Institute of Farm Management (410c)

University of Hohenheim

Computer Applications and Business Management in Agriculture

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Role of Irrigation Water Pricing in Sustainable Water Resources Management along the Tarim River, Northwest China

Dissertation

submitted in fulfillment of the regulations to acquire the degree "Doktor der Agrarwissenschaften"

(Dr.sc.agr. in Agricultural Sciences)

to the

Faculty of Agricultural Sciences

presented by

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Stuttgat-Hohenheim

2016

This thesis was accepted as a doctoral thesis (Dissertation) in fulfillment of the regulations to acquire the doctoral degree “Doktor der Agrarwissenschaften” by the Faculty of Agricultural Sciences at University of Hohenheim on. 20.01.2016

Date of the oral examination: 26.04.2016

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LIST OF ABRIVIATIONS AND ACRONYMS

AAI	Aggregated Advantage Index
ABWP	Area-based water pricing
APSYB	Aksu Prefecture Statistical Yearbook
ATR	Aksu-Tarim Region
ATR	Aksu-Tarim River
BN	Bayesian Networks
BSYB	Bayingolin Statistical Yearbook
BTSYB	Bingtuan statistical yearbook
CA	Comparative advantages
CAI	Comparative Advantage Index
CPLC	Cotton production and land use change
CPS	Contracted Purchasing Scheme
CPSYB	Population Statistical Yearbook of People's Republic of China
CPT	Conditional probability table
CSYB	China Statistical Yearbook
Div.1	Division 1
Div.2	Division 2
DRC	Domestic Resource Cost
DWP	differential water pricing
e.g.	For example
EAI	Efficiency Advantage Index
et al.	Et alii (and others)
FAO	Food and Agriculture Organization of the United Nations

FAOSTAT	Food and Agriculture Organization of the United Nations Statistical Databases
FCR	Full cost recovery
FYP	Five-year plans
g	Gram
GDP	Gross domestic product
GFG	Grain-for-Green Program
GOV	Gross output value
ha	Hectare
I&D	Irrigation and drainage
IWRM	Integrated water resources management
kg	Kilogram
km	Kilometer
km^2	Square kilometer
km^3	Cubic kilometer
l	Leter
m	Meter
m^3	Cubic meter
mm	Millimeter
NSP	Net Social Profitability
NVWP	Non-volumetric water pricing
O&M	Operation and maintenance
RMB	Renminbi, official currency of the People's Republic of China
SAI	Scale Advantage Index
SuMaRiO	Sustainable Management of River Oases along the Tarim River

TRBMB	Tarim River Basin Management Bureau
U.S.A.	United States of America
USDA	United States Department of Agriculture
VWP	Volumetric water pricing
WUA	Water user association
WUE	Water use efficiency
XJSYB	Xinjiang statistical yearbook
XPCC	Xinjiang Construction and Production Corps
XPCCIO	Xinjiang Production and Construction Corps Information Office
XUAR	Xinjiang Uighur Autonomous Region
yr	Year
℃	Degree Celsius
%	Percent

1 General Introduction

1.1 Background

Irrigated agriculture is the largest water consumer which accounts for about 70% withdrawal of the world's total fresh water (Falkenmark and Widstrand, 1992; Pimentel *et al.*, 2004). In some arid and semi-arid regions, irrigated agriculture is even responsible for more than 90% of total fresh water usage (FAO, 2013). However, irrigated agriculture is crucial for food production as well as generating employment opportunities in the rural areas, particularly in arid and semi-arid regions. Irrigated agriculture contributes about 40% of world's crop production (Howell, 2001; Tiwari and Dinar, 2002; Reddy, 2009).

Due to rapid population growth, urbanization as well as climate change, water resources have become more scarce throughout the world (Tsur, 2004; Ward, 2007). According to the Food and Agriculture Organization of the United Nations (FAO), one third of the world suffers from different degrees of water scarcity. Furthermore, a rapidly growing demand for urban and industrial use increase the competition between these sectors and the agricultural sector (Keith, 2006). With water scarcity becoming more evident, the main concern is focused on whether there are enough land and water resources in the next 50 years for an additional population of 3.7 billion (Fischer and Heilig, 1997). It is realized that efficient use of water resources in agriculture is essential for meeting the severe freshwater challenges (Wallace, 2000; Molden, 2007). Before the 1970s, water resource policies in many developing countries emphasized on supply augmentation, targeting to improve irrigation capacity and to guarantee the water supply to users. Massive amounts of capital were invested in building large dams, improving irrigation infrastructure facilities and other water related projects (Jones, 1995; Varela-Ortega *et al.*, 1998).

These investments, however, failed to achieve expected results in terms of productivity, efficiency and management. Furthermore, the economic returns of these investments were disappointing. Besides, questions and criticisms have been raised about the environmental effects of such projects (Sampath, 1992; Molle and

Berkoff, 2007). Consequently, there has been a sharp decline in both national expenditure and lending from major international donor agencies for irrigation (Rosegrant and Meinzen-Dick, 1996). Thus, the emphasis has shifted towards water demand management described as “doing better with what we have”, instead of steady supply increases (Winpenny, 1994).

Water demand management includes a variety of instruments such as water pricing, market mechanism, education and subsidy (Savenije and van der Zaag, 2002; Molle and Berkoff, 2006). However, irrigation water pricing is given the highest priority among these options, because immediate effects of water prices on water use are expected (Tsur and Dinar, 1995, 1997). However, until declaration of Dublin statement in 1992 there has been a disagreement on whether access to water is a basic human right or it should be treated as an economic good (Abu-Zeid, 2001). The principle 4 of Dublin statement clearly defines water resources as an economic good and thus, water pricing has been widely promoted as a solution to water scarcity problems and increasing water use efficiency in agriculture (Hamdy *et al.*, 1995; Dinar and Subramanian, 1998).

1.2 Irrigation water pricing theory

1.2.1 Water pricing

Theoretically, pricing of irrigation water refers to any charges paid by farmers for the access to water resources for irrigation (Tiwari and Dinar, 2002). Water pricing is believed to be the most effective economic instrument to promote water allocation and water conservation (Tsur and Dinar, 1997). Besides ensuring cost recovery from the users, and providing funds for a sustainable water supply system, irrigation water pricing also induces users to utilize the water resources more efficiently by giving them signals on water’s scarce value (Dinar and Subramanian, 1998; Abu-Zeid, 2001).

1.2.2 Full cost recovery pricing of water

Treating water as an economic good is widely accepted and water pricing as a policy intervention is given particular attention (Tsur and Dinar, 1995; Molle and

Berkoff, 2006). Yet, it is still unclear how to determine efficient water pricing which can induce conservation and better allocation of water in agriculture (Tsur, 2004). Traditionally, water pricing is fixed according to the operation and maintenance (O&M) cost of the supply system.

Economists argue that such a cost recovery pricing not only cannot reflect water's true value, but also it is too low to give incentives to the users to save water (Postel, 1992). Therefore, both economists and policy-makers suggest the use of full cost recovery (FCR) pricing (Ward and Pulido-Velazquez, 2009). Several definitions of FCR pricing can be found in the literature. As defined by Rogers *et al.* (2002), there are three main categories of FCR: full supply cost, full economic cost and full cost (Figure 1). The full supply cost includes operation and maintenance cost and capital charges, while full economic cost covers full supply cost, opportunity cost and economic externality. The full cost includes the full economic cost and environmental externalities.

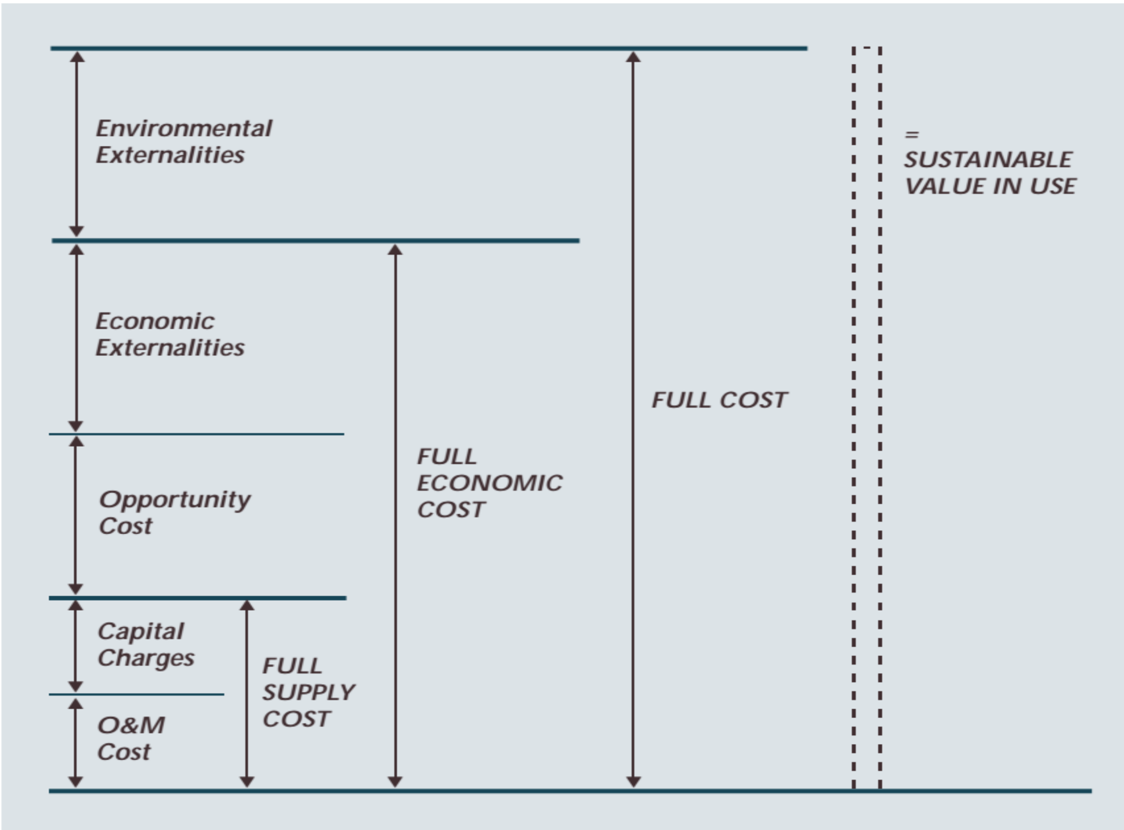

Figure 1. General principle of full cost (Source: Rogers *et al.*, 2002)

1.2.3 Water pricing practices

Water pricing practices refer to the methods employed in charging water fees to the users. There are varieties of water pricing methods in practice; however, these practices can be categorized into three basic water pricing practices (Table 1): non-volumetric water pricing (NVWP), volumetric water pricing (VWP) and differential water pricing (DWP).

Non-volumetric water pricing: In NVWP (also called area-based water pricing), water fees are charged per unit irrigated area (Johansson et al., 2002). NVWP is usually calculated by dividing the operation and maintenance cost by the total irrigated area. Advantages of NVWP include the simple calculation of water fees as well as easy implementation and management. NVWP is a popular method because of its simplicity and low implementation cost (Easter and Liu, 2005). A major disadvantage of NVWP, however, is that the marginal cost of using one more unit of water is zero in this system. Thus, water charges do not affect users' water consumption and may cause over-utilization of water resources. According to Bos and Wolters (1990), NVWP was used in more than half of the cases that they investigated worldwide. NVWP is common some countries such as Pakistan (Hussain *et al.*, 2005), India (Singh, 2007) and Palestine (Abu-Madi, 2009).

Volumetric water pricing: Water fee is charged per volume of water used by the user in VWP (Easter, 1986). Encouraging users to save water is the main advantages of this pricing system. However, high implementation cost is the main weaknesses of this method, as it requires the installation of special equipment to measure the volume. Furthermore, the implementing process is more complicated than NVWP (Johansson *et al.*, 2002; Easter and Liu, 2005). Besides, water pricing is a sensitive issue in developing countries where the farmers rely on irrigation water for guaranteeing their basic living conditions (Tsur *et al.*, 2004). Severely constraining farmers use of water or raising the water pricing strongly who rely on irrigation water for their living may cause some social problems (Molle, 2009). Use of VWP has been reported to exist in some parts of Spain and some states of the U.S.A. (Molle, 2009).

Differential water pricing: DWP considers charging a low water price within a pre-fixed volume of water consumption and a significantly higher water price when the pre-fixed volume is exceeded (Tsur, 2005). DWP can be used, when farmers' affordability is a main concern. Jordan (Molle *et al.*, 2008), Israel (Just *et al.*, 1999) and Botswana (Dinar and Subramanian, 1997) are some countries currently using the DWP.

Table 1. Main characteristics of pricing method

Water pricing practices	Advantages	Disadvantages	Country
Non-volumetric water pricing	• Easy to calculate • Easy to implement • Easy to administer • Low implementation cost	• Low effect on water consumption • May cause over-utilization of water	Pakistan, India, Palestine
Volumetric water pricing	• Effective on water conservation	• High implementation cost • Difficult to implement	USA, Spain
Differential water pricing	• Most effective on water conservation • Can deal with users' affordability problem	• Difficult to implement	Jordan, Israel, Botswana

Source: Adapted from Dinar and Subramanian (1997), Just *et al.* (1999), Johansson *et al.* (2002), Easter and Liu (2005), Hussain *et al.* (2005), Tsur (2005), Singh (2007), Molle *et al.* (2008), Abu-Madi (2009) and Molle (2009).

1.2.4 Potential effects of irrigation water pricing

***Cost recovery*:** Cost recovery is the first and most important role, when discussing the potential effects of water pricing. It is also called financial role of water pricing (Dinar and Mody, 2004). In many countries, governments are still managing and investing the supply system of irrigation (Tardieu and Préfol, 2002; Berbel *et al.*, 2007). However, rising costs of providing water services leads to great pressure on governments' budget capacity (Cornish *et al.*, 2004). Covering the full costs or part of the costs related to water services by water pricing may help to decrease government's financial burden (Abu-Zeid, 2001). Besides, when governments are unable to adequately fund operation and maintenance of the supply system due to the limited fiscal capacity, the basic infrastructure may deteriorate as well as quality of water services to the users (De Azevedo and Baltar, 2005). Thus, water pricing can improve operation and maintenance, ensure the sustainability of water supply system by providing funds, and improve water allocation among competing users, thereby maximizing the economic returns of water resources (Abu-Madi, 2009).

Adaption of water saving irrigation technology**:** When water prices increase, farmers basically can change their traditional flood irrigation to water saving irrigation such as furrow irrigation, sprinkler irrigation and drip irrigation in order to mitigate the impact of increased water charges on their profit by reducing water use (Molle *et al.*, 2008). Adoption of water saving irrigation can increase water use efficiency by reducing water demand and increasing the crop yield.

Shifting crop pattern**:** Rising water pricing also encourages farmers to rethink their crop choice. Farmers can alter their cropping pattern to other crops which have higher economic return and require less water demand, to deal with increased price of water (He *et al.*, 2006; Easter and Liu, 2007).

Improving on-farm management practices**:** Farmers can improve on-farm management practices aimed at achieving the desirable crop yield and minimizing water input by preventing the unnecessary losses of water resources (Molle and Berkoff, 2007). Improving on-farm management practices mainly include irrigation scheduling and improving the water distribution system at farm level (Jensen, 2007). Pereira *et al.* (2002) argues that efficient use of fertilizer and pesticide also increases water productivity by increasing yields of crops per unit of water used.

1.2.5 Constraints of irrigation water pricing

Effects on farmers' income distribution**:** The most controversial issue in water pricing might be its effects on farmers' income. It is argued that especially poor farmers cannot afford high water prices (Dinar and Mody, 2004). At a result, it will cause a reduction in agricultural production and increase rural poverty. Many studies have found that increasing water pricing resulted in a significant decline in farmers' income (Berbel and Gómez-Limón, 2000; Latinopoulos, 2008; Speelman *et al.*, 2009).

Price elasticity of demand**:** Price elasticity of demand can be defined as the level of responsiveness in the demand of a certain good to the price changes of that good (Mankiw, 2012). Estimating the elasticity of demand has great importance, as it can reveal the effectiveness of water pricing policy on water demand and conservation (Howe, 2005). A number of studies have been conducted to estimate price elasticity of irrigation water demand. However, these studies concluded that elasticity of demand was very low. Varela-Ortega *et al.* (1998) found that water demand is inelastic in a certain price range, and becomes elastic only when price exceeds this price threshold. Thus, irrigation water pricing requires a strong increase to achieve elastic demand. Some scholars warn against such strong increase in irrigation water prices considering its effect on farmers' income (Massarutto, 2003).

Other constraints

Results of several case studies indicate that farmers will choose drilling a well to gain groundwater, when water price increase, resulting in further exploitation of groundwater (Schuck and Green, 2003; Liao *et al.*, 2008). It is argued that water pricing is not effective when using non-volumetric water pricing, as there is no connection with water pricing and amount of water that user consumed (Molle, 2008). Finally, increasing water prices may cause conflicts with other agricultural policies. For example, China implemented a series of policies started from 2004 targeted at increasing rural income and decreasing the gap between rural and urban income level (Long *et al.*, 2011). Increasing water prices may have adverse effects on this national policy (Lohmar *et al.*, 2003).

1.3 Study area: the Tarim River

1.3.1 Location of study region

The 1,321 km long Tarim River is located at the southern part of Xinjiang Uyghur Autonomous region in northwest China (Figure 2). Originating from the high mountain, Tarim River passes the northern edges of the world's second biggest desert-Taklimakan desert, and finally ends in eastern Gobi. The Tarim River is a typical inland river which does not have its own runoff (Tang and Chen, 1992). Water resources are mainly provided by snow, glacier melting and precipitation from Tianshan and Kunlun mountains (La Paix *et al.*, 2012; Huang *et al.*, 2015). In the past, nine river systems consisting of 144 small rivers contribute to the Tarim River (Zhang *et al.*, 2009; Chen *et al.*, 2013). Due to human influence, such as high water abstraction by building large dams in headwater of those tributaries, only the Aksu River currently delivers water permanently to the Tarim River, while the Yarkan and Hotan Rivers discharge water only during the flooding period (Xu *et al.*, 2013). These three major tributaries of Tarim River contribute 78.11%, 0.54%, and 21.35% to its total discharge (Table 2), respectively (Song *et al.*, 2002).

Table 2. Composition of the water sources of the Tarim River

Items	Major tributaries of Tarim River		
	Aksu River	Yarkan River	Hoten River
Share of Contributions to the mainstream of Tarim River (%)	78.11	0.54	21.35

Source: Compiled from Song *et al.* (2002)

The Tarim River can be divided to three sub-sections: upper stream, middle stream and lower stream. Upper stream includes the section from Xiaozhake to Yingbazha with a length of 447 km, while middle stream includes the section from Yingbazha to Qiala with a total length of 398 km. The length of the lower stream, which starts from Qiala and ends in Taitema Lake, is 428 km (Xu *et al.*, 2013). In order to recover the ecological system, water from the Konqi River has been introduced to the lower reaches of Tarim River, which formulates the concept “four source rivers and one mainstream” (Ye *et al.*, 2006; Xu *et al.*, 2008).

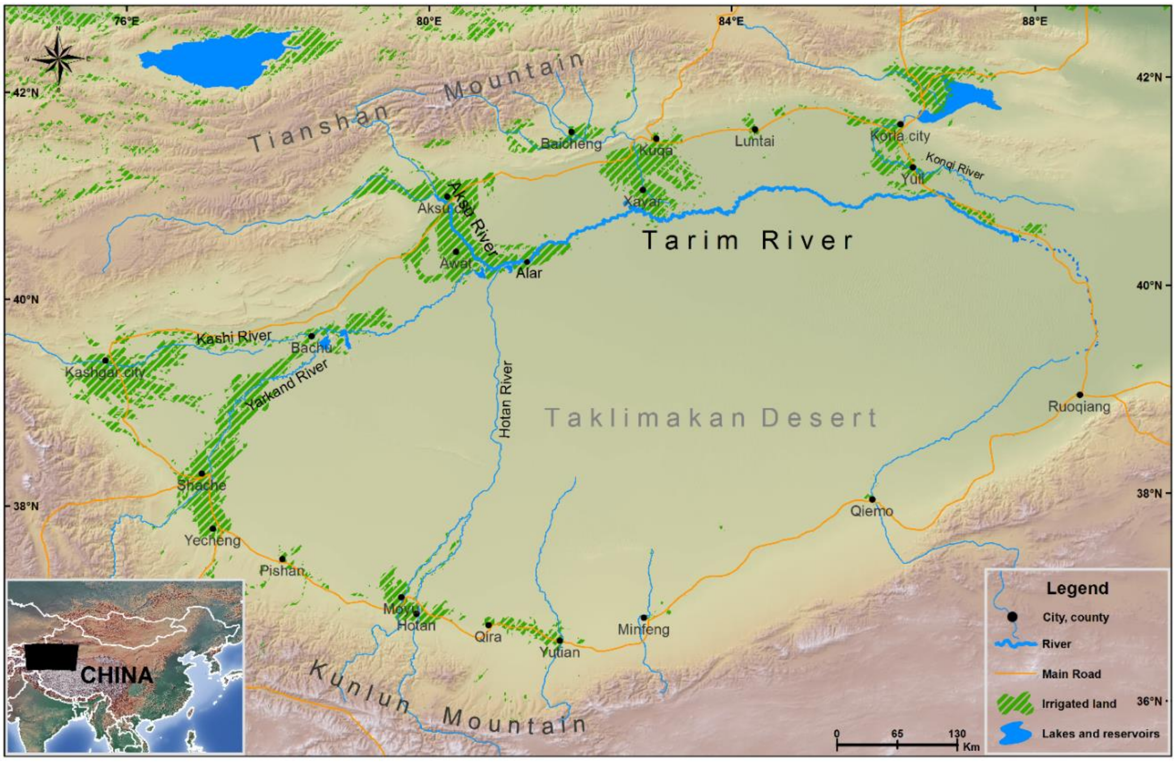

Figure 2. Map of Tarim River passing the northern edges of Taklimakan desert and its major tributaries (Source: Created by author after internal project data)

1.3.2 Climate and hydrology

The climate of the whole Tarim River Basin is extremely arid, continental climate with little precipitation, high evaporation, winter-cold and summer-hot (Huang *et al.*, 2011; Zhao *et al.*, 2013). The annual average temperature varies from 8.8 ℃ to 13.9 ℃. Maximum temperatures reach 43.6 ℃, and minimum temperatures -27.5 ℃. Annual precipitation ranges from 150 mm to 200 mm in the mountain areas, from 50 mm to 70 mm in the plains, while the potential evaporation varies from 2,100 mm to 3,000 mm (Han *et al.*, 2009; APSYB, 2014; BSYB, 2014). In the heart of the Taklimakan desert, there is almost no precipitation (Figure 3). The formation of continental climate condition is mainly due to its distant location from the oceanic influences, while the aridity of the river basin is mainly attributed to the fact that humid air which normally brings precipitation is cut off by surrounding mountains (Thevs, 2007).

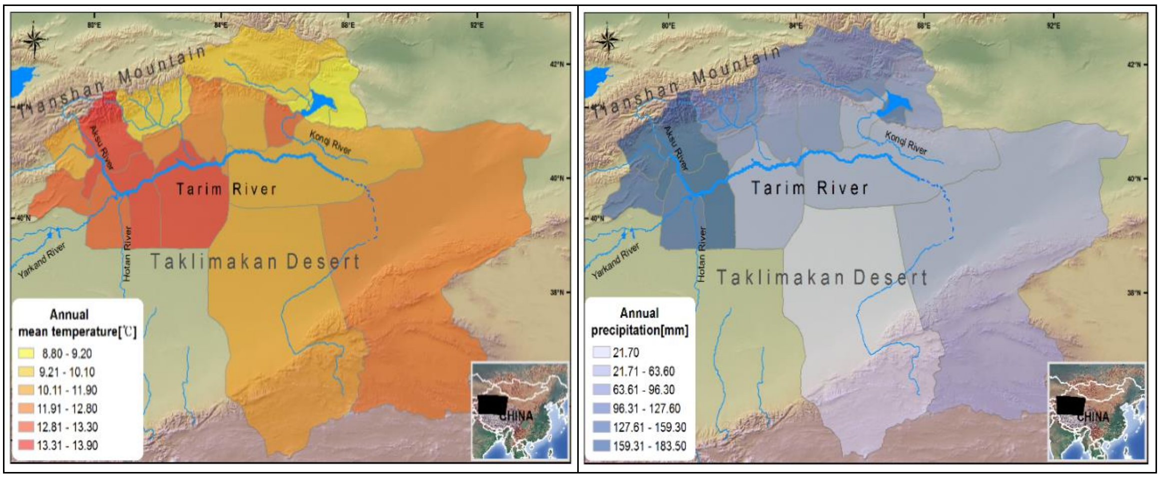

Figure 3. Map of annual mean temperature (left) and annual precipitation (right) in two administrative regions along the Tarim River (Source: Created using data from APSYB, 2014 and BSYB, 2014)

Due to such arid climate conditions, all activities including industry, domestic use, agricultural production as well as natural vegetation totally depend on the water from the Tarim River (Thevs, 2011). According to the Tarim River Basin Management Bureau (TRBMB), total water resources in 2003 were 43.2 km^3, of which surface water accounts for 40.2 km^3 and groundwater accounts for 3 km^3. The total water supply of Tarim River and four attributes was 19.58 km^3. Agriculture is the biggest user which consumes 19.40 km^3, accounting for 97.3% of total water supply (TRBMB, 2005). The total water supply of Tarim River is rather stable, because it is fed by snow, glacier melting and precipitation from the surrounding mountains (Jiang *et al.*, 2005). However, the monthly distribution of annual runoff is very uneven. Almost more than half of the annual runoff concentrates in the months of July, August and September (Ling *et al.*, 2014).

1.3.3 Socio-economic conditions

The Tarim River covers an area of 17,600 km^2. The Tarim River comprises four administrative regions, which include Aksu administrative region and Bayingolin mongol autonomous prefecture, as well as two divisions of Xinjiang Construction and Production Corps (XPCC), namely Division 1 located in the upper stream of Tarim River and Division 2 located in the lower stream. XPCC is a special economic and semi-military organization established by Chinese central government in the 1950s, in order to develop and stabilize the border regions in the Northwest of China (Xinjiang Production and Construction Corps Information Office, 2010).

The Tarim River is an important agricultural production base of China with very specific growing conditions (Wallace and Wouters, 2006). The region is well-known for cotton, grain and fruit production (Thevs *et al.*, 2015). Having little precipitation and abundant sunshine offers ideal conditions for producing the highest quality of cotton. According to the statistical data cotton production of whole river basin in 2012 was 3.54 million ton, which accounts for more than 50% of Chinese national cotton production and about 15% of world cotton production (CSYB, 2014). The Tarim River Basin also has abundant oil and natural gas, and plays an important role in Chinese energy supply (Wang *et al.*, 2002).

The total population of Tarim River was 1.99 million in 2002 (Meng *et al.*, 2009). Agricultural population accounts for more than 60% of total population (Wallace and Wouters, 2006). Agricultural land is also very scarce in this region; the average land area per household is rather small, approximately 1 ha per household (XJSYB, 2012). The military farmers in XPCC own larger land area. Average land area is about 4 ha per household according to farmers survey conducted in 2012. There are also some business farmers with a large land area ranging from 33 ha to 233 ha per household (Thevs, 2011).

