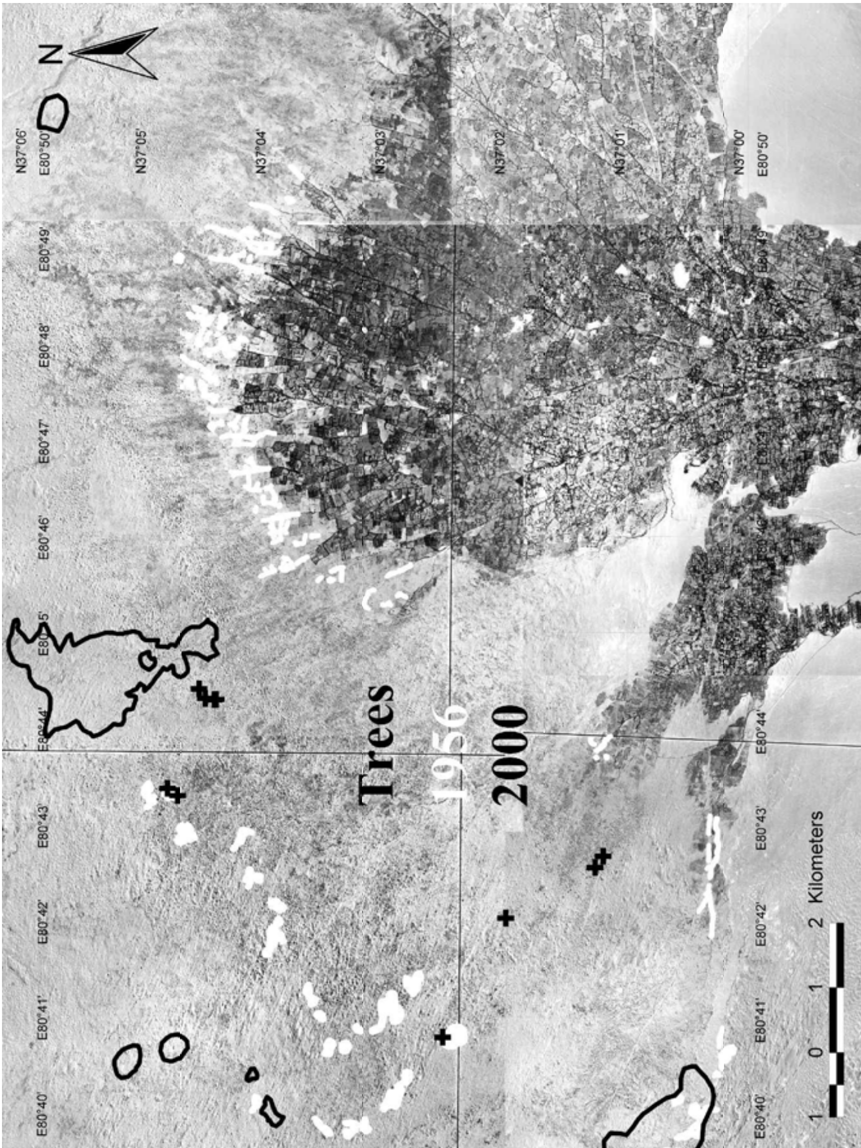


Fig. 7. Aerial photographs from 1956 with occurrences of tree vegetation in 1956 marked in white and in 2000 in black. The black crosses indicate locations where subfossil records of *Populus euphratica* were found in 1999 and 2000.

Fig. 8. *Populus euphratica* stand north of the oasis, approximately 22 years old and 4 to 6 m high (August 1999).

Discussion

The results confirm most of the points outlined in the Introduction. The landscape around the oasis is highly dynamic, due to sand drift and water erosion. The study has shown that these forces have resulted in distinct landscape changes within half a century.

The increase in the size of the oasis corresponds to the demographic growth trend in the human population. If there was a temporary loss in farmland area in the 1980s (Zhang 1993), it has been overcompensated since then. Compared to the overall situation in Xinjiang, the expansion of the Qira oasis is only moderate. According to Tian & Song (1997), the "oasification" efforts in Xinjiang have resulted in expansion of total oasis area by the factor 2.7 in the last four decades.

