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Climate change and human activities: a case study in Xinjiang, China

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Abstract We examined both long-term climate variability and anthropogenic contributions to current climate change for Xinjiang province of northwest China. Xinjiang encompasses several mountain ranges and inter-mountain basins and is comprised of a northern semiarid region and a more arid southern region. Climate over the last three centuries was reconstructed from tree rings and temperature series were calculated for the past 50 years using weather station data. Three major conclusions from these analyses are: (1) Although temperature varied considerably in Xinjiang over the last 200 years, it was non-directional until the last 50 years when a substantial warming trend occurred; (2) The semiarid North Xinjiang was representative of the northern hemisphere climate, while the more arid South Xinjiang resembled the southern hemisphere climate, meanwhile, (3) The entire Xinjiang province captured the global-scale climate signal. We also compared human contributions to global change between North and South Xinjiang, including land cover/land use, population, and greenhouse gas production. For both regions, urban areas acted as heat islands; and large areas of grassland and forest were converted to barren land, especially in North Xinjiang. Additionally, North Xinjiang also showed larger increase in population and greenhouse gas emissions mainly associated with animal

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production than those in South Xinjiang. Although Xinjiang province is a geographically coupled mountain–basin system, the two regions have distinct climate patterns and anthropogenic activities related to land cover conversion and greenhouse gas production.

1 Introduction

Temperature change since the second half of the twentieth century can only be explained by including anthropogenic forcing as suggested by the IPCC (2001). Previous studies modeled natural and anthropogenic forcing on climate change, and showed the latter as the dominant cause of recent warming (Knutson et al. 2006). Due to pronounced warming trends, studies of how human activities influence climate change have increased dramatically in recent years. However, few studies have examined physical climate change and major human impacts including population, land cover/land use and greenhouse gas production at regional scales. Climate models and policies typically ignore local drivers such as land use change, urban effects, conversion of natural ecosystems and agriculture, which generate inconsistent or even completely misleading results (Betts 2007).

Climate reconstruction using tree rings has revealed both fine and coarse scale climatic change (Briffa et al. 1992, 2001; Overpeck et al. 1997; Briffa 2000; Jones et al. 2001a; Esper et al. 2002; Moberg et al. 2005) as well as instrumental records (Jones et al. 1999, 2001b; Hansen et al. 1999; Folland et al. 2001; Jones and Moberg 2003). Information on past climate is of crucial importance for ascertaining the background natural climate variability, in order to understand recent temperature changes in light of possible human impacts.

Both empirical evidence and modeling studies have demonstrated that land cover change is a key global change process (Foley et al. 2005; Falcucci et al. 2007). Land cover and land use change, a combination of anthropogenic activities and changing climate, have great influence on terrestrial biogeochemical processes, and also impose feedbacks to current climate change (Brovkin et al. 2004; Houghton 2008). Land cover/land use change significantly contributes to atmospheric carbon dioxide concentrations, while agricultural activities are responsible for large methane and nitrous oxide emissions (IPCC 2007). Especially in semiarid and arid regions, severe overgrazing and land degradation significantly elevated temperatures (Balling et al. 1998). Land cover change can directly increase temperatures, and the most dramatic example is urbanization, inducing warming that overwhelms the background trend (Motha and Baier 2005).

A mountain–basin system is a geographical complex containing mountains and a mosaic of inner-mountain basins. It is unique due to its specific natural settings, heterogeneous landscapes and energy transfer among subregions, and is therefore highly susceptible to climate change (Lischeid 2006). Xinjiang is a typical mountain–basin system that lies in the semiarid and arid areas of northwest China. Despite Xinjiang being recognized as a single mountain–basin system, it is comprised of northern and southern regions that differ in both climate and land use. North Xinjiang is semiarid, and has lower temperatures and higher precipitation, with more habitable land and higher population density than the arid South Xinjiang.

We first examined both the climate variability over the past three centuries using tree ring records, and the instrumental record for the last half of the twentieth century to assess recent climate warming in a long-term context. Second, we addressed regional variation in land cover/land use, urban effects, population size and anthropogenic gas emissions. We examined these patterns for the entire province of Xinjiang, and also compared and contrasted North against South Xinjiang. Finally, we discuss management strategies for semiarid North Xinjiang and arid South Xinjiang in light of our results.

