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THEMATIC ISSUE

Development of agricultural land and water use and its driving forces along the Aksu and Tarim River, P.R. China

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Abstract The extremely arid Aksu-Tarim Region (ATR) in northwestern China is one of the country's most important cotton production bases. However, in recent years, the negative ecological consequences of the intensive agricultural production become apparent. Apart from the degradation of riparian vegetation, competition for scarce water resources among farmers tightens. To be able to develop solutions for the aggravating problems, and sustain the ATR as a favored agricultural production base, it is decisive to clearly understand the land- and water-use development and its driving forces in the ATR. Statistical yearbook data from 1989 to 2011, comprising the four administrative regions of the ATR, namely Aksu and Bayangol prefectures, as well as Division 1 and Division 2 of the military farms, and annual producer price data constitute the data base for the present study. Relevant policy documents and data obtained through a stakeholder workshop complement the analysis. It is shown that agricultural land area more than doubled during the 1989–2011 period. This is a result of the interaction of: (1) vast population growth and related increase in agricultural labor; (2) positive price developments for fruits and cotton; (3) strong increase in agricultural profitability, triggering further land reclamation; (4) afforestation programs pushing for the establishment of orchards; and (5) insufficient restriction of agricultural land expansion. It is recommended to step up the efforts to move people out of agriculture into other sectors, and significantly improve agricultural water productivity by increasing yield levels and shifting crop production towards labor-intensive high-value commodities.

Keywords Land-use change · Water use · Driving forces · Tarim River · Xinjiang · China

Introduction

The Aksu-Tarim Region (ATR) is located in the southern part of Xinjiang Uighur Autonomous Region (XUAR) in Northwestern China. In the extremely arid ATR the Tarim River and its main tributary the Aksu, which are nourished by snow and glacier melt from the Tianshan Mountains, constitute the major water source for human activities and natural ecosystems (Fig. 1) (de la Paix et al. 2012). The Aksu headstreams actually rise on Kyrgyz territory; however, with up-to-date insignificant human water consumption along the Kyrgyz part of Aksu River only Chinese territory is considered for the present study.

The ATR comprises four administrative regions, which include two prefectures, namely Aksu Administrative Offices (hereafter referred to as Aksu) in the west and Bayangol Mongol Autonomous Prefecture (hereafter referred to as Bayangol) in the east, as well as two divisions of the Xinjiang Construction and Production Corps (XPCC), namely Division 1 (Div.1) and Division 2 (Div.2). The XPCC, established by the Beijing government in the 1950s to develop and stabilize the frontier regions in the Northwest, is a separate administrative unit within the area of XUAR (XPCCIO 2010). Of its 14 divisions two are

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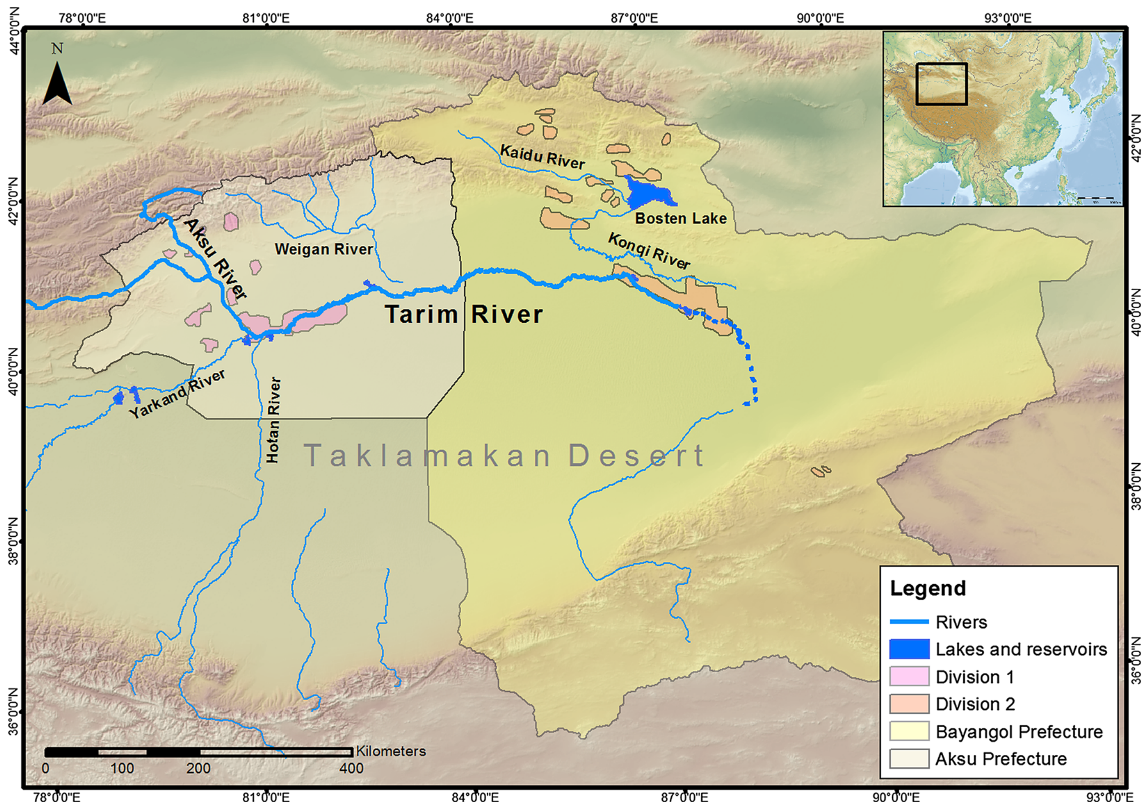

Fig. 1 The Aksu-Tarim Region with the location of Aksu and Bayangol prefecture, as well as Division 1 and Division 2 of the Xinjiang production and construction corps

located within the ATR, Div.1 in the lower Aksu region and Div.2 along the lower reaches of Tarim River.

The ATR is an important agricultural production region, contributing significantly to national cotton, grain and fruit supply (CSYB 2012; XJSYB 2012). The absence of rainfall coupled with abundant sunshine provides ideal cultivation conditions especially for cotton. However, in recent years the negative ecological consequences of the intensive agricultural production became apparent (Hao et al. 2010). In addition to the degradation of riparian vegetation, the overuse of surface and groundwater for irrigation of crops also led to an increased competition for water among farmers, often resulting in yield losses (Thevs 2011). Since the beginning of the twentieth century several research groups studied the water resource issue of the Tarim region, with a strong focus on the development of the hydrological situation within the basin (e.g., Bai et al. 2013; Turak et al. 2007; Xu et al. 2005), being influenced by climate change and human activities (e.g., Liu et al. 2013; Zhang 2001; Zhou et al. 2012), as well as its impact on the natural ecosystems (e.g., Hao et al. 2010; Xu et al. 2003; Zhang et al. 2003). To improve the ecological situation in the region, the existing body of literature concludes that the irrational use of water resources related to the tremendous increase of irrigation agriculture, needs to be strongly reduced, by improving agricultural water-use efficiency (e.g., Zhang 2001), to be achieved through extensive implementation of effective water-saving technologies (e.g., Chen et al. 2011).

However, the actual causes of the vast expansion of agricultural land area are heavily under investigated. To be able to develop more specific recommendations for overcoming the aggravating problems, it is vital to clearly understand the specific factors, which triggered the agricultural land expansion and related water use in recent decades. Therefore, the present publication analyses the development of agricultural land and water use, as well as its driving forces within the four administrative regions of the ATR. To be able to develop meaningful recommendations regarding future land and water-use management, the analysis focuses on the recent two decades comprising the timespan from 1989 to 2011.

