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Increasing cropping intensity in response to climate warming in Tibetan Plateau, China

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ABSTRACT

Effects of global warming on agriculture have attracted lots of attention; however, agricultural response to climate change has been hardly documented in alpine regions. The Tibetan Plateau (TP) has a low agricultural portion, but it is an increasing minority, which plays an important role in regional food security due to growing population. The region of Brahmaputra River and its two tributaries in Tibet Autonomous Region (BRTT) is the main alpine agricultural area in the TP. Rapid warming has substantially affected agro-climate resources there and altered cropland pattern as well as cropping intensity. In this study, we explored how climate warming affected cropping intensity in past decades in BRTT. The potentially spatial distributions of single and double cropping systems in different decades (1970s, 1980s, 1990s and 2000s) were simulated based on a cropping suitability model, considering climatic, terrain and water factors. The results showed a significant increase of cropping intensity in some regions, in response to climate warming. The area suitable for single cropping increased from 19 110 km^2 in 1970s to 19 980 km^2 in 2000s, expanding from the downstream valleys of Lhasa River and Nyang Qu River of the tributaries of Brahmaputra to upstream valleys. The area suitable for double cropping gradually increased from 9 km^2 in 1970s to 2015 km^2 in 2000s, expanding from the lower reaches of Brahmaputra River in Lhoka Prefecture to the upper ones, as well as the Lhasa River tributaries. The upper limit elevation suitable for single cropping rose vertically from 5001 m above sea level (ASL) to 5032 m ASL from 1970s to 2000s, meanwhile that of double cropping rose from 3608 m ASL to 3813 m ASL. Overall, increased cropland area and cropping intensity due to climatic warming could increase food production in BRTT to some extent. Further investigation about potential uncertain effects from warming is still needed for regional agricultural adaption to climate change.

1. Introduction

The agro-ecosystem is a critical artificial ecosystem that supports the food and livelihood for human being and is subject to climate (Tubiello et al., 2007; Xiao et al., 2007). The effects of climate change on agricultural ecosystem attracted much attention due to its significance to human well-being and food security (Fuhrer, 2003; Gregory et al., 2005; Piao et al., 2010). On one hand, agro-ecosystem affects climate change through influencing global carbon, water, and nutrient cycles (Bondeau et al., 2007); on the other hand, recent climate change, especially warming (IPCC, 2007), has substantial effects on agro-ecosystem through changing heat, water, and other environmental factors. The effects of climate change on crop yields have been widely explored (Lobell et al., 2007; Chavas et al., 2009), but its effects on cropping systems are still hardly documented (Feng and Hu, 2004; Miller et al., 2005; Cleland et al., 2007).

Climatic warming can change heat conditions in some regions, prolong potential growing season and affect cropping systems. In most parts of Europe, the cropping systems have been adjusted due to climate change (Tubiello et al., 2000; Menzel et al., 2006; Meza et al., 2008; Lhomme et al., 2009). Also, double cropping in northern Subtropical Region of eastern China was partly replaced by triple cropping (Zhao, 1995). Zou et al. (2001) presented that there was much surplus accumulated temperature above 0 °C after harvesting one crop in the winter and spring wheat transition zone of northern China, which could be adequately used for planting another succession crop. In addition, Dong et al. (2009) indicated that single cropping was replaced by three crops in two years in some regions in northern China due to increasing accumulated temperature.

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Climate warming has altered not only cropping intensity but also spatial distribution of crops. In Europe, the areas suitable for cropping would expand northward due to climate warming (Olesen and Bindi, 2002), and the expansion of climatically suitable areas are expected to dominate in northern Europe (Bindi and Olesen, 2011). In China, the boundaries of the main crops expanded to the northern regions where it was previously unsuitable for cropping due to insufficient thermal resources (Xu et al., 1999; Yun et al., 2007). For example, the planting center of corn belts in Jilin Province shifted eastward (Wang et al., 2006), the planting region of winter rapeseed in Gansu Province expanded northward by 100 km, and the upper limit elevation increased by 100–200 m (Pu et al., 2006).

The agricultural region in the Tibetan Plateau (TP) is a small portion in China at national level, but the alpine agriculture in the TP is unique and plays an important role in regional food security. Evident warming in past decades (Duan et al., 2006), especially since the late 1980s, has changed the agricultural suitability and substantially affected the cropping intensity in the TP. Most studies focused on the impacts of climate change on alpine grassland in the TP (Gao et al., 2009; Fan et al., 2010; Yu et al., 2010; Shen et al., 2011). However, it is still unclear how warming affects alpine agriculture in the TP (Paltridge et al., 2009). The cropland in the TP is mainly located in the central Tibet Autonomous Region (Tibet for short, hereafter), so-called the drainage basin of the middle reaches of Brahmaputra River and its two Tributaries (BRTT), including Lhasa River and Nyang Qu River in Tibet (Paltridge et al., 2009, 2011b). The area of BRTT is about 6.65×10^4 km^2, only accounting for 5.53% of the total area of Tibet; however, its cropland area (2295.70 km^2) accounts for 45% and its cereal production accounts for 55.27% in Tibet. Therefore, BRTT is the most important agricultural production area in Tibet and called “Plateau Granary” (Paltridge et al., 2009, 2011b). Agriculture in BRTT was single cropping system (with seeding in spring or previous winter) in 1980s (TPCSECAS, 1984). In recent years, significant climate warming (Liu and Chen, 2000; Liu et al., 2009; Lau et al., 2010; Zhang et al., 2010), especially warming in springs and autumns, makes the thermal resources surplus after cryophilic crop harvest in the valley area of the BRTT with low altitudes, and that would substantially affect the cropping system (Wei, 2006; Jin et al., 2007; Tseren et al., 2007). An extended growing season facilitates the advancement of crop sowing. Excessive heat resources after early-sowing crop harvest provide sufficient heat condition to plant another crop within one year in some regions. An important manifestation is the increase of the Annual Accumulated Temperature above 0 °C (AAT0). For example, according to crop phenology observations and thermal resources statistics of crop requirement, the surplus AAT0 ranges from 1055 °C d to 1137 °C d after the harvest of winter barley or winter wheat in the middle reaches of the Brahmaputra, accounting for 35–40% of AAT0 during the whole year (Tseren et al., 2007). Therefore, it is possible to plant another crop in the same year in these areas. However, a systematic study on effects of climate warming on cropping intensity and cropland expansion is hardly found in the BRTT (Paltridge et al., 2009, 2011a).

The objective of this study is to investigate the potential cropping intensity changes in the BRTT due to climate warming. We hypothesize that the warming improves the potential cropping intensity and drives agricultural expansion in alpine regions both horizontally and vertically. To verify this hypothesis, we simulated the spatial distribution of different cropping intensities based on a cropping suitability model by considering thermal, terrain and water factors. The potentially spatial distributions of single cropping and double cropping systems in the 1970s, 1980s, 1990s and 2000s were simulated, and the spatial pattern changes were analyzed.

