Agroclimatological Problems in the Taklimakan Desert and Its Surrounding Area in NW China

Masatoshi YOSHINO

(Professor Emeritus, University of Tsukuba, Japan
Senior Programme Advisor, SED, United Nations University, Japan and
Advisor, Metocean-Environment Inc., Japan)

Abstract

Agroclimatological problems in the Taklimakan Desert and its surrounding area in NW China were discussed with reference to the results of our previous studies carried on since the early 1990s, together with literature published in China. Farmers at the oases have been suffering from occasional heavy rainfall, causing floods and damaging construction works. It is worthy to note that human ecosystems in arid areas are more vulnerable to extremely wet conditions, which occur infrequently, than to dry conditions.

Agroclimatologically, strong sand-dust storms, called “Kara Bran (Black Wind),” also play a seriously negative role in the Taklimakan Desert. Cotton, which is cultivated as a main cash crop for the farmers, has frequently been damaged severely. The amount of water used for irrigation per family is decreasing because of population growth. Limits on the ratio of irrigated land to total cultivated land differ between the northern fringe and the southern fringe of the Tarim Basin. The tributary size (population) is also important in determining the limits. The crop calendar is decided by the amount of water available. The income of farmers’ families is very low, because of low production under the severe environmental conditions for cultivation, which are common at desert oases. Raising the income of the farmers is one way to decrease or alleviate desertification, because they wouldn’t have to go to the desert to collect firewood. The farmers who are living under the severe economic conditions cannot buy coal because of the price. The farmer’s recognition of an increasing trend in the frequency of very strong winds, Kara Bran, is quite accurate, according to the interview survey. The results coincide with the records at the local meteorological observatories.

Key words: Agroclimate, Oasis, Sand-dust storm, Taklimakan desert, Water-use.

1. Introduction

At the oases of the deserts in China, human activity started long ago. It is well known that trade between Europe and East Asia has a history longer than 2,100 years along the so-called “Silk Road,” but actually longer than such years.

Agricultural activities at the oases were developed in the Tang Dynasty. But high productivity at that time already required large amounts of water at the oases. In 1905, in the Qing Dynasty, agriculture developed more. It was recorded that the agricultural land area was 600,000 ha and there were 503 large

canals and 1,887 branch canals in total in South Xinjiang.

Agriculture at the oases is affected strongly by severe climatic conditions. They form a part of an ecosystem which includes a natural as well as socioeconomic environment.

In the present review paper, based mainly on our field studies carried out since the early 1990s, some aspects of the agroclimates of the oases in the Taklimakan Desert and its surrounding area are given.

2. Sketch of the Region Studied

2.1 Geography

The Taklimakan Desert, Xinjiang, NW China, is located in the innermost part of the Eurasian conti-

Fig. 1. Topographical sketch and names of places and rivers appeared in the text.

nent, which means the distance from the sea, as a source of water vapor, is the greatest. Also, the location is just under the mid-latitude anti-cyclone belt. According to the definition in China, "Desertification regions" are regions, in which 5% or more of the whole area is covered by desert or a desert-like ground surface. In line with this definition, the total desert area is calculated as 176,000 km² and the potential desertified area (considered a possible future desert area) is 158,000 km². In total, it amounts to 334,000 km² (Chao, 1984; Zhu, 1984).

The topography of the Taklimakan Desert is a basin named the Tarim. A sketch of it is given in Fig. 1. This means that the invading air streams become warmer and drier due to the so-called Föhn effect. The border of the northern fringe is the Tianshan Mountain Range and the southern fringe, the Kunlun Mountain Range; both are important sources of water for the oases.

2.2 Climate

Climate of the Taklimakan Desert is characterized by a wide range of annual as well as daily air temperatures, scarce precipitation and humidity, strong solar radiation, strong winds, etc. (Li, 2002). On the other hand, the desert has been suffering from

heavy rainfall and strong winds not infrequently (Yoshino, 1992).

There is lot of damage caused by the natural environment. Human societies have been developing and changing and, at the same time, adjusted to the environment. The amount of damage and losses caused by heavy rainfall are unexpectedly large (Editorial Committee "Mitigation of Natural Hazards in Xinjiang for 40 years", 1993). This means the ecological systems developed under dry conditions are weak under unusual wet conditions. Strong sand-dust storms, Kara Bran, cause huge amounts of socio-economic losses, in particular in the amount of agricultural production (Yoshino, 2000).

Water resources and drought (Li, 1996) are the basic climatic conditions for agriculture under the severe influence of desertification (Sun and Huang, 1998; Xia and Yang, 1996).

In the case of April 1983, severe storms cause damage to agricultural production in the 160,000 ha of field and direct economic losses amounted to 0.3 million US dollar. In the case of May 1986, they reached 14,000 ha and 5.7 million US dollars, respectively.

Climatic change (Du, 1993; Xu, 1997) in the oases

Fig. 2. Production (kg/head) of main crops in Turpan during the recent years. (Data source: Turpan Statistical Almanac, 1994)

is a major issue with regard to adaptation of human societies to the new environment on a local and micro-scale as well as on a global climatic change scale.