Materials and methods

To identify and rate driving forces of water and land-use development in the ATR, an expert workshop was conducted in Xinjiang's provincial capital Urumqi in August 2011. Experts from all major research institutions including academies and universities, which are involved in research on water use in agriculture as well as extension specialists, participated in the workshop.

Furthermore, statistical yearbooks, which constitute the major source of publicly available secondary data in China, were analyzed to clearly understand the historic developments of agricultural land and water use, and their respective driving forces. The database comprises the Xinjiang Statistical Yearbooks and Bingtuan Statistical Yearbooks from 1990 until 2012, which feature data from 1989 until 2011. Additionally, national producer price developments of major agricultural commodities, obtained from FAOSTAT were integrated in the analysis.

Moreover, relevant policy documents, first of all the recent and current "Five-year plans" (FYP) at prefectural and division level, as well as subject-related official ordinances were investigated to grasp the general policy orientation and specific intents related to agricultural land and water use in the respective administrative regions. The actual realization of the FYPs' policy targets were assessed by counterchecking against the yearbook data of the respective years. Finally, secondary scientific literature was utilized to evaluate and integrate the research findings.

Results and discussion

In this section we describe the development of agricultural land and water use, followed by a section which elaborates the driving forces responsible for those developments, while the third section analyses water-use efficiency and related water productivity, which are key variables for future water resource use planning.

Agricultural land-use development

Area of annual crops

A huge expansion of agricultural land-use area can be observed throughout the ATR from 1989 to 2011. The total area of annual crops increased very strongly in Aksu, Bayangol and Div.1 in the last 22 years, while the area in Div.2 hardly increased (Fig. 2a). The increases outside the military farms were much stronger, rising rapidly from 2004 and 2008 onwards in Bayangol and Aksu, respectively. The major annual crop is cotton, which experienced tremendous increases in sown area in all regions (Fig. 2b), while the area under cereal production stagnated at the same time (Fig. 2c). When looking at the area under vegetable cultivation (Fig. 2d), one can observe a sharp increase since the late 1990s in Aksu, Bayangol and Div.2, with vegetables occupying a relatively high share of cultivated land in Bayangol (14 %) and Div.2 (24 %) in 2011, compared to Aksu (4 %) and Div.1 (2 %).

Area of perennial species

Additionally, the area of orchards experienced a tremendous increase since the beginning of the new century

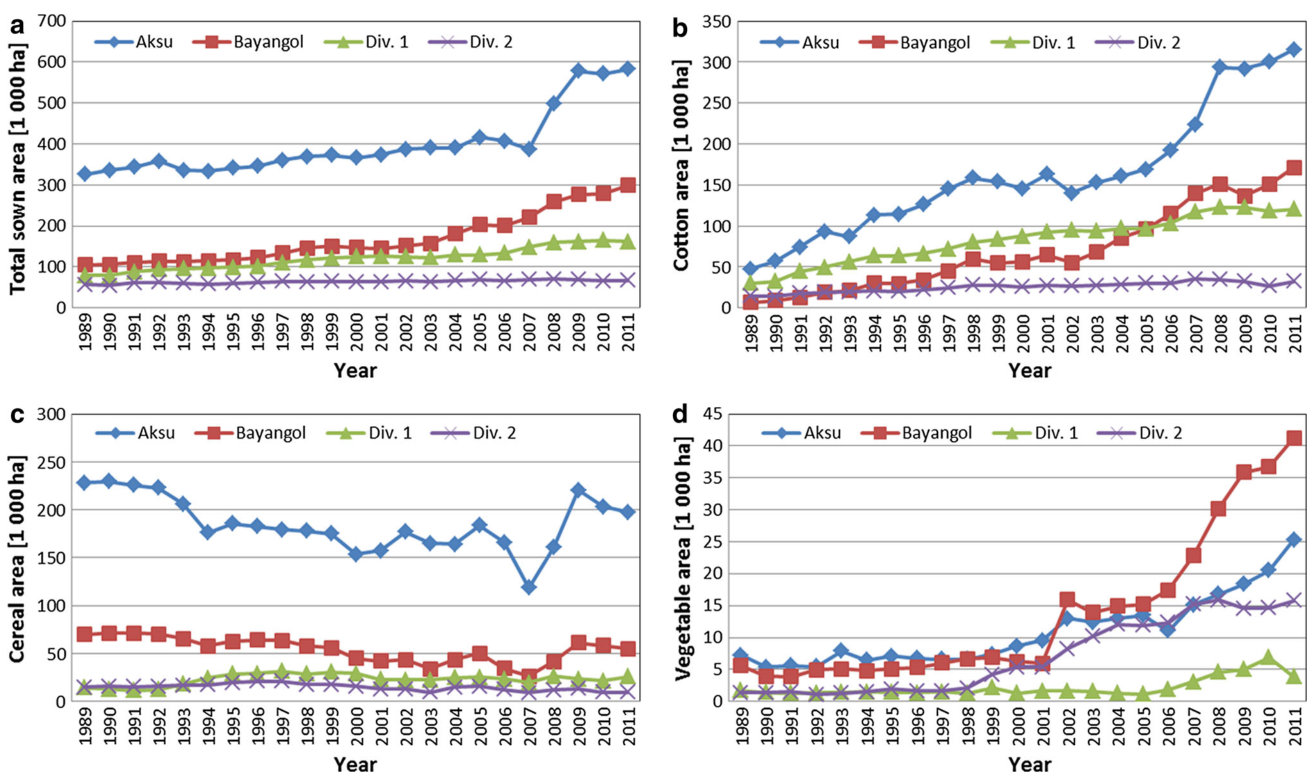

Fig. 2 Sown area of all annual crops (**a**), cotton (**b**), cereals (**c**) and vegetables (**d**) in four administrative regions of the ATR during 1989–2011 (compiled from BTSYB 1990–2012 and XJSYB 1990–2012)

(Fig. 3a). Both absolute and relative increase is strongest in Aksu, followed by Bayangol, Div.1 and Div.2. Since 2005 jujube (*Ziziphus jujuba* Mill.), endemic to the arid regions of Northwestern China, and thus adapted to low humidity and high temperatures (Su and Liu 2005), increased very rapidly, superseded pear and apricot in importance, and is by far the major fruit crop in the ATR in 2011 (BTSYB 1990–2012; XJSYB 1990–2012).

The upstream areas of ATR, namely Aksu and Div.1 feature a huge increase in afforestation area, while the area is much smaller in the downstream regions of Bayangol and Div.2 (Fig. 3b). The strong fluctuations in reported area are mainly caused by poor maintenance and related water shortage of newly established afforestation areas (Cao et al. 2011). While this area is reported as man-made forest in the year of planting, it is taken out of the accounts in the following years due to actual failure of establishment of forest (Yue and Su 2002).

Water-use development

Regarding agricultural water-use development only data of Aksu and Bayangol is available from 2004 onwards (Table 1). Until 2010 just a very marginal increase of total water supply is reported for both regions, while the amount of supplied surface water even decreased. Groundwater only contributed little to total water supply in the past. However, from 2004 to 2010 its share in total supply increased from 2 to 7 % in Aksu and from 9 % to more than 20 % in Bayangol, indicating its increasing importance.