2. Materials and methods

2.1. Study area

The BRTT is located in the central and southern parts of Tibet, between 89°00′–92°35′E and 28°20′–31°20′N. It includes 18 counties of Lhasa, Lhoka and Shigatse Prefectures (Fig. 1). It is adjacent to the Sangri County of Lhoka Prefecture to the east, Lhaze County of Shigatse Prefecture to the west, the valley area to the south, and the Changtse-Nyenchen Tanglha Mountains to the north. The cropland is mainly distributed in the flat and open terraces of valleys (see the photos in Fig. 1), such as river floodplain, low terraces and alluvial terraces, and could extend to the upper alluvial fan of tributaries with irrigation conditions (Wei et al., 2004; Zheng, 2008). The average elevation is 3500–4200 m, decreasing from west to east. It belongs to a temperate monsoon and semi-arid climate, affected by terrain evidently. Average annual temperature varies from 4.7 to 8.3 °C; the temperature ranges from 10 to 16 °C in the warmest month and from −12 to 0 °C in the coldest month. Average annual precipitation varies between 252 and 580 mm and mostly concentrates in the period from May to September, decreasing gradually from east to west. High temperature and rich precipitation occur simultaneously, and wet and dry seasons are distinct. Solar radiation is rich with average annual sunshine time 2800–3300 h. As valley direction is consistent with prevailing wind direction in winters and springs, wind is strong and there are many windy days (Yang et al., 1996; Zhao et al., 2003).

2.2. Data and methods

2.2.1. Meteorological data

The average daily temperature was used in this study, which was derived from the China Meteorological Data Sharing Service System. We used 38 meteorological sites in Tibet (including sites both inside and outside of BRTT) from 1970 to 2009 to interpolate into the spatial grid data. Of which, nine meteorological sites were located inside BRTT (Fig. 1). As some of the sites were built after 1980s, we realistically employed 27 sites for the spatial interpolation in 1970s and 1980s.

When temperature increases to be over 0 °C continuously in spring, soil begins to thaw. Therefore, 0 °C indicates the starting of agricultural activities and AAT0 is an important indicator for agriculture in the study area. In this paper, we take AAT0 as the main thermal indicator to determine spatial suitability of different cropping systems. AAT0 is the sum of average daily temperatures above 0 °C in a continuous range of time. Here we define 5 days as the threshold of the continuous range. Then AAT0 was calculated from the initial day of the first five days, so did the end day. It can be calculated with the following equation:

$$\mathrm{AAT0} = \sum T_{Ds} + \cdots + T_{De} \tag{1}$$

where T_{Ds} and T_{De} are the average daily temperatures in the starting day (Ds) and the ending day (De) of the continuous period, in which the average daily temperatures are over 0 °C. AAT0 is the annual accumulative temperature over 0 °C by summing average daily temperature from T_{Ds} to T_{De}.

Spatial interpolation of AAT0 was done by ANUSPLIN software, which can involve multiple factors as covariates and is widely used for the interpolation of meteorological data (Hutchinson, 2001; Yan, 2003; Liu et al., 2008). In this study, we took elevation factor as a covariate due to complex topography in BRTT. Spatial interpolation of AAT0 was carried out into 90-m raster grid to match the resolution of DEM (Fig. A1).

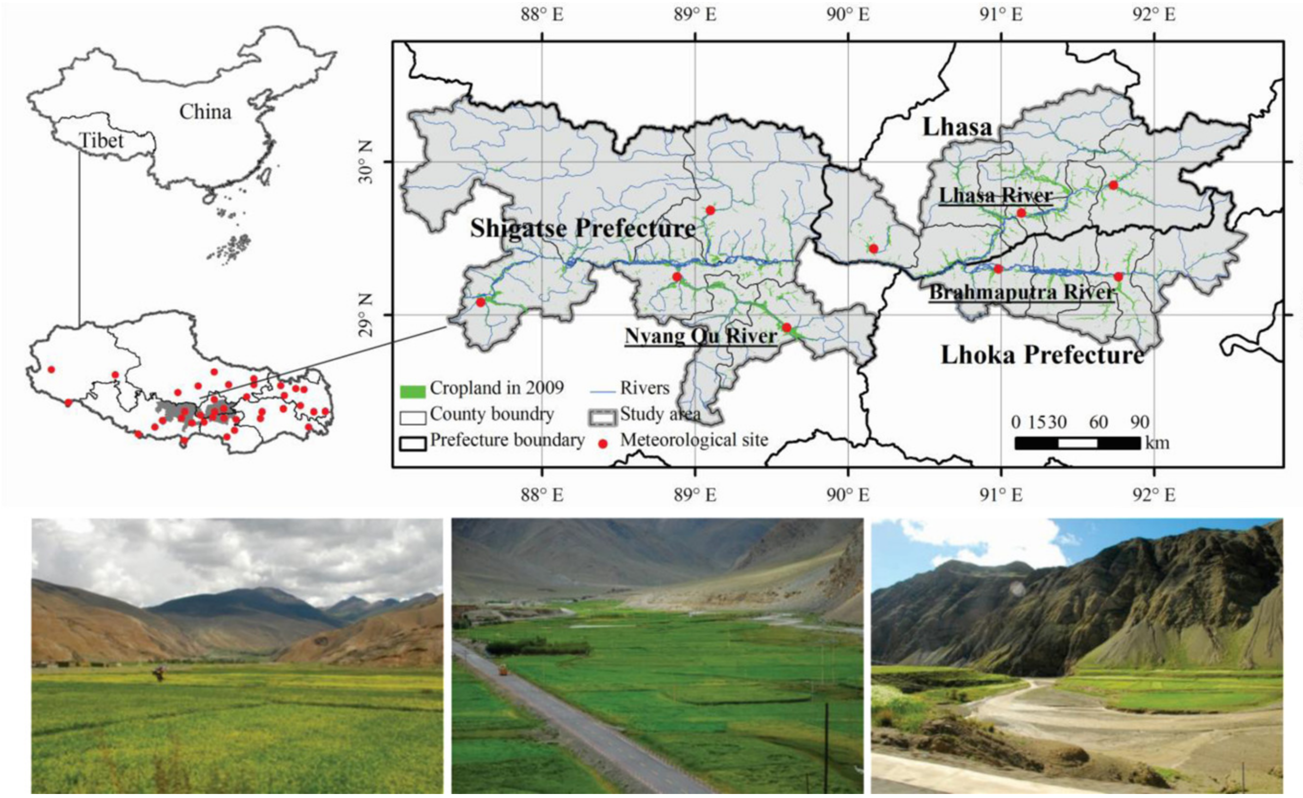

Fig. 1. Location of study area, as well as the distributions of meteorological observational sites, rivers and cropland in 2009. The pictures show the cropland in the valley, which were taken at the Nyang Qu River Valley of Gyangzê County in the summer of 2010.