In March 2001, the Chinese government decided to embark on ecological research and management in the Tarim and seven other tributaries in NW China: (1) to develop and apply the local climate and micro-climate theories of oases, (2) to mitigate and manage desertification and (3) to utilize the ecological and meteorological elements of the desert.

2.3 Agriculture and farmers

Ninety-eight to 99% of the farmers in the Taklimakan Desert are Uygur. Han Chinese are working in the industrial and commercial sectors, and other service industries of the oases. It is said that the total area of the oases in Xinjiang is about 70,000 km², which is about 3.5% of the total area of Xinjiang. According to other statistics, about 68% of the total oasis area in China is distributed in Xinjiang.

Rates of land cultivation depend upon the rate of irrigation of cultivated lands. But the ratio of irrigated lands decreases sharply, when the ratio of cultivated land becomes higher than certain threshold values, which differ between the northern and southern parts of the desert (Yoshino, 1997).

The population is concentrated around the oases:

95% of the total population is living at the oases, engaging in agriculture, urban service, industry, enterprise, construction, etc. The main factors in desertification originate from human activities: over-cutting and collecting firewood 31.8%, overgrazing 28.3%, over cultivation 25.4%, misuse of water resources 8.3%, invasion of sand dunes 5.5%, and vegetation destruction due to urbanization, industrialization, and roads 0.7%. These figures are averages for all of the arid and semi-arid regions in China (Huang, 2003). For the Taklimakan Desert, percentages may not show great differences from the average.

Agricultural production per unit cultivated area is about 300 US dollar/ha, which is about half the average value for China overall. In the second half of the 1980s, 3/4 of whole agricultural production was irrigated.

In 1997, the area of irrigated cotton fields reached about 67,000 ha along the middle course of the Tarim River, where water availability is relatively best in the Tarim Basin.

Production of the main three crops in Turpan during the past 20 years is shown in Fig. 2. Grapes as a cash crop have been increasing remarkably, but food crops and cotton are increasing very slowly. On the other hand, it has been shown that the total areas sown, particularly of cotton, have been increasing in

Fig. 3. Sown area of main agricultural crops in Turpan from 1949 to 1993. (Data source: Turpan Statistical Almanac, 1994)

Table 1. Frequencies of natural hazards in Turpan and Hami Basin, 1949–1990.

City or Xian	Natural hazard					Total
	Drought	Flood	Wind damage	Freezing and frost damage	Insects and disease	
Turpan						
Turpan-City	0	14	22	3	4	43
Shanshan-Xian	1	11	7	3	3	25
Toksun-Xian	0	5	21	0	3	29
Hami						
Hami-City	2	22	20	6	3	53
Barkol Kazak Zizhi-Xian	3	5	2	3	7	20
Yiwu-Xian	1	9	9	2	1	22

Qiemo County on the southern fringe since 1985. Wheat, corn and rice have been decreasing or almost at the same level. It has been said that almost all the newly reclaimed land was planted with cotton and melons (Jiang *et al.*, 2001).

Since 1949, secular variation of agricultural production has been influenced by the political situation. For example, the area sown with main agricultural crops in Turpan has been changing as shown in Fig. 3. During the period between 1960 and 1974 it was almost constant, in next period between 1975 and 1978 it reached a maximum and later the tendencies discussed in Fig. 2 were striking.

3. Climatic Resources and Disasters

3.1 Natural hazards to agriculture at oases

Unexpectedly, drought hazards are not serious at

the oases in the desert. Reasons for this are thought to be that people's livelihoods, cultivation techniques, social systems, etc., in agriculture have been adapted to dry conditions for many years.

As shown in Table 1, wind damage is first ranked in Turpan and flood damage in the Hami Basin. It is noteworthy that (1) the frequencies of "freezing and frost damage" and "insect and disease damage" are both greater than that of drought and (2) these damages are related mainly to agricultural cultivation and animal husbandry. These are important points from the viewpoint of agroclimatology.

The season of these natural hazards also hinders agriculture. The highest frequency of wind damage occurs from April to July, which is the most important season for growing crops. About half of the strong-wind days are concentrated in these months.

Strong and extra-strong sand-dust storms are called Kara Bran. The frequency of all kinds of strong winds defined by visibility are decreasing as revealed by the observation at the meteorological observatories (Yoshino, 2002a, b, c), but the extra-strong ones are increasing in the southern, south eastern and eastern parts of the Tarim Basin according to the farmers' experience as will be discussed in 3.2 later.

In addition to the strong sand-dust storms in spring, dry-hot winds (Ganrefeng) cause damage to crops from late spring to summer. In Turpan, they occur 131 times a year. They are concentrated from late spring to summer, but it should be noted that they happen almost every day during the season. This hot-dry wind commonly cause decreased wheat harvests (10% decrease or 20–30% in serious cases), dropping of seeds of cotton and fruits of grapes, and withering of watermelon leaves. To produce more Hami-melon, which is famous on national and international markets, counter-measures for preventing wind damage are on urgent concern.

Secular variation of the area of wind damage as shown in Fig. 4 reveals a quite apparent increase. Roughly speaking, in the first half of the 20th century, it was below 1,000 ha, but was 30,000 to 50,000 ha

in 1950s to 1970s, with an extreme maximum, 70,000 ha, in 1960. In the later 1980s it was 30,000 to 200,000 ha. This means that the area of wind damage became almost 200 bigger times during the later half of the 20th century. If we were to calculate the economic loss from the damage, it might be a huge amount.