The study revealed that the idea of an extensive forest belt in the Qira area half a century ago has to be revised. If this belt had ever existed, it had already been reduced to patches 44 years ago. The clonal regrowth of the *Populus euphratica* stand in the north is proof that it had been destroyed before, signifying that considerable deforestation had already taken place by 1956. It is not surprsing that the oasis' inhabitants have had a considerable impact on the forest area all along, but it is alarming that the remaining forest area of *Populus euphratica* of the 1950s has been further reduced by about 50 % until present in the entire Tarim Basin (Tian & Song 1997).

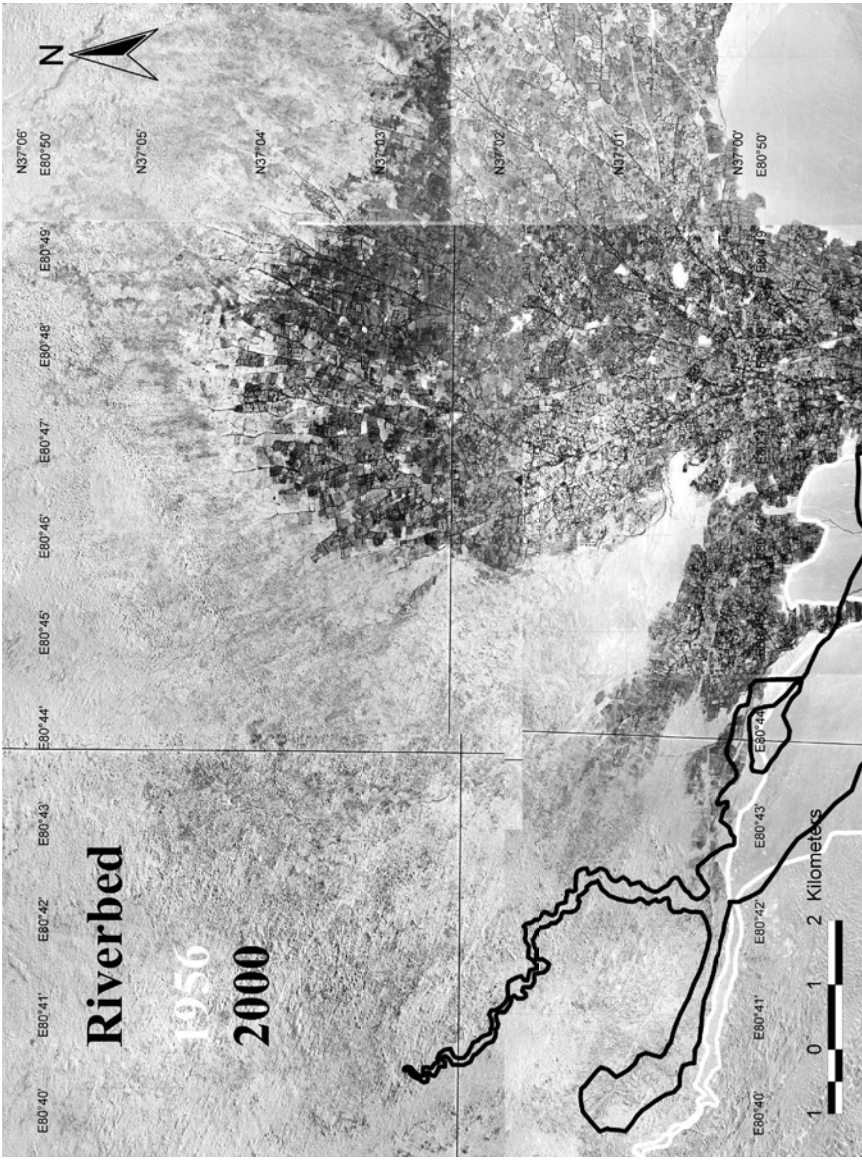


Fig. 9. Aerial photographs from 1956 with the riverbed of the Qira River in 1956 outlined in white and in 2000 in black.