Among the three sectors agriculture is the major consumer of water resources with a share of 97 % in Aksu and 93 % in Bayangol in 2010 (Table 2). However, a slight decrease in the share of agriculture can be observed in both regions in recent years.

Even though the developments reported for Aksu and Bayangol for the 2004–2010 period indicate that agricultural water use did not increase in recent years, these data do not reflect the actual developments in the entire ATR over the last decades.

With average precipitation in the region being far below 100 mm (Xu et al. 2005), all agricultural production as well as man-made forest cultivation inevitably depends on additional irrigation. Therefore, the rapid expansion of agricultural land, described in detail above, should have led to an increase of agricultural water consumption at a similar pace, which is confirmed by several studies. According to Thevs (2011), reclamation of new land steadily increased the withdrawal of irrigation water along the Tarim River and its tributaries. Tang and Deng (2010) describe a huge increase of water abstraction in the Aksu region between 1957 and 2002, which is also confirmed by Zhang (2001) for the 1990s to 2000s. Furthermore, Xu et al. (2005) quantified surface water withdrawal from Aksu River at 69 and 80 million m^3 in 1994 and 2003, respectively, indicating that agricultural water use actually increased very strongly in the ATR.

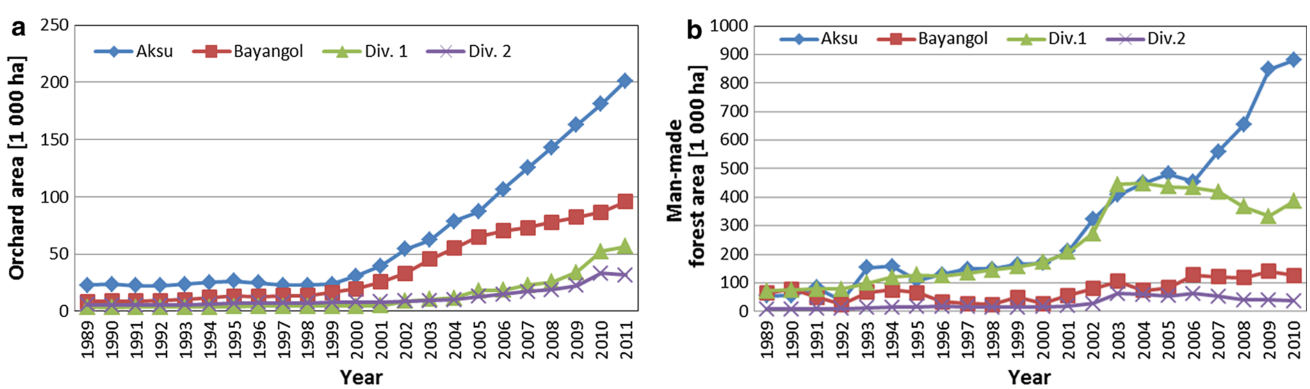

Fig. 3 Planted areas of orchards (**a**) and man-made forest (**b**) in four administrative regions of the ATR during 1989–2011 (compiled from BTSYB 1990–2012 and XJSYB 1990–2012)

Table 1 Development of total, groundwater and surface water supply in Aksu and Bayangol 2004–2010 (compiled from XJSYB 1990–2012)

Year	Water supply by source (10^8 m^3)					
	Total		Surface water		Groundwater	
	Aksu	Bayangol	Aksu	Bayangol	Aksu	Bayangol
2004	100.08	40.63	98.07	36.89	2.01	3.68
2010	100.24	44.10	93.19	35.04	7.05	9.01
Annual increase (%)	0.03	1.42	−0.83	−0.84	41.79	24.14

Table 2 Development of water consumption for all sectors and agriculture in Aksu and Bayangol 2004–2010 (compiled from XJSYB 2005–2012)

Year	Water consumption (10^8 m^3)				Share of agriculture (%)	
	All sectors		Agriculture			
	Aksu	Bayangol	Aksu	Bayangol	Aksu	Bayangol
2004	99.36	38.53	98.45	37.76	98.37	92.94
2010	98.49	42.33	97.50	40.90	97.27	92.74
Annual increase (%)	−0.15	1.64	−0.16	1.39	−0.19	−0.03

Driving forces

In the following section the driving forces of land and water use in the ATR and their developments are assessed.

Stakeholder ranking

Driving forces of regional land- and water-use development as identified and ranked by local experts during stakeholder workshop are presented in Table 3. The local experts rated population development and water resource availability as the strongest driving forces, followed by the development of agricultural yields, the technological progress regarding water-use efficiency and the overall economic development in the region. Furthermore, the developments of agricultural product quality as well as agricultural input and commodity prices are considered to have an impact on the regional development.

In the next step, the driving forces were categorized by the authors according to thematic focus, namely demographic, socio-economic, technological and natural factors. The developments of those categories of driving forces over the last two decades are illustrated and analyzed in the following chapters.

Table 3 Driving forces of land and water use in the ATR evaluated by local experts during stakeholder workshop

Category	Regional driving force	Importance (1 = weak, 5 = strong; $N = 10$)
Demographic	Population development	4.5
Socio-economic	Economic development	4
	World market prices	3.2
	Agricultural input prices	3.1
	Trade (to west)	3.1
	Food demand	3
	Bio-energy demand	1.6
Natural	Availability of water resources	4.5
	Availability of land	3.7
	Climate change	3.3
Technological	Agricultural yields	4.1
	Technological progress (WUE)	4.1
	Product quality	3.7

Demographic development

Population growth

Population growth was also identified as a major driving force for agricultural land expansion and related water consumption by Zhang et al. (2003) and Zhou et al. (2003) for different parts of arid Northwestern China, as well as by Wang et al. (2008) for the middle reaches of Tarim River. Looking at the statistical data, population in the ATR increased steadily at a high rate in Aksu, Bayangol and Div.1 since 1989, while it stagnated in Div.2 (Table 4).

When distinguishing between ethnicities, one can see that all groups contributed strongly to population growth. However, the causes of this massive increase have to be differentiated between the different ethnicities; Uighurs and other ethnic minorities (e.g., Kazak, Kirgiz, Mongol) feature a very high fertility. For those minorities one-child-policy does not apply in the same strictness as for the Han, who constitute the national majority. While minorities were allowed to have up to four children in the beginning of the 1990s (Attane and Courbage 2000), the regulations were tightened since the early 2000s, and nowadays allow two children in urban areas and up to three children in rural areas (NHFPC 2002). In comparison, Han can generally only have one and two children in urban and rural areas, respectively. Hence the tremendous increase in Han population in the ATR since 1989 is not the result of high fertility, but is caused by immigration. This is on one side due to the central government's policy of encouraging people to settle in the frontier areas since the early 1950s, aiming at stabilizing and strengthening those often minority-dominated regions (Cote 2011). On the other side, the implications of the "Develop the West" policies and related positive economic and trading possibilities encouraged hundreds of thousands of people to move from other parts of China to Xinjiang since the 1990s. This development is further amplified by the relaxation of the household registration system in recent years (Fan 2005). Zhao et al. (2013) confirm those findings in a GIS study that spans over the 1973–2005 period. They identified population growth caused by migration as a dominant driver for land cover change along the Tarim River.