On April 22, 1977, there occurred the most severe Kara Bran recorded in the Hexi Corridor of Gansu with an instantaneous wind velocity of higher than 25 m/s and visibility of less than 50 m. Many weather stations observed a mean wind velocity of more than wind force 12. The duration of wind force more than 8 was longer than 2 h at many stations. At the station with the worst conditions, it continued for 5 h. At the farm of No. 3 Group Aksu, a 16 cm thickness surface soil of the cultivated fields was carried away by the strong winds on April 14, 1977. It was estimated that 0.6 kg/a of organic matter was lost.

As mentioned above, drought damage is not frequent in Xinjiang. Droughts have also been recorded less frequently in the historical period and during the past 50 years (Song *et al.*, 2003). Rare cases of severe drought in Xinjiang occurred in 1638, 1640, 1643, 1936, 1941, 1943, 1962, 1992, and 1997. Another study (Shi, 2003) identified the dry periods (several decades) during the last 500 years, starting with the years 1480, 1580, 1710, 1830, and 1900. The reasons or causes for these changes have not been made clear yet.

3.2 Sand-dust storms and extra-strong winds

A boundary layer develops up to a height of 600 to 1,000 m above the ground. Within the layer, a thin local layer near the ground at 0 to 100 m above the ground exists, in which strong wind-blown sand, wind-sand-stream transport, and formation of sand dunes are active. Above this layer, an upper friction layer develops from 100 m to 1,000 m above the ground, in which strong sand-dust storms develop intensively. Strong vertical flows with sand develop higher than 1,000 m above the ground and floating sand reaches 3,000 to 4,000 m in the free atmospheric layer.

In Table 2, China's definition of dust storm is given. In the extra-strong case, the maximum wind velocity is more than 25 m/s and visibility is less than 50 m.

The number of dust storm days has been on a

Fig. 4. Trend of change in wind damage area in Xinjiang, 1910–1990.

Table 2. Definition of dust storm in China.

Level	Wind force class	Instantaneous max. wind velocity	Min. visibility
Extra-strong	$\geq$ Cl. 10	≥ 25 m/s	Cl. 0 < 50 m
Strong	$\geq$ Cl. 8	≥ 20	Cl. 1 < 200 m
Mediate	$\geq$ Cl. 6	≥ 17	Cl. 2 < 200–500 m
Weak	$\geq$ Cl. 4	≥ 10	Cl. 3 < 500–1,000 m
Floating dust	Less than 8 m/s		Less than 10 km
Blown dust	More than 8 m/s		1–10 km

Note : Cl means Class.

Fig. 5. Secular variations of dust storm days, average of 5 stations (Kashi, Hotan, Kuqa, Qiemao and Turpan). (Du *et al.*, 2004)

decreasing trend in the last 50 years in the Taklimakan Desert, as shown in Fig. 5 (Du, 1993; Yoshino, 2002a, b, c; Du *et al.*, 2004). It decreased from about 25 days in the 1950s to about 5 days in the 1990s. This is a unique contrast to the tendencies found in Central and NE China, Inner Mongolia and Mongolia.

The reason why the number of days with sand-dust storms is decreasing in Xinjiang, is that direct invasions of cold air from Siberia into this region are weakening because of global warming at the high latitudes (Yoshino *et al.*, 2005). Therefore, further decreasing tendencies of sand-dust storms will continue in the Taklimakan Desert, except its southern, southeastern and eastern regions.

Damage by sand-dust storms is causing a huge amount of loss in the Taklimakan Desert. During 1949 to 1990, in all of Xinjiang, the number of occurrence of wind damage was 195; deaths (number of people), 108; loss of animals, 46,000; and damage (destruction) to houses, 4,000; and the direct economic loss amounted to about 300,000 US dollars, which is third ranked following flood damage and snow damage.

Due to strong sand-dust storms, wind-eroded surface soil from the fields accumulates over cultivated fields down stream (Zhu, 1984). Agricultural crops and grasses tend to be buried under the transported sand and dust. The strong winds cause all the buds of the fruit trees to fall down and all the leaves of the vegetables to be injured. Strong winds take away fertile surface soil, stripping wheat, young cotton and other crops. In the case of extra-strong winds, agricultural construction, irrigation canals and farmers' houses are damaged seriously.

One observation in the case of a strong sand-dust storm which occurred on May 5, 1993, reported that the thickness of the eroded surface layer was generally 10 cm, but 50 cm in extreme places. The average amount of eroded soil was estimated as about 10 m³/a and the thickness of accumulated sand was generally 20 cm, but 1.5 m in extreme places. The number of telegraph poles toppled was 750; the total distance of broken electric wire, 225 km; the number of transformers and other electric machines for agricultural use broken, 89; the total number of hydrological buildings for irrigation destroyed, about 100; the total length of irrigation canals buried, 55 km; the number of trees for wind breaks or timber snapped or felled, 90,000; and the number of killed or missing sheep, about 32,000 (Yang *et al.*, 2003).