2.2.2. Spatial cropland data

We acquired agricultural land use data in 2009 via artificial interpretation based on Landsat TM images. The land use vector data from National Land Cover Dataset (NLCD) in 2000 was used as reference data, which was provided by the Data Center for Resources and Environmental Sciences (RESDC) of Chinese Academy of Sciences. NLCD 2000 data has a scale of 1:100,000 produced by screen-up interpretation of Landsat imagery covering the entire China with high accuracy (Liu et al., 2005; Liu and Deng, 2010). The Landsat TM/ETM data covering BRTT in 2000 and 2009 were acquired from the United States Geological Survey (USGS). As crops are easily identified during the growing season, we chose image data in June or August. The Landsat images were calibrated and geographically corrected, false-color composited (R/G/B = Band 5/4/3) and enhanced (Fig. A2). Land cover data in 2000 from NLCD was reconfirmed and improved according to the Landsat images, and then agricultural land use change from 2000 to 2009 was detected by comparing the images in 2000 and 2009. To validate the results, we collected 350 field survey samples via a field trip in the summer of 2010 for accuracy assessment, including geo-photos, GPS location information and landscape records. The resulting cropland/non-cropland map was proved with an overall accuracy of 91%.

2.2.3. DEM data

DEM data is from Shuttle Radar Topography Mission (SRTM) data product with 90 m resolution, provided by International Scientific & Technical Data Mirror Site, Computer Network Information Center of Chinese Academy of Sciences. It is jointly measured and published in 2003 by National Aeronautics and Space Administration (NASA) and National Imagery and Mapping Agency (NIMA). This version of DEM data is produced by the International Center for Tropical Agriculture (CIAT) using new interpolation algorithm (Reuter et al., 2007). Topography slope was generated based on this DEM data by using ArcGIS 10 software.

2.3. Cropping suitability assessment model

Potential distributions of cropping systems were assessed by considering several essential indicators, including thermal, water, and terrain factors. As all the indicators in our study are necessary for cropping, we adopted the Minimum Limiting Factor Method (namely Shelford Restrictive Law) to assess cropping suitability. That is, if any factor was unsuitable, the assessment result would be designated into the unsuitable level. So, the suitability assessment result was decided by the factor with the lowest suitability level. It can be calculated by the following equation:

$$X = \min(x_1, x_2, \ldots, x_n) \quad (2)$$

where X is the result of crop suitability evaluation; x_1, x_2 and x_n are the suitability levels of the different evaluation factors; n is the number of evaluation factors.

Three indicators were considered for the cropping suitability assessment, including thermal condition (AAT0), terrain condition (slope), and water condition (the distance to rivers). For double cropping and single cropping, the suitability levels of the indicators were defined individually (Table 1). Terrain and water factors were static and consistent in both single and double cropping systems. Therefore, the same thresholds were adopted for their suitability designation (Table 1). However, thermal requirements for single and double cropping systems are quite different. Double cropping needs more thermal resources than single cropping. In addition, different crops in single cropping system have different thermal requirements. For example, spring barley, winter barley, winter wheat, rapeseed, and pea have different accumulated temperature requirements (Table A1). Besides, different crop compositions

Table 1
Criteria of index system for potential suitability assessment of different cropping systems in BRTT. Thermal, terrain and water conditions are three main factors with AAT0, slope, and the distance to rivers as three indicators, respectively.

Index	Sub-index	Suitability levels			
		Highly	Moderately	Marginally	Unsuitable
AAT0 (°C d)	1 cropping	≥2600	2120–2600	940–2120	<940
	2 cropping	≥3150	≥3150	≥3150	<3150
Slope (°)	1 and 2 cropping	≤5	5–10	10–25	>25
Distance to rivers (m)	1 and 2 cropping: 4–7th level of rivers	≤1500	1500–3000	3000–4500	>4500
	1 and 2 cropping: 2–3rd level of rivers	≤500	500–1000	1000–1500	>1500

in double cropping systems have different requirements, such as “grain crop and cash crop or fodder crop”, “cash crop and fodder crop” (Jin et al., 2007). For the selection of crops in double cropping system, local farmers prefer one early-matured crop and one cash crop, such as winter barley and rapeseed (Tseren et al., 2007), as rapeseed is good for improving land fertility and economic income. Therefore, we took the composition of winter barley (previous crop) and rapeseed (succeeding crop) on behalf of double cropping to define the thermal resource requirement for double cropping in this study (Table 1).

2.3.1. Thermal condition criteria

The thermal thresholds for single cropping were determined based on previous studies (TPCSECAS, 1984; Hu, 1995). Three rules were adopted: (a) AAT0 requirements of various crops for normal growth were defined as the lower threshold of moderately suitable level (also the top threshold of marginally suitable level), so 2120 °C d was defined as the threshold as most crops grow normally when AAT0 is higher than that value (Table A1). (b) AAT0 requirements (~2584 °C d) of different crops in widely distributed regions was adopted by the lower threshold of highly suitable level (also the top threshold of moderately suitable level), so 2600 °C d was defined as the threshold (2584 °C d was shortcut into 2600 °C d). (c) AAT0 of 940 °C d was considered to be the lower threshold in marginally suitable level for single cropping in Tibet (Hu, 1995). As to double cropping (winter barley and rapeseed), we defined 3150 °C d of AAT0 as the lower threshold of marginally suitable level by accumulating AAT0 requirements of winter barley (1900 °C d) and rapeseed (1200 °C d) (Table A2). In addition, given the time-consuming of previous crop harvesting and succeeding crop cultivating, 50 °C d was added up. Finally, we acquired the thermal thresholds for both single cropping and double cropping in different suitability levels shown in Table 1, and spatial distributions in Fig. 2.

2.3.2. Terrain condition criteria

In general, the upland in the slopes of mountains in the BRTT region is very rough and rocky, and cultivation is possible only in the area with low slopes such as mild valley or lake basin where soil deposition happens due to water transportation. According to the requirements of the Sloping Land Conversion Program in China, cropland with slopes above 25° needs to convert into forest or grassland. Accordingly, slopes were divided into four suitable levels (Table 1 and Fig. 3a). Through exploring the cultivated land distribution in 2009, we found that about 65% of cropland areas were mainly distributed in highly suitable level; while about 13% of cropland was located in moderately suitable areas, about 17% of cropland in marginally suitable areas, and only 6% of cropland totally unsuitable for cropping.

2.3.3. Water condition criteria

Precipitation mainly concentrates on the period from heading to maturity of wheat in BRTT. However, precipitation is very limited there and cannot meet crop growth requirement for the entire growth stages, and thus irrigation availability is a key factor to guarantee water requirement for cropping in this region. Furthermore, the irrigations in this region rely on rivers to a large degree. Therefore, the distance to rivers was used as the indicator quantifying water condition. Different grades of rivers were extracted by using Hydrology Tool of Spatial Analyst Tools in ArcGIS based on 90-m DEM data and seven grade levels of rivers were generated (Fig. A3). The first grade level of rivers was not considered, as it was very small and difficult to form runoff. The rivers in the 4–7th grade levels had more water resources, a wider valley due to stronger water erosion, and, more cropland located; while the valley from the 2nd to 3rd grade levels of rivers were narrower with less water resource. The criteria of suitability levels were defined in 2–3rd grade levels and 4–7th grade levels of rivers (Table 1). The distances to rivers of different suitability levels were determined according to the knowledge from our local survey in field trip (Table 1 and Fig. 3b).