1.3.4 Population and land use development

Human settlement can be traced back to 2000 years ago along the Tarim River, according the archeological discovery (Zhou, 1989; Qi *et al.*, 2005). However, the massive population growth occurred after the foundation of the People’s Republic of China in 1949 as illustrated in Figure 4 (XJSYB, 1991; BTSYB, 1991; CPSYB, 1988; XJSYB, 2001; BTSYB, 2001; Liu and Chen, 2006; XJSYB, 2012; BTSYB, 2012). One reason for such massive population growth is mainly because the Tarim River became the biggest migrant-receiving region in the mid 20th century (Jiang *et al.*, 2005)

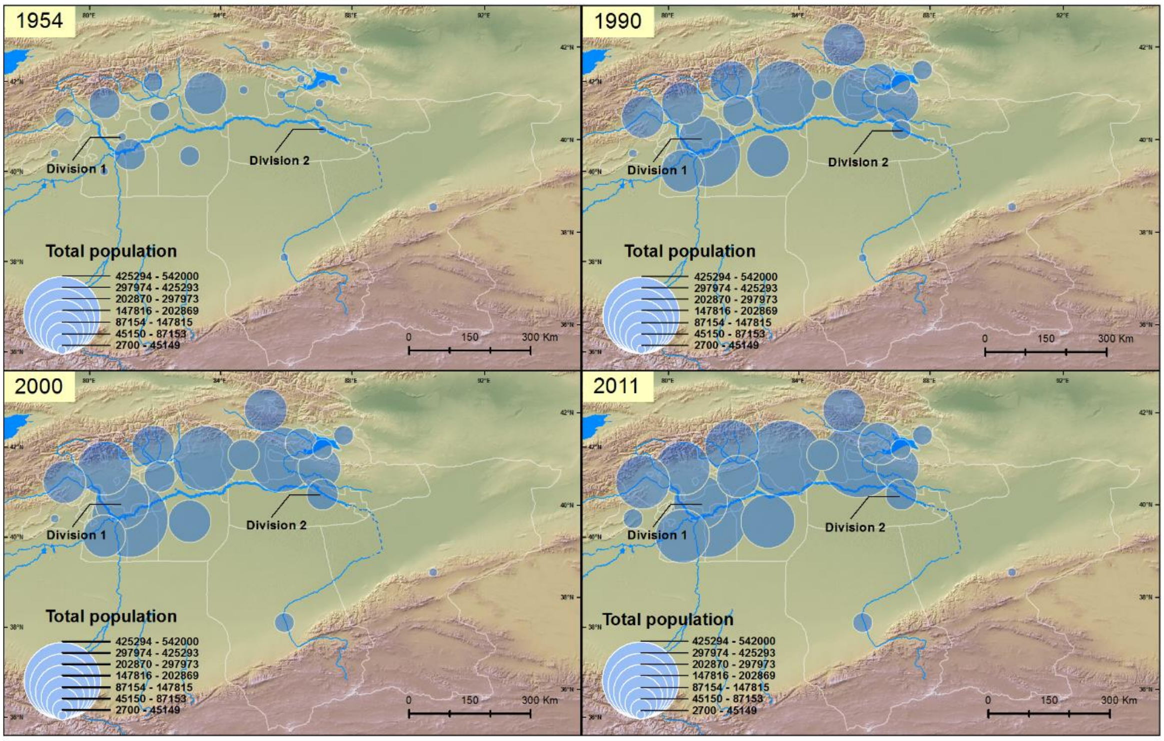

Figure 4. Population growth for the four administrative region along the Tarim River during 1954-2011 (Source: Created using data from XJSYB, 1991; BTSYB, 1991; CPSYB, 1988; XJSYB, 2001; BTSYB, 2001; Liu and Chen, 2006; XJSYB, 2012; BTSYB, 2012)

The migration is closely linked to the two national policy objectives: establishment of XPCC and central government's campaign of developing the western region (Peng, 2012). The population of Division 1 and Division 2 increased from less than 10,000 people in 1954 to over 350,000 in 1990. Beginning of the 1990s, the Tarim River experienced the second population growth period, while China became one of the world's biggest textile producers and exporters. Rising demand for cotton production led the highest ever recorded. Responding to rising demand and prices, many farmers converted their land use to cotton production. Being a high labor intensity crop, conversion to cotton absorbed a large amount of agricultural population (Jiang *et al.*, 2005). At the beginning of the 21st century, Chinese government established the "develop the western region" campaign and implemented large projects in the western region resulting in vast population increase and agricultural development (Lai, 2002).

Massive population growth resulted in a huge expansion of agricultural land along the Tarim River. This is also confirmed by several authors that population growth is one of the main driving forces for land use and land cover change along the Tarim River (Hong *et al.*, 2003; Zhao *et al.*, 2013). Using remote sensing data, Zhao *et al.* (2013) analyzed the land use and land cover change along the Tarim river and found that area of cropland increased from 106,156 ha in 1973 to 236,347 ha in 2005.

1.4 Irrigation water pricing and water pricing practices along the Tarim River

Early initiations for irrigation water pricing along the Tarim River date back to 1951, when the provincial government introduced water fees for the first time. About 22.5 kg to 52.5 kg ha^{-1} of grain produce were collected from the farmers as water fee. In 1956, it was officially decided by the provincial government that 2-5% yield of wheat should be handed over as water fee (Sun, 2009). During this time, the infrastructure construction was mainly completed by farmers' volunteer labor contribution. The water fee did not change until the declaration of the new water law in 1990. Since 1990s, water fee has been raised several times; recent adjustments were made in 2010. TRBMB announced in 2010 that irrigation water pricing increased to 0.019 RMB/m^3 in order to improve sustainability of the water supply system and encourage for water saving. Still, this water pricing only covers 37% of full supply cost, according to the XUAR Provincial Department of Water Resources (Zili Nian, 2012). Low water pricing is identified to be a major reason for low WUE results and over use of irrigation water along the Tarim River. According to XUAR People's Government, the water price will further increase and full supply cost recovery rate is planned to reach 70% at the end of 2015 and 100% at the end of 2020 (XUAR People's Government, 2013).

TRBMB is responsible for collecting the water charges from the local water station at county level. There are several sub-organizations of TRBMB that rely on the water charges. Non-volumetric water pricing is the main pricing practice at the farm level along the Tarim River. The local water station is responsible for collecting water charges from the farmers. Currently, farmers are not involved in the process of water resources management and collection of water charges along the Tarim River. A farm survey conducted in 2012 revealed that the average water fee that famers pay was about 1,200 RMB ha^{-1} yr^{-1}, giving an estimated volumetric water price of 0.14 RMB/m^3. The water fee for groundwater is slightly higher than the surface water fee.

1.5 Problem statement

Large scale expansion of arable land and intensive irrigation with low WUE in the upper and middle stream over the last serval decades resulted in significant changes along the Tarim River (Hao *et al.*, 2009). Thus, especially severe environmental problems such as vegetation degradation, soil salinization, desertification and sandstorm became apparent (Feng *et al.*, 2001; Fan *et al.*, 2002; Yang *et al.*, 2006). The area of *Populus euphraitica* riparian forest along the river basin sharply decreased from 454,000 ha in the 1950s to 247,300 ha in 2000 (Deng, 2004). Besides the severe environmental problems, intensive water use for agriculture in the upper and middle stream resulted in increased conflicts even among the farmers, effected crop production (Cyffka *et al.*, 2013). Furthermore, severe water scarcity and harsh environment in the lower stream of Tarim River resulted in an out-migration of local population (Jiang *et al.*, 2005). Ensuring sufficient water for eco-environment, social and economic development became key challenges along the Tarim River Basin (Chen *et al.*, 2013). It is realized that the unified management of water resources, efficient allocation as well as efficient use of water resources are the key factors for a sustainable development along the Tarim River (Xu *et al.*, 2005).

1.6 Objectives of the study

The overall goal of this study is to find out the role of economic incentives on the sustainable use of water resources along the Tarim River. The thesis is mainly focused on the impact of irrigation water pricing on efficient water use in the agricultural sector along the Tarim River. This research may help decision makers to gain a better understanding how water pricing as demand management option can elicit efficient water use.

The specific objectives of the Ph.D. thesis can be stated as follows:

1) Understand land and water use development and its driving forces
2) Identify farmers' ability to respond towards the changes in water pricing, and to indicate factors influencing farmers' choice towards changes in the irrigation water price
3) Identify the shortcomings of current water pricing practices in order to develop policy recommendations for improvement
4) Develop a model which estimates the effects of changes in water price policy and changes in water pricing practices for an increased water use efficiency
5) Evaluate effects of other agricultural policies on increasing water use efficiency and identify best policy scenarios aimed at achieving the highest water use efficiency
6) Develop policy recommendations for the successful implementation of an appropriate water pricing policy

2 Publications

2.1 Overview

The cumulative dissertation consists of four published papers in international journals. For the citation of the papers please use the reference blow. Full paper of publication I, II and III can be accessed via the presented link.

Publication I

Feike, T.; Mamitimin, Y.; Li, L.; Doluschitz, R., 2015. Development of agricultural land and water use and its driving forces along the Aksu and Tarim River, P.R. China. Environmental Earth Sciences, Volume: 73, Issue: 2, Page(s):517-531. ISSN/ISBN: 1866-6280

http://link.springer.com/article/10.1007%2Fs12665-014-3108-x

Publication II

Mamitimin, Y.; Feike, T.; Seifert, I.; Doluschitz, R., 2015. Irrigation in the Tarim Basin, China: farmers' response to changes in water pricing practices. Environmental Earth Sciences, Volume: 73, Issue: 2, Page(s):559-569. ISSN/ISBN: 1866-6280

http://link.springer.com/article/10.1007/s12665-014-3245-2

Publication III

Mamitimin Y, Feike T, Doluschitz R., Bayesian Network Modeling to Improve Water Pricing Practices in Northwest China. *Water*. 2015; 7(10):5617-5637.

doi:10.3390/w7105617

http://www.mdpi.com/2073-4441/7/10/5617/pdf

Publication IV

Appiah, M.K.; Feike, T.; Wiredu, A.N.; Mamitimin, Y., (2014): Cotton Production, Land Use Change and Resource Competition in the Aksu-Tarim River Basin, Xinjiang, China. Quarterly Journal of International Agriculture 53(3): 243-261.

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

Publication I

Feike, T.; Mamitimin, Y.; Li, L.; Doluschitz, R. 2015. **Development of agricultural land and water use and its driving forces along the Aksu and Tarim River, P.R. China.** Environmental Earth Sciences, Volume: 73, Issue: 2, Page (n):517-531. ISSN/ISBN: 1866-6280

Abstract

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Environ Earth Sci
DOI 10.1007/s12665-014-3108-x

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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Received: 19 July 2013 / Accepted: 27 January 2014

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

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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

Published online: 02 March 2014

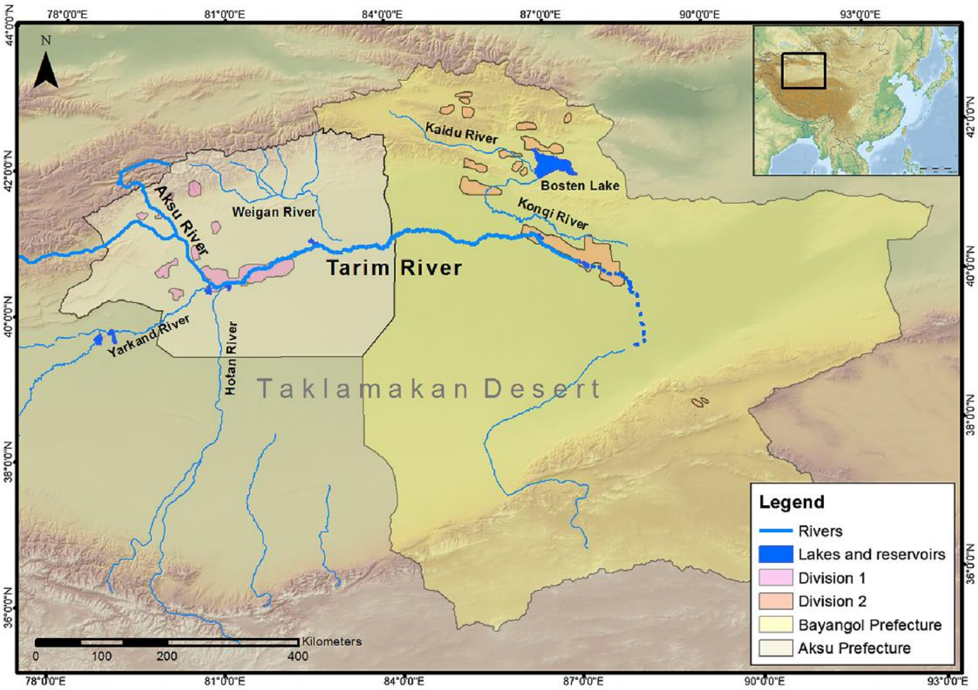

Fig. 1 The Aksu-Tarim Region with the location of Aksu and Bayangol prefecture, as well as Division 1 and Division 2 of the Xinjiang production and construction corps

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

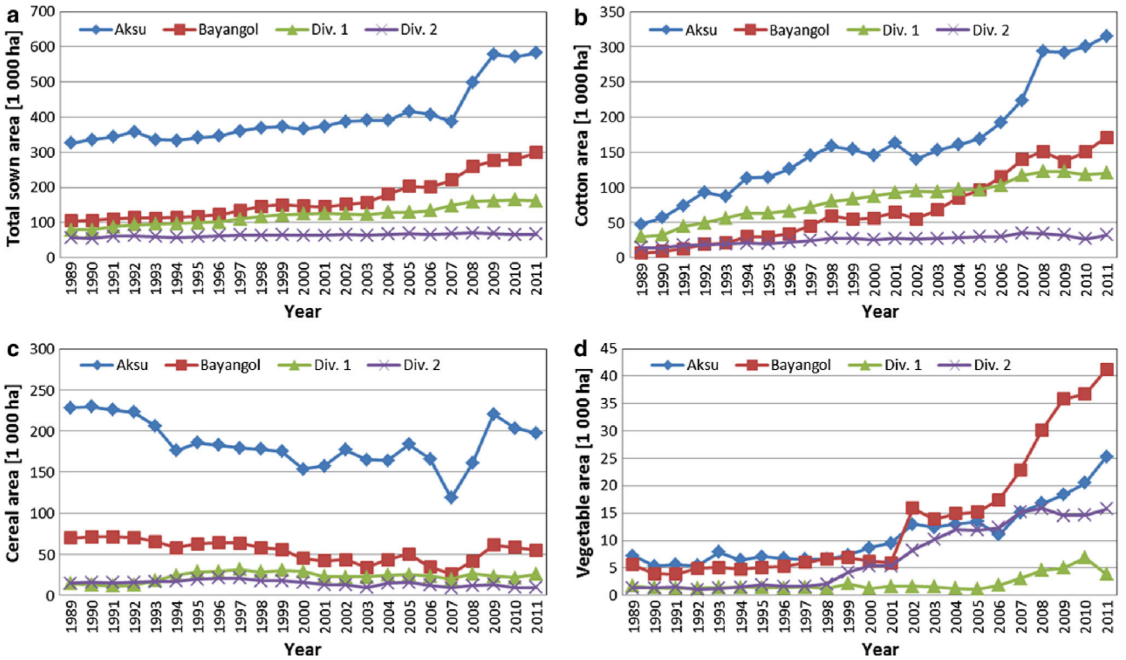

Fig. 2 Sown area of all annual crops (**a**), cotton (**b**), cereals (**c**) and vegetables (**d**) in four administrative regions of the ATR during 1989–2011 (compiled from BTSYB 1990–2012 and XJSYB 1990–2012)

(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.

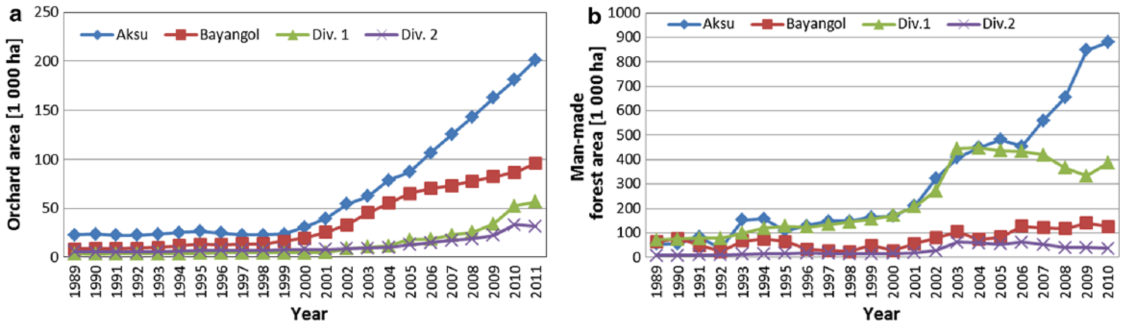

Fig. 3 Planted areas of orchards (**a**) and man-made forest (**b**) in four administrative regions of the ATR during 1989–2011 (compiled from BTSYB 1990–2012 and XJSYB 1990–2012)

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.

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

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).

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

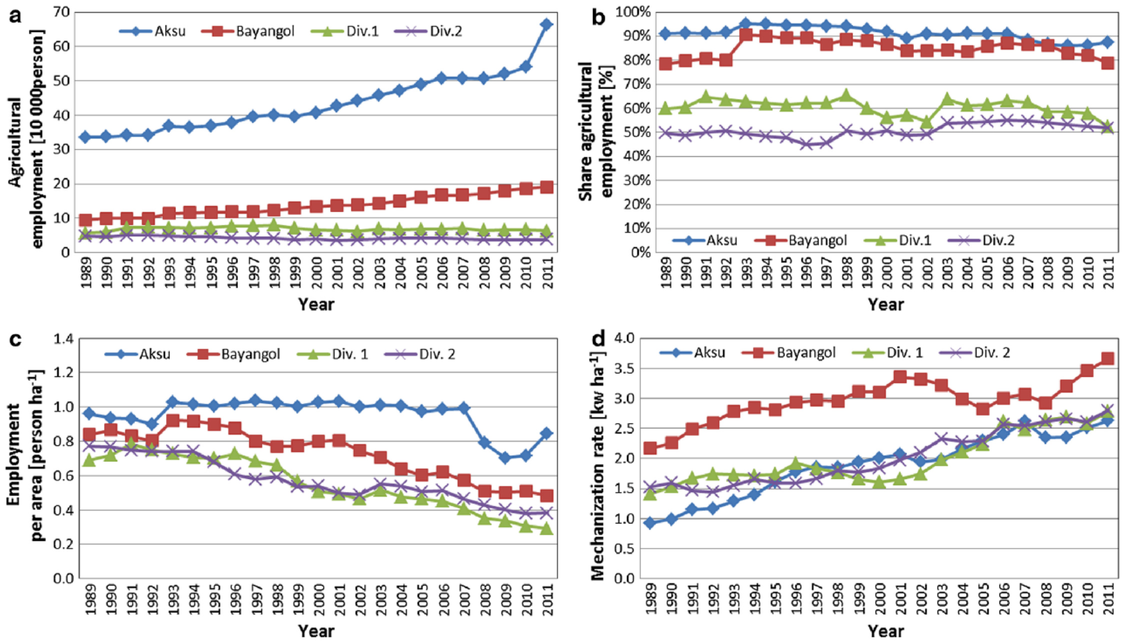

Fig. 4 Development of agricultural employment (a), share of agricultural employment in total employment (b), agricultural employment per agricultural land area (c), and degree of mechanization of agriculture in four administrative regions of the ATR during 1989–2011 (compiled from BTSYB 1990–2012 and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

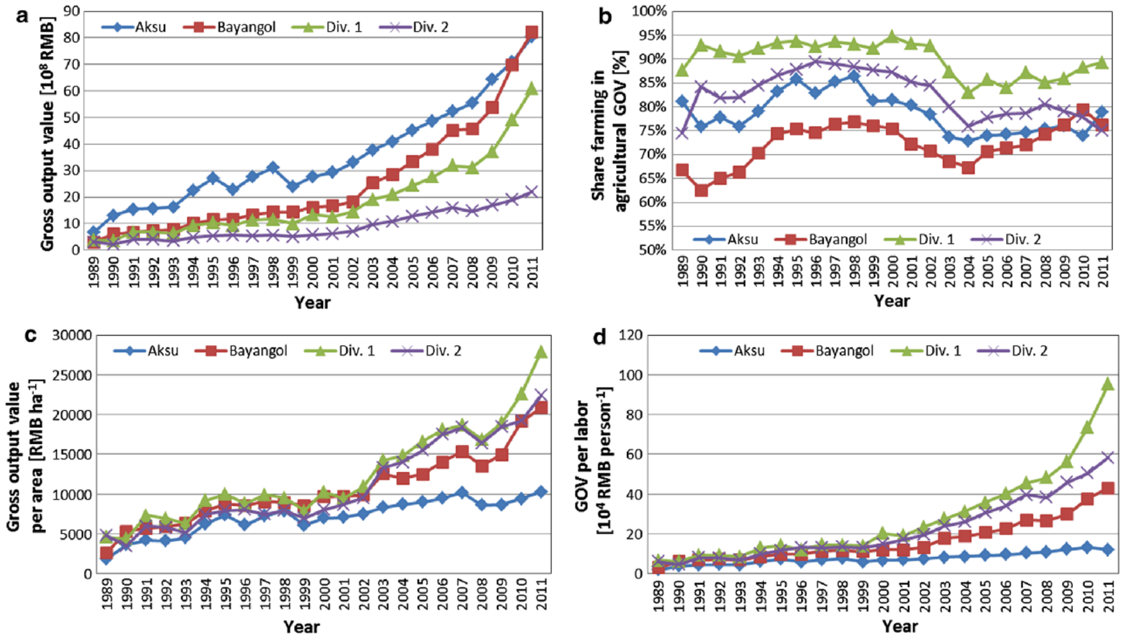

Fig. 5 Development of agricultural gross output value (**a**), share of farming in total agricultural gross output value (**b**), gross output value per area (**c**), and gross output value per laborer (**d**) in four administrative regions of the ATR during 1989–2011 period; monetary values are given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

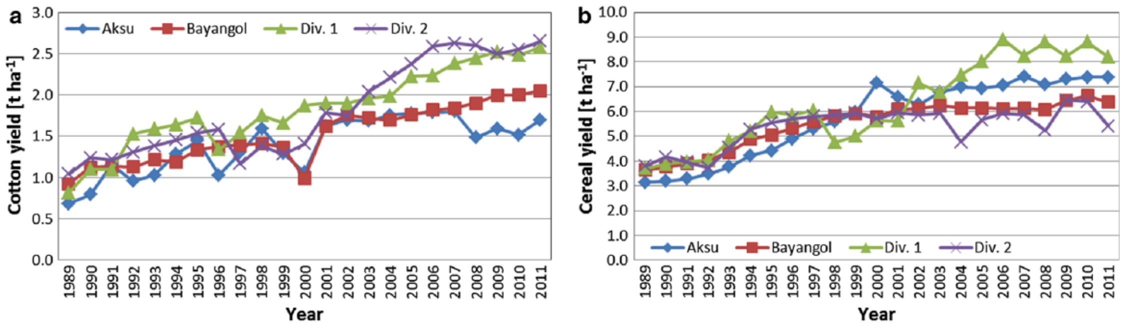

Fig. 6 Development of yields per hectare of cotton (**a**), and cereals (**b**) in the four administrative regions of the ATR during 1989–2011 (compiled from BTSYB 1990–2012 and XJSYB 1990–2012)

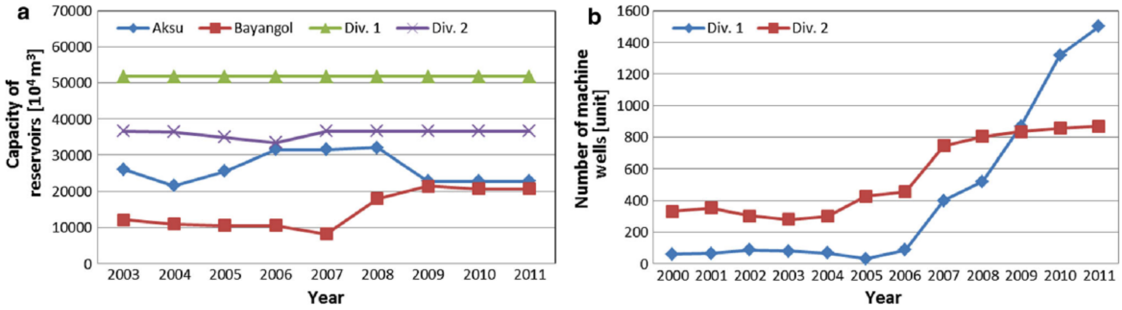

Fig. 7 Development of capacity of reservoirs in the four administrative regions of the ATR (**a**), and number of machine wells installed in Div.1 and Div.2 (**b**) over the last decade (compiled from BTSYB 1990–2012 and XJSYB 1990–2012)

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).

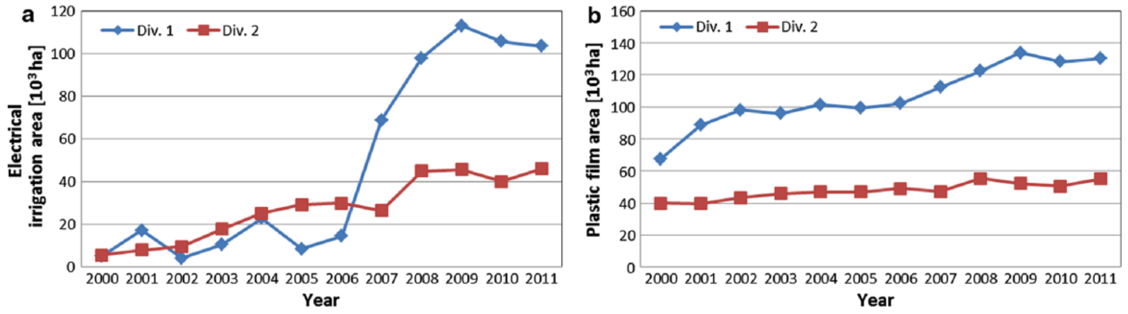

Fig. 8 Development of area under advanced irrigation technology (**a**) and plastic mulch (**b**) in Div.1 and Div.2 during 2000–2011(compiled from BTSYB 1990–2012)

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 28×10^8 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.

Acknowledgments This research was embedded in the Sustainable Management of River Oases along the Tarim River (SuMaRiO) project, funded by the German Federal Ministry of Education and Research through the "Sustainable Land Management" program. We furthermore want to express our deep gratitude to Dr. Yiliminuer Imit of SuMaRiO subproject 1.3 for her great support in organizing the expert workshop in Urumqi. Finally, we highly acknowledge the valuable suggestions provided by five anonymous reviewers.