According to the results of interviews of the farmers at the oases, their experiences have revealed that the frequencies of extra-strong and strong sand-dust storms (Kara Bran) and relatively strong (mediate) sand-dust storms (Serik Bran) are on an increasing trend, as given in Table 3. Namely, most of them are thinking that the frequencies of strong and extra-strong sand-dust storms have been increasing particularly during recent years.

So, it can be concluded that strong and extra-strong sand-dust storms have been becoming more frequent during the last several years, but the total number of dust storms, including weak ones, has

Table 3. Results of interviews of the farmers on the Kara Bran and Serik Bran in Dunhuang, August 2002.

	Kara Bran (Black wind)	Serik Bran (Yellow wind)
Frequency (time/year)	About 3 (Range: 1/2 to 4/5)	1-2 (Range: 1/2 to 4/5)
Season	March and April	February to May
Trends in recent years		
(1) Increase	7 Farmers	7 Farmers
(2) Not clear	2	2
(3) Decrease	0	0
Note	<ul style="list-style-type: none"> • Cl. 6-7 winds are increasing. • Increase since last 7-8 years. • Since 1996. • In 2002, two times. • Strong in 4 May 2002. • In old days, sand did not blown, but sand dust during the recent years. • It comes from NW. (Quite seldom from E) 	<ul style="list-style-type: none"> • Sky is red, yellow and black. • Increasing during 7-8 years (answered by two farmers). • One farmer said, it becomes more frequent due to the global warming.

been decreasing during the last 30 to 40 years.

3.3 Water problems on an oasis scale

Oases can be classified according to the following basic viewpoints (Huang, 2003): (i) human activities; natural oases, developed oases, and artificial oases, (ii) time scales; ancient oases (more than 1,000 years of existence), old oases (several hundreds years), and young oases (about several decades), (iii) water sources; spring-side oases or river-side oases (in other expression, oases irrigated by spring-water or river (ground surface)-water, (iv) geological and morphological conditions; oases at alluvial plain, at delta without river-water, at inner-mountain basin, etc., (v) land use; agricultural oases, animal husbandry oases, urban(ized)/industrial/mining oases, etc.

It is of importance to point out that these five viewpoints or conditions are all related to water problems. In other words, oases cannot be established/developed without water historically, economically, sociologically, and agriculturally. Natural conditions such as geological and geomorphological conditions are basic, but these control the transport or distribution of water to and at the oases for irrigation and human life.

If we confine the discussion on water problems to the standpoint of agricultural climatology, the amount of water available is the most basic criterion. Because precipitation is absolutely insufficient at the

oases, one must rely on inflow water from the ground's surface, such as rivers or underground water. Was it sufficiently available historically (with increasing population and irrigated land)? Was it available under any changing climatic conditions? Was it sufficiently available seasonally when changing crops for food or for cash, such as cotton or fruit? Was it sufficiently available for irrigation of the individual fields (time, depth, cost, electric power etc.)?

So, the amount of water available for irrigation is the basic condition for establishing, maintaining and developing human societies at the oases. The difference in economic conditions of human societies between the northern and southern fringes of the Taklimakan desert depends mainly upon the amount of water available. The relationship between water and development in the northern and southern fringe river drainage is shown in Fig. 6, taking the x -axis as the ratio of cultivated land (cultivated area/total land area) and the y -axis as the ratio of irrigated land (irrigated area/total cultivated areas).

It is interesting to note that the following facts are clear from this figure:

- Generally speaking, the ratio of irrigated land at oases is 90 to 100% on the northern fringe, which receives water from the Tianshan Mountain Range. On the other hand, it is 75 to 85% on the southern fringe, which receives water from the

Fig. 6. Relationship between the cultivated land ratio and the irrigated land ratio in oases in the Tarim Basin. White circle is drainage areas of the northern fringe, black circle the western fringe, and white square the southern fringe. Numerals denote the amount of water available ($\times 100$ million cubic meter) at present.

Kunlun Mountain Range. This difference is caused not only by the amount of water available, but also by climatic conditions. As a result, it can be said that the oases located on the southern fringe have worse conditions.

- (b) The ratio of irrigated land on the northern fringe starts to decrease at a point of about 4% cultivated land ratio, but decreases sharply after this point. The irrigated land ratio never exceeds 4.3%. This is very important because the irrigated land ratio cannot rise in the case of increased cultivated land ratios in the future. This means that agricultural production can not develop beyond a certain limit of cultivated land ratio. This is a simple fact based on the amount of water available for irrigation.
- (c) On the southern fringe, the curve shows a relationship similar to that of the northern fringe, but the absolute values are much lower. Namely, at a point with about 2.3% cultivated land ratio, the irrigated land ratio starts to decrease. Over a limit of about 2.5% cultivated land ratio, the irrigated land ratio may always be 75%.

The facts mentioned above are crucial to showing the role of available irrigation water in playing a limiting factor in development of oases in the future. In addition, the areas of glaciation in the Tianshan

Fig. 7. Relationship between the amount of water resources and irrigated land area in the ten main tributaries in the Tarim Basin.

and Kunlun Mountain Ranges are decreasing remarkably (Li, 1996). This may contribute to a negative factor, reducing the threshold values.

The relationship between the total amount of water resources and the irrigated land area is shown in Fig. 7 for the tributaries of ten main rivers in Tarim Basin. The data are from a report by Jiang (2003).