2 Study area

Xinjiang province of northwest China encompasses both semiarid and arid areas. It is a typical mountain–basin system including permanent snow and ice, high mountain forest, middle mountain forest–grassland, low mountain desert, agricultural oasis and diluvia fan shrub–grassland. There are three mountain ranges from north to south; these consist of the Altai Mountains, Tian Shan, and the Kunlun Mountains. There are two major basins between these three mountain ranges; the northern Junggar Basin consists of mostly steppe and semi-desert, and the southern Tarim Basin is represented more by desert (Fig. 1). The climate of Xinjiang province is typical of inner-continental land masses, with a wide daily temperature range, low precipitation and low humidity. The annual precipitation of North Xinjiang is 100 to 500 mm, while South Xinjiang is 20 to 100 mm. Annual average temperature in North Xinjiang ranges from 4°C to 8°C, and in South Xinjiang is 10°C to 13°C. In the hottest month of July, the temperature in Turpan of the South can reach as high as 48.9°C; whereas in the coldest month, the temperature is as low as −51.5°C in Fuyun of North Xinjiang. On average, South Xinjiang has frost-free days of 200 to 220 days/year, whilst less than 150 days in the North. Xinjiang is divided into two distinct subregions by its natural settings, resulting in two typical mountain–basin systems with different hydrology and heat conditions and therefore climate patterns.

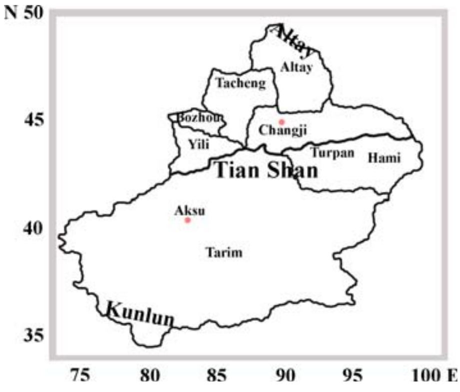

Fig. 1 Mountain–basin system in Xinjiang province of northwest China. Xinjiang is divided into North and South subregions by Tian Shan in the middle, the Altay Mountains in the north and the Kunlun Mountains in the south. Changji and Aksu shown in *red dots* are the two dendrochronology sites, located in the North and South respectively, and the other seven cells displayed (Altay, Tacheng, Bozhou, Changji, Yili, Turpan/Hami, and Tarim) represent areas where we obtained instrumented weather data

Since the foundation of the People's Republic, northwest China has become one of the most intensely cultivated areas of China. Home to various ecosystems and habitants as well as high biodiversity, this mountain–basin system has retained its natural setting for centuries until human habitation. People that live in Xinjiang have changed the land by exploiting resources, preserved the land by advocating protected areas, and irrevocably altered the landscape and ecological environment. Mining, farming, ranching and timber harvesting have changed the land-use as well as the climate in the region, and exhibited industrial civilization and urbanization. Rapid population growth and migration to the marginal land of semiarid and arid areas exacerbated the land degradation and water depletion. Understanding the climate, anthropogenic activities, and their interactions is critical to establish a framework for sustainable management of such semiarid and arid regions.

3 Methods

3.1 Long-term climate patterns from tree-rings

Tree rings are widely used to reconstruct past climate (Briffa et al. 1992, 2001; Briffa 2000). We used dendrochronology data to reconstruct past climate because of the availability of tree-ring series (Li et al. 1989) that could accurately resolve past climate for Xinjiang province. We used standardized annual tree-ring width to establish a set of 40 different climatic indices including monthly/annual/seasonal/growing season temperature and precipitation, accumulated temperature and warmth index. For the reconstructed Changji and Aksu sites (Fig. 1 and Table 1), we used monthly instrumental data from Meteorology Bureau of Xinjiang covering the period from 1955 to 2004, and investigated the relationships with dendrochronologies by correlation coefficients analysis. Among various indices, warmth index was the best performing. The definition formula of warmth index (WI) is as follows:

$$WI = \sum_{i=1}^{n} (t_i - 5),$$

where t_i is any monthly temperature that exceeds 5°C and n is the total number of corresponding months (Kira 1945). The 5°C threshold is a crucial temperature for soil thawing and blossom time, and therefore reflects biological responses of vegetation towards temperature and represents the amount of heat required to complete a normal annual cycle of vegetative and reproductive growth.