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2.3 Irrigation in the Tarim Basin, China: farmers' response to changes in water pricing practices

Publication II

Mamitimin, Y.; Feike, T.; Seifert, I.; Doluschitz, R. 2015. **Irrigation in the Tarim Basin, China: farmers' response to changes in water pricing practices**. Environmental Earth Sciences, Volume: 73, Issue: 2, Page (n):559-569. ISSN/ISBN: 1866-6280

Abstract

The extremely arid Tarim Basin in northwestern China is an important cotton and fruit production region. However, extensive agricultural land reclamation combined with unreasonable water use in recent decades resulted in degradation of ecosystems along the Tarim River. With declining water availability, it is becoming increasingly important to utilize this essential resource more efficiently. Water pricing is considered an effective way to advance water allocation and water conservation. To identify whether a strong increase in water price may lead to a wiser agricultural water use along Tarim River, 128 farmers were interviewed with structured questionnaire in different parts of the Basin. Multinomial logistic regression was employed to explain the factors influencing farmers' reaction towards a strong increase in water price. The results show that under increased water price less than half of the interviewed farmers would opt for decisions that lead to improved water use efficiency. Moreover, the price increase might lead to a further expansion of groundwater exploitation in the region. Fruit farmers, as well as farmers with less land and less cash income are reluctant to adopt advanced irrigation technology or improve their crop production in reaction to increased water price. It was furthermore revealed that the experience of slight water shortage in the past created awareness by farmers to use water more wisely. It is concluded that the sole increase of water price is not a viable option; an integrated approach is necessary, in which creation of awareness and improving agronomic skills of farmers play a key role to overcome the tight water situation and realize a more efficient use of water.

Environ Earth Sci
DOI 10.1007/s12665-014-3245-2

THEMATIC ISSUE

Irrigation in the Tarim Basin, China: farmers' response to changes in water pricing practices

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Received: 9 August 2013 / Accepted: 28 March 2014

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Keywords Water scarcity · Water pricing · Farmers' decisions · TARIM Basin, China · Multinomial logistic regression

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Introduction

Irrigated agriculture is the biggest consumer of water resources, accounting for more than 70 % of the world's fresh water usage. It plays an important role in global food production, nourishing the urban poor at affordable prices, while providing job opportunities in rural areas (Tiwari and Dinar 2001; Reddy 2009). Population growth and increased levels of income, however, have caused an increased water demand (Tsur 2005), making it a more and more scarce resource in many locations throughout the world.

With the decline of water availability becoming more evident, it is imperative to allocate and use this essential resource as efficiently as possible. In many arid regions of the world past water resource policies in many countries have fostered the development of irrigation capacities, while attempting to guarantee the supply of water to the residential users (Aishan et al. 2013; Chen et al. 2013a; Varela-Ortega et al. 1998). Water resource development was based on constant supply augmentation. As this was in many cases associated with high financial and environmental cost, the focal point has shifted towards demand-driven water management. Winpenny (1994) described this new viewpoint aptly as "doing better with what we have", in opposition to the theorem of steady supply increases.

Published online: 16 April 2014

The Tarim River is the longest inland river in China, located in the extremely arid southern part of Xinjiang Uyghur Autonomous Region. Even though very dry, the region is an important cotton and fruit production base. However, extensive land reclamation over the last 60 years combined with unreasonable water exploitation led to a continuous reduction of water flowing to the mainstream of Tarim River, which resulted in severe degradation of ecosystems along the lower reaches of the river (Jiang et al. 2005; Xu et al. 2012; Wu 2012; Fu et al. 2012; Zhao et al. 2013). In addition, water scarcity is considered the major factor impairing the ecological, social and economic development of the region (Chen et al. 2013a, b; Zhou et al. 2012). It is recognized that the rational distribution and effective utilization of water resources are the key to a sustainable development along the Tarim River (Xu et al. 2005; Ye et al. 2006).

Water pricing, as an important socio-economic tool, is considered the most effective way to advance water allocation and water conservation by several scholars (e.g., Tsur and Dinar 1997). Firstly, water pricing can help to ensure cost recovery from the users, which provides funds to sustain the water supply system (Abu-Zeid 2001). According to Dinar and Subramanian (1998) water pricing encourages water users to utilize this valuable resources more wisely by giving them information on water's economic, or scarcity value. Schoengold et al. (2006) confirmed that an increase in marginal water price leads to reduced water application and may encourage a shift in cropping patterns. In contrast, Molle (2008) argues that the potential of pricing irrigation water to improve water allocation and regulate water use is often lower than expected. In a case study in India only a substantial increase in water pricing rates showed the desired effects (Singh 2007). Perry (2001) already claimed that the price of water must be significant, and that the actual prices are generally too low to be effective. The downside of such proclaimed substantial increases in water prices is described by several research groups. Those argue that increasing water price may not only lead to a reduction in agricultural production, but may additionally increase rural poverty (Tardieu and Prefol 2002; Liao et al. 2007). Other case studies showed that increasing water pricing may cause over-utilization of groundwater resources (Schuck and Green 2003; Liao et al. 2008). Thus, the design and implementation of the water pricing process need to be conducted with great care, taking into account economic consequences and other external effects (Liao et al. 2007; Schuck and Green 2003; Tardieu and Prefol 2002; Tsur 2005). All requirements regarding legal and regulatory framework, operational criteria, and economic criteria need to be addressed to realize an effective water pricing system (Perry 2001).

In the Tarim Basin only very limited research on the role of water pricing in sustainable resource use has been conducted up to now. Shen and Haakon (2010) undertook a qualitative study in the Kaidu-Kongque River Basin, a sub-basin of the Tarim Basin, based on secondary data and a qualitative survey. They conclude that pricing of water did not contribute to a more efficient water use, but it mainly strengthened a growing bureaucratic body of water administration. Even though their investigations contributed to the general understanding of the role of water pricing in the region, the farmers, as the actual water users, holding a key role in sustainable resource use, are up to now insufficiently considered in the water pricing issue. Their perception of water pricing as well as their reaction towards changes in pricing policies is heavily under investigated in the Tarim Basin.

Therefore, the overall objective of this study is to identify whether a strong increase in water price may lead to a wiser use of scarce water resources by farmers along the Tarim River. The specific objectives are: (1) to find out farmers' response towards increase in water price, (2) to identify the factors influencing farmers' response towards increase in water price, and (3) to develop policy recommendations aiming at the wiser use of water by farmers, and related increase of water use efficiency (WUE) in the Tarim Basin.

Materials and methods

Study area

More than 1,300 km long Tarim River is located along the northern edge of Taklimakan Desert (Fig. 1). Its Basin is characterized by an extremely continental climate, arid with very little precipitation and very high evaporation (Huang et al. 2011). Snow precipitating in the mountainous areas constitutes the major part of total precipitation in the Basin. Water streams nourished by snow and glacier-melt from the surrounding mountain ranges form the Tarim River (Xu et al. 2005; de la Paix et al. 2012). Its three major tributaries—the Aksu River, Yarkant River and Hotan River contribute 78.11, 0.54 and 21.35 % to its total discharge, respectively (Song et al. 2002). Due to high water abstraction in the headwater of the tributaries, only Aksu River delivers water permanently to the Tarim River in recent years, while the other two rivers discharge water only sporadically during times of floods.

The Tarim River represents a closed and independent hydrological system. While the annual runoff is mainly determined by the volume of snow and glacier-melt, showing seasonal variation with the alteration of temperature, the total annual discharge is rather stable (Jiang et al. 2005).

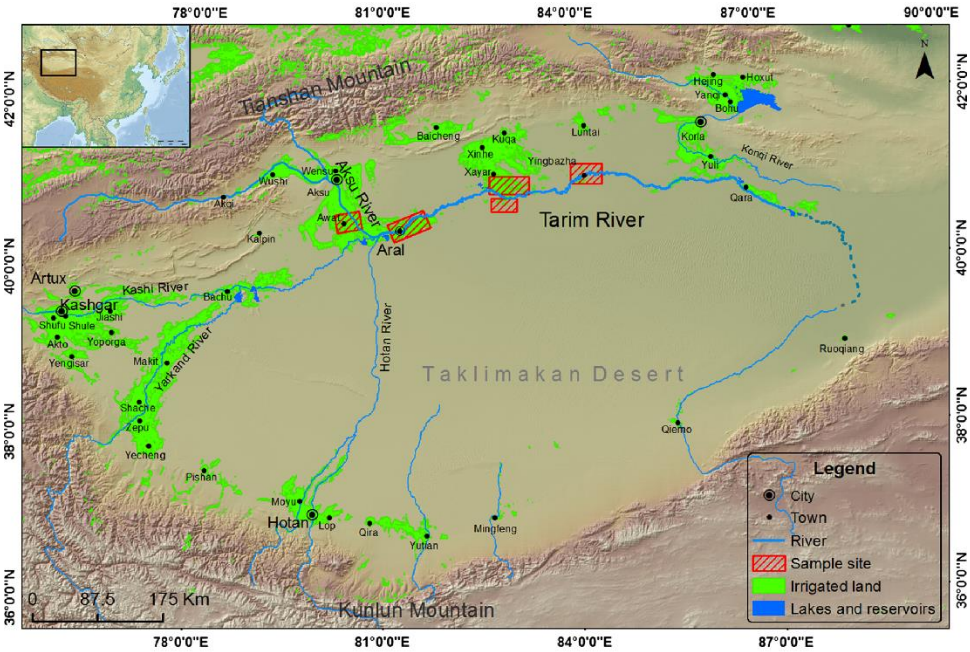


Fig. 1 Tarim Basin with the Tarim River stretching along the northern edge of the Taklimakan desert, and the location of the five survey sites along the river

Data collection

This study is based on data collected from 128 farm household interviews conducted with structured quantitative questionnaire. Five survey regions were selected purposefully based on their specific location in the direct vicinity of the Tarim River; agricultural production in those five regions solely depends on the fresh water resources provided by the Tarim, or its main tributary the Aksu River. The five regions are Aksu-Awat, Alar, Xayar-North (Xayar county north of Tarim River), Xayar-South (Xayar county south of Tarim River) and Yingbazha (Fig. 1). The number of surveyed farm households at each sample site is 28, 20, 45, 19 and 16, respectively. Respondents were selected randomly, and were informed at the beginning of the interview that the purpose of the interview was purely scientific. Before actual data collection, the quantitative questionnaire was subjected to pilot test to ascertain clarity. Specific changes regarding on-farm water management and experienced water scarcity were made after the pilot test. Except the Alar region, which comprises the Division 1 of the Xinjiang Production and Construction Corps (XPCC), a special economic and semi-military organization of Xinjiang province, the other four survey sites represent typical local regions. Therefore, the surveyed data can be considered to represent the general situation along the Tarim River. The survey was conducted in July and August 2012. The questions related to crop production and water availability comprised the previous year's conditions in 2011, as the cropping season 2012 was not yet finished during the time of interviews.

Estimating the effect of water price increase

To assess the impact of water pricing on farmers' decision making several research groups applied mathematical programming approaches that build on the concept of constraint profit maximization (e.g., Albiac et al. 2007; Berbel and Gómez-Limón 2000; Doppler et al. 2002; Gómez-Limón and Riesgo 2004). The challenges often occurring in those modeling approaches are overspecialization of production and unfeasible model calibration, as described by, e.g., Hazell and Norton (1986), Henseler et al. (2009), and Howitt (1995). By integrating the occurrence of inefficiencies in their models Speelman et al. (2009) as well as Frija et al. (2011) could overcome some of the previously described difficulties, enabling them to integrate the actual input and output data of all their sampled farms, thus generating more realistic results. Still the basic assumption of the farmer acting purely as a homo economicus, i.e., economic profit maximization is the farmer's only driver, has its obvious shortcomings. In

Table 1 Detailed description of five options to respond to a 100 % increase in water price as explained to the farmers during field survey

Options	Detailed description
Drill a well	Farmer drills a well to make groundwater available as alternative irrigation water source
Do nothing, just pay higher price	Farmer just accepts the higher water price, and continues crop production, farm management, and water resource use as before
Shift crop pattern	Farmer shifts crop pattern to crops with higher water productivity; i.e., crops that generate a higher return per invested unit of water
Optimize on-farm management practices	Farmer improves farm management aiming at a reduction of existing yield gaps and minimization of water losses
Adopt improved irrigation technology	Farmer shifts to advanced irrigation technology; technological levels are increasing with flood irrigation constituting the lowest level, followed by furrow irrigation, sprinkler irrigation, drip irrigation, and ultimately demand-driven drip irrigation

addition to the economic forces farmers' decision making is strongly influenced by their social and cultural context, as well as their personal experience and risk aversion attitude. Those factors can only insufficiently be handled in the above described modeling approaches.

Therefore, to assess the effect of a strong increase of water price on farm management and respective on-farm water resource management, we conducted an explorative study. We confronted the farmers in the study region with a potential 100 % increase in water price, and asked for their reaction in response to this increase. The possible options, which the farmers could choose from, were derived in a two-step procedure. First, potential reactions by farmers to an increase in water price were discussed with local experts in the frame of a stakeholder workshop on "Agricultural Water Use" conducted in the provincial capital Urumqi in August 2011. Second, the identified options were tested in the pilot survey. Finally, farmers were given five different options to answer the question: "What would you do if water price increases by 100 percent?" Those were (1) 'drill a well', (2) 'do nothing and just pay higher water price', (3) 'shift crop pattern', (4) 'optimize on-farm management practices', and (5) 'adopt improved irrigation technology', described in detail in Table 1. Even though the presented approach is not able to capture a potentially gradual reaction by farmers towards increasing water prices, as identified by Frija et al. (2011) and Speelman et al. (2009), the applied approach has strong merit going beyond the pure profit maximization approaches. The additionally obtained data on farm household characteristics, e.g., age and education level, as well as the farms' crop production characteristics, e.g., major crop types and respective yields, allow the assessment of the determinants of farmers' decision making. Building on those results specific recommendations can be developed targeted at the respective household groups.

Unfortunately available literature on current water pricing practices, agricultural production conditions, and farm management in the study region is extremely poor. Therefore, we mainly build on our surveyed data to provide important background information regarding current water pricing practices and the five offered choices. Water pricing in the region is generally conducted on a per area basis. The water price that farmers pay to the local water authorities per hectare and year ranges from 900 to 1,500 RMB. According to Xinjiang Statistical Yearbook (2012) and XPCC Statistical Yearbook (2012) average annual net incomes of farm households in the study region range from 7,700 to 12,300 RMB. Thus, a 100 % increase in water price would constitute a substantial decrease in farm incomes depending on the household's agricultural land use area. The cost for drilling a well is mainly determined by its depth. The costs for drilling a well strongly depend on the required depth to reach fresh water of sufficient quality, i.e., low salinity. As reported by the surveyed farmers the depths range from 20 m to more than 100 m. Furthermore, the location-specific soil parent material determines the amount of invested energy and wear out of drilling equipment, which additionally influence the cost of a well. The reported costs range from 10,000 to 60,000 RMB per well. Even though various irrigation methods potentially available to farmers in the region (Table 1) were introduced to the respondents during the interview, only two methods are actually applied; flood irrigation and drip irrigation. The additional costs for applying drip irrigation technology are estimated at 5,100–7,500 RMB per hectare (Xu et al. 2003).

Statistical analysis

Apart from descriptive statistics, multinomial logistic regression, a variation of ordinary regression, was selected for analysis of the collected quantitative dataset. It is especially suitable for research questions that feature two or more categorical-dependent variables, and several continuous as well as categorical explanatory variables. It is a well-tested methodological approach, regularly applied in farm, forest and irrigation research (e.g., Bakopoulou et al. 2010; Christopoulou and Minetos 2009; Demeke et al. 2011).

The possible responses on "What would you do if water price increases by 100 percent?" represent the dependent

Table 2 Description of variables used in the regression analysis

Variables		Type
Independent variables		
X_1	Age	Continuous
X_2	Total land area	Continuous
X_3	Total cash income	Continuous
X_4	Education	Categorical
X_5	Location	Categorical
X_6	Number of Crops	Categorical
X_7	Main crop	Categorical
X_8	Fruits	Categorical
X_9	Water shortage	Categorical
X_{10}	Irrigation method	Categorical
X_{11}	Existence of well	Categorical
Dependent variables		
Y_1	Drill a well	Multivariate
Y_2	Do nothing, just pay higher price	Multivariate
Y_3	Improve crop production	Multivariate
Y_4	Adopt improved irrigation technology	Multivariate

variables in the multinomial logistic regression model. The two responses 'optimize on-farm management practices' and 'shift crop pattern' were merged into a new category entitled 'improve crop production', due to the low number of farmers selecting those two choices (Table 2).

Multinomial logistic regression enables the comparison of each category of the dependent variable to a reference category, providing their probability. In this study, the dependent variable has four categories (Table 2). The first category Y_1 (drill a well) was selected as reference category. If there are z explanatory variables ($x_1, x_2, \ldots, x_z$) and k response categories ($Y_1, Y_2, \ldots, Y_k$), the logistic model can be written as:

$$\ln\left(\frac{P_{i-\text{category}}}{P_{j-\text{category}}}\right) = a + b_{i1}x_1 + b_{i2}x_2 + \cdots + b_{iz}x_z + \varepsilon_i \quad (1)$$

'$P_{i\text{-category}}$' represents the likelihood of the dependent variable being in the i-category, while '$P_{j\text{-category}}$' represents the likelihood of the dependent variable being in the j-category (the reference category). 'a' indicates the intercept of the regression curve, 'b' the coefficient of each predictor, and 'ε' represents the error term.

In this case, the three logits can be written as follows:

$$Y_2 = \ln\left(\frac{P_{Y_2}}{P_{Y_1}}\right) = a + b_{Y_2 1}X_1 + b_{Y_2 2}X_2 + \cdots + b_{Y_2 z}X_z + \varepsilon_{Y_2} \quad (2)$$

$$Y_3 = \ln\left(\frac{P_{Y_3}}{P_{Y_1}}\right) = a + b_{Y_3 1}X_1 + b_{Y_3 2}X_2 + \cdots + b_{Y_3 z}X_z + \varepsilon_{Y_3} \quad (3)$$

$$Y_4 = \ln\left(\frac{P_{Y_4}}{P_{Y_1}}\right) = a + b_{Y_4 1}X_1 + b_{Y_4 2}X_2 + \cdots + b_{Y_4 z}X_z + \varepsilon_{Y_4} \quad (4)$$

They express the log of the ratio of the probability a farmer chooses to 'adopt improved irrigation technology', 'improve crop production' and 'do nothing and just pay higher water price' compared to the probability a farmer chooses to 'drill a well' in case of increased water price.

Results and discussion

Characteristics of farm households

Table 3 illustrates the descriptive statistics of all variables used for multinomial logistic regression. The table shows the following continuous variables included in the analysis: farmers' age, total land area, and total cash income. The categorical variables included were: farmers' education level, ethnicity, location, number of crops, main crop, existence of water shortage, existence of fruit trees, existence of well and irrigation method.

The descriptive statistics show an average age of the surveyed farmers of 43 years, while average land area is 9.19 ha. Due to a few very huge land holdings surveyed in the Yingbazha area, which reach up to 233 ha, the average total land area per farm household is fairly large compared to provincial averages, reported at around 1 ha per farm household (Xinjiang Statistical Yearbook 2012). Thevs (2011) already reported about private investors reclaiming large areas of riparian land for cotton production especially along the middle reaches of the River, which confirms our observations revealed in a standard deviation of total land area of 26.32 ha. A similar discrepancy among farm households exists regarding their average total cash income, which was calculated from farmers' reported crop yields, sales prices and total production area of the respective crops. At a mean cash income of 351,109.58 RMB, standard deviation is more than 1 million RMB. Furthermore, a relatively low education level is prevalent among surveyed farmers, with 11 % illiterate, 77 % primary and middle school graduates, and only 12 % having a high school or college degree. The ratio of Uighurs (68 %) and Han (32 %) within the sample approximately displays their ratio in Aksu prefecture and Bayangol prefecture as reported for 2011 (Feike et al. 2014).

The vast majority of farmers specialized on the production of a single crop (82 %), while only very few produced more than two different crops. The main crops produced were cotton, apple and jujube, with cotton being by far the most important crop. Only 28 % of farmers produce fruits, while the majority does not. Queried about the water availability for crop production, more than half of the

Table 3 Descriptive statistics of the independent variables

Continuous variables	N	Minimum	Maximum	Mean	SD
Age (years)	126.00	20.00	81.00	43.25	12.83
Total land area (ha)	128.00	0.27	233.33	9.19	394.65
Total cash income (RMB)	128.00	0.00	9,400,000	351,109.58	1,046,278.51

Categorical variables	N	Percent (%)	Description
Education			
Illiterate	13	10.4	Illiterate = 1, others = 0
Lower education	97	77.6	Lower education (primary and middle school) = 1, others = 0
Higher education	15	12.0	Higher education (high school and college) = 1, others = 0
Ethnicity			
Uyghur	87	68.0	Uyghur = 1, other = 0
Han	41	32.0	Han = 1, other = 0
Location			
Aksu-Awat	28	21.9	Aksu-awat = 1, others = 0
Alar	20	15.6	Alar = 1, others = 0
Xayar-North	45	35.2	Xayar-North = 1, others = 0
Xayar-South	19	14.8	Xayar-South = 1, others = 0
Yingbazha	16	12.5	Yingbazha = 1, others = 0
Main crop			
Cotton	110	85.9	Cotton = 1, others = 0
Other crops	18	14.1	Other crops (Red dates and apple) = 1, other = 0
Number of crops			
One crop	105	82.0	One crop = 1, other = 0
Multiple crops	23	18.0	Multiple crops = 1, other = 0
Water shortage			
No	30	23.4	No = 1, others = 0
Slight	37	28.9	Slight = 1, others = 0
High	61	47.7	High = 1, others = 0
Fruits			
Yes	36	28.1	Yes = 1, other = 0
No	92	71.9	No = 1, others = 0
Existence of well			
Yes	67	52.3	Yes = 1, other = 0
No	61	47.7	No = 1, others = 0
Irrigation method			
Drip irrigation	36	28.1	Drip irrigation = 1, other = 0
Flood irrigation	92	71.9	Flood irrigation = 1, other = 0

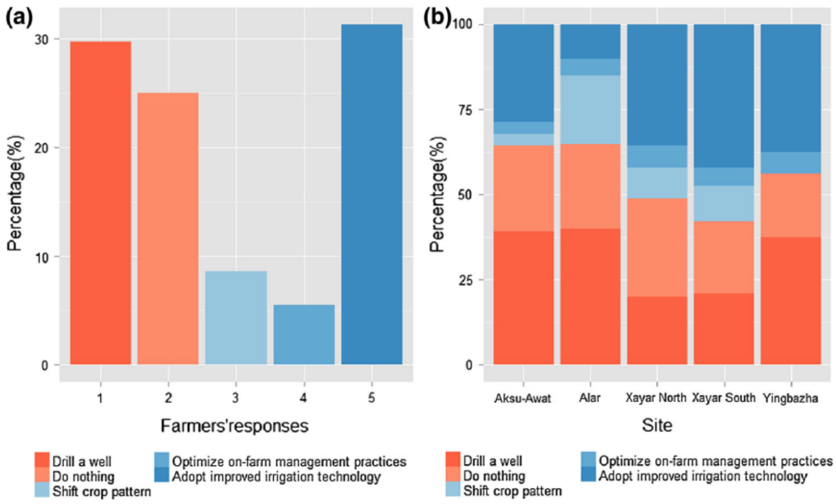
1RMB = 0.16 USD (2012)
(Source: World Bank Database)

interviewees stated that they suffered from different degrees of water shortage during the 2011 growing season. Regarding the irrigation method, the majority of farmers used flood irrigation (71.9 %), with the remaining farmers using drip irrigation. In addition, about half of the farmers already dug a well for alternative irrigation water supply in the past.

Farmers' response towards increased water price

Figure 2 illustrates farmers' response towards the increase in water price. It is shown that over the entire sample (Fig. 2a), roughly one-third of farmers selected 'drill well', one-third 'adopt improved irrigation technology', and one-fourth 'do nothing', with only very few farmers opting for 'shift crop pattern' and 'improve on-farm management practices'. As the increasing exploitation of groundwater resources is contributing to the aggravating water scarcity and consecutive degradation of natural ecosystems along the Tarim River in recent decades (Thevs 2011; Xu et al. 2005; Chen et al. 2013a, b), 'drill a well' should be considered the most undesirable reaction by farmers towards an increase in water price. Even though the responsible

Fig. 2 Farmers' response towards the increase in water price over the overall sample (**a**) and distinguished between the five survey sites (**b**)



authorities released an ordinance on restriction of groundwater resources (TRBMB 2008), still one-third of sampled farmers would circumvent this regulation. There is strong evidence that the drastic increase in water price might lead to a further expansion of groundwater exploitation in the Tarim Basin. This effect has already been recognized by Schuck and Green (2003) for arid western United States and Liao et al. (2008) for different parts of China.

Out of the 128 sampled farm households, 32 decided to 'do nothing, and just pay higher water price'. It may either be that those farmers suppose their water-related farming practices cannot be further improved, or that the water price only plays a marginal role in their total farm budget. Furthermore, only a small share of farmers decided to 'shift crop pattern' (8.6 %) or 'improve on-farm management' (5.4 %) as a reaction to increased water price. It reveals that the farmers' knowledge of alternative crops with reduced water requirements, as well as their understanding of improved water use efficiency through improved farm management is limited. Finally, 31.3 % of farmers decided to 'adopt improved irrigation technology' in case of increased water price. It indicates a high awareness among local farmers that improved irrigation technology can help to ease the tight water situation by improving water use efficiency.

Looking at farmers' reaction at the five survey sites, one can recognize only a slight variation over the locations (Fig. 2b). However, Xayar-North and Xayar-South feature a rather low rate of 'drill a well' compared to the other three sites. This may be a result of a more effective restriction of ground water extraction in the Xayar region compared to the other sites. Furthermore, farmers in Alar mentioned 'shift crop pattern' much more often compared to the other four sites, while they recognized 'adapt improved irrigation technology' much less an option towards increasing water price. All farmers in Alar belong to the XPCC. Therefore, a great share of crop production steps, including irrigation, is only in part managed by farmers, but mainly organized on tuan (regiment) or lian (company) level. Furthermore, the technological level is already relatively high within the XPCC compared to other regions in the Tarim Basin (Feike et al. 2014).

It seems that the sole increase of irrigation water price would have little prospect of success to increase water use efficiency at a substantial degree. The results show that only 45.3 % of sampled farmers opt for decisions that would support a more wise use of water and could lead to an actual improvement of water use efficiency. The majority of farmers would decide for either 'do nothing', or even worse 'drill a well', which would lead to a further aggravation of the water scarcity issue.