Table 4 Development of population in four administrative regions and development of different ethnic groups in the entire ATR during 1989–2011 (compiled from BTSYB 1990–2012 and XJSYB 1990–2012)

Year	Total population per sub-region (10^4 person)				Population per ethnicity in ATR (10^4 person)		
	Bayangol	Aksu	Div.1	Div.2	Han	Uighur	Others
1989	82.4	164.2	18.3	18.8	110.5	161.5	11.8
2011	136.6	258.1	29.7	19.1	189.7	236.0	17.8
Annual increase (%)	3.0	2.6	2.8	0.1	3.3	2.1	2.3

It that context it is important to recognize the awareness among local governments of rapid population growth being a major threat to sustainable development. Throughout the recent FYPs the governments' efforts to slow down population increase can be found, with the "implementation of family planning policy" and "stabilization of fertility level" strongly emphasized (e.g., DRCAP DRCAP 2006; DRCBP DRCBP 2006; DRCDO 2011). However, efforts to reduce immigration cannot be found. This may also be one reason, why the targeted population development was strongly exceeded in Aksu and Bayangol within the 11th FYP period (Table 5). The population decline in Div.2 is mainly a result of lacking water resources and related poor development conditions, elaborated in more detail below. For Div.1 no data were available.

Agricultural employment

Not only the development of population, but also the number of people depending on agriculture for their living has strong impact on agricultural land and water resource use (Barbier 2004). Therefore, Fig. 4 displays the development of employment in agriculture and related issues in the ATR. The employment in agricultural sector approximately doubled in Aksu and Bayangol since 1989 (Fig. 4a), while it maintained at a stable level in Div.1 and Div.2. A slight decline in the share of agricultural employment in total employment over the last 22 years can be observed. The agricultural employment per agricultural land area decreased constantly in Bayangol, Div.1 and Div.2 from around 0.8 person per hectare in 1989 to around 0.4 person per hectare in 2011. Only in Aksu the ratio hardly declined staying above 0.8 person per hectare in 2011.

It should be acknowledged that the local governments realized the importance of moving labor out of agriculture to alleviate the pressure on natural resources, recognizing "surplus labor force" (DRCDO 2011), "transfer of rural labor to urban areas" (DRCAP 2006) and "guide agricultural labor to non-agricultural industries" (DRCDT 2006). This shall be implemented by developing more job opportunities, especially in the construction and industrial sector (e.g., DRCAP 2006), recruiting local labor (e.g., DRCBP 2011), and improving the skills of local labor force through expansion of vocational training (e.g., DRCDO 2011).

Table 5 Planned vs. actual natural annual population growth for the four administrative regions of the ATR during the 11th FYP period (2006–2010) (compiled from BTSYB 2011; DRCAP 2006; DRCBP 2006; DRCDT 2006; XJSYB 2011)

2006–2010	Natural annual population growth (‰)			
	Aksu	Bayangol	Div.1	Div.2
Planned	12.0	8.5	nn	30.0
Actual	19.1	23.6	2.0	−16.7
Planned vs. actual (%)	+59.5	+177.5	nn	−155.8

In the context of agricultural labor, the mechanization of farm management, which is rapidly advancing throughout China (Feike et al. 2012), needs to be considered. Mechanization, displayed as total power of agricultural machinery per hectare in Fig. 4d, increased strongly in all four regions of the ATR. The lowest level of mechanization is found in Aksu, while Bayangol features the highest rate.

Socio-economic development

Gross output value of farming

Zhang (2004) identified economic development as the strongest trigger for land reclamation in the Yangtze River Basin, while Wang et al. (2007) attributed a great share of land-use change in Qinghai Province to be driven by economic development. This is in line with the findings of Yang and Li (2000), who stress the impact of economic development as a major driver of land-use change on national level. In the ATR profound changes can be observed looking at the economic development of agricultural sector. The total gross output value (GOV) of agriculture increased from 16 million RMB to 246 million RMB from 1989 to 2011 (Fig. 5a). This has to be acknowledged as a great achievement, contributing considerably to the improvement of rural livelihoods in the region. Rapid increases occurred in Aksu, Bayangol and Div.1 especially from 2000 onwards. Div.2 shows a significantly lower increase compared to the other three regions. The share of farming, meaning crop and fruit production, makes up the major part of total agricultural GOV (Fig. 5b), while livestock, fishery, forestry and

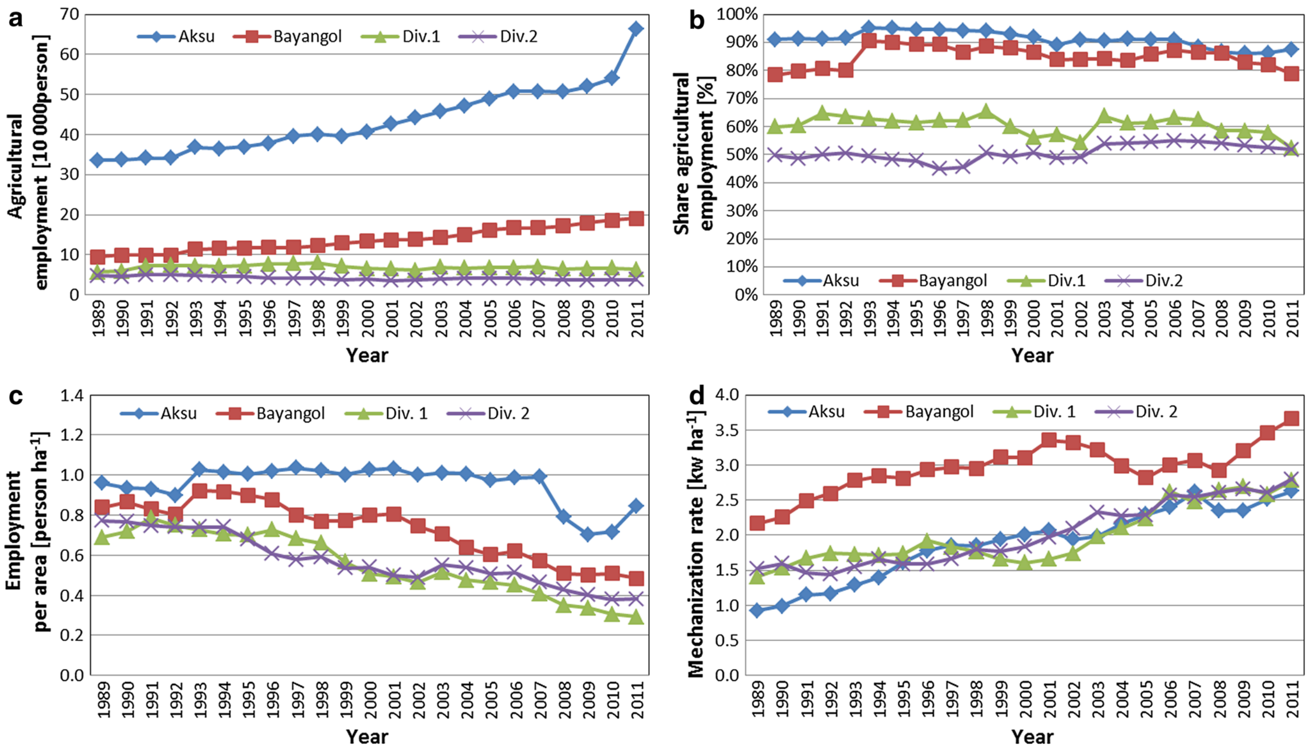

Fig. 4 Development of agricultural employment (**a**), share of agricultural employment in total employment (**b**), agricultural employment per agricultural land area (**c**), and degree of mechanization of agriculture in four administrative regions of the ATR during 1989–2011 (compiled from BTSYB 1990–2012 and XJSYB 1990–2012)

agricultural services play a minor role. In 2011, farming contributed 75–80 % to total agricultural GOV in Aksu, Bayangol, and Div.2, while it was responsible for nearly 90 % of total GOV in Div.1.