The total amount of water resources is the summation of the amounts of river water and underground water. Regardless of the different historical, geomorphological, or landuse background, the tendency curve can be divided into three parts, as seen in Fig. 7: Part I represents the largest amount of water (5 to 10 billion m^3) and irrigated area (250,000 to 300,000 ha) in which a positive relationship is clear; Part II has a range of the water resources from 4 to 6 billion m^3 and irrigated land area of about 100,000 to 250,000 ha, and shows a peculiar relationship, in other words, important, because the irrigated land area increases remarkably over a wide range with small increases in the amount of water resources,

Fig. 8. Relationship between river water amount and irrigated area ratio in the Tarim Basin.

indicating that, in Part II, natural and human impacts such as irrigation system techniques, agricultural land use or cultivation techniques are more effective at enlarging irrigation land area; and in Part III, where the range of water resources and irrigated land area are smaller than 5 billion m^3 and 120,000 ha respectively, a positive, linear relationship is clear as shown in Fig. 7. Roughly, the formula is:

$$y = 2.2x,$$

where x is the amount of water resources (billion m^3) and y is the irrigated land area (1,000 ha). It is worthy to note that the reaches of the Hotan River and the Kaidu River are located almost at the upper limit of Part III, but also, at the same time, at the lower limit of Part II. This means that, in these reaches, there is a possibility of enlarging remarkably the irrigated land area by developing irrigation and cultivation techniques and putting the infrastructure economically and sociologically in good condition.

In Fig. 8, the relationship between the amount of river water and the irrigation ratio is given. The distribution is relatively scattered but it shows a rough curve. In Fig. 8, there can be observed a sharp increase in the irrigation ratio in the range below

Table 4. Change of cultivation area and its rate in the Hotan oasis.

	Cultivation area (ha)	Cultivation ratio (ha/head)
1949	123,000	0.16
Mid 1950s	162,325	0.25
1976	192,866	0.17
1980	—	0.14
1985	—	0.12
1988	—	0.11

about 4 billion m^3 of river water. Therefore, in the Tarim Basin, relatively small river tributaries have a potential for large increases in their irrigation ratio. It should be stressed that these rivers are found mainly on the southern fringe of the Taklimakan desert in the Tarim Basin.

In short, the following should be kept in mind from the standpoint of agroclimatology. At oases, where the total available amount of water resources ranges from 5 to 6 billion m^3 , or total available amount of river water from 4 to 5 billion m^3 , irrigated land area (ratio) can be increased markedly, by introducing innovative cultivation/irrigation techniques. Agroclimatology can and should contribute to this at the oases.

4. Agroclimatological Problems in Cultivation Technique

4.1 Irrigation plans and cultivation calendars

In this part of the present paper, irrigation problems on the farmers' level or on a field scale are dealt with.

Taking an example in Hotan, decadal changes in the cultivated area and its ratio are shown in Table 4. Before the founding of People's Republic of China in 1949, the cultivated area was 123,000 ha and increased rapidly until the middle of the 1950s. The cultivation ratio also increased, from 0.16 to 0.25 ha/head. After that, however, the population growth rate grew more rapid, resulting in a decrease to 0.17 ha/head in 1976. By analyzing different sources of statistics, it can be said that the cultivation ratio also decreased.

In Table 5, changes in sowing techniques or area sown and yields of the three main crops at the Hotan oasis are given. An increase in the corn yield is particularly clear.

The fields are irrigated in most cases five times for

Table 5. Change of sowing amount or area and yield of main three crops in the Hotan oasis from 1956 to 1990.

	1956		1990	
	Sowing (t/ha)	Yield (t/ha)	Sowing area ($\times 1,000$ ha)	Yield (t/ha)
Wheat	2.7	21.8	7.14	36.9
Corn	2.7	28.8	6.48	73.7
Cotton	1.2	8.4	2.72	9.3

wheat, corn and cotton in Hotan and at other oases on the southern fringe of Taklimakan Desert and 6 times in Dunhuang. According to the conditions (distance from the main drainage, ground water use, sandy soil, severe drought years, etc.), the numbers of times vary within a range of ± 2 times.

Irrigation is done first before sowing in the cases of cotton and wheat, and after that, every 10 to 15 days in June, July and August. Because corn is sown between the rows of wheat before harvesting, corn is irrigated one or two times before the wheat is harvested. After that, the cornfields are irrigated three to four times. The ratio between the river water and other ground water used differs greatly from place to place, but they are almost equal in Dunhuang.

The cost of irrigation water from rivers is fixed annually by area, regardless the number of times of irrigation. Farmers, therefore, tend to use river water. But the river water available fluctuates widely from year to year, leading to unstable income, and is decreasing year by year, due to population growth.

The cost of river water differs according to conditions, as mentioned above. For example, in Dunhuang, the mean cost is 10.7 yuan per a per year, but it ranges from 7.5 to 12.8 yuan per a per year from field to field (farmer to farmer). In dry years with severe shortages of water, like 2001, the highest cost reached 15 yuan per a per year.