Factors influencing farmers' response

The multinomial logistic regression model shown in Table 4 is statistically significant ($x^2 = 51.112$; $p < 0.05$). The dependent variable was regressed against the following factors: total land area, age, total farm income, water shortage, ethnicity, education level, location, existence of fruit production and existence of well. Four independent variables, namely ethnicity, major crop, number of crops and irrigation method, were excluded from the regression, due to high correlation with other variables and consecutive redundancy. 'Drill a well' was selected as reference category in the multinomial logistic regression model. From sustainability point of view it constitutes the most undesirable reaction by farmers towards increases in water price. Therefore, comparing it to the other possible

Table 4 Results of the multinomial logistic regression analysis

Farmers' response[a]	B	SE	Sig.	Exp(B)	95 % Confidence interval for Exp(B)	
					Lower bound	Upper bound
Do nothing						
Age	0.044	0.024	0.067*	1.045	0.997	1.095
Area of total land	0.021	0.010	0.033**	1.021	1.002	1.042
Total farm income	0.000	0.000	0.043**	1.000	1.000	1.000
Location-Aksu-Awat	1.962	1.619	0.225	7.117	0.298	169.995
Location-Alar	1.815	1.461	0.214	6.141	0.351	107.564
Location-Xayar-North	1.412	1.120	0.207	4.105	0.457	36.890
Location-Xayar-South	1.124	1.273	0.377	3.078	0.254	37.348
Education-low education	1.721	1.067	0.107	5.592	0.691	45.259
Education-high education	0.306	1.273	0.810	1.358	0.112	16.449
Water shortage-slight	1.976	0.720	0.006***	7.213	1.760	29.567
Well-no	0.227	0.632	0.719	1.255	0.364	4.330
Fruits-no	2.081	1.101	0.059*	8.015	0.926	69.379
Improve crop production						
Age	−0.002	0.029	0.940	0.998	0.943	1.056
Area of total land	0.032	0.014	0.028**	1.032	1.003	1.062
Total farm income	0.000	0.000	0.036**	1.000	1.000	1.000
Location-Aksu-Awat	5.618	3.580	0.117	275.294	0.247	306,735.248
Location-Alar	6.768	3.522	0.055*	869.477	0.873	865,499.696
Location-Xayar-North	4.890	3.242	0.131	132.974	0.231	76,465.473
Location-Xayar-South	4.885	3.361	0.146	132.346	0.182	96,049.209
Education-low education	0.089	1.031	0.932	1.093	0.145	8.241
Education-high education	−0.813	1.306	0.533	0.443	0.034	5.736
Water shortage-slight	1.620	0.859	0.059*	5.051	0.938	27.182
Well-no	−0.382	0.777	0.623	0.683	0.149	3.128
Fruits-no	2.705	1.180	0.022**	14.954	1.479	151.151
Adopt improved irrigation technology						
Age	0.035	0.023	0.125	1.035	0.990	1.082
Area of total land	0.014	0.009	0.099*	1.015	0.997	1.032
Total farm income	0.000	0.000	0.142	1.000	1.000	1.000
Location-Aksu-Awat	2.221	1.527	0.146	9.220	0.462	183.966
Location-Alar	0.217	1.395	0.876	1.243	0.081	19.131
Location-Xayar-North	0.967	0.949	0.308	2.630	0.410	16.890
Location-Xayar-South	1.087	1.060	0.305	2.965	0.372	23.652
Education-low education	0.810	0.875	0.355	2.248	0.404	12.498
Education-high education	−0.617	1.088	0.571	0.540	0.064	4.556
Water shortage-slight	1.895	0.701	0.007***	6.656	1.685	26.284
Well-no	0.599	0.607	0.323	1.821	0.554	5.981
Fruits-no	3.173	1.231	0.010***	23.869	2.140	266.261

* Significant at $p = 0.1$

** Significant at $p = 0.05$

*** Significant at $p = 0.01$

[a] The reference category is: drill well

reactions helps to develop recommendations for a more sustainable water use.

When comparing the probability of farmers to 'dig a well' and 'do nothing, but just pay higher water price', five variables namely total land area, age, total farm income, slight water shortage and existence of fruit production had a statistically significant impact. The results show that farmers who had more land as well as higher income were more likely to 'do nothing' than 'drill a well'. This may be explained by the marginal share that water price constitutes in their total budget. At a cash income of more than 45,000 RMB per hectare observed for the 80th percentile of farm households a 100 % increase in water price from 1,000 to 2,000 RMB per hectare may not affect their decision in this respect. Furthermore, did older farmers show a slight tendency towards 'do nothing', which may be caused by their reluctance to undertake big investments in the light of the approaching retirement (Potter and Lobley 1992), instead of accepting the relatively small annual burden of water price increase. In addition, farmers who suffered from slight water shortage were more likely to choose 'do nothing' than 'drill a well'. Even this might seem paradoxical at first sight, it may also be the result of high investment costs of well drilling, being disproportionately high compared to the monetary losses caused by slight water shortage. Finally, the probability of farmers having no fruit production is higher to 'do nothing' than 'drill well'. As drilling of a well is a similar venture like the establishment of an orchard, regarding long-term planning and investment, it can explain the correlation between those two factors.

The model furthermore estimated five variables to be significant when comparing the choice of 'improve crop production' and 'drill a well'. The results illustrate that farmers who had more land and high income were more likely to choose 'improve crop production' under conditions of increased water price. This result is supported by the argument that larger land tenure, accompanied by higher capital capacity, allows bearing more risk, e.g., by shifting to other crops, compared to small-scale farmers (Norris and Batie 1987). Besides, farmers who did not have fruit trees were more likely to choose other options if water pricing increase. The major reason behind this may be the fact that farmers who only grow annual crops can easily shift to other crops compared to those farmers who established a fruit plantation on their land, and would lose their investment by shifting to other crops. In addition, slight water shortage and location showed a certain influence on farmers' choice.

The comparison between the choices of 'adopt improved irrigation technology' and 'drill a well' indicates that three variables, namely total land area, slight water shortage, and no fruits, were statistically significant. First of all, farmers with larger total land area were more likely to adapt improved irrigation technology. However, the level of significance was much lower compared to the impact of land area in the other two cases presented above. Furthermore, farmers who suffered from slight water shortage were more likely to adopt improved irrigation technology under increased water price. The results show that the odd of choosing 'adopt improved irrigation technology' was more than six times higher for farmers who suffered from slightly water shortage, than the odd of farmers who did not suffer from water shortage and the odd of farmers who suffered from severe water shortage. At the same time no significant impact is estimated for farmers who suffered high water shortage. As the adoption of improved irrigation technology can increase water use efficiency to a certain extent (Li et al. 2008), it seems a viable option to counteract slight water shortage, by allocating the limited water resources efficiently over the entire farms' cropping area. However, in case of severe water shortage and related times of complete absence of water, adoption of improved irrigation technology is obviously only a small part of the solution.

Finally, farmers who did not have fruit were more likely to adopt improved irrigation technology under increased water price. The odd of choosing 'adopt improved irrigation technology' for farmers who did not have fruit trees was almost 24 times that of farmers who had fruit trees. This vice versa indicates that farmers who had fruit trees were less likely to adopt improved irrigation technology. In recent years, several studies were conducted in arid northwestern China, testing the effect of the application of improved irrigation technology on major fruit trees' growth and yield. The results show that adopting improved irrigation technology can increase water use efficiency of fruit trees significantly (e.g., Cui et al. 2008; Du et al. 2008; Yang et al. 2013). However, fruit farmers in the Tarim Basin apparently are not convinced of the benefits related to adopting improved irrigation technology. The source of this problem may be the lack of effective transfer of the related research findings to the farmers, which is a common challenge in Chinese agricultural research (Feike et al. 2010).

Conclusion and recommendations

Farm household interviews were conducted to find out farmers' response towards a strong increase in water price along the Tarim River. The results show that increasing irrigation water price induces <50 % of the interviewed farmers to use water more wisely, by adopting improved irrigation technology, shift to crops which need less water, or improve farm management to generate higher returns with less water. On the contrary, more than 50 % of farmers would either implement no changes in their farm management practices, or—even worse—would feel encouraged to drill a well and establish their own source of water. Thus, the increase in water price may actually foster the overexploitation of ground water resources in the Tarim Basin.

When determining which factors influence farmers' reaction towards the increase in water price employing multinomial logistic regression, the results show that farmers with larger land area tended to opt for other options than 'drill well'. In reverse farmers with smaller land area felt more encouraged to 'drill well' when water price increases. Furthermore, slight water shortage decreased the probability that farmers 'drill well' compared to the probability that they 'do nothing' or 'adopt improved irrigation technology'. Finally farmers involved in perennial fruit production are more likely to 'drill well' compared to the other three options. Conversely, farmers only producing annual crops are more motivated to 'do nothing', 'improve crop production' and 'adopt improved irrigation technology'.

The results indicate that solely increasing water price at a high rate is not a viable option to improve water resource use in the study region. To overcome the tight water situation and realize a wiser use of water, it is indispensable to develop and implement an integrated approach. First of all, it is essential to create awareness among all agricultural water users that their unwise use of water may cause water shortage for other farmers. There is strong indication that farmers who already suffered slight water shortage are more willing to opt for wiser water use decisions. Furthermore, agricultural extension service needs to be advanced to enable local farmers to increase their monetary benefits from the limited water resources. Up to now, the majority of farmers seem to lack knowledge and skills of how to improve their farms' water productivity. In addition, an effective control of ground water drilling needs to be enacted to avoid further environmental degradation. Special attention should be put on small-scale farmers, and especially fruit farmers, who up to now seem not convinced of the benefits of using advanced irrigation technology in orchards.

Acknowledgments This research was embedded in the SuMaRiO (Sustainable Management of River Oases along the Tarim River) project, funded by the German Federal Ministry of Education and Research through the "Sustainable Land Management" program. We furthermore acknowledge the support of Dr. Ling Yee Khor regarding the choice of regression model.

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2.4 Bayesian network modeling to improve water pricing practices in NW China

Publication III

Mamitimin Y, Feike T, Doluschitz R. **Bayesian Network Modeling to Improve Water Pricing Practices in Northwest China**. *Water*. 2015; 7(10):5617-5637. doi:10.3390/w7105617

Abstract

Water pricing is regarded as the most important and simplest economic instrument to encourage more efficient use of irrigation water in crop production. In the extremely water-scarce Tarim River basin in northwest China, improving water use efficiency has high relevance for research and policy. A Bayesian network modeling approach was applied, which is especially suitable under data-scarce conditions and the complex geo-hydrological, socioeconomic, and institutional settings of the study region, as it allows the integration of data from various types of sources. The transdisciplinary approach aimed at understanding the actual water pricing practices, the shortcomings of the current system, and possible ways of improvement. In an iterative procedure of expert interviews and group workshops, the key factors related to water pricing and water use efficiency were identified. The interactions among specific factors were defined by the respective experts, generating a causal network, which describes all relevant aspects of the investigated system. This network was finally populated with probabilistic relationships through a second round of expert interviews and group discussions. The Bayesian modeling exercise was then conducted using Netica software. The modeling results show that the mere increase of water price does not lead to significant increases in water use efficiency in crop production. Additionally, the model suggests a shift to volumetric water pricing, subsidization of water saving irrigation technology, and advancing agricultural extension to enable the farmer to efficiently react to increased costs for water. The applied participatory modeling approach helped to stimulate communication among relevant stakeholders from different domains in the region, which is necessary to create mutual understanding and joint targeted action. Finally, the challenges related to the applied transdisciplinary Bayesian modeling approach are discussed in the Chinese context.

Water **2015**, *7*, 5617-5637; doi:10.3390/w7105617

OPEN ACCESS

water

ISSN 2073-4441

www.mdpi.com/journal/water

Article

Bayesian Network Modeling to Improve Water Pricing Practices in Northwest China

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Academic Editor: Miklas Scholz

Received: 3 August 2015 / Accepted: 12 October 2015 / Published: 19 October 2015

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participatory modeling approach helped to stimulate communication among relevant stakeholders from different domains in the region, which is necessary to create mutual understanding and joint targeted action. Finally, the challenges related to the applied transdisciplinary Bayesian modeling approach are discussed in the Chinese context.

Keywords: water pricing; water use efficiency; Bayesian network modeling; causal networks; transdisciplinary research

1. Introduction

The Tarim River is located in the southern part of Xinjiang Uyghur Autonomous Region (XUAR) in northwest China. The Tarim River Basin is one of the driest areas in the world, with annual precipitation of less than 50 mm and potential evaporation of more than 2000 mm [1,2]. The snow and glacier melt from the surrounding mountains is the main water resource of the Tarim River (Figure 1). Because of the low precipitation, all human activities and natural ecosystems depend on the water from the Tarim River [3,4].

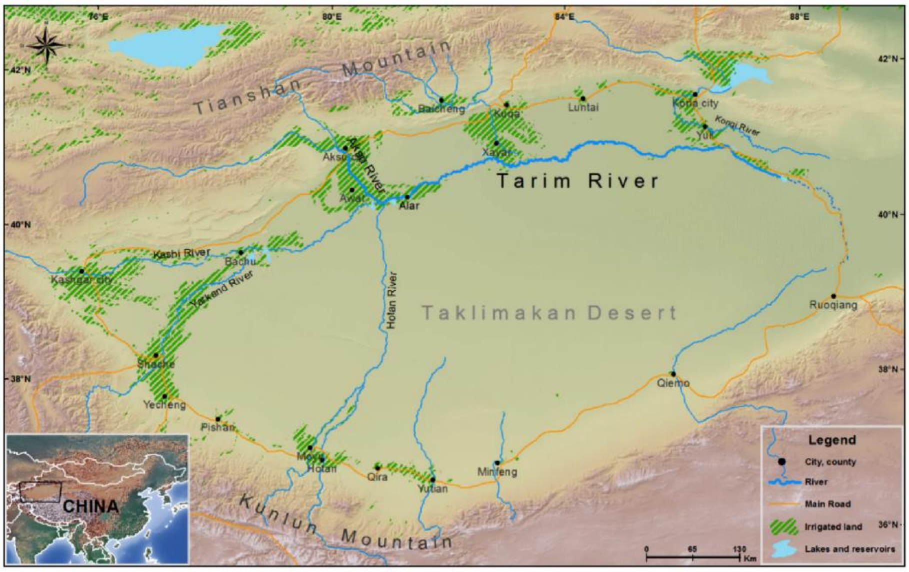

Figure 1. Map of the study region.

The Tarim River Basin is an important cotton, grain, and fruit production base in China. Low precipitation and rich sunshine offer favorable crop production conditions, especially for producing high-quality cotton. According to the Chinese statistical yearbook, regional cotton production in 2012 contributed to more than 50% of Chinese national cotton production and accounted for about 15% of world cotton production [5].

However, intensive agricultural production is the main consumer of water in this arid region, accounting for more than 90% of total fresh water consumption along the Tarim River [6]. Over the last decades there has been strong intensification of agricultural activities and consecutive overutilization of water resources, which resulted in severe environmental problems in the region [7–10]. Furthermore, the diversion of more and more water to agricultural production in the upper stream and middle stream of the river has led to increased conflicts among the farmers, resulting in yield losses [3]. In addition, current irrigation water pricing is believed to be too low to cover the full supply cost. According to the XUAR Provincial Department of Water Resources, irrigation water pricing in 2010 was 0.019 RMB/m^3, only covering 37% of the full supply cost [11]. Underpricing is recognized as one of the major causes of overutilization of water resources, low water use efficiency (WUE), and aging infrastructure along the Tarim River Basin [12]. It is recognized that effective allocation and conservation of water resources has become a major issue in sustainable development along the Tarim River [13,14]. As an important policy option, irrigation water pricing was integrated into the agenda of the government's future plan targeting water saving, sustainable water use, and increasing WUE. According to the XUAR People's Government, full supply cost recovery levels should reach 70% at the end of 2015 and 100% at the end of 2020 [15].

Irrigation water pricing is regarded as the most important and simplest economic instrument for promoting WUE [16]. Irrigation water pricing is believed to have two major roles in terms of promoting WUE. Firstly, it provides funds to sustain the supply system by guaranteeing the cost recovery from the water users [17]. Secondly, it gives incentives to use water resources more wisely by encouraging people to use advanced irrigation methods and technologies. Water pricing furthermore encourages them to choose crops that generate higher returns and require less water, and to improve farm management practices with the aim of reducing water losses [18–20]. However, there is a lot of debate about the externality and uncertainty of raising irrigation water pricing. Tardieu and Prefol [21] and Liao *et al.* [22] argue that besides leading to a reduction in agricultural production, raising irrigation water pricing also counteracts the sustainability of rural development by increasing rural poverty [23]. In addition, some case studies showed that increasing water pricing did not result in stopping overutilization of water resources and related environmental problems [24,25]. Furthermore, Liao *et al.* [22] added that irrigation water pricing is not effective without additional agricultural policy interventions. Such ineffectiveness of water pricing can largely be explained by water being a rather inelastic production factor, *i.e.*, an increase in water price by a certain percentage will not lead to a reduction in water consumption at a similar rate. As farmers in arid and semi-arid regions essentially rely on water for growing crops, they might not easily reduce their consumption amount [26,27].

Various methods have been applied to find the impacts of water pricing on WUE including mathematical programming [28–32], econometric analysis of survey data [33,34], and various other modeling approaches [35,36]. However, those approaches mainly simulate the impact of changed water pricing practices on the farm level. As such, the institutional aspects related to agricultural water policies, which are of utmost importance for successful policy design, can only be considered insufficiently.

Therefore, Bayesian Networks (BN) modeling was employed in the present study, which is better able to consider the crucial institutional aspects of agricultural water policy design. BN modeling is a popular tool, especially when dealing with decision-making in the face of uncertainty and limited data availability [37]. It has been widely used in environmental sciences and natural resources management with a focus on ecosystem service modeling [38,39], climate change impact assessment [40,41], watershed management [42–44], and ground water protection [45,46]. Its ability to clearly explain complex relations, easily compare alternative management scenarios, and determine the important driving factors makes BN modeling an extremely useful approach to support natural resources management under complex settings [47]. Another important advantage of BN modeling is its flexibility with regards to data sources. Especially under data-limited conditions, as is the case with the present study in the Tarim Basin, its potential to meaningfully integrate data from different sources, including stakeholder and expert knowledge, empirical data, and data from the literature, is of vital importance [37,48].

There has been extensive research on the Tarim River focusing on water resource variations [49–52], land use and land cover change [53,54], climate change impact [55–57], and the ecological restoration efforts along the lower reaches of the river [58–60]. However, very little research has been conducted on the role of water pricing for sustainable water use in the Tarim River up to now. Thus, there is an urgent need to determine the effects of water pricing on WUE along the Tarim River.

Therefore, the overall objective of this paper is to find out whether increasing water pricing will lead to more efficient water use along the Tarim River. The specific objectives are: (1) to develop a model to determine the effects of water pricing policies on increasing WUE; (2) to improve current water pricing practices; (3) to evaluate the effects of alternative measures on increasing water use efficiency; and (4) to develop policy recommendations aimed at more effective water pricing policies.

2. Materials and Methods

2.1. Bayesian Networks

BN, also called Bayesian belief networks, form the conditional probability model, which can be described as a directed acyclic graph consisting of a series of variables and their conditional dependencies [61]. Each BN is composed of three elements: nodes, directed edges or links between nodes, and a conditional probability table (CPT). Nodes represent the variables in the graph, while directed edges or links visualize the casual relations between these nodes. The CPT is used for defining the conditional probability of the casual relations. The conditional probability relies on Bayes's theorem, for which the mathematical equation can be written as:

$$\boldsymbol{P}(\boldsymbol{i}|\boldsymbol{j}) = \frac{\boldsymbol{P}(i)\boldsymbol{P}(\boldsymbol{j}|\boldsymbol{i})}{\boldsymbol{P}(j)},$$

where "***i***" and "***j***" are the two random events, "**P(*i*)**" represents the probability of event ***i***, and "**P(*j*)**" represents the probability of event ***j***. "**P(*i*|*j*)**" is the conditional probability of event ***i*** under the condition that event ***j*** occurs [62–64].

A number of commercial and open source software packages are available for BN modeling. In this study the most commonly used software package, "Netica," was employed, which has all necessary features, flexibility, and a user-friendly interface.

2.2. Model Development Process

A number of guidelines are available for developing BN (e.g., [65–67]). For this study, the seven-step guideline developed by Bromley [67] was applied for establishing the BN model. Detailed information on the applied process including the modeling process, objectives, research activity dates, research activity format, research participants, number of participants, and the collected data type is shown in Table 1.

Table 1. Bayesian network modeling process to evaluate the impacts of water pricing on water use efficiency.

Modeling Process	Objectives	Date	Format	Participants	No. Participants	Data Type
Define the problem and context	(a) Define the problem and objectives (b) Identify and select potential participants and stakeholders	July 2011	Group discussions	Research team	3	Expert knowledge
Identify the variables and indicators	(a) Identify all relevant variables and key indicators (b) Identify the possible scenarios	August 2011	Workshop	Local experts	13	Expert knowledge
Design the preliminary network	(a) Construct the pilot network, insert links and variables (b) Generalize/finalize the network for consistency, logic, and focus	August 2012	Face-to-face interview and workshop	Local experts	6 + 15	Expert knowledge
Gather relevant data	Collect and analyze the relevant data from all sources	March 2013	Face-to-face interview	Local experts, water authorities	17	Expert knowledge, empirical data
Construct and populate the CPT	(a) Enter the interview data manually (b) Enter the empirical data by parameter learning	April 2013	--	--	--	--
Evaluate and validate the network	(a) Present the final results (b) Evaluate the model process and final results of the model	April 2013	Workshop	Local experts, water authorities	19	Expert knowledge

2.3. Construction of Networks

The construction of the causal networks was conducted in an iterative procedure following three major steps. After the definition of research objectives, a first group workshop with previously identified key stakeholders was held. Possible scenarios for future agricultural water resource management were discussed and the related variables and key indicators were identified. In the second step, interactions between all relevant factors were defined via one-to-one discussions with experts in the fields of water infrastructure, crop irrigation, and agricultural extension. Partial interaction graphs of specific parts of the system were defined by the respective experts. The research team then integrated the partial interaction graphs to generate a single pilot causal network that represents the major relevant aspects related to water pricing and water use efficiency in the region. In this process regional senior researchers from the field of water resource management were consulted to help refine the pilot causal network accordingly. In the final step, a consultation workshop was arranged with the same local experts. In several parallel group discussions, experts were asked to evaluate the pilot network and add, remove, or change the variables included in networks or modify the relationships according to their perception. The recommended adjustments proclaimed by the different groups were finally discussed to achieve consensus on the major aspects of the network. Following the workshop, specific variables of limited importance and relevance were removed from the network, and some variables that were missing thus far but considered important were added. In the pilot network there were 25 nodes (variables) and 36 links, while in the finalized network there were nine nodes and 12 links. In addition, the number of nodes was kept at a maximum of three in order to guarantee the accuracy and optimum size of the model as suggested by Cain [65]. The finalized causal network and a detailed description of the variables and their states are shown in Figure 2 and Table 2, and explained in detail below.

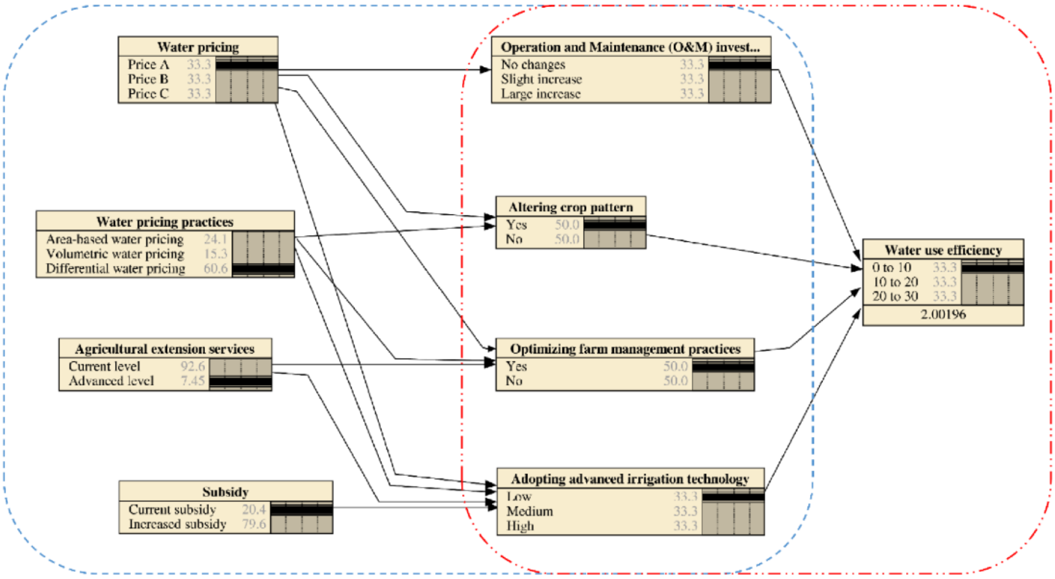

Figure 2. Causal networks for modeling the impact of water pricing on water use efficiency.

Water pricing practices determine the methods for charging water fees. There are three basic water pricing practices: Area-based water pricing (ABWP), volumetric water pricing (VWP), and differential water pricing (DWP). ABWP charges the water fee according to each unit of irrigated area. ABWP is a popular and widely used method because it is easy to implement and administer. Moreover, it entails rather low implementation costs. However, ABWP does not prevent overutilization of water resources, because there is no direct link between water charges and thee amount of water actually used for irrigation [68]. VWP charges the water fee according to each unit of volume water used [69]. VWP encourages users to save water and reduce consumption, because the charged water fee is directly linked to the amount of water consumed. However, VWP generally entails higher costs compared to ABWP because specific measuring equipment needs to be installed at the level of the final user [68,70]. VWP for agricultural water use is common in some states of the U.S. and some regions of Spain [71]. Finally, DWP considers a standard (rather low) price below a certain threshold of water consumption, and a significantly higher WP when the threshold is exceeded. DWP can be adjusted to local crop water requirements under good agricultural practice, and can therefore better address the aspect of farmer's affordability [70]. In Israel and Jordan DWP is reported as existing water pricing practice [20,72].

Table 2. Variables, variable states, and detailed description of the variables in the Bayesian networks (1 RMB = 0.16 US$).

Variables	States	Description
Water pricing	Price A (1500 RMB/ha; 0.18 RMB/m^3; 0.18 RMB/m^3 for standard consumption, 0.36 RMB/m^3 for surplus consumption)	Increased water price levels based on the government's policy documents. Prices listed as follows (area-based water price; volumetric water price; differential water price); Price A equals an increase of 25%, Price B of 50%, Price C of 100%, all compared to current prices.
	Price B (1800 RMB/ha; 0.22 RMB/m^3; 0.22 RMB/m^3 for standard consumption, 0.44 RMB/m^3 for surplus consumption)	
	Price C (2400 RMB/ha; 0.3 RMB/m^3; 0.3 RMB/m^3 for standard consumption, 0.6 RMB/m^3 for surplus consumption)	
Water pricing practices	Area-based water pricing (ABWP)	Water pricing practices determine the methods of charging the water fee; ABWP: per unit irrigated area; VWP: per volume of water used; DWP considers a low price below a certain threshold of water consumption, and a significantly higher WP when the threshold is exceeded.
	Volumetric water pricing (VWP)	
	Differential water pricing (DWP)	
Agricultural extension services	Current level	Training farmers with regards to good crop management practices and advanced technologies to improve yield levels, resource use efficiency and profits.
	Advanced level	
Subsidy	Current subsidy	Subsidizing agricultural producers for implementing advanced irrigation technology and converting from flood irrigation to sprinkler irrigation or drip irrigation.
	Increased subsidy	
Operation and Maintenance (O & M) investment	No change	Investments for running the water supply system including planning, construction, monitoring, and repair of water storage and distribution infrastructure as well as planning and distribution of water resources.
	Slight increase	
	Large increase	
Altering crop pattern	Yes	Shifting towards crops with higher water productivity.
	No	
Optimizing farm management practices	Yes	Improving farm management practices to increase yields and minimize water losses.
	No	
Adopting advanced irrigation technology	Low	Adapting advanced irrigation technology such as sprinkler irrigation or drip irrigation.
	Medium	
	High	
Water use efficiency	Increased by 0%–10%	WUE in agriculture is defined as the economic yield of crops produced per unit of water; the three states correspond to low, medium, and high levels of increase in WUE.
	Increased by 10%–20%	
	Increased by 20%–30%	

Along the Tarim River ABWP is commonly used in the agricultural sector, while in the industrial and domestic sectors VWP is applied. The farm household survey conducted in the study region in 2012 revealed an average water fee that farmers pay to the water authorities of approximately 1200 RMB/ha and year. According to the average water amounts consumed for crop production by farmers in the region, as determined from the farm survey data, farmers currently pay an approximate volumetric water price of 0.14 RMB/m^3. This water price determined from primary farm data is significantly higher than the water price officially announced at the county level by the XUAR Provincial Department of Water Resources in 2010. Obviously the final water price paid by the farmers entails additional costs arising from water allocation on the town and village level. Those include costs for construction and maintenance of local water infrastructure, as well as administrative costs.