The GOV per area (Fig. 5c) developed very positive in the ATR, with the best developments in Div.1, Div.2 and Bayangol, while Aksu lacks far behind. A similar development occurred for the GOV per labor force, with the highest values in Div.1 (95,000 RMB), Div.2 (58,000 RMB) and Bayangol (43,000 RMB) in 2011. Aksu again lags far behind at 12,000 RMB per labor force. The relatively poor performance of Aksu is on one side the result of the high ratio of newly established orchards in Aksu (Fig. 3a), which do not yield high revenues in the first few years after establishment. On the other side, the small land area per farm household is highly unfavorable.

The huge increase in monetary output per land area (Fig. 5c), has to be recognized as a strong trigger of continuous agricultural land expansion in the ATR, by providing the financial resources and strengthening the expectations for high returns of investments for farmers. This is in line with Angelsen (1999) who state that profitability of farming has a strong influence on reclamation of new land. Additionally, Li et al. (2011) confirm that Chinese farmers' land-use decisions are often governed by profit maximization (Li et al. 2011).

Agricultural commodity prices

In the next step, how far economic considerations govern farmers' crop choice in the ATR was assessed. According to Kleiber (2009) and Mullen et al. (2005), farmers' decision on which crop to grow is in large part influenced by its sales price. Therefore, previous years' national commodity prices of cotton, aggregated tree fruits (apple, pear, peach, grape, date), aggregated cereals (barley, wheat, maize), and dates (jujube) obtained from FAOSTAT (2013) were correlated with current year's cultivated area of the respective crop or aggregation of crops within the four administrative regions, as well as the entire ATR (Table 6). A strong positive correlation can be observed in all regions for cotton, and especially for tree fruits and dates, while for cereals no significant correlation exists. Since cotton production is of great strategic importance to China's textile industry (Ju et al. 2011), it is stabilized by the government through market control and subsidization of production (Meador and Wu 2013; Han et al. 2013). This partly explains why correlation coefficient of lagged price and area is not higher than 0.62. The very high correlation coefficient for tree fruits and dates indicates a strong impact of price on farmers' decision to produce them. Regarding cereal production, there are two reasons for the nonexistent

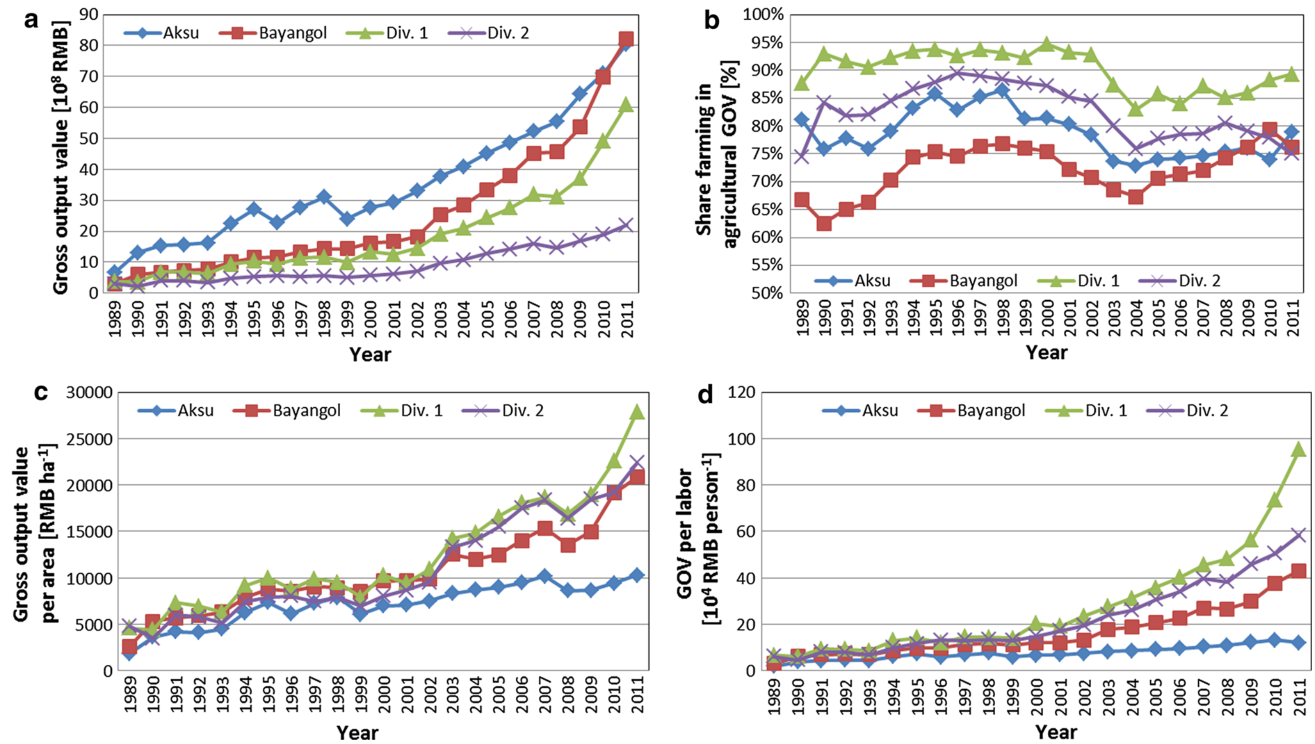

Fig. 5 Development of agricultural gross output value (**a**), share of farming in total agricultural gross output value (**b**), gross output value per area (**c**), and gross output value per laborer (**d**) in four administrative regions of the ATR during 1989–2011 period; monetary values are given in real price (1989 RMB) (compiled from BTSYB 1990–2012 and XJSYB 1990–2012)

correlation. Firstly, the high rates of subsidization, which are paid in the form of direct grain subsidies, quality seed subsidy and input subsidies, buffer the fluctuations in actual market price volatility (Meng 2012). Secondly, but even more important is the fact that cereal producers in China often belong to the more backward and disadvantaged farmers, who neither have the financial resources nor the agronomic skills to opt for the production of alternative cash crops like cotton or fruits in times of low cereal price.

Technological progress and development of natural conditions

The availability of water resources is a result of changes in natural conditions as well as human activities related to water use. Therefore, the "technological" and "natural" categories of drivers are assessed jointly in the following section.

Agricultural yields

The level of agricultural yields has a significant impact on resource use efficiency of land and water, and therefore needs to be considered as a vital driver of regional land and water use. In the ATR the yields of the major agricultural crops experienced strong increases since the late 1990s (Fig. 6). While the yield of cotton is between 0.6 and 1.1 tons per hectare in 1989, average yields per hectare reached 1.7 tons in Aksu, 2.1 tons in Bayangol and more than 2.5 tons in the two divisions in 2011 (Fig. 6a). For cereals a similar increase can be observed, rising from 3 to 4 tons in 1989, to 7.4 tons in Aksu, 6.4 tons in Bayangol, 8.2 tons in Div.1 and 5.4 tons in Div.2 in 2011 (Fig. 6b). Despite the very positive development over the 22-year period, a slight stagnation of yield levels can be observed in recent years. Nevertheless, yield increase overcompensated the decrease in production area of grains, leading to a slight increase of annual per capita production of grain from 455 to 470 kg in the ATR from 1989 until 2011. Regarding the yields of fruits and vegetables, no consistent data can be presented. For fruits the high share of recently established non-fruiting plantations, impede the calculation of yields from production amount and area data.