Bias in estimating the variance of independent identically distributed random variables was avoided by using autocorrelated data (Trenberth 1984). In addition,

Table 1 Standard tree-ring chronologies for Xinjiang

Site		Coordinates	Type	Altitude (m)	Species	Years
Changji	Fukang	44 N, 88 E	TRW	1,953	*P. schrenkiana*	1692–1977
	Hutubi	43 N, 86 E	TRW	1,750		1686–1977
Aksu	Shaya	40 N, 83 E	TRW	965	*P. euphratica*	1780–1983

Two most optimum chronologies were selected for Changji (North) and one for Aksu (South). Reconstruction periods vary from 203 to 291 years based on time span of available chronologies climate in a specific year may affect tree-ring width (TRW) in one or more subsequent years (Fritts 1976), so a 1-year lag was also considered in our reconstruction. Based on the correlation between WI_n and TRW_n/TRW_{n+1}, we then established a transfer function by regressing tree-ring data against instrumental record (Fritts 1976; Schweingruber et al. 1979). Combining autocorrelation and maximum likelihood methods (SAS 8.0, SAS Institute Inc., Cary, NC, USA), a regression model was developed and fed with proxy data to reconstruct past climate. Finally, we employed a cross-calibration and verification procedure using instrumental data and reconstructed series to test the regression model (Louis 1993).

3.2 Recent climate change

In order to understand possible human-related changes to climate we examined the instrumental record from 1955 to 2004. To interpret the current climate in the context of historical change, we calculated the warmth index using monthly data for the two reconstructed sites, and compared their slopes with reconstructed series by analysis of covariance in JMP (JMP 7.0, SAS Institute Inc., Cary, NC, USA). We then divided Xinjiang into North and South subregions by Tian Shan in the middle, and further seven cells based on distinct mountains and basins (Fig. 1 and Table 2). We obtained meteorological records of temperature measurements from Meteorology Bureau of Xinjiang, and calculations of surface temperature were based on cells and further averaged into subregions, and then the entire area. There are several complete instrumental temperature series on the hemispheric or global scale using the grid-box method (Hansen et al. 1999; Jones et al. 1999, 2001b; Folland et al. 2001; Jones and Moberg 2003). Here we also employed a similar grid-box method, and performed Climate Anomaly Method to avoid bias from data gaps (Peterson et al. 1998). Finally, we compared low frequency behaviors of calculated surface temperature records of North, South and entire Xinjiang with larger scale series.

3.3 Land cover change

The increase in human population of Xinjiang province has lead to extensive local and regional changes in land cover and land use, as well as enhanced urban sprawl. We explored all available data for the region to assess land cover change for the past

Table 2 Subregion and cell divisions in Xinjiang

Subregion	Cell		
	Graphical range		No. of in situ stations
North Xinjiang	Junggar Basin area	Altay District (Altai Mountain)	4
		Tacheng District (Tacheng Basin)	5
		Bozhou District (Bozhou River Basin)	6
		Changji District (inter-mountain basins)	8
	Yili District (Yili River Basin)		6
South Xinjiang	Turpan/Hami District (Turpan Basin/Hami Basin)		2
	Tarim Basin area		9

Each cell of Xinjiang represents at least one mountain or basin, and the seven cells are consistent with climate division established by accumulated temperature two decades. First, we obtained 1km pixel land cover data for years 1985 and 1995 from the Resources and Environmental Sciences Data Center of Chinese Academy of Sciences. Each classified vegetation type in these two images is presented in percentage cover, and the images are available till 2000. Second, we then used Moderate Resolution Imaging Spectroradiometer/Terra (MODIS) global land cover data for years 2001 and 2004. Both data types are 1 km in resolution, georeferenced and classified into vegetation classes. Both image types were consistent in land cover classifications, and showed a continuous change pattern. We analyzed the land change patterns for various land cover types from 2001 to 2004 using Land Change Modeler (LCM, Clark labs, Worcester, MA, USA) to identify which particular land cover types experienced the most extensive change.

3.4 Population growth

The effect of urbanization on temperature was determined by comparing weather station temperature data from 1955 to 2004. We selected rural and urban areas on the basis of population size in 2000 (Xinjiang Statistical Yearbook 2000). For Xinjiang province, we defined districts with populations less than 100,000 as rural areas because of greatly reduced population density and human activities; we designated districts with populations over 200,000 as urban areas. In this way, we summarized and interpreted temperature series of seven rural areas and 20 urban areas, with one weather station in each area.