On the other hand, the mean cost of other ground water in Dunhuang is 0.65 yuan per te (the unit te is presumably kilowatt-hours). However, it differs from 0.4 to 1 yuan per te from field to field (farmer to farmer) and year to year. For example, it was 1.7 times higher in 2001, a dry year, than in 2002, a wet year. Under extremely favorable conditions, one field had a rate as low as 0.01 yuan per te in 2002.

Because of such differences between the costs of river water and other ground water and because of

the low salinity of river water, the farmers use more river water than other ground water. For example, they use river water one to two days for irrigation, but ground water 6 to 10 h or one day at most. The depth of irrigation water is 17–20 cm in the case of river water, but less in the case of other ground water.

These differences between locations (distances from the main channel for irrigation) result from the availability of cheaper, low salinity water from the river. From the standpoint of agroclimatology, it should be stressed that these differences are more pronounced, greater, for fields (or farmers) in dry years, when total harvests are low. Also, regional differences are not small. It has been reported that the depth of irrigation water is 7 cm for the first and second irrigation, but, after the third, it is 12 cm at the Minfen oasis, where available water is regionally scarce (Sawada, 2001).

Data on actual amounts of irrigation water by crop and by an oasis were not available for the studies reviewed here. A plan at an oasis, Cela, for 1985 (Yoshino, 1995) was available as shown in Table 6. It is clear that the annual totals of irrigation water per ha are greater not only for wheat, corn, and cotton, but also for vegetables, rape seed and cereals. Because the total field areas of these last three crops are small, the total amount of demand for irrigation water for alfalfa is relatively greater, as it is part of the second group of crops following the first group composed of the three main crops, wheat, corn, and cotton.

It is worth noting that the total amount of demand for irrigation water reaches 121.22 million m^3 a year in Cela, a relatively small oasis. It is necessary to study a detailed plan, considering the water demand from month to month, the crop calendar, and the amount of water actually available under the influences of climatic fluctuation and changes on the field (farmer) level.

4.2 Crop production and costs

According to the results of an experimental cultivation (Li, 1998), the mean production of corn was 11,708 kg/ha, 334 g/1,000 seeds, and 217 kg/ m^3 when irrigation was done five times. These amounts may have been obtained in the most favorable case from the viewpoint of irrigation water available.

Because we do not know the actual amounts, we tried to interview several farmers at each oasis in the

Taklimakan Desert. The results are summarized in Table 7. The following facts can be seen from Table 7: (1) cotton gives a lower yield in Hotan and Cela or the southern fringe than in Corla and Dunhuang, (2) in good harvest years like 1993, yields may be two or more times those of normal average year, (3) wheat does not show a clear contrast between the southern and northern fringes and Dunhuang, (4) paddy rice production in Aksu is relatively good as compared with the average of other humid regions, and (5) the increase in Cela is about two times for

cotton during the last 20 years and six to seven times for corn and wheat during the last 10 years. Even if we consider that 1993 was an exceptionally good harvest year, a gradual increase should be observable.

The costs of main crops at Aksu are: cotton 9 yuan/kg in 1993, but greater than 9 in 1994; corn 0.6–0.65 yuan/kg in 1993; wheat higher than 0.6 yuan/kg in 1993; rice 1.3–1.5 yuan/kg normally, but 2 in 1993.

In Dunhuang in 2002, the village office bought

Table 6. Demand of irrigation water by crops in Cela in 1985.

	Number of times of irrigation	Amount of irrigation water (m ³ /ha)	Annual total of irrig. water (m ³ /ha)	Total amount of irrig. water demand (×10,000 m ³)	Periods of irrigation
Winter wheat	7	4.9	34.3	3,640	Sept.–Dec. Mar.–June
Summer wheat	4	6.0	24.0	1,692	May–Aug. Nov.–Dec.
Corn	5	5.6	28.0	3,679	May–Sept.
Second crop corn	3	6.3	18.9	570	May–Sept.
Rye	4	5.5	22.0	172	July–Sept.
Cereals	4	5.5	22.0	172	Mar.–June
Rape seed	5	5.3	26.5	96	Jan.–Mar. May–Aug.
Cotton	3	5.5	16.5	550	Feb. June–Aug.
Gourd	3	5.3	15.9	220	Mar.–July
Vegetables	7	4.9	34.3	78	Mar.–Sept.
Winter greens	4	5.7	22.8	54	July–Sept.
Alfalfa	3	6.3	18.9	789	June–July
Green manure	1	6.7	6.7	410	July
Total	—	—	—	12,122	—

Data source: Yoshino, 1995.

Table 7. Production of main crops at the several oases according to interview of the farmers.

	Hotan	Cela	Aksu	Corla	Dunhuang
Cotton (t/ha)	3	2.3–3 (1972) 3.8 (mean) 5.3–6 (1993)	?	4.5	4.5–6 (mean, 2002) 7.5 (max)
Corn (t/ha)	7.5	1.5 (1983) 3–3.8 (recent) 8.6–9 (1993)	7 (1994) 9.8 (mean in recent years)	?	?
Wheat (t/ha)	?	1.1 (1983) 6.8–7.5 (1993)	5.9 (winter wheat) 7–7.4 (1994)	?	6–7.5 7.5 (max)
Paddy rice (t/ha)	—	—	8.3 (1994)	7.5	?

Note: mark (?) means “did not receive answer” and (—) “not cultivated.”