3. Results

3.1. Spatiotemporal change of single cropping system suitability

The highly suitable level for single cropping was a small portion accounting for less than 5% of the BRTT area, mainly distributed in the basins of the Brahmaputra River, the Lhasa River and the Nyang Qu River (Fig. 4). The area increased from 2224 km^2 in 1970s to 2543 km^2 in 1980s, to 2831 km^2 in 1990s, and to 3147 km^2 in 2000s (Table 2). It gradually extended to the upper reaches of the Lhasa River, the Nyang Qu River and the Brahmaputra in the west of study area (Fig. 4). The moderately suitable for single cropping had a larger portion and mainly distributed in the outskirts of highly suitable level, particularly concentrating in the Nyang Qu River region. The area with the moderately suitable level decreased from 3293 km^2 in 1970s to 2798 km^2 in 2000s (Table 2), shifting from the eastern valleys to the western ones in BRTT, particularly evident from the lower reaches to upper reaches of Nyang Qu River in the western area. The decrease partly resulted from the area increase of highly suitable level for single cropping. The marginally suitable area for single cropping had a huge area relative to the areas with highly and moderately suitable levels, located in both sides of the western valleys. Its area increased from 13 593 km^2 in 1970s to 14 035 km^2 in 2000s (Table 2).

The whole suitable area for single cropping (including highly, moderately and marginally suitable levels) increased from 19 110 km^2 in 1970s to 19 980 km^2 in 2000s. It gradually expanded to the Brahmaputra Valley in the western study area and the upper reaches of the Nyang Qu River Valley (Fig. 4). The expansion of potential suitable agricultural planting region was reflected in both horizontal and vertical directions.

The upper limit elevations of different suitability levels increased evidently from 1970s to 2000s. Highly suitable area increased from 3994 m above sea level (ASL) in 1970s to 4097 m ASL in 2000s, while that of moderately suitable area increased from 4249 m ASL in 1970s to 4382 m ASL in 2000s

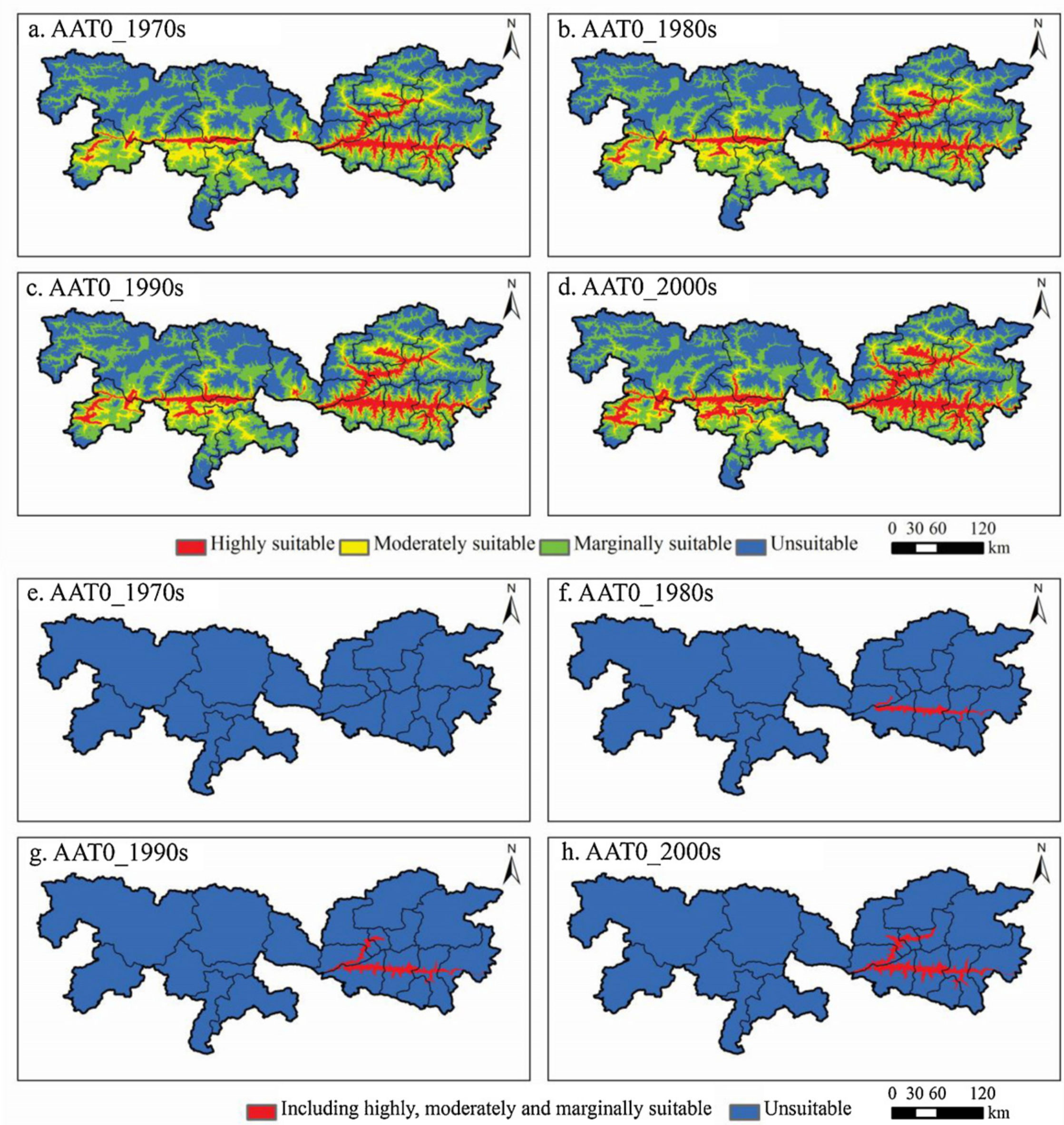

Fig. 2. Spatial distributions of different suitability levels of thermal conditions for (a–d) single cropping and (e–h) double cropping systems in 1970s, 1980s, 1990s, and 2000s.

(Fig. 5). In addition, the upper limit elevations of different suitability levels differed and higher suitability levels had lower upper limit elevations. The multi-year average upper limit elevation of highly suitable level was 4036 m; those of moderately and marginally suitable levels were 4303 m and 5032 m, respectively.

3.2. *Spatiotemporal change of double cropping system suitability*

Double cropping suitability area is the sub-collection of the suitable area (particularly the subset of highly suitable area) of single cropping. Generally, the potential area for double cropping (including the regions in highly, moderately and marginally suitable levels)

Table 2
Area statistics at different suitability levels for single cropping in BRTT in 1970s, 1980s, 1990s and 2000s (km^2, %).