Table 6 Pearson correlation coefficient of last year's price and current year's area of major agricultural commodities of the ATR during 1992–2011 period

Item	Aksu	Bayangol	Div.1	Div.2	ATR
Seed cotton	0.56	0.62	0.69	0.81	0.62
All tree fruits	0.90	0.89	0.88	0.90	0.91
Dates	0.90	0.82	0.87	0.87	0.90
Cereals	−0.20	−0.23	0.41	−0.33	−0.19

As all vegetables whether they have very high (e.g. water melons) or very low (e.g. dried chili) per hectare yields, are aggregated in the statistics as "vegetables", and the production of the different vegetables is very distinct between the four regions and changing over time, a comparision of yield levels over regions and years has little validity, and was therefore not conducted.

Availability of land

Loss of arable land due to increasing industrial, infrastructural and residential area is considered a serious issue in China by many authors, threatening China's food security in the long run (e.g., Lin and Ho 2003; Wang et al. 2012; Zhang 2004). However, Deng et al. (2006) identified a national net increase of agricultural land from 1986 to 2000, with one of the strongest increases occurring in Xinjiang. This is in line with the strong expansion of cultivated land area in the ATR described above.

Even though industrialization and urbanization in the ATR increased in recent years and this trend is most likely to continue (DRCDO 2011), strong competition for land resources is limited to the few urban areas and industrial centers of the ATR, with the vast majority of cultivated land being unaffected. Furthermore, a range of farmland protection policies were enacted in recent years to prevent massive conversion of arable land towards other uses (Lichtenberg and Ding 2008).

However, arable land in the ATR has other crucial factors limiting its extent. Salinization of agricultural soils, caused by unreasonable irrigation and insufficient drainage, is severely compromising agricultural production. According to Wang et al. (2003) nearly 40 % of arable land in the ATR faces serious salinity problems. To remediate saline land, washing out of salts through extensive flooding is the major choice. Near the headwaters of the river, where sufficient fresh water is available farmers flush their fields frequently. As a consequence, salinity of Tarim River water measured at its starting point in Alar increased from less than 1 to more than 5 g/l from 1960 to 2000 (Wang et al. 2010). This qualitative degradation of water resources, along with the fact that a high share of farmers along the middle and lower reaches of Tarim River additionally suffer frequent quantitative water shortage (Thevs 2011) leads to the conclusion that land is not the key limiting factor of development in the region, but water.

Climate change and availability of water resources

Water availability within the ATR is first of all determined by the rivers' water discharge. In a very comprehensive study Xu et al. (2005) determined that a slight increase in temperature over the second half of the last century led to a significant increase in river discharges, mainly caused by increased glacier melt. Precipitation only increased insignificantly in the same period. Especially Aksu River, which contributes in average about 77 % of total water to the Tarim mainstream, experienced a significant increase in runoff in recent years, with a 6.7 % increase for the 1994–2003 period compared to the average of 47 years since 1957. Accordingly, the total annual water volume in the headstreams of Tarim River increased by more than 25 million cubic meters during the 1994–2003 period. Similar increases in Aksu River headstream runoff are reported by Tang and Deng (2010), and Zhang (2001).

Despite the increase in headstream water availability, the mainstream of Tarim River experienced reduced water flow. The annual discharge of Aksu River into the Tarim River decreased from 33.7 million m^3 in the 1980s and 34.1 million m^3 in the 1990s to 26.9 million m^3 in the 2000s (Zhang 2001). This discrepancy is obviously caused by the strongly increased water consumption in the headstream areas (Thevs 2011; Turak et al. 2007; Wang et al. 2003; Wu 2012; Xu et al. 2003; Zhang 2001).

In addition, one has to consider that water availability is not only determined by river discharge, but also by water

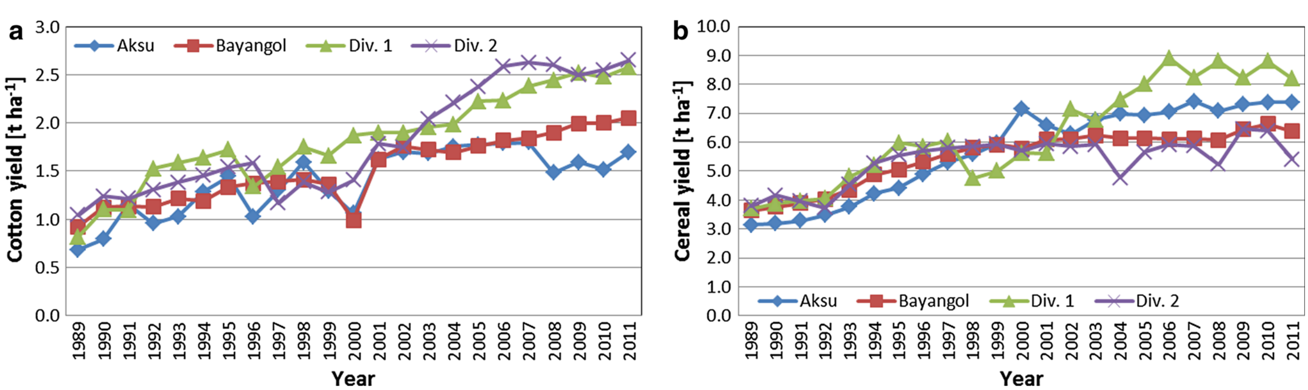

Fig. 6 Development of yields per hectare of cotton (**a**), and cereals (**b**) in the four administrative regions of the ATR during 1989–2011 (compiled from BTSYB 1990–2012 and XJSYB 1990–2012)

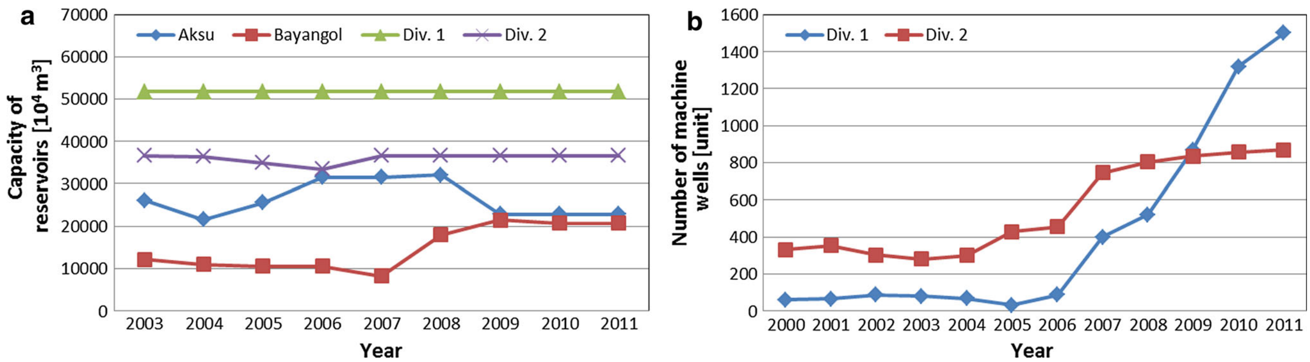

Fig. 7 Development of capacity of reservoirs in the four administrative regions of the ATR (**a**), and number of machine wells installed in Div.1 and Div.2 (**b**) over the last decade (compiled from BTSYB 1990–2012 and XJSYB 1990–2012)