3.5 Calculation of methane and nitrous oxide emissions

We calculated greenhouse gas production based on livestock numbers obtained from Xinjiang Statistical Yearbook (1991, 1997, 2005). Both CH_4 and N_2O are emitted from livestock and their waste, and the digestive process in ruminant livestock accounts for a large portion of methane emissions (McRae et al. 2000). Ruminant animals such as cattle, buffalo, sheep and goats were calculated here, as well as non-ruminant domesticated animals including swine, horses and mules. The CH_4 and N_2O emissions associated with these animal production systems were calculated according to 2006 IPCC Guidelines for National Greenhouse Gas Inventories. We calculated CH_4 and N_2O emissions per administrative district of Xinjiang over the period of 1990 to 2004, and analyzed their relationship with human population growth. We also compared slopes of linear fit of greenhouse production between North and South Xinjiang by analysis of covariance in JMP (JMP 7.0, SAS Institute Inc. Cary, NC, USA).

4 Results and discussion

4.1 Past climate reconstruction

Tree-ring reconstructions over the past three centuries showed natural warming and cooling events (Fig. 2). However, with alternating warm and cold periods, there was no trend in North Xinjiang and a slight but significant warming for the South

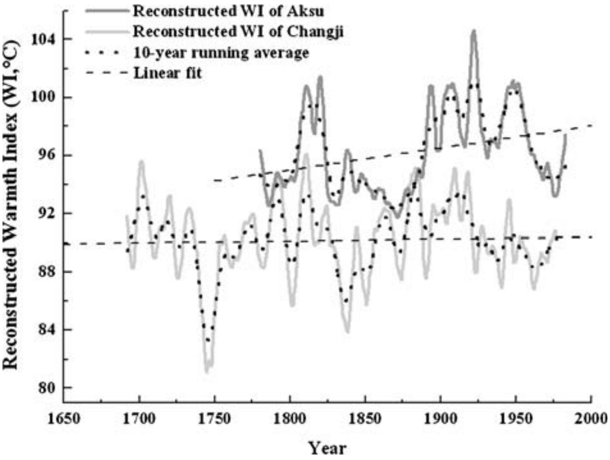

Fig. 2 Reconstructed WI variance of Xinjiang. Two reconstructed subregions are Changji (North) and Aksu (South). Reconstruction period varies from 203 to 291 years according to chronologies availability. *Dotted lines* are 10-year running average, and *dashed lines* are linear fit for each site

Xinjiang ($F = 20.01$, $p < 0.0001$). Long term tree-ring chronologies also yielded similar results in other areas; a 1,000-year TRW chronology was used to reconstruct summer temperature of Calimani Mountains in Romania (Popa and Kern 2009). They showed alternating warm and cold periods until recent warming three decades ago. Reconstructed 425-year temperature of Tibetan Plateau was very variable with cooling and warming events until an abrupt increase since 1941 (Gou et al. 2007). Temperature of the past two centuries was reconstructed from Qinling Mountain range TRW series, showing a pronounced warming only since mid-twentieth century (Liu et al. 2009). Recent warming was shown to be unprecedented in the past 2,000 years from tree-ring chronologies in northwest Eurasia (Briffa et al. 2008) and western China (Holmes et al. 2009). Climate patterns of Xinjiang not only agree with other reconstructed series, but the temperature variability of North Xinjiang is also significantly different from that in the South (Table 3).

4.2 Instrumental temperature record

We first correlated the instrumental WI and the WI reconstructed from tree-ring series for the past 50 years, and found a significant positive correlations ($r = 0.78$ for Changji, and $r = 0.72$ for Aksu, $p < 0.0001$). There were significant warming trends for both North and South Xinjiang (Fig. 3), which is unprecedented over the past three centuries from the reconstruction (Table 3). Furthermore, North Xinjiang has been increasing at a faster rate than South Xinjiang (F ratio $= 5.7$, $p = 0.0188$), with

Table 3 Test of slopes for the linear fit of reconstructed warmth index (WI) from dendrochronologies and instrumental WI from weather station records in Changji (North) and Aksu (South)

	Reconstructed WI		Calculated WI	
	Changji	Aksu	Changji	Aksu
Slope	0.001	0.015	0.247	0.193
P value	< 0.0001		< 0.0001	

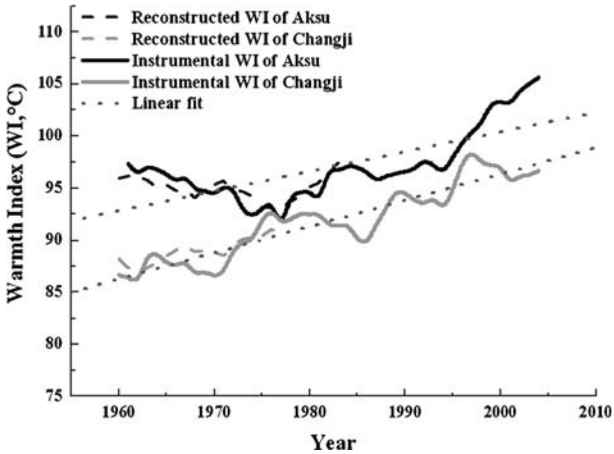

Fig. 3 Comparison between reconstructed warmth index (WI) from tree rings and instrumental WI from weather station records for the past 50 years. Instrumental WI is presented with a 5-year running smooth. *Dotted lines* show the linear trend of instrumental WI

an increase in temperature of 0.03°C/year, while the South has been warmed only 0.01°C/year.