Periods	Area/percent	Highly suitable	Moderately suitable	Marginally suitable	Total
1970s	Area	2223.8	3293.1	13592.7	19109.7
	Percent	3.3	5.0	20.4	28.7
1980s	Area	2543.3	3076.3	13621.4	19240.9
	Percent	3.8	4.6	20.5	28.9
1990s	Area	2831.3	2936.0	14052.9	19820.3
	Percent	4.3	4.4	21.1	29.8
2000s	Area	3147.4	2797.9	14034.8	19980.2
	Percent	4.7	4.2	21.1	30.0

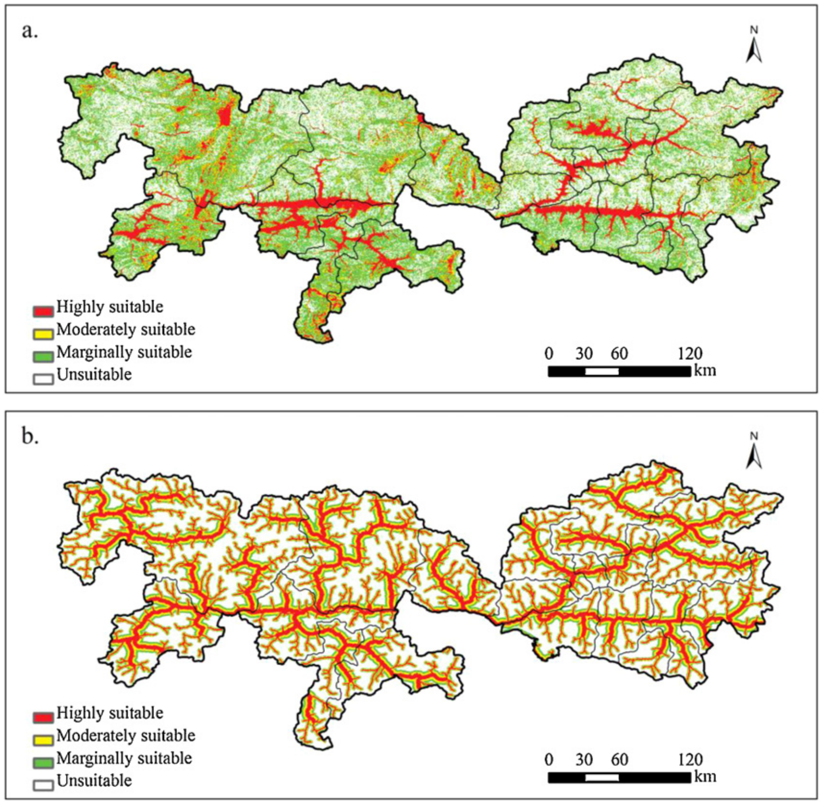

Fig. 3. Spatial distributions of different suitability levels for (a) slope factor and (b) water factor according to the distance to rivers.

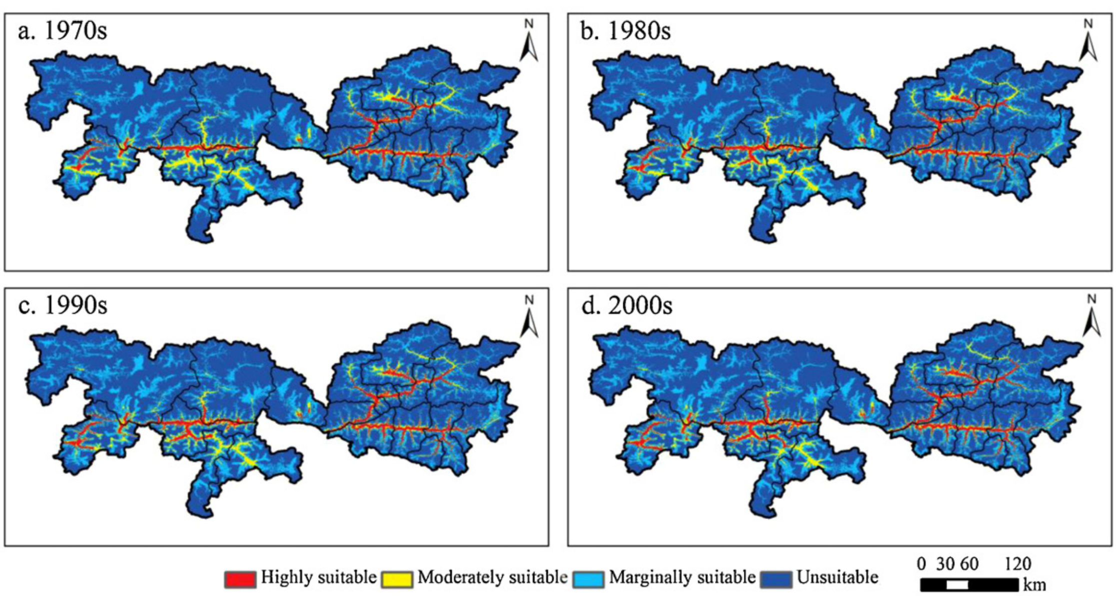

Fig. 4. Spatial distribution of different suitability levels for the single cropping system in BRTT in (a) 1970s, (b) 1980s, (c) 1990s, and (d) 2000s.

Table 3
Area statistics at different suitability levels for double cropping system (winter barley and rapeseed) in BRTT in 1970s, 1980s, 1990s and 2000s (km^2, %).

Period	Highly suitable	Moderately suitable	Marginally suitable	Total	Area percent of suitable region in study area (%)
1970s	4.4	1.1	3.3	8.8	0.01
1980s	584.0	204.9	73.8	862.7	1.3
1990s	900.0	347.4	187.9	1435.3	2.2
2000s	1144.6	467.1	403.7	2015.4	3.0

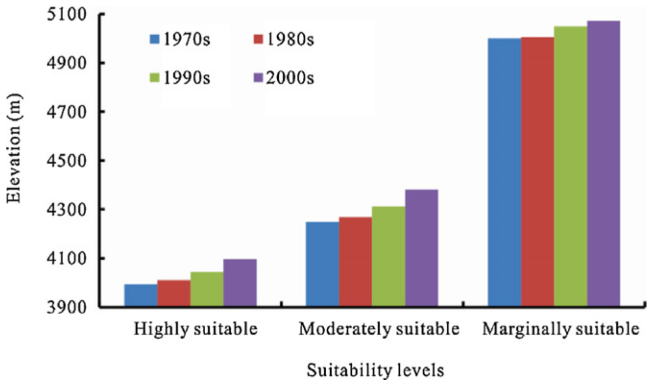

Fig. 5. Upper elevation limits of the single cropping system at different suitability levels in BRTT in 1970s, 1980s, 1990s and 2000s.