Fig. 9. An example of greenhouses at Dunhuang. (Ref. Photo 1)

cotton for 2.9 yuan/kg from the farmers, but brokers bought it at 3.0 yuan/kg. As was shown in Table 7, the mean production of cotton is about 45–60 kg/a in Dunhuang, i.e., 135–180 yuan/a. If a farmer cultivates 66.7 a (ten mu) cotton field, he gets 9,000–12,000 yuan per year. However, he must pay money for manure, disinfectants, irrigation water, electricity and miscellaneous expenses. This results in a low net income.

Fruit cultivation is not dealt with in detail in the present paper. As a source of income for the farmers, however, it has been more important. There is an example of a farmer getting an annual income of 3,000 yuan from grape cultivation. An orchard in Hotan is cultivating more than 14 kinds of fruits: grapes, apricots, pears, peaches, almonds, tarachi (a kind of almond), apples, walnuts, pomegranates, einura (a specialty of Hotan), etc.

4.3 Greenhouses

We know that greenhouse cultivation has been developing at oases during recent years, using the very advantageous situation of heat resources in the desert, but little information has been obtained so far. Taking an example at Dunhuang, a description is presented here.

At Dunhuang, greenhouses have been developed since the early 1990s and in particular, since about 2000. A sketch of a greenhouse at Dunhuang is given in Fig. 9. Its area is 100–120 m (length) by 10 m (width). In most cases, they are built in pairs. In the case of those 50 m in length, four greenhouses are built in groups. It is said, however, that 60–70 m length is the best for temperature efficiency, management, temperature control, etc. The total cost of materials for maintenance using vinyl sheets, seeds,

Fig. 10. Cultivation calendar in the greenhouses at Dunhuang.

water, reed-matting, cover blankets, bamboo poles etc. amounts to 170 yuan/m (length). The average income is 100 yuan/m with a best case of 200 yuan/m. In the worst case, they net only 10 yuan/m.

In the village in which the greenhouses are the most concentrated, 50 greenhouses have been built by 30 farmers (about half in the village). In the green houses, the calendar, shown in Fig. 10, is as follows: on about September 20, they are covered by vinyl sheeting; in the middle of November, they are covered by straw, but without heating; in the middle or at the end of November, they are covered by hemp-matting; when heating starts, the temperature is kept 40°C at a maximum and 15°C at a minimum (for winter vegetables, 30°C at a maximum and occasionally 0°C at a minimum). In February, cultivation of tomatoes, eggplant and sweet green peppers start with heating, as shown in Fig. 10, and in summer, of course, they use as the open greenhouses. Photo 1 shows the greenhouses in Dunhuang.

Because of increasing demand for fresh vegetables at the markets in the city of Dunhuang, greenhouse cultivation should be developed, but countermeasures to wind damage caused by the strong sand-dust storms are necessary.

5. Summary and Conclusion

Reviewing the results of field studies carried out in the Taklimakan Desert and its surrounding area since 1990, the following can be summarized:

1) The relationship between the amount of water resources and irrigated land area along the ten main tributaries is classified into three parts. They are, Part I along tributaries with more than 6 billion m³ of water resources, which is a sum of river water and other ground water; Part II, between 4.5 and 6 billion m³; and Part III, less than 4.5 billion m³.

Photo 1. (Top) Greenhouse in Dunhuang and (Bottom) its back-side. (Taken by Yoshino on August 11, 2002)

2) Along the tributaries in Part II, the irrigated land area (and its ratio) increases sharply in accordance with small increments in the amount of water resources. In other words, development of cultivation techniques, irrigation techniques and reasonable use plans is reflected strongly in the increase of irrigated land (and its ratio).

3) Based on the statistical data published, the cultivation ratio (ha/head) was at a maximum in the mid 1950s and then decreased continuously. This is because of a more rapid increase in population at the oases. The wheat yield (t/ha), however, increased 1.7 times, that of corn 2.7 times, and that of cotton 1.1 times in Hotan from 1956 to 1990, for example.

4) According to interviews with farmers at several oases, the actual statuses of production, income, costs, and wind damage from heavy dust storms were obtained as shown in the tables. The annual net income is very low, resulting in poverty among the farmers at the oases in this region.

5) Introduction of new agricultural technology,

such as greenhouses and fruit production can be supported for future development, but countermeasures to wind damage caused by Kara Bran (extra-strong and strong sand-dust storm) and Serik Bran (relatively strong or mediate sand-dust storm) in spring.

6) Cash crop cultivation such as cotton is sensitive to dryness in spring. The amount of water resources available at oases, which are strongly affected by year to year fluctuations and long-term global climate change, and population growth, will be fundamental factors in the study area.

Acknowledgements

The field studies reviewed here were carried out as a part of the Japan-China Cooperation Studies on Desertification Mechanism, 1992–1995, and ADEC (Asian Dust Impact on Environment and Climate), 2000–2004. To the collaborators, Prof. Y. Fujita, Prof. S. Arizono, Prof. T. Miyazawa, Mr. J. Suzuki, Dr. M. Du, Mrs. Dilber Turdi, and Prof. J. Lei, the present writer wishes to express his sincere thanks for their work, support and assistance.