2.4. Data Collection

For the development of the BN model, data from purposefully selected sources such as expert interviews, expert workshops, policy documents, scientific literature, and official statistics was collected, analyzed, and integrated. For the core part of the BN model development, which is populating the CPTs, mainly expert knowledge and empirical data from Xinjiang Production and Construction Corps (XPCC) statistical yearbooks [73] was used. Experts from major research institutions including universities and academies that specialize in water resources management, water conservation, agricultural economics, ecology, and forestry were interviewed face to face. In addition, experts from major water management agencies including the Xinjiang Uyghur Autonomous Region Provincial Department of Water Resources, the Tarim River Basin Management Bureau, and the Tarim River Basin Aksu River Management Bureau were also interrogated within the frame of the current study (Table 3).

Table 3. Detailed information regarding the interviewed local experts and water authorities who helped to populate the conditional probability table.

Institutions	Institution Type	No. of Participants
Xinjiang Uyghur Autonomous Region Provincial Department of Water Resources	Regional Government	2
Xinjiang Institute of Ecology and Geography	Research Institution	1
Xinjiang Institute of Water Resources and Hydropower Research	Research Institution	1
Xinjiang Academy of Forestry Sciences	Research Institution	1
Xinjiang University	University	2
Xinjiang Agricultural University	University	4
Xinjiang Financial University	University	1
Tarim River Basin Management Bureau	River Basin Authority	2
Tarim River Basin Aksu River Management Bureau	River Basin Authority	2
Xinjiang Tarim University	University	3

Elicited expert knowledge from face-to-face interviews was used to estimate probabilistic relationships among specific variables of the causal network in the blue rectangle in Figure 2. In the beginning of the interview, the probabilistic concept of Bayesian modeling and the previous construction of the finalized causal networks were explained carefully. Building on a simple example, the procedure of populating the causal network with respective CPTs was illustrated to help local experts understand conditional reasoning. In the final step, the experts were asked to fill in conditional probability tables according to their knowledge and expert judgment. The collected data were ultimately integrated by the research team and entered into the model using Netica software.

Additionally, empirical data was used to estimate the probabilistic relationships of specific parts of the causal networks in the red rectangle in Figure 2. The data collected and analyzed from XPCC statistical yearbooks included data from 2000 to 2012 on area of irrigated land, area of micro-irrigated land, total investment for water conservation, area of major crops (e.g., cotton, fruit trees, and vegetables), main inputs for farming (e.g., fertilizer, pesticides, and labor), total output value from farming, and the total amount of water consumption for farming. After data collection, the following steps were applied to estimate the probabilities. First, all related variables were converted manually to discrete variables according to the state of the previously finalized nodes. Then, possible combinations of the states in the parent nodes were listed, and the frequencies of the occurrence of the states of child nodes were counted. In the end, the final probability was estimated by dividing the frequencies of the occurrence of the states of the child nodes by the total number of each parent states' combination. This estimation procedure was completed using the Bayesian learning algorithm featured in the Netica software package.

2.5. Scenario Management

Thirty-six scenarios were developed in order to evaluate the impact of water pricing and other relevant adjustments and agricultural policy interventions on WUE (*cf.* Table 4). Scenario 0, which constitutes the baseline scenario, simulates the impacts of increasing water price at a rather low level, while scenarios 1 and 2 simulate the impacts of increasing water price at a medium and high level without considering any other changes or policy interventions. Scenarios 4–8 consider increasing water prices at a different level in combination with changes in water pricing practices towards volumetric and differential water pricing. In 2009, the XUAR Provincial Department of Finance began to subsidize drip irrigation by 1500 RMB/ha to promote advanced water-saving irrigation. The subsidy for drip irrigation officially increased to 4500 RMB/ha in 2011, which almost covers the cost of drip irrigation [74,75]. However, the farm survey conducted in 2012 revealed a much lower financial support for advanced irrigation technology of approximately 1500 RMB/ha. Additionally to the high investment costs, farmers also stated that they lacked knowledge of how to install and operate such irrigation systems, which deterred them from adopting water-saving irrigation. Therefore, scenarios 9–11 were used to test a combination of increasing water pricing and the policy intervention of advancing agricultural extension services. Moreover, scenarios 12–14 consider a combination of increasing water pricing and the policy intervention of increasing subsidies for drip irrigation. Scenarios 15–17 test a combination of increasing water pricing and both policy interventions, advancing agricultural extension services and increasing subsidies. Finally, scenarios 18–35 deal with multiple combinations of water pricing, water pricing practices, and both policy interventions.

Table 4. Probability value of increases in WUE under different water pricing scenarios.

Scenario	Water Pricing	Water Pricing Practices	Subsidy	Agricultural Extension Services	Probability Value for Increase in WUE			Probability Change for Increase in WUE		
					0%–10%	10%–20%	20%–30%	0%–10%	10%–20%	20%–30%
Scenario 0	Price A	ABWP	Current subsidy	Current level	39.49	30.69	29.82	--	--	--
Scenario 1	Price B	ABWP	Current subsidy	Current level	34.20	33.73	32.07	−5.29	3.04	2.25
Scenario 2	Price C	ABWP	Current subsidy	Current level	31.19	34.70	34.11	−8.3	4.01	4.29
Scenario 3	Price A	VWP	Current subsidy	Current level	37.93	31.46	30.61	−1.56	0.77	0.79
Scenario 4	Price B	VWP	Current subsidy	Current level	33.27	33.96	32.77	−6.22	3.27	2.95
Scenario 5	Price C	VWP	Current subsidy	Current level	30.80	34.68	34.52	−8.69	3.99	4.7
Scenario 6	Price A	DWP	Current subsidy	Current level	37.33	31.87	30.80	−2.16	1.18	0.98
Scenario 7	Price B	DWP	Current subsidy	Current level	32.90	33.99	33.11	−6.59	3.3	3.29
Scenario 8	Price C	DWP	Current subsidy	Current level	29.83	34.96	35.21	−9.66	4.27	5.39
Scenario 9	Price A	ABWP	Current subsidy	Advanced level	37.67	31.84	30.49	−1.82	1.15	0.67
Scenario 10	Price B	ABWP	Current subsidy	Advanced level	33.44	34.03	32.53	−6.05	3.34	2.71
Scenario 11	Price C	ABWP	Current subsidy	Advanced level	30.84	34.96	34.20	−8.65	4.27	4.38
Scenario 12	Price A	ABWP	Increased subsidy	Current level	35.49	33.33	31.18	−4	2.64	1.36
Scenario 13	Price B	ABWP	Increased subsidy	Current level	32.53	34.60	32.87	−6.96	3.91	3.05
Scenario 14	Price C	ABWP	Increased subsidy	Current level	30.67	34.90	34.43	−8.82	4.21	4.61
Scenario 15	Price A	ABWP	Increased subsidy	Advanced level	34.71	33.67	31.62	−4.78	2.98	1.8
Scenario 16	Price B	ABWP	Increased subsidy	Advanced level	31.98	34.73	33.29	−7.51	4.04	3.47
Scenario 17	Price C	ABWP	Increased subsidy	Advanced level	30.18	34.92	34.90	−9.31	4.23	5.08
Scenario 18	Price A	VWP	Current subsidy	Advanced level	36.58	32.30	31.12	−2.91	1.61	1.3
Scenario 19	Price B	VWP	Current subsidy	Advanced level	32.82	34.15	33.03	−6.67	3.46	3.21
Scenario 20	Price C	VWP	Current subsidy	Advanced level	30.53	34.74	34.73	−8.96	4.05	4.91
Scenario 21	Price A	VWP	Increased subsidy	Current level	34.96	33.44	31.60	−4.53	2.75	1.78
Scenario 22	Price B	VWP	Increased subsidy	Current level	32.07	34.57	33.36	−7.42	3.88	3.54
Scenario 23	Price C	VWP	Increased subsidy	Current level	30.31	34.88	34.81	−9.18	4.19	4.99
Scenario 24	Price A	VWP	Increased subsidy	Advanced level	34.50	33.61	31.89	−4.99	2.92	2.07
Scenario 25	Price B	VWP	Increased subsidy	Advanced level	31.85	34.58	33.57	−7.64	3.89	3.75

Table 4. *Cont.*

Scenario	Water Pricing	Water Pricing Practices	Subsidy	Agricultural Extension Services	Probability Value for Increase in WUE			Probability Change for Increase in WUE		
					0%–10%	10%–20%	20%–30%	0%–10%	10%–20%	20%–30%
Scenario 26	Price C	VWP	Increased subsidy	Advanced level	30.14	34.87	34.99	−9.35	4.18	5.17
Scenario 27	Price A	DWP	Current subsidy	Advanced level	36.23	32.56	31.21	−3.26	1.87	1.39
Scenario 28	Price B	DWP	Current subsidy	Advanced level	32.60	34.08	33.32	−6.89	3.39	3.5
Scenario 29	Price C	DWP	Current subsidy	Advanced level	29.68	34.96	35.36	−9.81	4.27	5.54
Scenario 30	Price A	DWP	Increased subsidy	Current level	34.18	33.81	32.01	−5.31	3.12	2.19
Scenario 31	Price B	DWP	Increased subsidy	Current level	31.77	34.51	33.72	−7.72	3.82	3.9
Scenario 32	Price C	DWP	Increased subsidy	Current level	29.57	35.01	35.42	−9.92	4.32	5.6
Scenario 33	Price A	DWP	Increased subsidy	Advanced level	33.95	33.77	32.28	−5.54	3.08	2.46
Scenario 34	Price B	DWP	Increased subsidy	Advanced level	31.65	34.49	33.86	−7.84	3.8	4.04
Scenario 35	Price C	DWP	Increased subsidy	Advanced level	29.41	34.98	35.61	−10.08	4.29	5.79

2.6 Validation of the Model

For most modeling exercises a validation of simulation results should generally be conducted to ensure model accuracy and reliability. However, in the present study a validation of the developed BN model is not feasible at this stage, as the model investigates potential future impacts of different management actions that are not yet implemented. Therefore, the judgment of local experts and water authorities was used to validate the model. A workshop with local experts and water authorities was carried out to evaluate the plausibility and acceptability of the modeling results. Additionally, the modeling results were checked with respective scientific findings from literature to ensure consistency and identify potential implausibilities.

3. Results and Discussion

Table 4 illustrates the probability values of an increase in WUE under different water pricing and other management scenarios. To access the impact of the other management actions and agricultural policies, and to determine the best scenario that leads to the highest WUE, a change in the probability value of WUE in the 35 scenarios is compared to the basic scenario (scenario 0), in which water prices only increase at a low level. The magnitude of the probability changes represents the strength of the impact of different scenarios.

3.1. Impacts of Water Pricing on WUE (*Scenarios 0–2*)

When looking at the baseline scenario (scenario 0) (Price A) with a slightly increased water price and *ceteris paribus* conditions, the results show that there is a high chance (39.49%) of increasing WUE by 0%–10%. In Scenario 1 (Price B) the WUE still has a higher chance (34.20%) of increasing by 0%–10%. The results indicate that water pricing may not lead to a significant increase in WUE when irrigation water pricing varies between the current water price (1200 RMB/ha) and the increased level Price B (1500 RMB/ha). There is strong evidence that this level of water price increase is still not sufficient to affect users' behavior and improve the capacity of the supply system. Those results corroborate the findings of Amayreh *et al.* [76] and Vasileiou *et al.* [77], who found that the price for irrigation water is rather inelastic, which means that there is no significant agricultural water demand reduction with a slightly increased price. In contrast, there is a higher chance (34.70%) of WUE increasing by 10%–20% under Scenario 2 (Price C). This shows that a significant increase in water price (by 100%) may lead to higher WUE. However, stronger increases in water price may also lead to a significant reduction in crop production and farm income [21]. Thus, economic consequences and external effects need to be assessed with great care before the implementation of such significant increases in irrigation water price.

3.2. Impacts of Water Pricing and Changes in Water Pricing Practices on WUE (*Scenarios 3–8*)

In scenarios 3 (Price A + Volumetric water pricing) and scenario 6 (Price A + Differential water pricing), WUE still has a higher chance (37.93% and 37.33%) of increasing by 0%–10%. However, the probability shows a slight decrease (1.56% and 2.16%) compared to the base case. Under scenario 4 (Price B + Volumetric water pricing), scenario 5 (Price C + Volumetric water pricing and scenario 7

(Price B + Differential water pricing), WUE has a higher chance (33.96%, 34.68% and 33.99%) of increasing by 10%–20%, while Scenario 8 results in a significant increase in water WUE, meaning that WUE has a higher chance (35.21%) of increasing by 20%–30%. The results of these scenarios indicate the importance of changing the water pricing system to volumetrically measured systems such as volumetric water pricing and differential water pricing. They also indicate that the impacts of differential water pricing are much stronger than volumetric water pricing, which leads to a significant increase in WUE. Water users have no incentive to save water when the water price is determined on a non-volumetric basis. Therefore the volumetric water pricing system clearly is the preferable option when advancing water pricing policies in the region [70,78]. Still, a mere adjustment of water pricing practices will most likely not lead to a substantial increase in water use efficiency, as identified by several case studies (e.g., [24,25,33]). If farmers have no capacities (financial, technological, know-how) to adjust their crop management to efficiently react to the increased cost of water, the proposed policies will most likely not lead to the desired water conservation, but instead have a substantial negative impact on rural development [21]. It is therefore crucial to integrate additional (supportive) agricultural policies to improve the effectiveness of water pricing, as the results below show.

3.3. Impacts of Water Pricing and Agricultural Policy Intervention on WUE (*Scenarios 9–14*)

3.3.1. Impacts of Advancing Agricultural Extension Services (Scenarios 9–11)

Under scenario 9 (Price A + Advanced agricultural extension), WUE has a higher chance (37.67%) of increasing by 0%–10% compared to baseline conditions. Similarly, the probability decreased slightly (−1.82%) compared to the baseline. Under scenarios 10 (Price B + Advanced agricultural extension) and 11 (Price C + Advanced agricultural extension), there is a higher chance (34.03% and 34.96%) of WUE increasing by 10%–20%. The results show that advancing the agricultural extension system has a positive effect on WUE improvement. A major global challenge in advancing agricultural production is that research findings and new technologies are not effectively transferred to farmers [79], which causes an increasing gap between actual agricultural practices and the potentials of modern agriculture. In this respect, advancing agricultural extension services may constitute a key trigger to improving farmers' WUE and overall agricultural productivity.

3.3.2. Impacts of Increasing Subsidies (Scenarios 12–14)

Under scenario 12 (Price A + Increased subsidy), WUE has a higher chance (35.49%) of increasing by 0%–10% compared to the baseline. Under scenarios 13 (Price B + Increased subsidy) and 14 (Price C + Increased subsidy), there is a higher chance (34.60% and 34.90%) of WUE increasing by 10%–20% compared to the baseline. The results show that fully increased subsidies for advanced irrigation technology lead to a strong increase in WUE. Under the non-volumetric water pricing system, farmers are obviously less willing to conduct the necessary investments for advanced irrigation technologies, as they do not benefit directly from saving water. Also, the subsidization of advanced irrigation technology will be more effective under the volumetric pricing mechanisms presented by VWP and DWP [20].

3.4. Comparison of Baseline and Most Promising Scenario (Scenarios 0 & 35)

The results show that scenario 35, which is a combination of increasing water pricing at a high level, changing the water pricing system to differential water pricing, increasing subsidies for advanced irrigation technology, and advancing agricultural extension services, is the most effective scenario, leading to the highest WUE. Scenario 35 suggests remarkable changes in the probability of WUE compared to the baseline scenario 0 (*cf.* Figure 3). These results demonstrate that adoptions in water pricing mechanisms need to be supported by additional adjustments and agricultural policies to achieve significant increases in WUE.

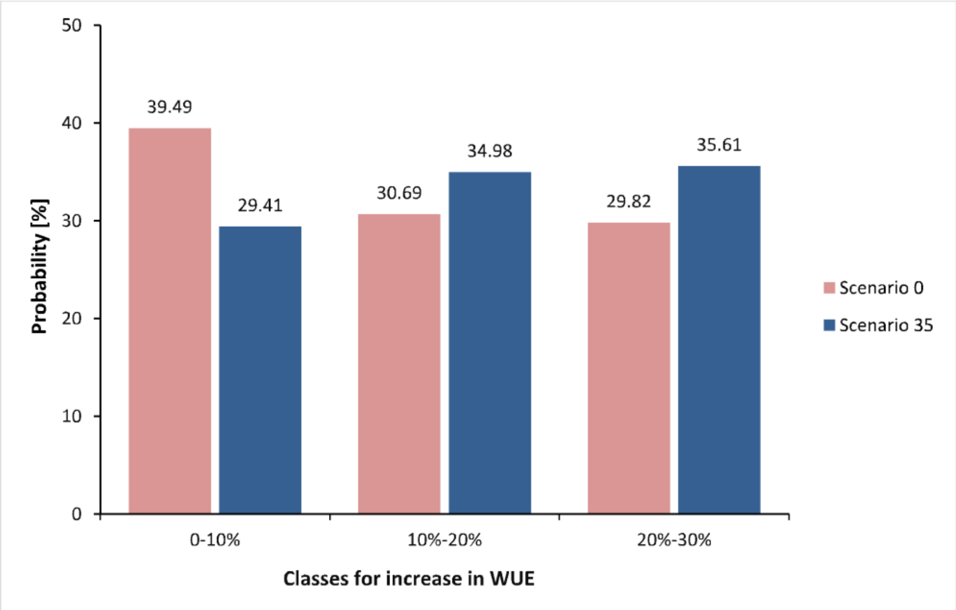

Figure 3. Probability value of the increase in WUE under baseline conditions (scenario 0) and the best combination of policy measures (scenario 35).

3.5. Challenges and Limitations of the Participatory BN Modeling Approach

Despite the obvious advantages of BN modeling, including its ability to integrate data from different disciplines and sources and its potential to clearly visualize complex interrelations, the approach also has several limitations. For instance, the participatory BN modeling approach is very time- and energy-consuming, and the outcome of each individual expert interview, including its viability and usefulness for the overall research procedure, cannot be planned in advance. A high rate of flexibility and persistence is crucial to keep the involved stakeholders motivated throughout the participatory exercises. In this regard, the methodological complexity of Bayesian modeling constitutes a specific challenge, with the local Chinese experts being rather inflexible to leave their trained domain and get involved with systems thinking.

Furthermore, a general reluctance of local Chinese experts to express their personal perception of potentially critical issues (in our case water scarcity) to members of foreign institutions needs to be recognized. Similar challenges were also faced by other foreign research groups conducting participatory research in China, as described by Siew and Döll [80] and van den Hoek *et al.* [81]. It is therefore critical to establish sufficient trust between the research team and the local experts to avoid a pure repetition of official opinion during interviews. Besides, the participatory process requires substantial time investments by the participating local experts, which they have to arrange under the condition of completing their actual tasks and responsibilities. Under these conditions, it is essential to convince the participants of the importance of the research topic and the usefulness of the research method.

Furthermore, the trade-off between completeness of the factors to be considered in the causal networks and manageability of the causal networks requires careful consideration and target-oriented communication with the involved experts during group discussions. Intensive mediation is also crucial, when a minimum consensus is required among members of different domains (e.g., ecological and agricultural experts) regarding the causal and probabilistic relationships among factors.

A specific limitation of the applied approach lies in its limited capability to consider the spatial and temporal variation of the water resource status within the study region. In the study region the water resource situation varies along the 1321-km Tarim River, with water quantity and quality generally degrading downstream and fluctuating seasonally [9]. Specific approaches exist in BN modeling to cope with such spatial and temporal dynamics. They may either be considered by an additional node [82], or separate casual networks can be prepared for each temporal and spatial state [83], which is tedious [38] and adds additional complexity in the participatory process. Similarly, the potential integration of empirical models into BN modeling, as suggested by Castelletti and Soncini-Sessa [84], was considered improper in the present study, due to increasing complexity being undesirable for the participatory approach applied.

4. Conclusions

A Bayesian network model was developed to determine the effects of water pricing policy on WUE along the Tarim River. Together with local experts from different relevant domains, the key factors of the current agricultural water management system were identified, their relationships determined, and their probabilistic interdependencies quantified. Through the participatory modeling approach, expert knowledge and empirical data could be integrated and a clearer picture of the current situation and the opportunities related to improving WUE in the Tarim region could be drawn. For conducting the participatory approach it was crucial to develop sufficient trust between the local experts and the research team to be able to make the experts' knowledge and perceptions operational. The complexity of the probabilistic concept of BN modeling furthermore required strong effort and persistence from the research team to keep participants motivated throughout the iterative participatory approach.

The BN model results show that a mere increase in water price, even to a high level, would have only a limited positive impact on regional WUE. Moreover, the results show that additional adjustments and supportive agricultural policies such as adoption of volumetric water pricing, increasing subsidies for advanced irrigation technology, and advancing agricultural extension services are necessary to significantly improve WUE. The model finally suggests that a strong increase in water price combined with differential water pricing, increased subsidization for irrigation technology, and improved agricultural extension services proved the best scenario, leading to the highest increase in

WUE. Such adjustments in the current agricultural water management system would require substantial efforts from both the agricultural and the water-related administrative bodies in the Tarim region. As such, the participatory modeling exercise realized joint communication, understanding, and mutual learning among different stakeholders for better decision-making.

Acknowledgments

This research was embedded in the SuMaRiO (Sustainable Management of River Oases along the Tarim River) project, funded by the German Federal Ministry of Education and Research through the "Sustainable Land Management" program. We furthermore want to thank all SuMaRiO partners who contributed to this research.

Author Contributions

Yusuyunjiang Mamitimin, Til Feike and Reiner Doluschitz participated in the design of the study. Yusuyunjiang Mamitimin performed the data collection, analysis, and preparation of the first draft of the manuscript. Til Feike and Reiner Doluschitz supervised the data collection and analysis, and Til Feike helped with the preparation of the final manuscript. All authors reviewed the final manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

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2.5 Cotton Production, Land Use Change and Resource Competition in the Aksu-Tarim River Basin, Xinjiang, China

Publication IV

Appiah, M.K.; Feike, T.; Wiredu, A.N.; Mamitimin, Y. (2014): **Cotton Production, Land Use Change and Resource Competition in the Aksu-Tarim River Basin, Xinjiang, China**. Quarterly Journal of International Agriculture 53(3): 243-261.

Abstract

This paper assessed cotton production and land use change (CPLC) and resource competition along the Aksu-Tarim River (ATR) of Xinjiang, China. Trend analysis, correlation analysis, and the Comparative Advantage Indicies (CAI); Efficiency Advantage Index (EAI), Scale Advantage Index (SAI) and Aggregated Advantage Index (AAI) analysis were used in guiding efficient resource allocation for sustainable cotton production; minimize resource competition and conflict in the arid region. The results revealed a relative variation in comparative advantages (CA) in cotton produc¬tion among upstream and downstream farms, and inside and outside Bingtuan between the years 1989 to 2009. CA for cotton production and agricultural land use area was observed for counties along the upper reaches of the ATR than their counterparts. Furthermore, CPLC were more responsive to policies than market price. Also, human, population, proximity of cotton farms to a water source, and cotton production was the major drivers of land use. Finally, key measures that could impact future sustainable cotton development were discussed based on CAI and ecology.

Quarterly Journal of International Agriculture 53 (2014), No. 3: 243-261

Cotton Production, Land Use Change and Resource Competition in the Aksu-Tarim River Basin, Xinjiang, China

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Abstract

This paper assessed cotton production and land use change (CPLC) and resource competition along the Aksu-Tarim River (ATR) of Xinjiang, China. Trend analysis, correlation analysis, and the Comparative Advantage Indicies (CAI); Efficiency Advantage Index (EAI), Scale Advantage Index (SAI) and Aggregated Advantage Index (AAI) analysis were used in guiding efficient resource allocation for sustainable cotton production; minimize resource competition and conflict in the arid region. The results revealed a relative variation in comparative advantages (CA) in cotton production among upstream and downstream farms, and inside and outside Bingtuan between the years 1989 to 2009. CA for cotton production and agricultural land use area was observed for counties along the upper reaches of the ATR than their counterparts. Furthermore, CPLC were more responsive to policies than market price. Also, human, population, proximity of cotton farms to a water source, and cotton production was the major drivers of land use. Finally, key measures that could impact future sustainable cotton development were discussed based on CAI and ecology.

Keywords: cotton, resource competition, efficient resource allocation, comparative advantage, Xinjiang, China
JEL: Q00, Q1

1 Introduction

Xinjiang leads in agricultural outputs in China, especially cotton production (SCULL, 2008) and is ranked first among all the other cotton producing provinces in the country. Cotton is one of the major crops grown in the region which provide employment for over 10 million people through the textile industry, hence serving as a major source of livelihood of the people (UNEP, 2002). The Tarim River lies in the Northwest China and is the country's largest inland river that supply all human water activities in the region, as similarly found by SCULL et al. (2008) and LEIWEN et al. (2005) (n.d). The river receives its sources from snow and glacier melt in addition to the rainfall from the surrounding mountain ranges. Xinjiang is located in the northwest of China. Xinjiang prefecture is the largest province among the five autonomous regions. It has an area of 1,600,000 sq km (625,000 square miles), and a population of at least 16 million. In 2004, the region harvested 1,345,000 tons of cotton on 997,000 hectares of arable land (XINJIANG STATISTICAL YEARBOOK, 1990-2010, and XPCC, 2010 (XPCC or Bingtuan = Xinjiang Production and Construction Corps)). Multi-faceted factors such as favourable climatic conditions along the Aksu-Tarim River; yearly sunshine between 2,500 to 3,000 hours, average annual rainfall around 150 millimeters (ml), and pivoted the successful higher productivity in cotton production in the region over the last two decades (from 1989-2009).