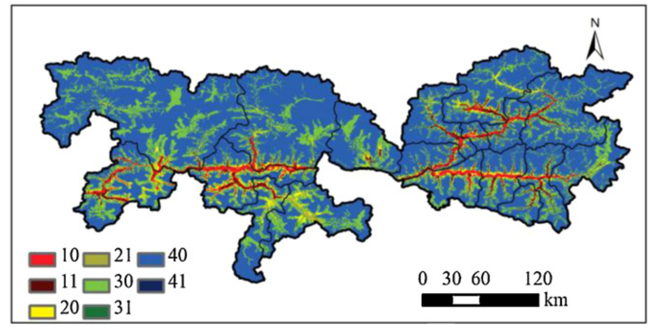

Fig. 7. Spatial distribution of potential land reclamation area by overlapping potential cropping suitability map in 2000s and cropland distribution in 2009. The code of double figures ("ab") means the cropping suitability (a: 1, 2, 3, and 4 means highly, moderately, marginally suitable and unsuitable, respectively) and current land cover type (b: 1 means cropland, and 2 means non-cropland).

was small and mainly distributed in the Brahmaputra Valley of Lhoka Prefecture and Lhasa Valley (Fig. 6 and Table 3). As such, the highly suitable area was larger than the moderately and marginally suitable areas.

In 1970s, the potential area for double cropping was only 9 km^2, dispersedly located in the Brahmaputra Valley of Lhoka Prefecture. It increased to 863 km^2 in 1980s, accounting for 1.3% of BRTT, mainly distributing in the Brahmaputra Valley of Lhoka Prefecture. In 1990s it increased to 1435 km^2, gradually expending from the lower reaches of the Lhasa River valley to upstream areas. It reached to 2015 km^2 (accounting for 3%) in 2000s, and spread to upper reaches of the Lhasa River valley (Fig. 6 and Table 3).

The extension of potential area for double cropping led to the increase of upper limit elevation in vertical direction. The upper limit elevation of the potential double cropping area increased from 3608 m ASL in 1970s to 3645 m ASL in 1980s, to 3714 m ASL in 1990s, and then reached 3813 m ASL in 2000s.

3.3. Cultivation potential in BRTT

The current cropland concentrates in the valley basin along the rivers with a total area of 2492 km^2 based on a remote sensing survey in 2009. By overlaying the remotely sensed cropland map in 2009 (Fig. 1) and spatial distribution of single cropping suitability map in 2000s (Fig. 4d), we can deduce the cropping status of current cropland and the land reclamation potential in future. Most of cropland in 2009 was located in the highly and moderately suitable levels, with area percentages of 43% and 35%, respectively, while the cropland in marginally suitable level covered 18% of all cropland area (Table 4). Therefore, most of the cropland distribution in 2009 is reasonable.

The potential of future cultivation is still large (Fig. 7). In 2009, cropland covered 1.6% and 1.3% of BRTT area in the highly suitable and moderately suitable area, respectively. There was still 3.1% and 2.9% of BRTT area available for land reclamation in the highly and moderately suitable levels, respectively, which is located in the main stream valley of Brahmaputra River and the tributary valley of Lhasa River in the north of study area. All the regions would be the potential areas for land reclamation.

4. Discussion

The cropping structure and pattern is the reflection and results of long-term agricultural adaptation to climate change, and previous studies showed cropping systems would change due to the evident global warming in non-alpine regions (Tubiello et al., 2000; Menzel et al., 2006; Meza et al., 2008; Lhomme et al., 2009). Our previous study showed that the temporal and spatial warming trend in spring and autumn was very significant in BRTT since

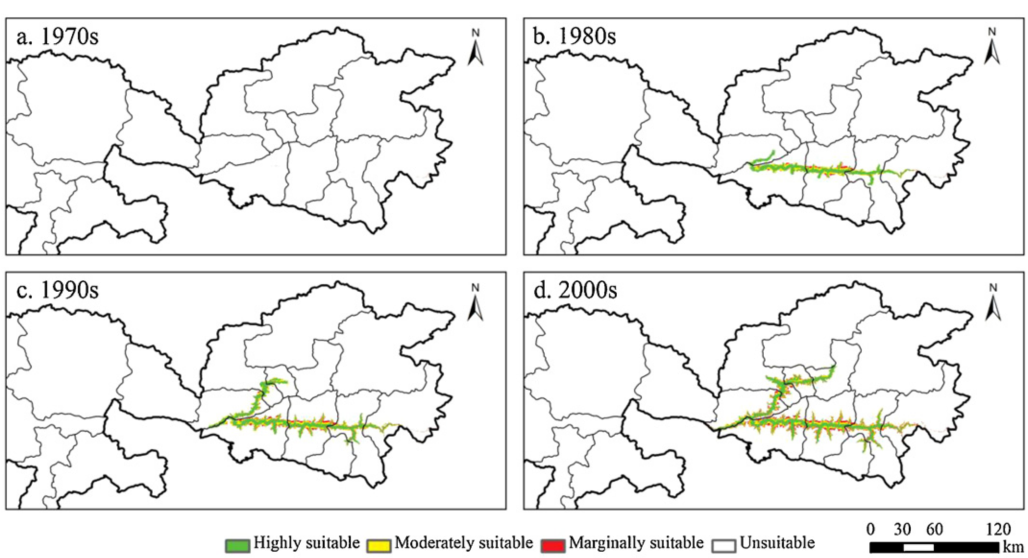

Fig. 6. Spatial distribution of different suitability levels for the double cropping system (winter barley for previous crop and rapeseed for succeeding crop) in BRTT in (a) 1970s, (b) 1980s, (c) 1990s, and (d) 2000s.

Table 4
Area percent of cropland in 2009 in different suitability levels for single cropping system (%).

Suitability levels	Area percent of different suitability levels in study area	Area percent of cropland in 2009 in different suitable level area	Area percent of cropland in 2009 in study area
Highly suitable	4.7	42.8	1.6
Moderately suitable	4.2	34.6	1.3
Marginally suitable	21.1	17. 9	0. 7
Unsuitable	70.0	4.7	0.2

1960 (Zhang et al., 2010), which could lead to the increasing of cropping intensity. This study verifies our hypothesis that climate warming affects the potential cropping intensity and drives alpine agricultural expansion both horizontally and vertically in BRTT. In this study, we find the increase of cropping intensity in BRTT is attributed to the evident warming, and particularly accumulated temperature plays an important role in cropping intensity increase.