The perspectives for the future of the Qira oasis are even more alarming. If no effective countermeasures are taken against the overuse and degeneration of the foreland vegetation, it can be expected that the front of the open desert will move further inwards in the next few decades, and ultimately reach the oasis border. The local authorities in Qira have recognized this threat and have forbidden the extraction of winter forage (mainly *Alhagi sparsifolia*) and fuel wood (mainly *Populus euphratica* and *Tamarix ramosissima*) from a zone of 3 km around the oasis. However, since grazing is not affected by this legislation, it might prove ineffectual.

Once destroyed, the foreland vegetation can only be re-established with great difficulty. Regeneration experiments have shown that the natural regeneration of all dominant species by seeds, with the exception of *Tamarix ramosissima*, is an extremely rare event (Bruelheide et al. unpubl.). Especially *Populus euphratica* has difficulties to regenerate itself. When natural regeneration from seeds was observed, this always occurred on the river plains after flooding (Bruelheide pers. obs., Jäkel & Hövermann 1991, Tian 1991). This fact emphasizes the importance of river dynamics for the maintenance of viable plant populations of all species. However, the dynamics observed over the last 44 years in this study have been probably much smaller than in previous times, due to the increasing water demands of the expanding oases that allow ever decreasing amounts of water to flow into the desert (Zhu & Lu 1991, Zhou 1993). This trend is obvious in the number of reservoirs built in the last decades. At present, there are 466 reservoirs in the whole of Xinjiang with a storage capacity of $5.93 \cdot 10^9$ m^3 (Tian & Song 1997), which corresponds to almost the magnitude of the annual discharge of the Tarim River (Cheng 1997). The oases in Xinjiang account for 4.3 % of the total area but consume 55.5 % of the surface runoff and take up 72 % of the actually diverted discharge (Tian & Song 1997).

In the upper reaches of the Qira River new reservoirs are planned that will further decrease the amount of surplus water. It can be predicted that this development will drastically reduce the distance the rivers intrude into the desert, the area of river flood plains, and finally, the area of potential regeneration sites for all plant species. Another, poorly investigated, aspect of reducing the discharge by reservoirs and oasis water consumption is to which degree the recharging of groundwater is affected. Since all dominant plant species in the foreland are phreatophytes (Thomas et al. unpubl., Gries et al. 2003), a decreasing water table in the foreland might have dramatic effects with a total die-off of plants at the landscape level. Such effects have already been observed in the lower reaches of the Tarim River where the groundwater level dropped by 6 to 8 m (Meckelein 1988, Zhou 1993). The vegetation die-off with changes in the hydrological regime is also a well-known feature in other arid regions, e.g. for *Acacia tortilis* and *A. raddiana* in the Southern Negev Desert in Israel (BenDavid-Novak & Schick 1997). If the phreatophytes vanish there will be nothing left to stop the sand encroachment of the oases.

Acknowledgements. We would like to express our gratitude to all colleagues, students and workers at the Qira desert research station of the Institute of Ecology and Geography in Urumqi, to the Chinese Academy of Science for providing the aerial photographs and to the European Community for generous funding (Contract Number ERBIC18CT980275).

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Addresses of the authors:

Dr. Helge Bruelheide, Dr. Ute Jandt, Dr. Dirk Gries, Dr. Frank M. Thomas, Andrea Foetzki and Prof. Dr. Michael Runge, University of Goettingen, Albrecht-von-Haller-Institute for Plant Sciences, Dep. of Ecology and Ecosystem Research, Untere Karspüle 2, D-37073 Göttingen, Germany, e-mail: hbruelh@gwdg.de, Fax. ++49-5 51-39 35 56.

Prof. Dr. Andreas Buerkert, University of Kassel, Institute of Crop Science, Dep. of Crop Production in the Tropics and Subtropics, Steinstr. 19, D-37213 Witzenhausen, Germany.

Prof Dr. Wang Gang, Lanzhou University, Department of Biology, State Key Laboratory of Arid Agroecology, 730000 Lanzhou, China.

Prof. Zhang Ximing, Chinese Academy of Sciences, Xinjiang Institute of Ecology and Geography, 40 South Beijing Road, 830011 Urumqi, China