In the light of recent warming, we were interested in comparing our regional results with climate patterns at different scales (Wu et al. 2007). North Xinjiang, resembled the Northern Hemisphere (Fig. 4a and Table 4) and South Xinjiang series showed close correspondence to the southern hemisphere temperature (Fig. 4b and Table 4), while the whole Xinjiang area resembled global temperature variance (Fig. 4c and Table 4). North Xinjiang and South Xinjiang were different and each represented a distinct hemispheric signal. Although Xinjiang is considered to be an integrated geographic entity, our results suggest that it is rather unique in having two regions within a geographic unit that are so different and collectively representative of global patterns.

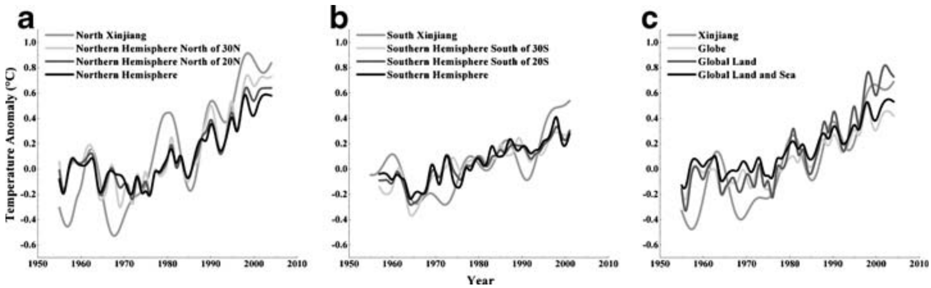

Fig. 4 Instrumental temperature anomalies of Xinjiang. **a** Smoothed temperature anomalies using a 5-year FFT filter for North Xinjiang, compared with anomalies of Northern Hemisphere North of 20/30° N and Northern Hemisphere. **b** Smoothed temperature anomalies using a 5-year FFT filter for South Xinjiang, compared with anomalies of Southern Hemisphere South of 20/30° S and Southern Hemisphere. **c** Smoothed temperature anomalies using a 5-year FFT filter for the entire Xinjiang, compared with anomalies of Globe, Global land surface temperature (Global Land), and Global combined land and sea surface temperature (Global Land and Sea). Reference period for Global Land and Global Land and Sea established by Jones et al. (1999) is 1880–2004, and others with a reference period of 1961–1990; all anomalies are in degrees Celsius

Table 4 Pearson's correlation coefficients for smoothed temperature anomalies of Xinjiang with larger scale surface temperature series

	Northern hemisphere north of 20 N	Northern hemisphere north of 30 N	Northern hemisphere
North Xinjiang	0.82145	0.80880	0.81597
	Southern hemisphere south of 20 S	Southern hemisphere south of 30 S	Southern hemisphere
South Xinjiang	0.74611	0.70486	0.72564
	Globe	Global Land	Global Land and Sea
Xinjiang	0.84097	0.85969	0.86477

For all the correlation coefficients: $p < 0.0001$, and $n = 50$. All temperature anomalies were smoothed by a 5-year FFT filter

4.3 Land cover change

Land cover change refers to the spatio-temporal changes in the structure of vegetation cover. Land cover and land use interact with atmospheric conditions to determine the overall climate, which have great impacts on various ecosystems from regional to global scales (Pyke and Andelman 2007). Climate change analysis results can often be misleading when land cover and land use are not considered (Briggs et al. 2005). This analysis identifies how land cover and land use change interact with a warming climate and may explain in part the increase in temperature observed.

The vast majority of Xinjiang landscape is covered by barren deserts, semiarid grasslands and open shrubland. From 1985 to 1995, grassland cover was significantly reduced, while the change was more dramatic from 1995 to 2004, where large areas were converted from grassland to barren land. Barren land, mostly comprised of the vast desert area in South Xinjiang, underwent little change; however, barren land increased in North Xinjiang especially in the mountain forests. We presume that the increasing population and ensuing growth of the timber industry largely contributed to the loss of forest cover for both North and South Xinjiang since 1985 (Fig. 5).