The suitability results of single and double cropping were validated by referring to previous literatures and investigations. The evidences of increasing cropping intensity in BRTT from historical records were shown in Table 5. For example, in 1970s, researchers from the Commission for Integrated Survey of Natural Resources, the Chinese Academy of Sciences conducted several field surveys in the Tibet and summarized cropping systems of different counties (TPCSECAS, 1984). They found that only single cropping with winter barley or spring barley happened in Lhasa, including Lhoka Prefecture and Shigatse Prefecture. In mid-1980s, a series of experiments for double cropping (intercropping winter wheat with buckwheat, green manure, or fodder crops) were tested successfully in some river valleys of Lhasa and Lhoka Prefectures. Double cropping was proven feasible with elevation under 3800 m ASL in the period (Tseren et al., 2007). Lhasa and Lhoka Prefectures were suitable regions for developing double cropping during this period (Jin, 2005; Jin et al., 2007). Since 1995, farmers in Najin Village of Lhasa area began to plant double crops in a year with technicians' guidance and they succeeded. For example, in 1998, Najin Village received a large harvest of rapeseed after harvesting winter wheat or winter barley. In addition, the farmers in Seda Village of Qüxü County in Lhasa area tried to plant turnip after harvesting winter barley, and acquired a yield 80–100 kg/ha and even the maximum yield as high as 187 kg/ha (Jin et al., 2007).

Generally, existing evidences showed that there was hardly double cropping area in 1970s; double cropping feasibility was tested by a series of experiments since 1980s; in 1990s, the experimented experiences were popularized and the farmers started to conduct double cropping in Lhasa region. In the field survey in 2009, we observed that there were large areas of double cropping in the downstream area of Lhasa River and the middle reaches of the Brahmaputra in Lhoka Prefecture. Overall, it is consistent with the simulated scenarios of the potential double cropping distributions in different periods.

The scenario analysis about the cropping system suitability could contribute to regional agricultural development. Our results indicate that it is possible to increase cropping intensity in the main stream valleys of Brahmaputra River and the tributary valleys of Lhasa River in BRTT (Fig. 7), which could contribute to crop production and release the pressure of food requirement for an increasing population.

Increasing cropping intensity leads to many positive effects. For example, if the fodder crop is planted as a succession crop after harvesting the first crop, it could increase the fodder crop production and reduce the forage stress from the livestock industry (Paltridge et al., 2009). Climatic warming provides potential opportunity to develop the intensive agriculture taking advantage of the thermal resource. However, there is still some uncertainty about the effects of warming on agriculture. Increasing thermal conditions could lead to some crop diseases and insect pests; extreme weather events increase in climate warming process and could lead to negative impacts on crop growth. In addition, increasing cropping intensity could plunder soil nutrients and accelerate land degradation. One suggestion is to plant green manure crops as succession crops (e.g., rapeseed, pea, turnip, alfalfa, and vicia), which could help to improve soil.

Thermal indicator is a critical factor affecting spatial distributions of different cropping systems in BRTT. Thermal requirements of single and double cropping systems were defined according to existing literatures and experiments data in this study. However, it is difficult to define the criteria of AAT0 quantitatively for certain crops. Potential uncertainties are mainly derived from two aspects: First, thermal requirements of different crops are different. Second, the crop habits could change at different altitudes or with changed climates. Therefore, it is difficult to determine the specific

Table 5
Evidences for cropping index increase in BRTT from previous literatures.

Locations	Year	Cropping system	References
Balang commune in Qüxü County	1975	Single cropping in winter	Field survey in 1975 (TPCSECAS, 1984)
Gonggar County	1986	Winter wheat + Vicia sativa	Experiments (Hu, 1995)
Seda village in Qüxü County	1987	Winter barley + Vicia sativa	Same with above
Seda village in Qüxü County	2000s	Early winter barley + turnip	Jin et al. (2007)
ChengguanQu in Lhasa	1970s	Not suitable for double cropping	Field survey in 1975 (TPCSECAS, 1984)
Dagzê County, Maizhokunggar County	1975	Single cropping in spring	Same with above
Doilungdêqên County	1975	Single cropping in winter	Same with above
Naiqiong village in Doilungdêqên County	1987	Winter wheat + Vicia sativa	Experiments (Hu, 1995)
Bangdui Village in Dagzê County	1987	Winter barley + Vicia sativa	Same with above
Najin Village in Lhasa	1998	Winter barley/winter wheat + rapeseed	Web reference[a]
Nyêmo County	2000s	Early barley + turnip	Jin (2005)
Zedang County	2004	Winter barley + garlic/watermelon with plastic mulch	Tseren et al. (2007)
BRTT	2000s	Double cropping system	Web reference[b]

Note: "+" means planting two crops in a year.
[a] http://www.tibetinfor.com/tibetzt/tibet50/xz50/xz_jj/jj_26.htm.
[b] http://www.gov.cn/jrzg/2009-09/26/content_1427424.htm.

criteria in thermal requirement. Double cropping would be even more complex, so in this study a common composition (winter barley and rapeseed) was taken as an example to explore the effects of climate warming on cropping system, which could not completely reflect other compositions.

5. Conclusion

The increasing food requirement for a growing population is a large challenge for agriculture development. Climate change effects on agriculture are substantially affecting food security situations. However, our understanding about climate change effects is still limited; in particular, one of the insufficient knowledge is from alpine agriculture. This study explored the response of potential cropping intensity to climate warming in BRTT (the core agricultural production region) in four periods (1970s, 1980s, 1990s and 2000s), based on a cropping suitability assessment model by considering thermal, terrain and water factors. Literature-based validation proved the feasibility of the simulated suitability scenarios of cropping intensity. Our results showed that the potential area suitable (including highly, moderately and marginally suitable levels) for single and double cropping systems increased in both horizontal and vertical directions due to climate warming in last decades. Cropping intensity has the potential to change from single cropping system to double-cropping system in some regions, and cropping structure would be modified from the single structure of 'a single grain type' to the dual structure of 'grain and cash type' or 'grain and fodder type'. Under the background of climate change, a positive adaption strategy by absorbing these cropping system evolutions should be considered for regionally agricultural development and food security. This study provides some implications for land reclamation, and the priority should be given to highly suitable area; meanwhile, the land reclamation should be avoided in the unsuitable area or marginally suitable area.

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Appendix A.

See Tables A1 and A2 and Figs. A1–A3.

Table A1
Classification basis of thermal index of potential suitability assessment of different crops.

Crop	Variety	AAT0 acquirement for growth (°C d)	Upper limit of altitude of widely distribution and the corresponding AAT0 (°C d)	References
Spring barley	Highly early mature	1330	<4300 m; 2000	1. The heat required by crops decrease about 200–400 °C d of AAT0 with altitude increasing
Winter barley	Early mature	1900	<3800 m; 2584	2. The heat during growing season should not be less than 940 °C d of AAT0 (Hu, 1995)
Winter wheat	Mid-late mature	2120	<3800 m; 2584	
Rapeseed	Early mature	1200	<4000 m; 2100	
Pea	Early mature	1300	<4300 m; 2000	

Table A2
Grades of thermal index for potential suitability assessment of different crops (°C d).