Table 7 Planned vs. actual area of fruits and cotton in the four administrative regions of the ATR in 2010 as planned in the 11th FYPs (compiled from BTSYB 2011; DRCAP 2006; DRCBP 2006; DRCDT 2006; XJSYB 2011)

	Area of fruits in 2010 (10^4 ha)				Area of cotton in 2010 (10^4 ha)			
	Aksu	Bayangol	Div.1	Div. 2	Aksu	Bayangol	Div.1	Div. 2
Planned	166.4	66.7	nn	40.0	200	93.3	nn	nn
Actual	181.0	86.7	52.1	33.1	300	150.5	118.5	27.1
Planned vs. actual (%)	8.8	30.1	nn	−17.3	50.0	61 %	nn	nn

storage infrastructure as well as drilling facilities for abstraction of groundwater. Related data are limited, both in time and space. The capacity of reservoirs was very stable in the two divisions since 2003, while it increased strongly in Bayangol since 2007, and declined slightly in Aksu until 2011 (Fig. 7a). Compared to the huge increase of agricultural land-use area in the same period (Figs. 2a, 3a), a tremendous decrease in storage capacity per land area has to be recognized. Partly this decline may have been buffered by the increased use of groundwater, which is indicated by the rapid increase in machine wells installed in Div.1 and Div.2 since 2005 (Fig. 7b). For Aksu and Bayangol no yearbook data are available. However, a further increase in "utilization of groundwater resources" is planned in Aksu during 12th FYP period (DRCAP 2011).

The impact of water availability on agricultural land area development is impressively revealed when comparing the planned and actual area of fruits and cotton in the ATR (Table 7). While Aksu and Bayangol, feeding not only on the Aksu River, but also on numerous smaller rivers like Weigan, Kaidu and Konqi River, strongly exceeded their development goals of fruit and cotton area, as planned in their 11th FYPs, Div.2 significantly failed its target of fruit production area for 2010. Being mainly located at the lower reaches of the Tarim River, Div.2 solely depends on its surface water provision. Only Konqui River water is additionally allocated from time to time to Div.2; however, the amount is strongly limited by the increasing water demand of the booming city of Korla. Thus, lack of water resources is ranked first in its recent FYP under the challenges faced, being recognized as "seriously affecting economic development" (DRCDT 2006).

When looking at the role that water resource conditions play in land and water use in the ATR as a whole, one has to recognize that the improved water availability in the upper reaches resulted in better production conditions for farmers and related increased agricultural profitability, leading to reclamation of new land, which finally induced a decline in water availability in the lower reaches. This development might have been further intensified by migration towards the headstreams of the rivers, which feature abundant water.

Even though prefectural governments strive to "stabilize" agricultural production areas (e.g., DRCAP 2006; DRCBP 2006), being aware that the further expansion of land worsens the tight water resource situation, the targets were heavily exceeded during the past FYP period (see Table 7). Moreover, the official ordinances enacted on the regional level to control the expansion of agricultural land (SCXPC 1997) and restrict the extraction of groundwater (TRBMB 2008) showed limited success. The implementation of such regulations is to a large part the responsibility of local administrators. For them it is very difficult to effectuate ordinances, which—as a negative externality—restrict local people from improving their economic situation (Zhang et al. 2009).

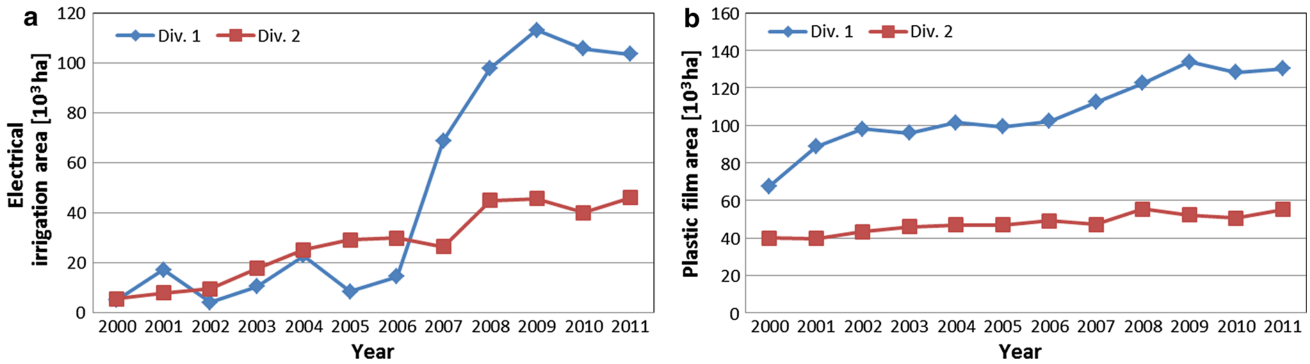

Fig. 8 Development of area under advanced irrigation technology (**a**) and plastic mulch (**b**) in Div.1 and Div.2 during 2000–2011(compiled from BTSYB 1990–2012)

Water-use technology

Throughout the ATR strong efforts are undertaken to increase the area of cultivated land using advanced irrigation technology, with reliable data available only for Div.1 and Div.2 (Fig. 8). Both drip irrigation and plastic mulching area increased over the last decade with the increases being much stronger in Div.1. In the 11th and 12th FYPs of all regions, intents are formulated to reduce water losses by increasing the area using advanced irrigation measures. In this respect, Bayangol prefecture plans to increase the "high-efficiency water-saving area" to more than 5,000 ha and achieve a gross irrigation quota below 9,000 m^3 per hectare (DRCBP 2011).

However, it is vital to recognize that the sole increase of application of drip irrigation technology by the local farmers can only be a small part of the solution to realize a sustainable water resource use along the Tarim River.

Afforestation programs

Even though not mentioned by the local experts, China's massive afforestation programs have to be recognized as another vital land-use driver in the ATR, being responsible for a great share of the increase in man-made forest area (Fig. 3b). Among them the "Three-North Shelterbelt Forest Program" and the "Grain-for-Green Program" (GFG) are the most prominent, with the latter having by far the strongest impact in the ATR. Implemented nationwide in 2001, GFG aims at returning farm land to forest to control erosion while supporting rural development (Cao et al. 2011; Fang et al. 2012). Farmers receive subsidies in the form of money or grain for the first five and eight years after conversion into economic (orchards) and ecological forest, respectively. At least 80 % of land needs to be converted to ecological forest, with not more than 20 % converted to economic forest (Liu and Wu 2010).

Even though GFG and other afforestation programs follow very honorable motives and desirable goals, Cao et al. (2011) claim that their massive extent may have overshot the target, resulting in ecological deterioration especially in arid and semi-arid regions of China (Zhang and Sun 2003). This may as well be the case in the ATR, where water is the scarcest resource, and its overuse causes severe environmental degradation (Thevs 2011; Xu et al. 2005). Even though wind erosion in the afforested areas along the headstream waters in Aksu and Div.1 may be controlled effectively, the degradation of natural riparian ecosystems down the river caused by reduced water supply may lead to a strong overall increase of erosion.