References

- Chao, S.-ch., 1984: The sandy deserts and the Gobi of China. In *Deserts and arid lands* (ed. by El-Baz, F.). Martinus Nijhoff Pub., The Hague, pp. 98–113.
- Du, M.-y., 1993: Is it a global change impact that the climate is becoming better in the western part of the arid region of China? *Theor. Appl. Climatol.*, **55**, 139–150.
- Du, M.-y., Chen, H.-w. and Ren, Y.-y., 2004: Recent climate change in the Taklimakan Desert. *J. Arid Land Stud.*, **14**, 53–60 (in Japanese with English abstract).
- Editorial Committee, 1993: *Mitigation of Natural Hazard in Xinjiang for 40 years*, Earthquake Press, Beijing, 312 pp. (in Chinese).
- Huang, Sh.-zh., 2003: *Oasis studies* (National Natural Science Foundation of China). Science Press, Beijing, 205 pp. (in Chinese).
- Jiang, D.-h., 2003: Model of irrigation-agriculture development in the oases in Xinjiang. In *Oasis studies* (ed. by Huang, Sh.-zh.). Science Press, Beijing, pp. 56–61 (in Chinese).
- Jiang, Q.-g., Takamura, H. and Goto, Sh., 2001: Human induced LUCC in Qiemo oasis, Xinjiang Uygur Autonomous Region, China. In *Land degradation in the oases on the south side of the Taklimakan Desert. Result Reports of Research*

- Project (A) (2)* (ed. by Takamura, H.). Rissho Univ., Tokyo, pp. 131–139.
- Li, B.-r., 1996: Water resources, drought and desertification. In *Report of the 2nd Session of the CCI Working Group on operational use of climatological knowledge*. WCASP-37, WMO/TD-No. 774, pp. 21–31.
- Li, J.-f., 2002: *Desert climate*. Meteorological Press, Beijing, 185 pp. (in Chinese)
- Li, Sh.-g., 1998: *Agricultural ecosystems in desert oases*. Meteorological Press, Beijing, 138 pp. (in Chinese).
- Sawada, H., 2001: The irrigation agriculture in an oasis and the lives of villagers of a sheep-grazing village in the southern margins of the Taklimakan desert. In *Land degradation in the oases on the south side of the Taklimakan Desert. Res. Rep. Pas. Project Grant-in-aid for Sci. Res., (A) (2)* (ed. by Takamura, H.). Rissho Univ., Tokyo, pp. 119–129 (in Japanese with English abstract).
- Shi, Y.-f., 2003: *An assessment of the issues of climatic shift from warm-dry to warm-wet in Northwest China*. Meteorological Press, Beijing, 124 pp. (in Chinese).
- Song, L.-ch., Deng, Zh.-y. and Dong, A.-x., 2003: *Ganhan (Drought)*. Meteorological Press, Beijing, 162 pp. (in Chinese).
- Sun, L. and Huang, Ch.-y., 1998: *Some aspects of about desertification deriving from sand and dust storms in Northwestern China*. WMO/TD-No. 864, pp. 313–318.
- Xia, X.-ch. and Yang, G.-sh., 1996: *Damages by sand and dust storms and countermeasures for them in Northwest China*. Chinese Science-Environment Publisher, Beijing, 128 pp. (in Chinese).
- Xu, G.-ch., 1997: *Climatic change of arid and semi-arid areas in China*. Meteorological Press, Beijing, pp. 45–98 (in Chinese).
- Yang, D.-b., Shang, K.-h. and Wang, Sh.-g., 2003: *Shachenbao (Sand dust storm)*. Meteorological Press, Beijing, 181 pp. (in Chinese).
- Yoshino, M., 1992: Wind and rain in the desert region of Xinjiang, Northwest China. *Erdkunde* (Bonn), **46**, 203–216.
- Yoshino, M., 1995: Environment and human activities in Hotan and Cela oases on the southern fringe of Taklimakan Desert. *Aidai-shigaku*, **3**, 1–27 (in Japanese).
- Yoshino, M., 1997: *Desertification in China*. Taimeido, Tokyo, 300 pp. (in Japanese).
- Yoshino, M., 2000: Problems in climatology of dust storm and its relation to human activities in Northwest China. *J. Arid Land Stud.*, **10**, 171–181.
- Yoshino, M., 2002a: Secular variations of sand-dust storm and blown sand occurrence in the Taklimakan Desert, NW China. *J. Arid Land Stud.*, **11**, 253–258.
- Yoshino, M., 2002b: Kosa (Asian dust) related to Asian Monsoon System. *Korean J. Atmos. Sci.*, **5** (S): 93–100.
- Yoshino, M., 2002c: Climatology of yellow sand (Asian sand, Asian dust or Kosa) in East Asia. *Sci. China Ser. D*, **45** (Suppl.): 59–70.
- Yoshino, M., Yamamoto, T., Shimizu, G. and Suzuki, J., 2005: A synoptic climatological study on the regional differences of occurrence frequencies of dust storm in East Asia during the recent years. *J. Met. Soc. Jpn.* (to be published).
- Zhu, Sh.-d., 1984: Aeolian landforms in the Taklimakan Desert. In *Deserts and arid lands* (ed. by El-Baz, F.). Martinus Nijhoff Publ., The Hague, pp. 133–143.