Since the late 1990s, due to China Central Government's new western development strategy, large numbers of immigrants arrived in Xinjiang. Extensive regions were overgrazed, replaced by cropland, urbanized, and ultimately converted to landscapes with largely reduced vegetation, or even barren land. These changes were more pronounced beginning in the late 1990s, so we quantified the net change, gains

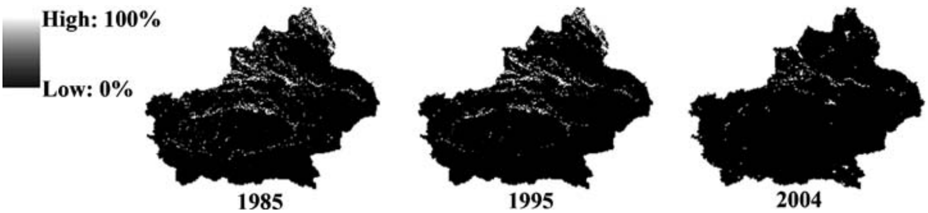

Fig. 5 Forest cover in Xinjiang for the past 20 years. Land cover is presented in percentage: lighter color (*white*) represents higher cover, and darker color (*black*) represents lower cover

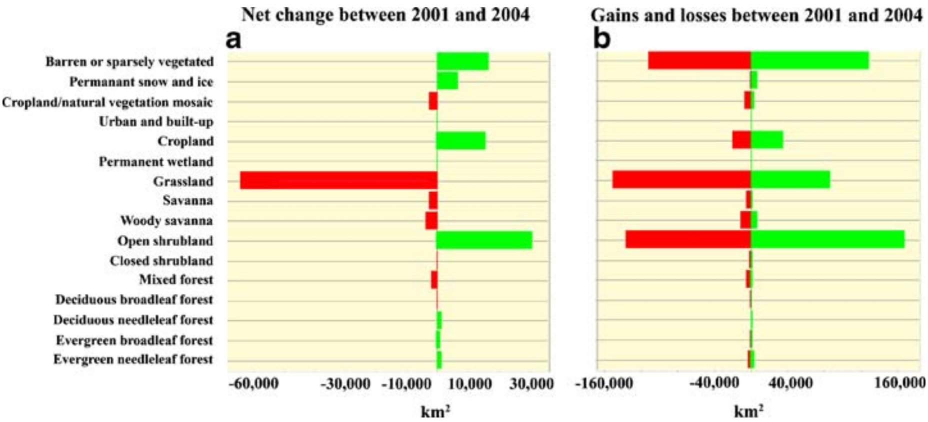

Fig. 6 Land cover change in Xinjiang from 2001 to 2004. Bar charts of **a** net change and **b** absolute gains and losses of 16 land cover types of Xinjiang, in square kilometers

and losses for each vegetation type of Xinjiang from 2001 to 2004. In examining absolute changes in cover, grassland experienced the largest net loss, while there were moderate net gains in barren land, cropland and open shrubland (Fig. 6a). For all four of these land cover types there were both extensive gains and losses in absolute cover (Fig. 6b). This is as expected because collectively these four land cover types comprise over 90% of the area in Xinjiang (see land cover map in Fig. 7). Furthermore, grassland losses contributed most to the expansion of barren land (62%), which was partly counteracted by the shrubland expansion (22%) in areas previously classified as barren land. To compare the land cover change between North and South, we then examined the losses and gains of three major land cover types—grassland, barren land and open shrubland in Xinjiang (Fig. 7). The vast area of grassland in North Xinjiang experienced more extensive losses than South Xinjiang; meanwhile, North Xinjiang also gained more barren land and shrubland where were previously classified as grassland.

The changes in land use and ensuing land cover seen in Xinjiang are representative of global patterns, for example, in North America. Briggs et al. (2005) reported large areas of grassland losses and increases in shrubland. Woody plant expansion into