For the ATR one additionally has to recognize that the huge implementation of GFG-area did not lead to a reduction or at least stagnation in area used for annual crops. Since 1989 all three categories of land use, namely annual crops, orchards and ecological man-made forest increased.

Ecological water demand and water conveyances

Not apparent at first glance and overlooked by the local experts, the water demand of the natural ecosystems in the ATR needs to be considered another driving factor. As a result of ever increasing human activities and related water exploitation since the middle of last century, the ecological water requirements of the ATR could not be met (Deng et al. 2013; Thevs 2011; Ye et al. 2010). Since the construction of Daxihaizi water reservoir in 1972, the lowest 350 km of the Tarim received hardly any runoff (Song et al. 2000). As a consequence, groundwater levels declined leading to a steady decay of the natural vegetation (Chen et al. 2013; Huang and Pang 2010; Ye et al. 2010).

To maintain a "green corridor" between the Taklimakan and the Kuluk deserts, and protect important infrastructure from wind erosion and desertification, the Chinese government launched the biggest water diversion project in western China in 2000 (Hou et al. 2007). From beginning of 2000 to the end of 2011 more than 28 $\times$ 10^8 m^3 of water was allocated in 12 ecological water diversion campaigns

Table 8 Development of water use per area (m^3 ha^{-1}) and productivity of agricultural water (GDP per invested unit of water and labor) (RMB m^{-3} $person^{-1}$) in agricultural sector of Aksu and Bayangol during 2004–2010; GDP given in real price (2004 RMB) (calculated from XJSYB 2005–2012)

	Water use per area (m^3 ha^{-1})		Water productivity (RMB m^{-3} $person^{-1}$)	
	Aksu	Bayangol	Aksu	Bayangol
2004	20,951	15,986	167	948
2010	12,966	11,185	256	1,748
Annual increase (%)	−6.4	−5.0	8.9	14.1

to the lower reaches of the Tarim (Aishan et al. 2013a). The water is mainly diverted from Bosten Lake, located in the Kaidu-Konqi watershed (Hou et al. 2007). The impact of the project on the ground water developments and the riparian ecosystem are in the focus of several research groups, and have been published in numerous articles (e.g., Aishan et al. 2013b; Chen et al. 2013; Xu et al. 2012). The research findings attest a remarkable revitalization of riparian ecosystems as a consequence of water diversion. However, the positive effects concentrate on the first 200 m close to the river (Aishan et al. 2013b), and are mostly limited to the already existing tree stock. Rejuvenation of the riparian forests through successful establishment of tree seedlings is still negligible (Zhao et al. 2006).

To maintain an intact riparian ecosystem in the long run, Wang and Lu (2009) recommend a restoration and stabilization of the groundwater table at about 4 m depth. To achieve this, a delivery of about 2.5×10^8 m^3 a^{-1} to the lower reaches would be necessary during the first 5 years of restoration, followed by 2.0×10^8 m^3 a^{-1} from then on. From the 12 water diversion campaigns conducted since 2000, six did not reach the level of 2.5×10^8 m^3 a^{-1} (Aishan et al. 2013a). To close the gap between necessary and available water resources for ecological restoration of the lower Tarim, the responsible administrative bodies might extend the water source from Bosten Lake to the upper Tarim and Aksu River in the future; this would result in reduced water availability for human activities in those areas.

Water-use efficiency

Finally, the actual water resource use efficiency within the ATR is assessed. As official water-use data are not available for the two divisions, the analyses focuses on Aksu and Bayangol. On the first glance Aksu, located at the upper reaches of the ATR, and thus abundant in water resources, shows a very positive development over the last two decades. Cultivated land area increased strongest of all four sub-regions (Figs. 2a, 3a), and agricultural yields did not differ significantly from those of Bayangol prefecture (Fig. 6). At the same time the water use per area improved strongly since 2004 reaching a similar level as in Bayangol (Table 8) in 2010.

However, as water scarcity has to be recognized the bottle neck for regional development, with the vast majority of rural population being employed in the agricultural sector, and thus depending on this scarce water for living, it is essential to consider the productivity of agricultural water as a key variable for sustainable development. Agricultural water productivity is therefore defined as agricultural GDP per invested unit of water and labor force. Due to the strong increase in population (Table 4) and consequential agricultural employment (Fig. 4a), coupled with a fairly low monetary output per labor force (Fig. 4d), Aksu features a seven times lower water productivity compared to Bayangol in 2011 (Table 8).

It becomes obvious that the implementation of water-saving irrigation technology and related improvement of water use per area is not the universal remedy to reduce overuse of water resources and maximize regional benefits. Bayangol recognized the necessary development steps already in its 11th FYP, aiming at the increase of farm land per farm household by moving agricultural labor into other sectors (DRCBP 2006). Additionally, its share of labor-intensive and high-value crops like vegetables (Fig. 2d) increased sharply in recent years, which strongly contributed to increasing its agricultural water productivity.

A much more efficient water use compared to the agricultural sector was achieved in the other two sectors of economy in both prefectures (Table 9). Compared to the agricultural sector, the monetary output per invested unit of water in 2010 was more than 100 times higher in the industrial and construction (secondary) sector and even 400–900 times higher in the service (tertiary) sector in Bayangol and Aksu, respectively. Therefore, the attempts to move labor out of agriculture into other sectors of industry, described in detail above, should receive maximum efforts by local governments.

Conclusions and recommendations

From 1989 until 2011 a tremendous increase in land and water use for agriculture can be observed in most regions of the ATR. The analysis shows that this development is a result of the interaction of (1) vast population growth and

Table 9 Development of GDP per invested unit of water (RMB m^{-3}) for the three sectors of industry in Aksu and Bayangol during 2004–2010; GDP given in real price (2004 RMB) (calculated from XJSYB 2005–2012)

	Water productivity (RMB m^{-3}) in different sectors of industry							
	Total		Primary sector		Secondary sector		Tertiary sector	
	Aksu	Bayangol	Aksu	Bayangol	Aksu	Bayangol	Aksu	Bayangol
2004	1.5	5.6	0.6	1.1	41.0	188.3	90.9	88.3
2010	2.8	12.0	0.9	2.2	105.6	258.3	803.1	891.3
Annual increase (%)	13.6	18.7	7.7	17.4	26.2	6.2	130.5	151.6

related increase in agricultural labor; (2) positive price developments for fruits and cotton; (3) strong increase in profitability of agriculture, triggering the reclamation of more land; (4) afforestation programs pushing for the establishment of orchards; and (5) insufficient restriction of agricultural land expansion. As a consequence, reduced water availability in the lower reaches of the river impairs the development in Div.2, which faces declining agricultural production area and outflow of people in recent years. Even though strong efforts to promote water-saving irrigation technology exist, the improvements in water-use efficiency per land area are far from sufficient to outweigh the expansion of agricultural land and especially the increasing number of farmers depending on the scarce water resources throughout the ATR. Thus, the local governments and administrators need to step up their efforts to move people out of agriculture, increase agricultural area per farm household without further reclamation of land, and significantly improve agricultural water productivity by increasing yield levels and shifting crop production towards labor-intensive high-value commodities like vegetables. Additionally, the further development of second and third industrial sector offers great opportunities to increase gross regional product, while decreasing overall water consumption for human purposes. Apart from tackling high fertility as cause of overpopulation, effective control of immigration should also be put on the agenda. Only then can the ecological water demand along the river be met, without comprising the local population's aspirations.

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