However, the capability of Xinjiang to keep China's number one cotton production status in the world (MEYER et al., 2008) has suffered setbacks from resource compete-tion that emanate from persistent water scarcity and increasing irrigated agricultural land over the last twenty years in the Aksu-Tarim River. Strong resource competition and conflicts among the different user groups, creates pressure on the scarce water and land resources that threatens the sustainability of cotton production along the river in the arid region. Furthermore, the increasing demand for a higher percentage of cotton produced from the local region (SINDELAR et al., 2011), pose ecological problems in the downstream cotton farms as the population settlement towards the upper reaches of Tarim River is at an alarming rate. The Chinese government's policy of bridging the cotton trade balance deficit by encouraging higher production to meet industrial demand, further worsen the intense competition for water and land resources among different users. Hence, all threatening the livelihood of farmers and cotton related workers within and around the various counties, Bingtuan or Xinjiang Productions and Construction Corps (XPCC), as well as the Aksu Administrative Offices and the Bayangol Mongol Autonomous prefectures.

Effort from previous studies that have evaluated comparative advantage of cotton production such as YU et al. (2006), only focused on the whole of Xinjiang using data from 1996 to 2003 and found that China enjoyed comparative advantage. Whilst comparing sustainability of cotton production between China and Australia, ZHAO et al. (2009), used time series trends and correlation estimates between 1980 and 2006. The study found that China's relative access to reliable water supply enabled cultiva-tion of larger area and resulting higher cotton output than that of Australia. In addition ZHONG et al. (2000) on the other hand, only evaluated comparative advantages in grain production in China. In that study, indicators such as Domestic Resource Cost (DRC), Net Social Profitability (NSP), Efficiency Advantage Index (EAI), Scale Advantage Index (SAI) and Aggregated Advantage Index (AAI) were used. They found that efficiency advantages in grain varied across China and that efficient allocation of resources would improve grain production.

Unlike YU et al. (2006) who focused on the period between 1999 and 2003, this paper extended the period from 1989 to 2009. The earlier studies considered the whole of Xinjiang province as a single unit. This paper disaggregates the analysis by location (i.e. inside XPCC or Bingtuan and outside XPCC, and upstream - downstream). More so, the paper combines trend analysis, and estimate of comparative advantage indicators to evaluate the economics of cotton production and agricultural land use change along the Tarim River. Correlation analysis was used to assess the relationship between the world market price of cotton and cotton production in China.

2 Material and Methods

2.1 Study Area

The objective of the study was to assess the economics of cotton production and land use change development along the Aksu-Tarim Region – a sub region of the Xinjiang Uighur Autonomous Region (XUAR). Xinjiang is located in the northwest of China. Xinjiang prefecture is the largest province among the five autonomous regions. These regions include Guanqxi, Inner Mongolia, Ninqxia, and Tibet. It lies within longitudes 79' N and longitude 63' E. Xinjian's area, 1,600,000 sq km (625,000 square miles), which is about one-sixth of China's land mass is greater than the size of California (YU et al., 2006). Its mean annual rainfall is just around 150 millimeters (ml) on average. This provides a low humidity appropriate for the production of high quality agricultural products especially different types of cotton. The region recorded total grain output of 7.06 million tons and more than 34.59 million head of livestock in the year 2004 (YU et al., 2006). The output of staple crops increased significantly, with exceptional production amounts of sugar beets and cotton.

The Aksu-Tarim River is known for its economic support of the Xinjiang autonomous region by way of offering a distinctive, dynamic climate conditions that support all types of economic activities, especially cotton production. As a result of this and other factors such as changing climatic condition in the region, the Tarim River Basin Water Resource Commission founded in 1997 to oversee the management of the river. The commission was mandated to protect the river from over withdrawal and complete drying up. In addition, the commission fixes and allocate water quota for all economic activities in the arid region, including farming activities (THEVS, 2011). It has five bureaus under its control, including Aksu and Bayangol Prefectures, with the exception of the XPCC whose operate under the army and therefore cannot be controlled by the commission (see THEVS, 2011, for more details).

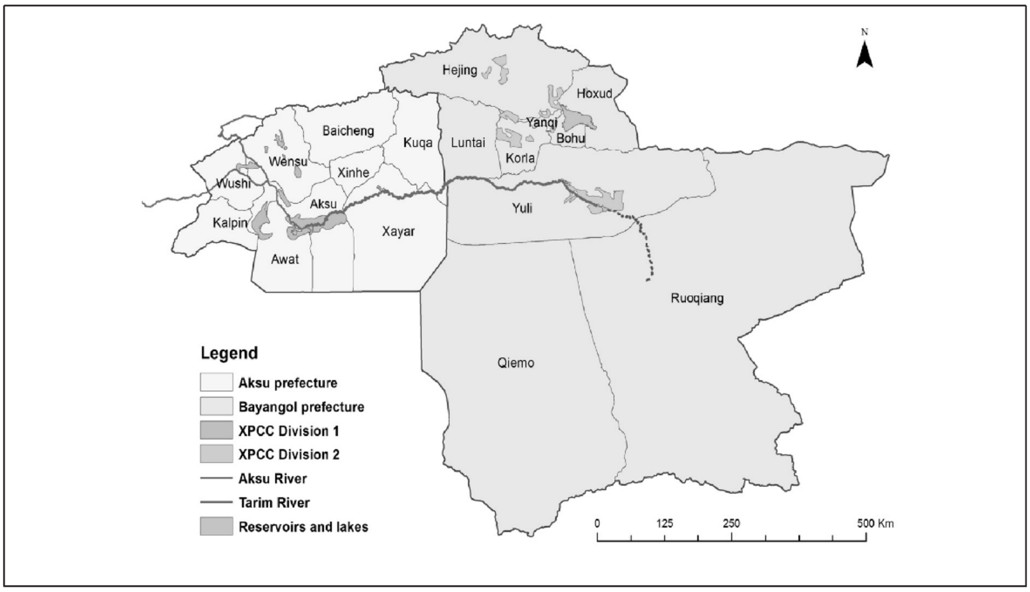
Most farmers in this region use drip irrigation; more especially the state farms (XPCC) and the rest result to the flooding method. More importantly, about 70% to 80% of irrigation water for agriculture in the region comes from the Aksu-Tarim River. Land area is therefore, reclaimed from the desert land in this arid region, and converted to agricultural land conditioned that irrigation water is available. Among the major crops grown in the Xinjiang over the periods from 1989 to 2009, include cotton, grain, sugar beets, and oil bearing crops. Other crops such as watermelon, soy bean, apricots, tubers, lucernes, medicinal plants, apple, and other fruits are considered minor crops.

The study area covers 2 autonomous prefectures (Aksu and Bayangol), 2 cities, 17 counties and the Xinjiang Production and Construction Corps (XPCC Bingtuan) divisions one and two. Both Aksu and the Bayangol prefectures have autonomous status under the Chinese administration orders and comprise the entire Aksu-Tarim-Basin on the Chinese territory (Figure 1a). The XPCC farms are state farms under the control of the military and all production decisions are taken at the state level (top-down approach; by the military regulations) (XPCC, 2010). They have mechanized and modern farming structures and well planned system of farming units called 'divisions'. The divisions are not single farm unit rather collection of several farm units. Contrary, outside XPCC farms are private household mostly un-organized (with few cotton farmer groups linked to licensed cotton buyers associations) farmers who take decisions at the grass root (farm level), and significantly lag behind state farms in terms of organization, access to inputs, technology and research findings.

The selected counties (Figure 1a) under Bayangol prefecture comprises of Korla City, Luntai (Bugur) County, Yuli (Lopnur) County, Ruoqiang (Qarkilik) County, Qiemo (Qarqan) County, Hejing County, Hoxud County, Bohu (Bagrax) County; Aksu Administrative Offices also consists of the Aksu city, Wensu (Onsu) County, Kuqa County, Xayar County, Xinhe (Toksu) County, Baicheng (Bay) County, Wushi (Uxturpan) County, Awat County, and the Kalpin County.

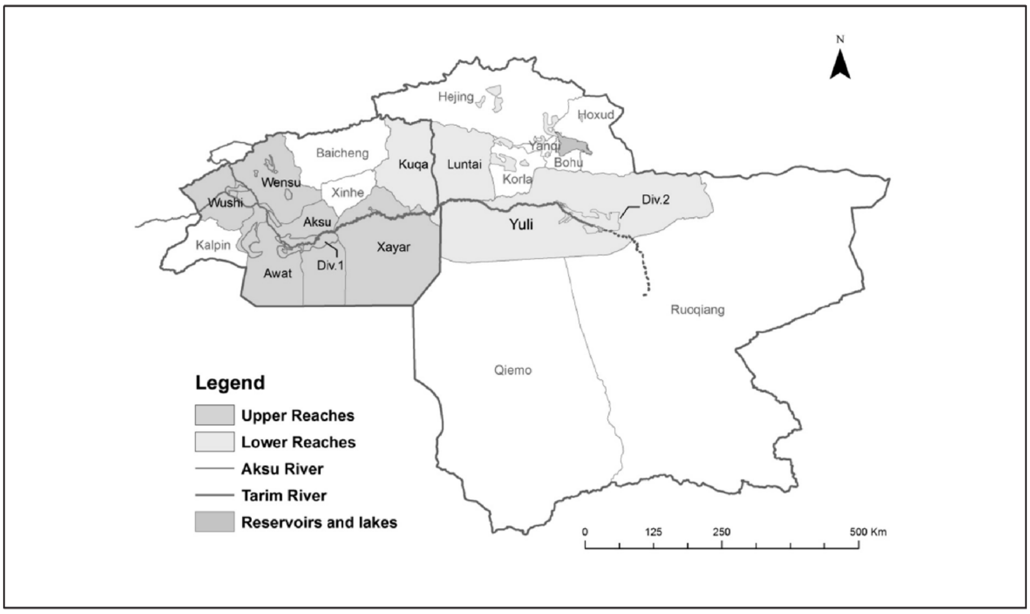
The three administrative areas were purposefully and strategically stratified according to the geographical location of various farming sites in relation to the reaches of Tarim river (Figure 1b) into; the Total Xinjiang, which includes all the farms in the three prefectures; upstream county level also contains farms in Wushi, Wensu, Aksu City, Awat, Xayar, and Division one; the downstream county level, which also comprises of farms located at Kuqa, Luntai, Yuli and the Division 2; outside XPCC farms, which also consists of Wushi, Wensu, Aksu city, Awat, Xayar, Kuqa, Luntai and Yuli; and finally inside XPCC farms (state farms), which also consisting of Divisions one and two.

Figure 1a. Prefectures of Aksu-Tarim River Basin



Source: generated using Xinjiang Statistical Yearbook (1990-2010)

Figure 1b. Farm locations along Aksu-Tarim River



Source: generated using Xinjiang Statistical Yearbook (1990-2010)

2.2 Method

This study first employed trend analysis to show the extent to which land resource is indirectly influenced by water resource availability and its accompanying cotton output. Secondly, the EAI, SAI and AAI, in addition to the statistical correlation estimates were employed to estimate efficiency and patterns of cotton production over the 20 year period. The trend analysis explained how the historical cotton production and yield levels per hectare of arable land resource varied among farmers in the study region. That is the period between years 1989 to 2009, given the scarce nature of water resource in the arid region. In addition, market price-output linkages were established. However, the paper did not attempt to evaluate profitability nor total factor productivity due to local price distortions and unavailability of cost components such as input prices of factors of productions. In Equation 1, EAI measure how efficiently a crop grows in a given region relative to the growing of other crops in that same region. It is calculated as the relative yield ratios of one crop in one region to the average yield of all crops in that same region to the yield of the same crop in the nation related to the average yield of all crops in the nation. The relative yield of the *i*th crop in the region is given as $(\mathrm{Yc1}/\mathrm{Aa1})$, the relative yield of all crops in the region also given as $(\mathrm{Nyc}/\mathrm{Nya})$.

$$EAI1i = ((Yc1i/Aa1i))/((Nyc/Nya)) \tag{1}$$

Where, EAI1i = the efficiency advantage index of the *i*th crop - cotton, grown in region 1, Yc1i = the yield of the *i*th crop - cotton, in region 1, Aa1i = the average yield of all crops in region 1, Nyc = the national yield of the *i*th crop - cotton, in the Aksu-Tarim region (ATr), Nya = the national yield of all crops in the ATR. EAI calculations (Table 3) assume that; (some level of) competitive market structures exists in that region's economy, and there exists flexibility in mobility of technological diffusion YU (2006). In addition, the adoption of agricultural production system in that region or country is also assumed feasible. Hence, the EAI is used as a tool to measure the relative efficiency based on existing natural resource endowment, and other socio-cultural factors as well as other economic factors peculiar to the local conditions. If EAI1i value is greater than or equal to 1, it is interpreted as the yield of the ith crops - cotton, in region 1 on average, relative to yield of all other crops grown in the same region as being higher than that of the national average. That is, a region 1 has a comparative advantage in growing the ith crop - cotton, as compared to all other crops grown in the region. However, EAI1i value less than 1, indicates that the yield of ith crop - cotton, in the region 1, relative to yield of all other crops in the same region, is lower than that of the national average, and therefore has no yield or efficiency advantage for growing) ith crop - cotton, in region 1. The scale advantage index (Table 4) shows the extent to which certain crop(s) - cotton, is (are) grown in a particular region is (are) intense relative to that at the national average. The relative planted area of the ith crop-cotton, in the region is given as $(Ac1i/Aa1i)$, the relative planted area of all crops in the region given as (Nci/Na).

$$SAIij = ((Ac1i/Aa1i))/((Nci/Na)) \qquad (2)$$

Where: SAI_{1i} = the scale advantage index of crop i -cotton, in region 1, $Ac1_i$ = the planted area of ith crop - cotton, grown in region 1, $Aa1_i$ = the total planted area of all crops grown in region 1, Nc_i = the total planted area of the ith crop - cotton, grown in the Aksu-Tarim Region and Na = the overall (total or national) planted area of all crops grown in the region. If SAI > 1, then the scale of the concentration of the ith crop - cotton, grown in region 1, is higher than the average national ratio of concentration in the Aksu-Tarim Region. This means that producers in region 1 prefer to grow more of the ith crop - cotton, compared to other producers in the nation. An SAI value less than 1 indicates that the degree of concentration of the ith crop - cotton, in region 1 is lower than that of the average national ratio in the region. This implies that, it is less profitable for farmers in region 1 to grow crop i - cotton, as compared to growing other crops in the region and vice versa. It indicates that producers in region 1 prefer to grow less of the crop i - cotton, as compared to other producers in the nation. Warranting the underlying assumptions that competitive market structures exist; farmers have control over crop mix, and can respond to either the market price or cost variability or both, the concentration levels are determined by economic factors or the profit margins of certain crops grown in the region. Larger index values are preferred and farmers are expected to commit more resources to the production of those crops concerned in the region. AAI (Figure 4) is an index for estimating cumulative advantage of specific crops in one region relative to the national average. It is calculated as the geometric average of the EAI and SAI as shown below

$$AAIji = \sqrt{((EAIji*SAIji))} \qquad (3)$$

AAIji (Table 5) value greater than or equal to 1, means that the jth region has an overall comparative advantage over the national average for the growing of ith crop in the region, whilst AAIji value less than 1, means that the jth region does not have the overall comparative advantage over the national average of growing ith crops. (The ‘overall values’ = the Total Tarim County Level- in the Aksu-Tarim Region, were used as the 'Regional or national values').

3 Data

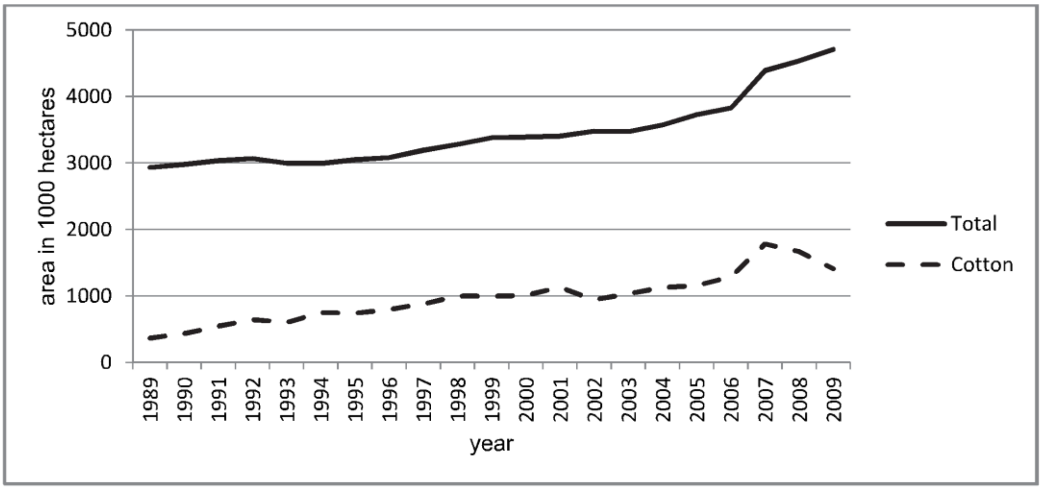
The study was based on time series data collected from the Xinjiang Statistical Yearbooks of China Statistical Service and the XPCC (appendix), the USDA, and IndexMundi commodities listings. Specifically, the data included land-use measured in hectares for the periods between the years 1989 to 2009. For the same period, data on output, measured in tons, of cotton and other crops were used. In addition, domestic and world market prices of cotton were used. The prices were quoted in US dollars.

4 Results

4.1 Analysis of Relative Land Use Changes and Cotton Production Trends

The results indicate that land use change in general for all farming activities increased significantly (2.8%) in the region over the period from 2,934 thousand hectares in the beginning year to over 4,700 thousand hectares at the terminal period (Figure 2). Table 1 summarizes the average growth of an area of land reclaimed for growing all the various farming crops over the period in Xinjiang. With the 2.8 % increase in land for farming in Xinjiang, upstream farms reclaimed 0.8% over downstream farms, whereas outside XPCC had 1.3% over the state farms (XPCC). However, farmers reclaimed 7.9% area for cotton cultivation as against 1.8% for other crops. Land reclaimed for cotton production analogously followed suit in terms of upstream-downstream, and outside - inside XPCC farms respectively in order of magnitude. In contrast, the rate of change for other crops was at a decreasing rate for downstream and XPCC farms.

Figure 2. Overall land use change trend in the Aksu-Tarim region



Source: generated using Xinjiang Statistical Yearbook (1990-2010)

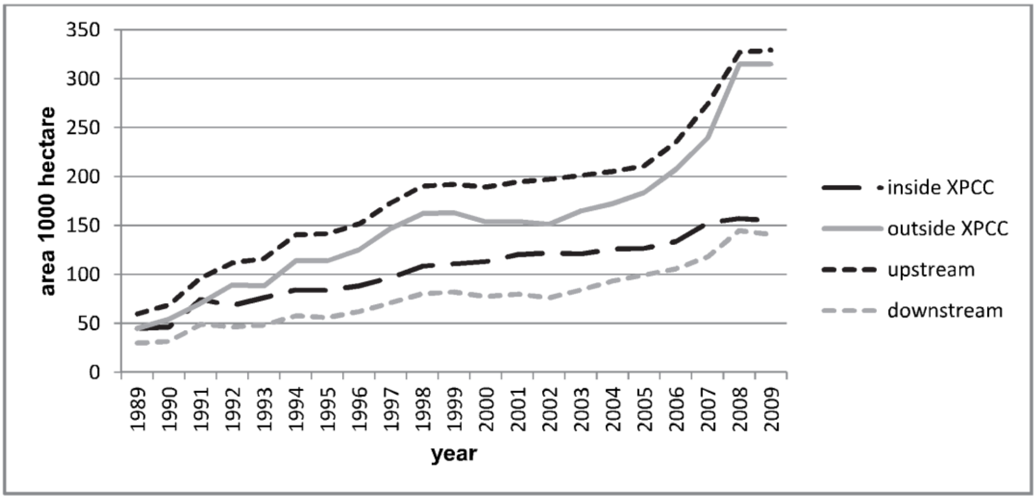
Table 1. Growth of an area of land reclaimed for all farm crops

	Xinjiang	Upstream	Downstream	XPCC	Outside
Xinjiang	2.8	4.0	3.2	2.9	4.2
Cotton	7.9	10.3	9.8	7.4	12.3
Other	1.8	1.0	-0.4	-0.3	0.9

Source: generated using Xinjiang Statistical Yearbook (1990-2010)

However, examining the absolute land use trend for cotton below (Figure 3) gives a lucid pattern over the period. The Figure depicts the initial galloping increasing pattern for all the areas with the exception of the XPCC until the year 1999, afterwards both upstream and outside XPCC farms sagged in to assume their initial pattern. In converse, the XPCC and downstream farms' trend were smooth with a tendency of decreasing in land reclamations.

Figure 3. Land use trend for cotton cultivation in the Aksu-Tarim region



Source: generated using Xinjiang Statistical Yearbook (1990-2010)

The tremendous increases in land use in this arid region were attributed to human population growth in the region. This is in agreement with the results by Scull et al. (2008), YU et al. (2006), MEYER et al. (2008) and TANG and DENG (2010). As more people settle close to a water source for cotton production, more hectares of desert and virgin lands are converted for agricultural activities.

Analogously, farming output production levels for all crops over the 20 year period increased on average per year by 8.6% provincially, 0.6% of upstream less than that of downstream, and 0.2% in outside XPCC farms less than that of the state farms (Table 2). With a 13.2% as against 1.5% (other crops) increased in cotton output amount, on average, per year, upstream farms enjoyed a higher increase in cotton production, 15.9% as against 13.2% for downstream farms. Whereas outside XPCC farms realized 17.7% growth in cotton output, farms within XPCC only observed 12.7% growth. Implicitly, higher human population in upstream (SHEN et al. 2010), lead to the use of more water resources for cotton production to the disadvantage of downstream farms, hence reflecting in cotton production amounts.

Table 2. Growth of output of all farm crops

	Xinjiang	Upstream	Downstream	XPCC	Outside
Xinjiang	8.6	5.8	6.4	6.2	6.0
Cotton	13.2	15.9	13.2	12.7	17.7
Other	1.5	5.6	6.0	5.7	5.4

Source: generated using Xinjiang Statistical Yearbook (1990-2010)

4.2 Comparative Advantage in Xinxiang's Cotton Production along the Aksu-Tarim River (ATR)

The results of comparative advantage in cotton production and land use developments along the reaches of ATR in Xinjiang from 1990 to 2009 are summarized in Tables 3 through 5, and Figure 4. Over the 20 year period, most farms upstream of ATR had an efficiency in cotton production with a rising pattern (EAI = or >1) (Table 3), ahead of downstream farmers with only Division one achieving efficiency in 1/20 years. Meanwhile, Inside and Outside XPCC exhibit a wide difference in efficiency between, 1990 to 1999, and 2009 onwards. The development was supported by available land use for cultivating cotton through conversion of land use for other crops to cotton production (CHINA GOVERNMENT FIVE YEAR PLAN POLICY), proximity and availability of water supply.

Table 3. Efficiency Advantage Index values for cotton (estimated using Eqn. 1 and data at appendix 1 and 2)

Year/ EAI	Up-stream	Down-stream	Outside XPCC	Inside XPCC	Year/ EAI	Up-stream	Down-stream	Outside XPCC	Inside XPCC
1990	1.27	0.90	0.95	1.16	**2000**	1.50	0.75	1.35	1.01
1991	1.35	0.82	0.81	1.43	**2001**	1.37	0.74	0.94	1.20
1992	1.38	0.96	1.28	1.13	**2002**	1.46	0.81	1.00	1.27
1993	1.48	0.94	1.28	1.18	**2003**	1.51	0.83	0.95	1.37
1994	1.40	0.82	1.11	1.19	**2004**	1.55	0.81	0.94	1.41
1995	1.42	0.83	1.06	1.26	**2005**	1.57	0.82	0.98	1.37
1996	1.27	1.04	1.21	1.12	**2006**	1.61	0.83	0.97	1.44
1997	1.40	0.89	1.11	1.27	**2007**	1.84	0.82	1.07	1.50
1998	1.42	0.89	1.16	1.25	**2008**	1.76	0.9	1.14	1.49
1999	1.44	0.85	1.16	1.20	**2009**	1.83	0.88	1.19	1.50

Source: generated using Xinjiang Statistical Yearbook (1990-2010)

The SAI results (Table 4) showed a relatively high concentration of cotton cultivation per hectare of land available for cotton production in upstream farms over the 20 year period at a decreasing rate as against downstream farms with opposite trend. These were due to the differences in available arable land which is relatively limited to down-stream farms as compared to upstream farms. Thus farmers at downstream increased concentration of cotton cultivation in order to increase marginal profit (compete for market share). A similar pattern is observed for inside and outside XPCC, with the exception of farms in Division one. This could be attributed to factors such as better administrative management, availability of modern farm machinery, access to research findings, sustained water supply (LEIWEN et al., 2005) which Division one benefited as compared to other farms outside XPCC regions.

The AAI results (Table 5) depict that cotton farms located upstream of the river enjoyed the overall comparative efficiency in production of cotton above downstream farms. Farmers in areas such as Wushi County, Wensu, Aksu city, Awat, Xayer and Division one, achieved efficiency, scale and overall comparative advantages in cotton production. A similar pattern is observed for farms outside XPCC over inside XPCC farms with the exception of the years 2003 till 2009 where reverse occurs.