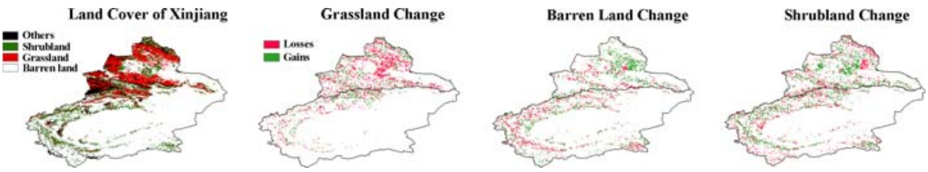

Fig. 7 Spatial distribution of gains and losses of three major land cover types in Xinjiang from 2001 to 2004. Land cover map of Xinjiang highlights the three major land cover types—grassland, barren land and shrubland, followed by spatial distribution maps of gains and losses of grassland, barren land and shrubland, with a *solid line* in the middle representing Tian Shan that divides Xinjiang into North and South

grassland has also been observed across semi-arid regions of the US (Van Auken 2000; Cabral et al. 2003). With increasing population in Xinjiang, cultivated land expanded in areas that were previously forest and grassland. Land use conversions, such as, urbanization, forest clearing, and intensive agriculture have been identified as the most important threats to biodiversity (Wessels et al. 2004); all of these changes have occurred in Xinjiang. Coupled with a changing climate and areas of intense transformation, especially prominent in North Xinjiang, this region could undergo even more dramatic change in the future under a warmer and drier climate. Land cover and land use changes interact with atmospheric compositions that modify the regional climate, and generate positive feedbacks that magnify climate change and land cover conversion.

4.4 Population growth and greenhouse gas emissions

From the early 1950s to the 1970s the population has doubled, and then remained relatively stable through the 1980s (Jiang et al. 2005). As China Central Government adopted western development policies in the 1990s, population growth has resumed as well as intense human activities. Population growth and urban expansion has increased significantly in Xinjiang just since 1991 (Fig. 8 and Table 5). The temperature change for rural and urban areas was 0.25°C/decade and 0.32°C/decade increase respectively for the past 50 years. CH_4 and N_2O emissions also increased dramatically over the past 15 years (Fig. 8 and Table 5). The impacts of increased urban populations and agricultural development on climate change are evident in Xinjiang. There was a linear relationship between the CH_4/N_2O emissions and population size, with a Pearson's correlation coefficient varying from 0.70 to 1.00 for different districts, which in all have an average of 0.87 ($p < 0.05$) for the entire Xinjiang. On a per square kilometer basis, North Xinjiang has a significantly faster growth of population, methane and nitrous oxide emissions (Table 5). Together with the pronounced upward temperature trend illustrated above, the effects of human activities on surface temperature are reinforced by the simultaneous increase

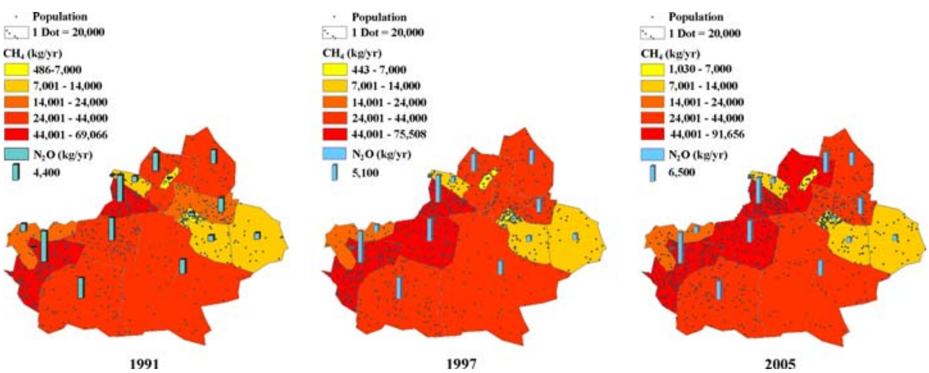

Fig. 8 CH_4 and N_2O emissions from livestock and population distribution in the past 15 years of Xinjiang. Calculation is region-specific based on the administrative boundaries. Population is shown in *dots*, each representing 20,000. CH_4 emissions are classified into five classes (break values are 7,000, 14,000, 24,000, and 44,000 kg/year) for all 3 years, shown from *yellow* to *red*. N_2O emissions are shown in *blue bars*, with increasing unit bar value each year

Table 5 Test of slopes for the linear fit of population, methane and nitrous oxide emissions of North and South Xinjiang

	Population (/year/km^2)		Methane emissions (kg/year/km^2)		Nitrous oxide emissions (kg/year/km^2)	
	North	South	North	South	North	South
Slope	0.336	0.140	0.013	0.004	0.002	0.001
P value	0.0002		0.0027		0.0023	

and close relationship between surface temperature, population and greenhouse gas emissions.