Crop	Variety	Suitability level			
		Highly	Moderately	Marginally	Unsuitable
Spring barley	Highly early mature	≥2000	1330–2000	940–1330	<940
Winter barley	Early mature	≥2600	1900–2600	1500–1900	<1500
Winter wheat	Later mature	≥2600	2120–2600	1720–2120	<1720
Rapeseed	Early mature	≥2000	1200–2000	940–1200	<940
Pea	Early mature	≥2000	1300–2000	940–1300	<940

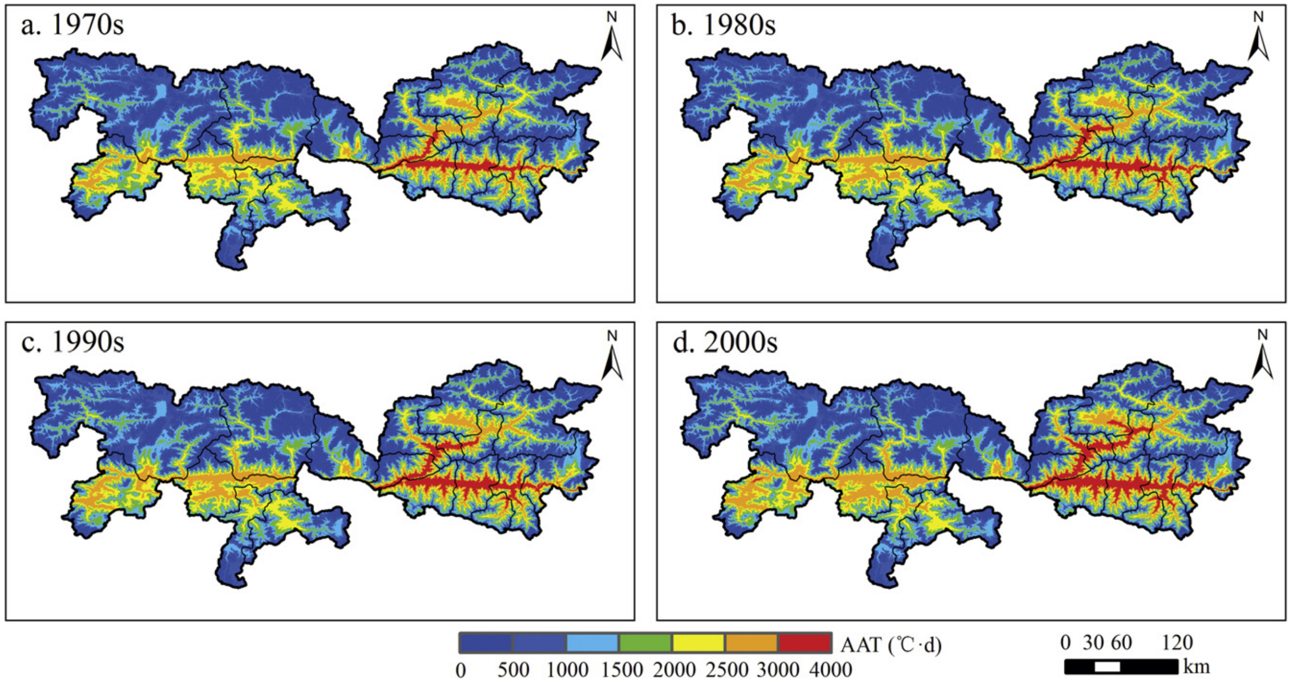

Fig. A1. Spatial distribution of AAT0 in BRTT in 1970s, 1980s, 1990s and 2000s.

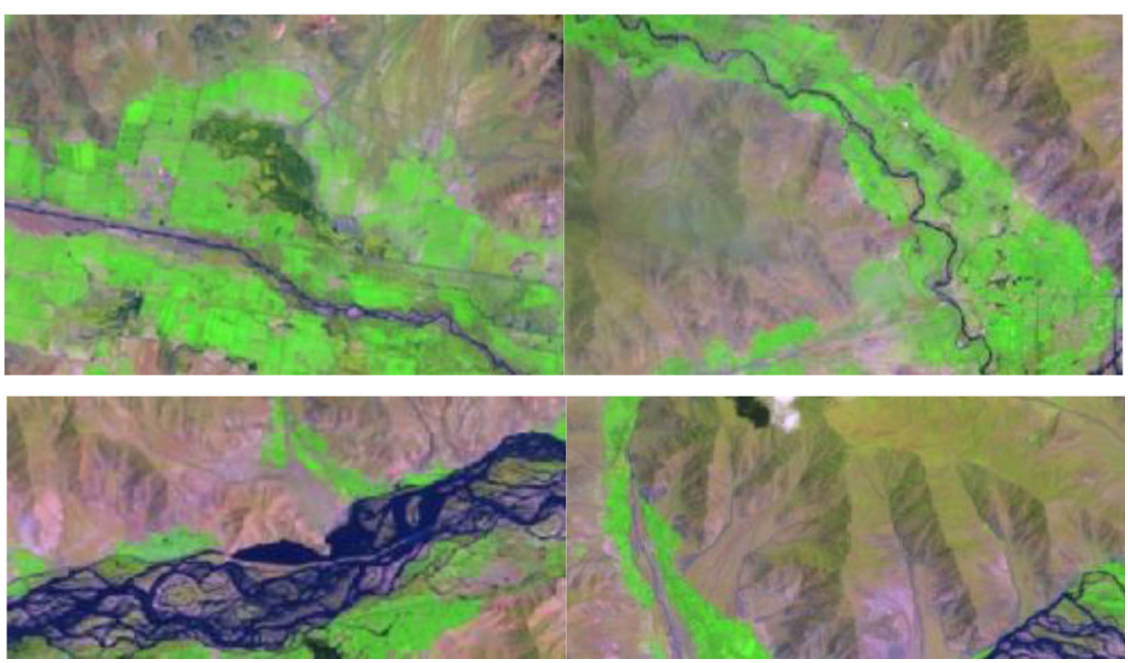

Fig. A2. Scene samples from visual interpretation for cropland. The cropland was highlighted in green color in the false color composition map (R/G/B = Band 5/4/3). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

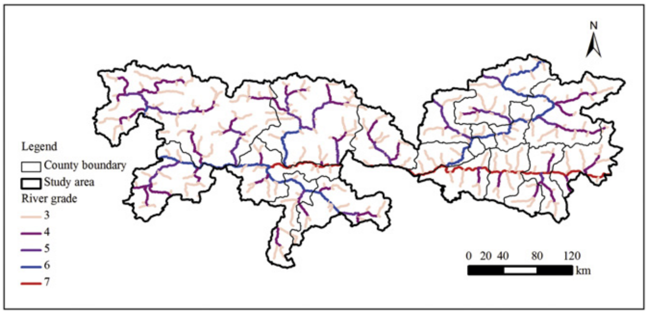

Fig. A3. Spatial distribution of different grades of rivers in study area. Different grades of rivers were extracted by Hydrology Tool of Spatial Analyst Tools in ArcGIS based on 90-m DEM data. The numbers of 3–7 are the river grades. The first and second grades are not shown in the figure due to dense distribution of rivers.

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