Table 4. Scale Advantage Index for cotton (estimated using eqn. 2 and appendix 1 and 2 data)

Year/ SAI	Up-stream	Down-stream	Outside XPCC	Inside XPCC	Year/ SAI	Up-stream	Down-stream	Outside XPCC	Inside XPCC
1990	1.27	1.18	1.76	0.99	**2000**	1.20	1.06	1.34	1.05
1991	1.23	1.24	1.86	0.91	**2001**	1.22	1.11	1.43	1.04
1992	1.28	1.03	1.52	1.03	**2002**	1.23	1.02	1.47	0.99
1993	1.20	0.99	1.49	0.93	**2003**	1.19	1.04	1.39	1.01
1994	1.25	1.04	1.44	1.04	**2004**	1.15	1.06	1.32	1.01
1995	1.27	1.01	1.43	1.05	**2005**	1.14	1.07	1.32	1.01
1996	1.24	1.02	1.37	1.06	**2006**	1.12	1.02	1.22	1.01
1997	1.22	1.02	1.29	1.08	**2007**	1.12	0.96	1.12	1.04
1998	1.18	1.05	1.28	1.05	**2008**	1.14	1.01	1.12	1.09
1999	1.22	1.08	1.32	1.09	**2009**	1.13	1.12	1.25	1.07

Source: generated using Xinjiang Statistical Yearbook (1990-2010)

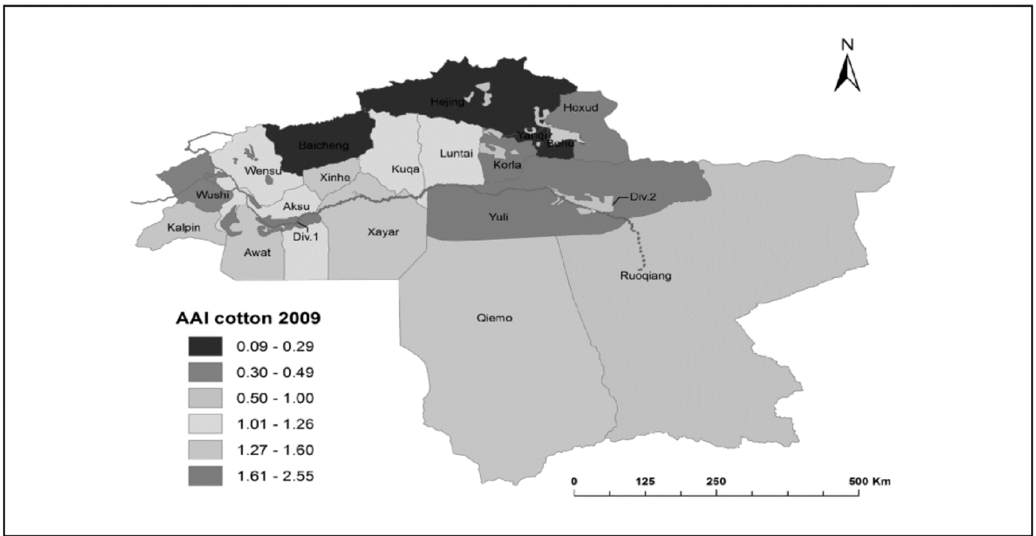
Table 5. Aggregated Advantage Index for cotton (AAI), estimated using Eqn. 3

Year/ AAI	Up-stream	Down-stream	Outside XPCC	Inside XPCC	Year/ AAI	Up-stream	Down-stream	Outside XPCC	Inside XPCC
1990	1.27	1.03	1.29	1.07	**2000**	1.34	0.89	1.34	1.03
1991	1.29	1.00	1.23	1.14	**2001**	1.29	0.90	1.16	1.12
1992	1.33	1.00	1.39	1.08	**2002**	1.34	0.91	1.22	1.12
1993	1.33	0.96	1.38	1.05	**2003**	1.34	0.93	1.15	1.18
1994	1.32	0.92	1.26	1.11	**2004**	1.34	0.93	1.11	1.19
1995	1.34	0.92	1.23	1.15	**2005**	1.34	0.94	1.14	1.18
1996	1.25	1.03	1.29	1.09	**2006**	1.34	0.92	1.09	1.21
1997	1.31	0.96	1.20	1.17	**2007**	1.44	0.89	1.10	1.25
1998	1.29	0.97	1.22	1.15	**2008**	1.41	0.95	1.13	1.27
1999	1.33	0.95	1.24	1.14	**2009**	1.44	0.99	1.22	1.27

Source: generated using Xinjiang Statistical Yearbook (1990-2010)

The current trend of overall CAI (AAI>1) for all counties and Division one and two in the region (Table 5 and Figure 4), indicate an increasing trend of cotton production in terms of comparative advantage, hence showing Xinjiang's potential as a higher cotton producing province over the rest of cotton producing provinces in China. These capacities are high for farms at Aksu prefecture and Division one.

Figure 4. Overall Aggregated Advantage Index values for cotton in the Aksu-Tarim Region



Source: generated using Xinjiang Statistical Yearbook (1990-2010)

4.3 Correlation and Cotton Price Analysis

Table 6 shows correlation estimates between cotton prices and cotton output among various farms along the reaches of the ATR. The price analysis shows that there is a weak linear relation between cotton prices both in China and the world market, and cotton production as well as land resource allocated for cotton farming in the Xinjiang province. The price - output relation for both prefectures from the years1989 till 2009 were positive for the world market prices (current and previous years) and cotton output in Xinjiang (even though not significant) this shows the extent of cotton market openness in China, whilst current and immediate past year's local prices had a negative linear relation to output, with a moderate effect.

Table 6. Correlation values for cotton prices and yield amounts in the Aksu-Tarim Region

Cotton price	Cotton Output	Upstream	Downstream	Inside XPCC	Outside XPCC
World market	0.295	0.261	0.312	0.258	0.293
China	-0.531	-0.545	-0.532	-0.576	-0.512
Wpc_1	0.263	0.206	0.282	0.148	0.296
P1_1	-0.575	-0.609	-0.565	-0.647	0.493

Wpc_1 = the lagged values for cotton prices in the world market and
P1_1 = the lagged values of cotton prices in China.

Source: own calculation using data from P1 from Xinjing Statistical Yearbooks 1990-2009. World market prices from Index Mundi annual commodity prices for the month of March 1990 to March 2009

5 Discussion

The study suggests that the high land reclamation in the region between 1989 and 2009 was mainly due to high human population influx to the region for agricultural activities especially cotton production and human settlements for farm workers. The land resource expansion was higher in both the upstream of the ATR and farming communities outside the XPCC farms than their counterparts. Strategically, higher percentage of hectares of the reclaimed land were allocated for cultivation of cotton, one of the major cash crops grown in the region, around upstream of Tarim river and outside XPCC state farms (STATISTICAL YEARBOOK, 1990-2010, and XPCC, 2010). As postulated by comparative advantage methodology above, farmers only (are willing to) allocated productive resources to the cultivation of crops in which they enjoy comparative advantages. As a result, upstream and outside XPPC farms, with the exception of division one enjoyed a comparative advantage in cotton production over the last 20 years (1989-2009).

Furthermore, significant land use activity around the upstream river may be due to the reason of proximity to water sources, constant water availability and supply for cotton farming (irrigation). Among the key reasons that accounted for the high land use activities for cotton production outside the XPCC farms over their counterparts included; different land control rules for within and outside XPCC farms, decision making process, and the level of technology in cotton production. XPCC farms have a strict land control rules and centralized decision making process which makes land use expansion rate slow as compared to outside XPCC farms. In addition to that, cotton farmers inside XPCC have access to research findings and highly farm machinery that could capitalize on high cotton yield with the same available land as compared to farms outside the XPCC (XPCC, 2010).

The cotton price policy analysis shows an indirect effect of price policy instruments such as Contracted Purchasing Scheme (CPS) in 1999 on decision to convert a piece of land from other uses (such as the growing of other crops) for cotton cultivation. Thus, the policy lead to an increase in cotton production irrespective of market mechanism since the prevailed market prices did not have any significant influence on cotton production amounts. Through the policy, Chinese government gives an advance payment guarantee price between 20% to 25 % to cotton farmers, CHENG et al. (2003), JIA (2004) and FAN et al. (2006) and farmers in return signed an undertaking to supply government with specific cotton output quota. This confirms the vital role played by the provincial government structures in setting cotton prices in the region. This is in agreement with the findings of YU et al. (2006). The same policy might have also accounted for the XPCC's use of more land for the production of other crops than cotton (0.3% higher than outside XPCC, Table 2 above) as they might not have received the CPS from the provincial government, since the XPCC is not under the provincial government.

6 Conclusion

This study analyzed the economics of cotton production and land use change along the Tarim River in Xinjiang-China from 1989 till 2009. The analysis showed that the region enjoys a significant comparative advantage in cotton production along the reaches of the ATR for both Aksu and Bayangol Prefectures. Cotton production amounts in the region are high and vary significantly in comparative advantage wise across the various counties and divisions along the reaches of the ATR. More so, competition for land and water resource use exist due mainly to population increase, cotton production and other agricultural activities which threatens the sustainability of Xinjiang's cotton potentials. Nonetheless, there is tremendous potential to improve resource allocation and to increase cotton production above the potential of transforming the Chinas economy. As cotton producers face more competition from worldwide cotton producing countries such as the United States and Australia, ensuring efficient resource allocation around the Aksu-Tarim River would improve the livelyhood of cotton farmers as well as cotton related workers-textile industries (China, number one in the world). It can be therefore deduced that, water in this arid region is the driving force of income for rural farming households, and therefore, no water supply, no income. Furthermore, embarking on activities other than cotton production at downstream would ensure full allocation of water resource for maximum cotton production at upstream. In addition, reducing human settlement upstream through alternative policies will safeguard the Aksu-Tarim River from a complete drying up at downstream. Thus reducing, the water tension and disputes among farmers at opposing sides of the main water source. And finally, not the least, integrating community based water resource management into the state water management systems, would ensure the life span of the ATR to support cotton production in the region.

In summing up, the suggested policies may be introducing incentives for farmers outside XPCC to use natural resources in a more sustainable way. In other words, to maintain a sustainable agricultural production in Xinjiang, an integrated framework of policies for production, natural resources, and environment is required. The current fragmented institutions and policies inside and outside XPCC should be revised.

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Appendix

Table 7. Crop yield (kg ha^{-1}) between 1990 and 2009

Year	Upstream		Downstream		Outside		Inside		National output	
	All crops	Cotton	All crops	Cotton	All crops	Cotton	All crops	Cotton	All crops	Cotton
1990	3.82	0.96	5.56	0.99	4.49	0.83	6.05	1.14	4.85	0.96
1991	3.57	1.11	4.91	0.93	4.40	1.16	5.05	0.95	4.56	1.06
1992	3.65	1.27	4.31	1.05	4.60	1.01	4.54	1.46	4.61	1.17
1993	3.63	1.35	4.77	1.12	4.58	1.07	4.78	1.54	4.68	1.18
1994	3.76	1.51	5.30	1.25	4.78	1.32	5.03	1.60	4.84	1.39
1995	3.79	1.64	5.48	1.38	4.90	1.49	5.22	1.68	4.98	1.52
1996	4.06	1.18	5.41	1.29	5.34	1.08	5.07	1.40	5.27	1.21
1997	4.23	1.45	5.69	1.24	5.68	1.35	5.35	1.45	5.59	1.37
1998	4.31	1.71	5.96	1.48	5.87	1.63	5.11	1.66	5.67	1.58
1999	4.08	1.47	6.25	1.32	5.68	1.33	5.39	1.57	5.60	1.40
2000	4.30	1.45	6.87	1.15	5.65	1.07	5.84	1.77	5.78	1.30
2001	4.44	1.87	7.81	1.77	5.82	1.82	6.49	1.87	5.87	1.81
2002	4.86	1.80	8.66	1.79	6.87	1.74	7.32	1.87	6.98	1.77
2003	4.67	1.82	8.81	1.88	6.63	1.74	8.06	1.98	6.99	1.80
2004	4.76	1.87	9.27	1.92	6.75	1.78	8.54	2.04	7.21	1.83
2005	4.73	1.98	9.16	2.01	6.78	1.81	8.66	2.26	7.18	1.92
2006	4.79	1.98	9.85	2.10	7.04	1.83	9.32	2.32	7.60	1.95
2007	4.37	2.03	10.46	2.17	7.50	1.84	9.02	2.44	7.90	1.99
2008	4.51	1.85	9.33	1.95	7.46	1.58	9.33	2.48	7.89	1.84
2009	4.92	1.94	10.36	1.96	8.73	2.51	9.84	1.67	8.97	1.93

Source: XINJIANG STATISTICAL YEARBOOK (1990-2010)

Table 8. Land use (ha) between 1990 and 2009

Year	Upstream		Downstream		Outside		Inside		National output	
	All crops	Cotton	All Crops	Cotton	All crops	Cotton	All crops	Cotton	All crops	Cotton
1990	278.4	68.8	138.5	31.7	134.6	54.4	138.5	46.2	576.4	112.3
1991	293.0	96.3	148.1	49.0	150.2	70.7	148.1	74.6	605.2	161.7
1992	304.7	111.7	156.0	46.2	157.3	89.5	156.0	68.5	629.7	180.4
1993	296.4	116.4	149.8	48.5	156.3	88.5	149.8	76.4	605.1	198.0
1994	297.7	140.4	147.4	57.7	155.3	113.8	147.4	84.3	603.6	227.7
1995	304.4	141.8	150.1	56.0	159.5	114.0	150.1	83.7	617.9	227.3
1996	310.5	151.6	154.9	62.2	164.0	125.3	154.9	88.4	632.5	248.8
1997	332.0	173.2	161.6	71.0	175.0	147.2	161.6	97.0	669.0	287.2
1998	345.1	190.4	163.5	80.4	181.0	162.2	163.5	108.6	696.4	327.0
1999	350.0	192.0	169.0	82.1	185.8	163.1	169.0	111.0	709.3	320.0
2000	351.8	189.4	163.6	77.5	188.7	153.7	163.6	113.2	702.4	315.3
2001	362.0	194.6	163.9	80.0	190.0	154.3	163.9	120.2	744.7	328.5
2002	369.1	197.2	171.5	76.3	190.5	151.5	171.5	122.0	729.2	317.2
2003	362.9	201.3	174.9	84.4	187.0	164.8	174.9	120.9	734.5	341.7
2004	367.7	205.2	181.5	93.3	196.9	172.5	181.5	126.0	769.4	372.9
2005	385.8	211.0	192.7	99.4	199.0	183.7	192.7	126.7	817.9	393.7
2006	386.6	235.5	190.2	105.9	199.9	207.7	190.2	133.7	808.4	441.5
2007	388.3	274.1	195.1	118.1	217.6	239.5	195.1	152.6	825.7	518.1
2008	468.8	326.9	234.3	145.0	230.2	314.7	234.3	157.2	988.1	604.8
2009	545.2	329.4	233.8	140.8	231.8	315.1	233.8	155.2	1086.0	583.2

Source: XINJIANG STATISTICAL YEARBOOK (1990-2010)

3 General discussion

This general discussion deals with the major findings of the research. This section does not discuss each paper one by one; the discussion of each paper can be read at its end. The general discussion is divided in five subsections. The first and second section are focused on the major results of the research. The third section focuses on policy recommendations that are aimed at more efficient water use along the Tarim River. The fourth section addresses the application of Bayesian Networks in water resource management. The final section discusses some open questions such as farmers' affordability and institutional aspects of water pricing.

3.1 Irrigation water pricing as a demand management option along the Tarim River

Irrigation water pricing was given particular attention and higher priority dealing with water scarcity problems especially after declaration of the Dublin Statement in 1990s. Some countries have already considered and applied the water pricing policy as the main policy dealing with their water scarcity issues (Dinar, 2000). However, there has been little agreement on the effect of pricing to promote water allocation and water conservation. To date there is a large number of fundamental studies describing the effect of water pricing policies (Caswell *et al.*, 1990; Quba'a *et al.*, 2002; Gómez-Limón and Riesgo, 2004; Noéme and Fragoso, 2004; Bartolini *et al.*, 2007; Dono *et al.*, 2010; Gallego-Ayala, 2012; Medellín-Azuara *et al.*, 2012). In most of these studies, the mathematical programming approach, which is built on the concept of maximizing profit, has been applied to find out the effect of water pricing. The main assumption is that farmers are perfectly rational, and they will make proper changes to increased water price, in order to maximize their profit. The most serious disadvantage of these assumptions is that they fail stimulating the farmers' behavior. Farmers' rationality may be driven by various objectives, which do not fully conform to profit maximization, for instance risk minimization, reduction of workload, or maintaining the access to resources (Ellis, 1993). In addition, farmers may not have comprehensive information on production alternatives available to perform the most adequate changes to their production methods. Thus, the approach of exclusive mathematical programming was criticized that results of the studies that employed profit maximization may be over-estimated or implausible, because they do not fully consider the farmers' particular rationality (Lin *et al.*, 1974; Hazell *et al.*, 1986). To overcome some of the shortcomings above-mentioned, Speelman *et al.* (2009) and Frija *et al.* (2011) applied data envelopment analyses to find out farmers' responses to the changes in irrigation water pricing in South Africa and Tunisia. Still their analyses are based on the assumption that farmers are price responsive to changes to the irrigation water prices. The effectiveness of irrigation water pricing depends on how farmers are able to respond to irrigation water pricing and make proper changes (Ray and Williams, 1999). Thus, there is great importance identifying how farmers respond towards changes to irrigation water pricing.

To find out farmers' responses towards changes of irrigation water pricing, 128 households were interviewed in different parts of the Tarim River Xinjiang Uyghur Autonomous Region, P.R. China in July and August 2012. The results of the study, which are embedded in the second article, indicate that less than 50% of the interviewed farmers would choose to use water more wisely by adopting irrigation technology, shifting crop patterns, or improving farm-management practices. A case study by Liao *et al.* (2008) which used a sample data from 204 farmers in the Sichuan, Shaanxi, and Hebei provinces of China also found similar results that irrigation water pricing may not encourage farmers to use water more efficiently. They also found that most farmers had no incentive to use water saving irrigation, even when water prices doubled or tripled over the current level. On the contrary, almost one-third of interviewed farmers would drill wells to guarantee their water supply and irrigation timing, while 32 of the 128 farmers would choose not to respond to changes in water pricing and will pay higher prices. The results also reveal that increased water prices may further result in the over-exploitation of groundwater resources.

The results of the second paper describe the general situation well and show how farmers respond to changes in water pricing. Several issues, however, need further investigation. First, it is important to find out effects of different price levels and changes in the water pricing practices to the WUE. Second, institutional aspects also need to be considered for the successful implementation of pricing policies. Finally, it is argued that increasing water pricing may not lead to the efficient use of water, unless other relevant agricultural policy options are considered. Thus, it is important to investigate what other agricultural policies are available and how they affect water usage together with irrigation water pricing. In order to find out answers to these issues, a Bayesian network (BN) modeling approach was applied. For the development of the BN model data was collected from preselected sources such as farm surveys, expert interviews and workshops, policy documents, official statistics, and scientific literature. The results presented in the third article show that irrigation water pricing will not lead to efficient water use, when it increases at a low and medium level. Only a strong increase in water pricing will lead to higher WUE. The results also show that adoption of volumetric water pricing systems, guaranteeing the subsidies for advanced irrigation technology, as well as advancing agricultural extension services are necessary for further improving WUE. The results of the study conform to the findings of the case studies by Bazzani *et al.* (2004) and Huang *et al.* (2006), who found that mixed pricing policies, rather than single pricing instruments, were important to achieving efficient water use in agriculture. By reviewing the six case studies, a discussion paper by the World Bank also identified that the availability of a volumetric measuring system, water saving technology and education for public awareness of saving water as well as the education or technological support for irrigation were the key factors to reducing water use, when implementing water pricing as a demand management option (Easter and Liu, 2005).

3.2 Underlying reasons of inefficiency of water pricing along the Tarim River

The results from the both second and third article imply that irrigation water pricing alone fails to achieve efficient water use along the Tarim River. In the next section, we will give a detailed analysis with regard to the reasons why water pricing does not lead to efficient water use.

3.2.1 Water pricing and cost recovery

There is no controversy that the financial role of the water pricing ensures the cost recovery of the supply system (Chohin-Kuper *et al.*, 2003). In general, improving the cost recovery rates will improve the supply system and water delivery services. However, according to the policy document from the XUAR Provincial Department of Water Resources, it seems there is no clear connection with the water fees collected and operation and maintenance funds to sustain the infrastructure. It means that the maintenance, replacement, rehabilitation, and modernization of basic infrastructure are independent of the charge collection itself. The funds for the supply system are mainly decided by the Provincial Department of Finance according to the budget calculated by the water authority (XUAR, 2000). Besides, distribution of the operation and maintenance expenditure also determines sustainability and quality of water delivery services of the supply system. Burton (2010) defined the irrigation and drainage (I&D) expenditures into three categories: operation, maintenance and management. He argued that maintenance expenditure should be 70% of total expenditure as shown in Figure 5. He also added that in most cases, the expenditure of management especially for staff salaries is much higher than other costs, which leads to the deterioration of I&D systems. Shen and Lein (2010) reported that administrative expenditures accounts for 85% of the total expenditures in 2002 in the study region. They also conclude that increases in water prices may not result in improvement of I&D systems along the Tarim River. It can be concluded that increased water prices may have limited impact on the efficiency of the water supply system, but disproportionately increase the administrative affords.

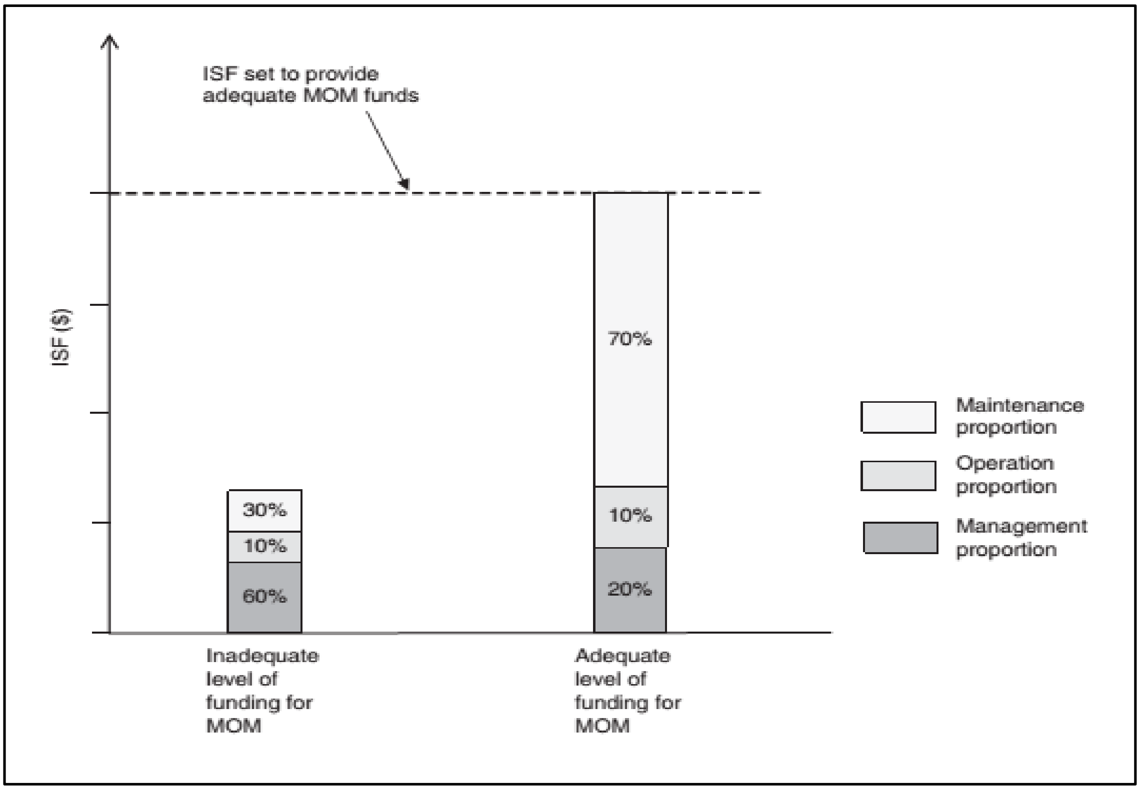

Figure 5. Settings of operation, maintenance and management expenditure with inadequate levels of funding and adequate levels of funding (Source: Burton, 2010)

3.2.2 Water pricing and the adoption of advanced water-saving technology

The results of the second article indicate that quite a number of farmers will have an intention to adopt advanced irrigation technology, when water prices increase. However, there are still several constraints to prevent the farmers adopting advanced irrigation technology along the Tarim River. First of all, it is costly. The importance of subsidies for the adoption of water use efficient irrigation technologies is discussed in detail in section 3.3.1. According to (Li *et al.*, 2006), management and installation of a drip irrigation under cotton production costs around 4,000 RMB ha^{-1}. Research findings conducted by Thevs (2011) along the middle stream of the Tarim River also indicate that the reason why farmers are not willing to use drip irrigation is mainly because it is costly and farmers lack of capital for adoption. As discussed by Shiferaw *et al.* (2009), farmers' decision on adoption of new technologies are mainly determined by additional gains such as higher economic returns or lower risk. This is also supported by findings from a case study by Liao *et al.* (2008) that farmers have little incentives to adopt water saving irrigation when water prices increase. This is mainly because farmers thought they could not gain promising economic returns by investing in costly water saving-irrigation. Besides, the adoption of such water-saving technology needs certain installation and operational skills. Training at the farm level is needed to encourage them to adopt. Furthermore, area-based water pricing is used at the farm level along the Tarim River. There is no connection between water pricing and the amount of water that farmers consume under such a pricing system. Therefore, increasing water pricing cannot send them the right signal to save water. Finally, farmers are not willing to adopt advanced irrigation technology, when they do not realize the scarcity of water resources. Farmers do not consider saving water, especially when farmers have enough water, or are at the upper stream of the river basin. Thus, public education or training is needed to increase the awareness of farmers to help persuade them to conserve water (Easter and Liu, 2007).

3.2.3 Water pricing and shifting crop patterns

The main idea of shifting crop patterns is that shifting current crops to other crops that have higher economic benefits and require less water demand to deal with increased irrigation prices. Currently, cotton production dominates the crop production along the Tarim River. The first and most important issue is the availability of such crops that have higher economic returns and require less water than cotton. There are at least two species that may theoretically fit these requirements: *Ziziphus jujube*.Mill (also called jujube) and *Apocynum venetum*.L (Figure 6). The jujube is a multipurpose fruit tree that can be used as a fruit and remedy (Gao *et al.*, 2013). Guo and Luo (2014) reported that the area planted with jujube have increased rapidly in last two decades along the Tarim River, and the economic benefit of jujubes is sometimes up to 150,000 RMB ha^{-1}. *Apocynum venetum* is multifunctional plant that is largely distributed in Central Asian deserts (Chen *et al.*, 2015). Leaves of the plant can be used as medical tea while natural fiber can be obtained from the stem of the plant for textiles (Wang *et al.*, 2007; Xie *et al.*, 2012). A research group led by Thevs *et al.* (2013) argued that cotton can be replaced by the Apocynum species in order to deal with water scarcity problems and to protect the local environment. According to Thevs et al. (2013), the Apocynum species can grow in harsh environments, such as arid climates and saline soil, without irrigation. The Apocynum species can also generate income for locals. There is no sufficient evidence yet, however, supporting that both species can generate higher economic benefits and require less water demand than cotton. Besides, farmers are usually risk adverse (Mendola, 2005). Farmers do not take the risks to shift to more intensive, time and input-consuming crops without rather stable market opportunities (Venot *et al.*, 2007). Lipion (1968) argues that small farmers usually do not change their cropping patterns aiming at higher income, because they concern more about securing their basic needs for living.

Figure 6. *Ziziphus jujube*.Mill. and *Apocynum venetum*.L. (Source: Gao *et al.*, 2013 and author)

3.2.4 Water pricing and optimizing on-farm management practices

Better timing of irrigation and controlling the amount of irrigation (irrigation scheduling) are given particular attention when considering optimizing on-farm management practices (Endale and Fipps, 2001). Jensen (2007) argues that irrigation scheduling can improve water use efficiency and productivity with no additional costs or special skills such as drip irrigation. However, some authors argue that irrigation scheduling requires knowledge on crop water requirements and crop yield responses to irrigation (Allen, 1998). Still, farmers need certain guidance from the government or from agricultural agents. This indicates that water pricing may not encourage farmers to use irrigation scheduling unless important knowledge and practices about irrigation scheduling are delivered to farmers effectively. Among the 128 farmers interviewed in 2012 along the Tarim River, none used irrigation scheduling practices. Farmers decide the irrigation time and amount purely according their experience and the availability of water for irrigation. This is mainly because the government focused on drip irrigation and not enough attention was given to the importance of irrigation scheduling and its popularization among farmers. It is recommended that farm level training and education on irrigation scheduling, as well as other water-saving technologies, are essential to help farmers develop their skills and enhance their awareness of water conservation (Zhu *et al.*, 2015).

3.3 Policy recommendations

The policy recommendations developed in this dissertation mainly focus on two requirements; subsidies and improved extension service. The following section deals with the role of subsidies for the implementation of water saving irrigation technologies. Subsequently, the importance of integrated agricultural extension service is discussed.