The agricultural sector produces a great amount of methane emissions (Desjardins et al. 2001), mostly from livestock (Hellebrand and Kalk 2001). Agriculture plays an important role in feeding the increasing population in Xinjiang; however, it also contributes as the largest sources of the greenhouse gases CH_4 and N_2O. In the past several decades, overstocking is believed to be one of the principle reasons for land degradation in this area, as shown in the land cover change that we found in this study. Grazing changes both soil hydrology and daily temperature range (Eastman et al. 2001). In addition, agriculture can be particularly vulnerable to climatic change, especially extreme climate events such as drought (Motha and Baier 2005; Salinger 2005). In this way, agriculture and climate are inextricably linked, and efficient management strategies in agriculture can have a remarkable influence on managing the sources and sinks of greenhouse gases, especially in slowing the buildup of greenhouse gases (Motha and Baier 2005).

The synergistic effects of population growth, land cover/land use change and greenhouse gas emissions can influence regional climate (Grimm et al. 2008). We also detected that increasing populations are correlated with elevated temperature, which is consistent with the study of continental United States (Kalnay and Cai 2003), where urban areas can act as heat islands and exacerbate global warming (Oke 1997). In addition, growing populations exert an increasing demand for food and land cover conversion, which leads to expansion of cultivated and urban areas at the expense of forests and grasslands (Meyerson et al. 2007). Livestock grazing has expanded from lowlands to even more vulnerable mountain areas. The conversion to economic croplands in lower basin areas has led to extensive losses of grassland, salinization and desertification, rendering the land unusable for agriculture. If the current land use trends accelerate as anticipated, there is an urgent need to adjust current policies and management to alleviate the stress for such vulnerable environments.

4.5 Developing sustainable management strategies

Xinjiang province is faced with both climate change and land cover conversions that will constrain population growth and development. The ability to respond to climate change is somewhat limited in that even reducing greenhouse gas emissions will not necessarily affect climate change without a global response. Climate change mitigation strategies will be more critical to implement for North Xinjiang compared to South Xinjiang due to a higher rate of warming in the last 50 years. We did not examine precipitation patterns and undoubtedly changes in precipitation will exacerbate or ameliorate these increasing temperatures.

Xinjiang province is rich in natural resources but continues to be impacted by human activities especially in North Xinjiang. For example, the mountains of Xinjiang are an important source of water and provide recharge of groundwater that feeds both lotic and lentic water sources and allow for drilling of wells. However, recent extensive deforestation, water diversion, and groundwater pumping have lead to increased soil erosion, and over-drafting of water resources by at least 112% of recharge, which dramatically reduced the volume of available water, resulting in land degradation and reduced water delivery of the lowland basin areas (Zhang 2003).

There are several management options that can minimize future land cover conversions and create a more sustainable management of resources. We suggest several possible ways to ameliorate the impact of human activities on Xinjiang that are related to the use of forests, grasslands and water resources. First, timber plantations could be initiated in lowland basins, where artificial oases can supply the necessary water (Han 2001; Zhang 2003). For this to be a successful conservation strategy it is important that the establishment of plantations replaces deforestation of native forests. Plantations would then simultaneously provide needed wood for building, firewood, and possibly biomass generators and conserve natural forests. Second, grazing could be shifted from native grasslands to diluvia fan areas, where already established wells (i.e. artificial oases) exist (Han 2001). These areas could provide highly productive pastureland, which will reduce grazing pressure in grasslands of North Xinjiang that are susceptible to being converted to barren lands, and preserve biodiversity in South Xinjiang by restoring habitats for precious desert animals. The alternative forms of development we suggest need to be integrated into a regional conservation plan that incorporates ways of mitigating and adapting to global change.

5 Conclusion

Climate, population, land cover/land use change, and greenhouse gas emissions are inextricably linked, which collectively mediate options for mitigating and adapting to global change. We reconstructed natural climate variability for the past three centuries from dendrochronology proxies, and showed alternating warm and cold periods with no substantial warming trend. In contrast, surface instrumental temperature series for the past 50 years showed a remarkable upward temperature trend, especially for North Xinjiang. Temperature series for the last 50 years in North and South Xinjiang resembled northern and southern hemispheres respectively, and the combination of both corresponded to the global signal. In this sense Xinjiang is a heterogeneous region that can serve as a unique area for future climate change study. North Xinjiang has exhibited a faster population growth, higher greenhouse gas emissions, and more extensive land cover change; with a faster rate of global warming, it faces greater environmental challenges than the South. Conserving mountains in North Xinjiang and restoring desert basins in South Xinjiang as well as developing industry and agriculture in artificial oases may achieve sustainable development under ongoing climate change.

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