3.3.1 Importance of subsidy

As discussed above, increasing water prices are not sufficiently effective for the adoption of advanced irrigation technology along the Tarim River. Capital constraints are identified as the main reason for not adopting advanced irrigation technology such as sprinkler irrigation and drip irrigation. Bjornlund *et al.* (2009) used a sample of 150 irrigators in Canada and found similar results that financial constraints have been the main reason for not adopting improved irrigation technology. Blanke *et al.* (2007) conducted a survey in six provinces in Northern China and found that farmers' decision of investing in water saving irrigation is limited by their economic capacity. Therefore, the demand management option subsidy is needed to encourage farmers to adopt advanced irrigation technology by reducing the costs of installation and management (Brinegar and Ward, 2009).

Subsidy policies targeting at water saving in agriculture have already existed along the Tarim River since 2009. The source of the subsidy is mainly from the XUAR Provincial Department of Finance, and the local government. In 2009, the XUAR Provincial Department of Finance invested 180 million RMB and subsidized drip irrigation by 1500 RMB ha^{-1}. Total investment for the subsidy officially increased to 900 million RMB and subsidy for drip irrigation increased to 4,500 RMB ha^{-1} in 2011. It is reported that the area of water-saving irrigation in 2011 significantly increased compared to 2009 (Yong, 2014). However, in the farm survey conducted in 2012, farmers revealed that they were still receiving the much lower financial support for drip irrigation, which was approximately 1,500 RMB ha^{-1}. The main factor hindering the diffusion of water-saving irrigation in the region is the limited financial capacity of local government. It is suggested that the amount of total investment for water-saving irrigation are needed to further increase, and government should guarantee farmers' subsidy for advanced irrigation technology adoption.

3.3.2 Importance of agriculture extension

Agricultural extension services are some of the most common and important types of knowledge diffusion and technology transfer (Birkhaeuser *et al.*, 1991). By bridging the gap between traditional agricultural practices and modern agriculture, effective agricultural extension services can raise agricultural productivity and improve rural conditions (Swanson, 2008). Several authors acknowledge the importance of agricultural extension especially in the adoption of water-saving technologies. Abdulai *et al.* (2005) found that farmers who could access agricultural extension services had higher rates of adoption of water-saving technology in China's Hubei province. Karami (2006) found that having access to information from the extension agents is one of the important factors affecting farmer's choice of irrigation methods in Iran. Using data from a sample of 360 farmers, Ahmad *et al.* (2014) also found that a lack of information and experience is one constraint preventing farmers from adopting water-saving irrigation in Pakistan's Indus Basin.

As discussed in previous sections, besides capital constraints, a lack of knowledge and capability is the main factor preventing farmers from conducting proper changes, which results in inefficient irrigation water pricing policies along the Tarim River. This raises questions about the efficiency of agricultural extension systems in this region. In China, Agricultural extension systems have been developed rapidly in recent decades according to several authors (Nie *et al.*, 2002; Jin *et al.*, 2010). It is reported that the rapid agricultural productivity growth was highly related to the development of agricultural extension (Huang and Rozelle, 1996). However, several common challenges resulting in the inefficiency of Chinese agricultural extensions need to be addressed (Lohmar *et al.*, 2009). First, Chinese agricultural GDP shares about 10% of total GDP in 2013 (CSYB, 2014). Most importantly, Chinese agriculture feeds almost one fifth of the world's population (Tilt, 2008; Zhang *et al.*, 2015). However, expenditures for agriculture, especially for agricultural extensions, is relatively low and unstable (Fan, 2000). The share of investment for agricultural research and development in the total agricultural GDP of China was 0.5% in 2008. It is much lower when compared to the average share of investment for agricultural research and development in the total agricultural GDP of developed countries (about 2.4%), and is even lower than the average for developing countries (about 0.6%) (Chen *et al.*). Agricultural agents had a little incentives in agricultural activities, because they were paid in a poor level (Hu *et al.*, 2009). Secondly, there is no doubt that China possesses one of the largest agricultural extension teams in the world. There were almost more than one million agricultural extension specialists in the end of 2000 (Hu *et al.*, 2012). However, the ratio of extension agents to farmers was only 1:714. The ratio was much higher compared to some countries, such as India (1:5,000) and Nigeria (1:3,333) (Davis *et al.*, 2010), but was still lower when compared to the average ratios of developed counties (1:400) (Feder *et al.*, 1999). Besides, the rapid growth of agents' numbers and insufficient budget spending on retraining agents resulted in decreasing the quality of agricultural extension team. Thirdly, sufficient funding and high-quality agricultural extension teams are important for the efficiency of extension systems. However, the key challenges currently faced by Chinese agricultural extension system may be the lack of effective transfers of related research findings and new technologies to farmers (Feike *et al.*, 2010). Identifying farmers' real needs, transferring research findings and new technologies from the laboratory into practice through collaboration with researchers, extension agents, farmers and related institutions are the most important tasks of agricultural extension systems (Lee, 2005; Hu *et al.*, 2012).

It is recommended that governments should increase the investments in agricultural research and extension (Fan *et al.*, 2004; Gao and Zhang, 2010). Substantial investments are needed for extensions to provide adequate incentives to agricultural extension agents (Hu *et al.*, 2012). Besides, it is also suggested that special attention should be given to the human resources development of agricultural systems focusing on the quantity and quality of extension staff (Wesley and Faminow, 2014). Motivated and highly-qualified extension agents are believed to be key players who can effectively deliver new technologies and knowledge to farmers (Baig and Aldosari, 2013). Furthermore, great efforts are needed to build strong linkages between research institutions, extension agents, farmers, and other organizations in order to effectively deliver new findings, technologies, and knowledge from laboratories to the farmers (Ekboir and Initiative, 2012). This leads to the conclusion that measures towards a comprehensive vocational training are crucial to sustainably improve agricultural extension. Provision of educational programs for farmers, such as workshops or trainings, may complement these measures.

3.4 Application of Bayesian networks (BN) in water resources management

As elaborated in the third article, BN is a powerful tool to deal with uncertainty and limited data availability in the respect of water resource management. Through increased demand for fresh water and widespread water scarcity emerged an integrated water resources management approach (IWRM), which takes into account all factors including the complexity of the water supply system, various factors in the spatial and time dimension, and involvement of stakeholders in the water resource management (Al Radif, 1999; Thomas and Durham, 2003; Biswas, 2004; Savenije and van der Zaag, 2008). The BN model is especially useful when it clearly explains complex problems, easily simulating and comparing the impact of different management scenarios as well as determining the driving factors by using sensitivity analyses (McCann *et al.*, 2006). Such an advantage of the modeling approach is also supported by many case studies such as Quinn *et al.* (2013), Gawne *et al.* (2012) and Shenton *et al.* (2014). The model successfully simulates impact of different water pricing scenarios and other policy changes. The model also well integrates expert knowledge and empirical data. Additionally, the model is validated by the judgement of local experts and water authorities and confirms that simulation results are acceptable.

Recently, an increasing number of scientific literature can be observed using BN as a modeling approach in water resources management, with a focus on groundwater protection (Farmani *et al.*, 2009; Aguilera *et al.*, 2013; Giordano *et al.*, 2013; Molina *et al.*, 2013; Giordano *et al.*, 2015), irrigation management (Robertson and Wang, 2004; Blanco-Gutiérrez *et al.*, 2013), and catchment management (Stewart-Koster *et al.*, 2010; Keshtkar *et al.*, 2013). For example, a case study by Molina *et al.* (2013) using BN assessed the impacts of climate change on groundwater systems in the arid and semi-arid region of Spain, while a case study by Robertson and Wang (2004) that used BN as a decision tool examined farmers' decisions on a selection of irrigation systems. A case study by Keshtkar *et al.* (2013) uses BN modeling to explore the best management scenarios to improve water quality in the Hablehrood river catchment in Iran. Besides, the disconnection between scientific evidence and decision making in water resources management and planning emerged participatory approach which includes scientists, decision makers and other stakeholder (Al Radif, 1999; Liu *et al.*, 2008). The ability of BN to easily integrate data from different sources and discipline makes the approach more popular tool in participatory modeling process of water resource management (Uusitalo, 2007; Duespohl *et al.*, 2012). Many authors have applied BN as their main modeling approach in their participatory research (Molina *et al.*, 2011; Carmona *et al.*, 2013b; Liedloff *et al.*, 2013; Carmona *et al.*, 2013a).

3.5 Open questions

3.5.1 Farmers' affordability

Farmers' affordability is the most controversial issue when considering the water pricing as a demand management option (Sampath, 1992). Besides its impact on farmers' income distribution, critics concern more about its impacts on food security in the long run. A case study by Latinopoulos (2008) simulated the impacts of water pricing on farmers income in Loudias River Basin in Northern Greece and he found that farmers' income losses may range up to 35% by introducing water pricing. Using mathematical programming, Berbel and Gómez-Limón (2000) simulated impacts of water pricing on farmers' income distribution in three irrigated areas in Spain. They found that farm income may drop by 40%, until the water pricing reaches a significant level, which results in water demand reduction. A case study by Huang *et al.* (2006) also found that increasing water pricing may result in reductions in crop production, especially it may have significant effect on the production of grain crops in the Hebei Province of China.

The water pricing policy dealing with water scarcity is already on the way along the Tarim River. There are expected to be further increases in water price levels. The government reported that cost recovery is very low. However, there is a big difference between the water price reported by the government and ultimate water pricing that farmers paid. It seems farmers pay much more than required. Shen and Lein (2010) also reported that water pricing that famers paid already reached the full supply cost. Even a slight increase in water pricing may result in significant reductions in farmers' income. The results of the third article of this Ph.D. thesis indicate that differential water pricing practices preferable concerning the farmers' affordability. At present, these issues are still uninvestigated. Thus, further investigation and careful assessment of the impacts of water pricing are necessary to mitigate its effect on farmers' welfare and food security.

3.5.2 Institutional aspects of water pricing

In the third article, parts of the institutional aspects of irrigation water pricing are discussed. However, water institution is a broad term including the legal, administrative, and policy environments targeted at water allocation (Global Water Partnership, 2000). In the next section, it will be discussed some important topics related to water institutions.

Transferable water rights

As defined by Holden and Thobani (1995) “ tradable water rights are that they are secure and can be legally traded under the guidelines established by a legal, regulatory, and institutional framework”. Well-defined water rights are believed to have several advantages in terms of improving water use and water allocation. First of all, well-defined water rights can improve the reallocation of water by shifting water resources from lower value uses to higher value uses (Thobani, 1995). Besides, well-defined water rights can increase water productivity by putting strong incentives the users to conserve water (Rosegrant and Binswanger, 1994). Furthermore, farmers can also generate extra income by selling their saved water to the others, when the water rights are well-defined (Thobani, 1995). Schleyer (1996) reported that the establishment of tradable water rights in Chile not only increased water use efficiency, but also encouraged farmers to alter their crops to high value crops that use less water. A case study by Brooks and Harris (2008) also confirmed that economic efficiency was gained in Australia by introducing tradable water rights.

According to the Chinese water law, the state owns the water resources. Water rights systems are not well-defined and well-developed. As stated by Jiang (2009), an undeveloped water rights systems is one of the major factors causing inefficiency of water use and water scarcity in China. Since 2000, China’s government conducted a series of pilot water transfer projects described by Speed (2009b). These pilot reforms, however, mainly focus on water rights transfer in river basin and county level, a little case can be observed at farm level (Liu, 2003). Besides, these limited numbers of water rights transfer projects at the farm level were reported unsuccessful because of different barriers, such as management, legal, and fiscal constraints (Zhang, 2007; Cai, 2008). Speed (2009a) compared the water right system of China and Australia and emphasized the importance of clearly-defined water rights and more liable market trading for China’s water right system. Further research for achieving efficient water use along the Tarim River may focus on tradable water rights, and special attention should be given on how to clearly define, monitor, and enforce water rights.

Water user association (WUA)

WUA refers to the special organization that is operated and managed by the water user (Johansson *et al.*, 2002; Lin, 2003). In theory, the WUA involves water resource management and decision making as well as collecting water charges (Abdullaev *et al.*, 2010). Involvement of WUA in water management activities may not only reduce transaction costs related with water pricing implementation, but also improve the transparency of water pricing and increase collection rates (Johansson *et al.*, 2002). There is quite a numbers of scientific literature that shows the positive effect of WUA in water resource management. Koc *et al.* (2006), using 1010 random samples of farmers' interviews, evaluated the performance of WUA in the Great Menderes Basin in Turkey. They found that users were very positive about the performance of WUA in operating, managing, and maintaining the irrigation infrastructure and their services. A case study by Batt and Merkley (2010) found that involving WUA in water management improved the availability of water to the farmers in Egypt. McCarthy and Essam (2009) also found that involvement of WUA in Chile may improve agricultural productivity by well maintaining the canal system. User participation in water resource management developed rapidly since the 1990s in China. According to the statistics, there were more than 50,000 WUAs nationwide in China, which manage more than 20 million ha irrigated land (World Bank, 2011). However, according to expert interviews conducted 2013, farmers are currently not involved in water resources management along the Tarim River. They also stated that the government tried to implement WUA in the region, but it was unsuccessful. Still, it is not clear why it did not work successfully. Besides, implementation of WUA requires well-defined water rights that are currently absent along the Tarim river. Thus, there is great importance of further research examining how to successfully implement the WUA for achieving more efficient water use along the Tarim River.

4 Summary

Underpricing of irrigation water is recognized as one of the primary causes of overutilization of water, low water use efficiency, and aging as well as degrading of infrastructure in arid and semi-arid regions, such as Tarim River Basin. Irrigation water pricing as an important economic instrument, is believed to not only encourage the users to use water more carefully, but also provide funds for sustaining the water supply system.

The main objectives of the study are to explore whether irrigation water pricing can lead to efficient water use in agriculture along the Tarim River. In particular, the study aims at addressing the following research questions: (1) Which developments in land use and water use can be observed, and what are driving forces for these developments? (2) How farmers respond to changes of water pricing, and what are factors influencing their choice? (3) What are the positive effects of different levels of water pricing and changes in water pricing practices on increased water use efficiency? (4) What are the positive effects of other agricultural policies on increased water use efficiency? (5) What policy options can be recommended for the successful implementation of an efficient water pricing policy?

This work was accomplished within the framework of Sino-German Project SuMaRiO (Sustainable Management of River Oases along the Tarim River) funded by the German Federal Ministry of Education and Research under the “Sustainable Land Management” program. To understand land and water use development and driving forces along the Aksu-Tarim Basin, a workshop was conducted in Urumqi which is capital city of Xinjiang Uyghur Autonomous Region. Local experts from different research disciplines as well as relevant stakeholder participated in the workshop. Besides, data were collected and analyzed from preselected sources such as statistical yearbook and government’s official document. Research results embedded in the **first article** revealed that there was a huge land expansion and increase in water use for agriculture during the period from 1989 to 2011. The results also indicate that interaction of vast population growth, positive price development, agricultural profitability increase, government’s afforestation program

(Grain for Green) and insufficient control of land expansion were the main driving forces for those developments.

Farmers' behavior towards the changes of irrigation water pricing is one of the important factor determining efficiency of water pricing to elicit water conservation and demand reduction. Therefore, a total of 257 farm household interviews were conducted, of which 128 served to find out farmers' responses towards the changes of water pricing in different parts of Tarim River in July and August 2012. The results of statistical analyses are presented in the **second article**. Results show that only less than half of the interviewed farm households would react to increased water prices with proper changes of their farming practices leading to a more efficient water use. Results also show that increasing water prices encourage the farmers to shift their irrigation from surface water to groundwater which may result in further environmental problems. It can be concluded that increasing water prices alone are not enough to increase water use efficiency. Furthermore, the implementation of strict regulations of groundwater use is highly recommended to prevent its overexploitation.

Irrigation water price levels and water pricing practices are the most important parts which need to be taken into account in the research of an irrigation water pricing reform leading to a more sustainable water use. Unfortunately, in the second article it is not possible to access the impact of different water price levels and changes in the water pricing practices because of its technicality and complexity. Besides, an irrigation water pricing reform needs to consider institutional aspects which are usually ignored in research on water pricing. Therefore, an innovative approach, Bayesian network modeling, was employed to find out the effects of different water price levels, changes in water pricing practices, and other agricultural policy options on the water use efficiency along the Tarim River. Compared to findings from previous research, the Bayesian network approach perfectly integrated crucial institutional aspects as well. For the model development, data from expert interviews, workshops, policy documents, official statistics, and scientific literature were collected, analyzed, and integrated into the Bayesian networks. Results

presented in the **third article** show no significant impact of water prices increased by 0-50% on water use efficiency. Solely an increase of 100% may have a relevant positive effect on water use efficiency. The model results also reveal that water pricing may provide a promising option to increase water use efficiency provided that volumetrically measuring systems, subsidies for water saving technologies, and technical support are available.

The **fourth article** discusses the economics of cotton production and land use changes along the Tarim River from 1989 to 2009 using data from official statistical yearbooks. The results of a trend analysis indicate that the land area of cotton increased. In contrast, the area of other crops slightly decreased. Results of comparative advantage index of cotton production show that most farmers in the upper stream are more efficient in cotton production compared to farmers of the lower stream, whereas farmers in Xinjiang Production and Construction Corps are more efficient than farmers outside the Xinjiang Production and Construction Corps.

The overall results of the study indicate that irrigation water pricing is not the best option to achieve an efficient water use in agriculture along the Tarim River. It requires additional adjustments and supportive agricultural policies such as the availability of volumetric measuring systems, subsidies for water-saving technologies, technological support for farmers, as well as a further institutional reform. Besides, special attention should be given to the protection of groundwater resources, especially when water prices increase. Furthermore, additional research is needed to examine the impacts of water pricing on farmers' welfare, and the role of transferable water rights and water user associations in terms of an efficient water use along the Tarim River.

5 Zusammenfassung

Niedrige Wasserpreise für die Bewässerung landwirtschaftlicher Nutzflächen werden als einer der Hauptgründe für übermäßige Wassernutzung, niedrige Wassernutzungseffizienz und den Verfall von Bewässerungsinfrastruktur in ariden und semi-ariden Regionen angesehen. Die Situation im Tarimbecken in Nordwestchina stellt ein gutes Beispiel für diese Problematik dar. Es wird davon ausgegangen, dass das Erheben von Wasserpreisen im Bewässerungslandbau ein wichtiges wirtschaftliches Instrument darstellt, welches Wassernutzer zu einem verantwortungsvolleren Umgang mit der Ressource bringen kann. Erzielte Einkünfte aus Wasserpreisen können zudem der Verbesserung der Wasserversorgungsinfrastruktur dienen.

Das Hauptaugenmerk dieser Dissertation war auf die Frage gerichtet, ob Wasserpreise in der Bewässerungslandwirtschaft entlang des Tarims zu einer effizienteren Wassernutzung führen können. Im Speziellen, wurden folgende Fragestellungen behandelt: (1) Welche Entwicklungen konnten in der Land- und Wassernutzung entlang des Tarims beobachtet werden und was waren die treibende Kräfte für diese Entwicklungen? (2) Wie reagieren Landwirte auf veränderte Wasserpreise und welche Faktoren beeinflussen deren Entscheidungen? (3) Welche positiven Effekte haben verschiedene Wasserpreise und Wasserpreismaßnahmen auf die Wassernutzungseffizienz? (4) Welche positiven Effekte weiterer agrarpolitischer Maßnahmen existieren bezüglich der Wassernutzungseffizienz? (5) Welche Möglichkeiten können politischen Entscheidungsträgern aufgezeigt werden, um eine effiziente Wasserpreispolitik einzuführen?

Diese Arbeit wurde im Rahmen des chinesisch-deutschen SuMaRiO-Projektes (Nachhaltiges Flussoasenmanagement entlang des Tarims) durchgeführt und vom Bundesministerium für Bildung und Forschung (BMBF) im Rahmen des Programmes „Nachhaltiges Landmanagement“ gefördert. Um die aktuellen und historischen Entwicklungen hinsichtlich der Land- und Wassernutzung und deren treibenden Kräfte im Aksu-Tarimbecken zu identifizieren, wurde ein Workshop in

Urumqi, der Hauptstadt der Autonomen Uigurischen Provinz Xinjiang, durchgeführt. Teilnehmer waren lokale Experten verschiedener Forschungsdisziplinen sowie weitere relevante Akteure, beispielsweise politische Entscheidungsträger. Ergänzend wurden Sekundärdaten aus statistischen Jahrbüchern und offiziellen politischen Dokumenten erhoben. Ergebnisse zeigten, wie im ersten Artikel dargestellt, dass im Zeitraum von 1989 bis 2011 eine enorme Expansion landwirtschaftlicher Nutzflächen und damit ein stark erhöhter Wasserverbrauch stattgefunden hat. Es konnte gezeigt werden, dass diese Entwicklung durch eine Kombination der folgenden Faktoren bedingt wurde: (a) starkes Bevölkerungswachstum, erhöhte Erzeugerpreise, (c) gesteigerte landwirtschaftliche Produktivität, (d) das Regierungsprogramm zur Aufforstung (Grain for Green) und (e) mangelhafte Kontrolle der Expansion landwirtschaftlicher Flächen.

Die Reaktionen von Landwirten auf veränderte Wasserpreise ist ein entscheidender Faktor bei der Bestimmung von effizienten Wasserpreisen zur Einsparung und Nachfragereduzierung der knappen Ressource. Von Juli bis August 2012 wurde in verschiedenen Regionen entlang des Tarims eine Farm-Haushaltsbefragung mit insgesamt 257 Interviews durchgeführt. 128 dieser Interviews dienten der Analyse der Reaktionen von Landwirten auf erhöhte Wasserpreise. Die Ergebnisse dieser Analysen sind im zweiten Artikel beschrieben. Es konnte gezeigt werden, dass lediglich die Hälfte der befragten Betriebe ihre Bewässerungsmethoden zu Gunsten einer effizienteren Wassernutzung anpassen würden. Viele Landwirte kündigten hingegen an, dass sie einem erhöhten Preisdruck mit einer vermehrten Grundwassernutzung entgegenwirken würden, was jedoch schwerwiegende ökologische Folgen haben kann. Daraus kann abgeleitet werden, dass die bloße Erhöhung der Wasserpreise für eine effizientere Ressourcennutzung nicht ausreicht. Ferner wird eine strenge Regulierung der Grundwassernutzung empfohlen, um die Ausbeutung der knappen Ressource einzuschränken.

Bei der Ermittlung von geeigneten Reformen von Wasserpreisen zur nachhaltigeren Wassernutzung stellen Preisniveau und Art der Preiserhebung die wichtigsten zu untersuchenden Eigenschaften dar. Auf Grund des Umfangs und der Komplexität des Themas, war es bei der direkten Befragung der Landwirte nicht möglich, die Reaktionen auf verschiedene Preisniveaus zu ermitteln. Zudem müssen institutionelle Aspekte bei einer umfassenden Wasserpreisreform berücksichtigt werden. Aus diesem Grund wurde im dritten Artikel der Einfluss verschiedener Wasserpreise, verschiedener Praktiken der Gebührenerhebung, sowie weiterer agrarpolitischer Maßnahmen auf die Wassernutzungseffizienz mittels Bayesschen Netzwerken modelliert. Im Vergleich zu vorhergehenden Studien, konnte die Verwendung Bayesscher Netzwerke die notwendige Berücksichtigung institutioneller Faktoren gewährleisten. Zur Entwicklung des Modells wurden Daten mittels Experteninterviews, Workshops sowie der Analyse von Sekundärquellen – beispielsweise politische Dokumente, Statistiken oder wissenschaftliche Veröffentlichungen – ermittelt. Bei um 0-50% erhöhten Wasserpreisen konnte kein signifikanter Einfluss auf die Wassernutzungseffizienz nachgewiesen werden. Lediglich eine Verdopplung der aktuellen Wasserpreise hatte einen nachweisbar positiven Effekt auf die Wassernutzungseffizienz unter der Voraussetzung einer verbrauchsorientierten Preisermittlung (=volumetrischer Wasserpreis). Das entwickelte Modell konnte zudem zeigen, dass volumetrische Wasserpreise, kombiniert mit der Förderung effizienter Bewässerungstechnologie und landwirtschaftlicher Beratung die Möglichkeit bieten, die Wassernutzungseffizienz zu erhöhen.

Im vierten Artikel wurde die Wirtschaftlichkeit des Baumwollanbaus und der Landnutzungsänderungen entlang des Tarims im Zeitraum von 1989 bis 2009 analysiert. Hierfür wurden Sekundärdaten aus statistischen Jahrbüchern verwendet. Die Ergebnisse einer durchgeführten Trendanalyse zeigen eine Expansion des Baumwollanbaus während sich die Fläche alternativer Nutzpflanzen in geringem Umfang verringerte. Außerdem konnte im Baumwollanbau am Oberlauf des Tarims eine höhere Produktivität als flussabwärts nachgewiesen werden. Landwirte der Militärfarmen des „Xinjiang Production and Construction Corps“ waren hierbei effizienter als Landwirte außerhalb der Militärfarmen.

Aus den Ergebnissen der einzelnen Artikel kann gefolgert werden, dass Wasserpreise als alleinige Maßnahme zur Erhöhung der Wassernutzungseffizient entlang des Tarims nicht genügen. Für die erfolgreiche Implementierung eines effizienteren Wassermanagements sind zusätzliche Anpassungen der Preismechanismen, sowie gezielte agrarpolitische Maßnahmen notwendig. Volumetrische Wasserpreise, Subventionen effizienter Bewässerungstechnologien, landwirtschaftliche Beratung sowie grundlegende institutionelle Reformen erscheinen unausweichlich, um eine nachhaltigere Wassernutzung in der Studienregion zu ermöglichen. Ein besonderes Augenmerk sollte auf der Nutzung der knappen Grundwasservorräte liegen, insbesondere bei erhöhten Wasserpreisen. Zusätzlicher Forschungsbedarf besteht bei den Auswirkungen von Wasserpreisen auf das landwirtschaftliche Betriebseinkommen, der Übertragbarkeit von Wassernutzungsrechten und bei der Rolle von Vereinigungen und Genossenschaften von Wassernutzern bezüglich einer effizienteren Wassernutzung entlang des Tarims.

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7 Acknowledgement

First of all, I would like to thank my supervisor Prof. Dr. Reiner Doluschitz for giving me the opportunity to work on this project and fulfil my destiny. I would especially like to express my deepest gratitude to him for his excellent guidance, advice, encouragement, and great patience throughout the project.

Thanks to Prof. Dr. Joachim Müller and Prof. Dr. Michael Ahlheim for kindly agreeing to be the co-examiners of this dissertation.

I would like to thank Dr. Til Feike for his tireless support, guidance, and advice as well as his generous time for proofreading of all my manuscript. I learned many things from him. Without his support, my research would not have been possible.

I also want to thank my former Prof. Nurbay Abdusalih from Xinjiang University and Prof. Lilin from Tarim University for their support during the field work in China. I also thank students from Xinjiang University and Tarim University for their assistance during the household interviews. Special thanks also go to Dr. Yiliminuer Imit for the excellent organization of the workshop and for arranging the expert interviews.

Many thanks to all colleagues of the Institute of Farm management (410c) for their help, support and encouragement. Special thanks to Dr. Christa Hoffmann, Mrs. Renate Bayer, Heinrich Hagel and Nicola Gindele for their tireless help during my studies.

Last, not least I would like to thank to my family for their encouragement, support, patience and love. I would like to dedicate this study to my father Mamitimin Mangsur and my mother Marajihan Kadir.