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THEMATIC ISSUE

Spatiotemporal dynamics of land cover and their impacts on potential dust source regions in the Tarim Basin, NW China

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Abstract Human-driven dynamics of land cover types in the Tarim Basin are able to affect potential dust source regions and provide particles for dust storms. Analyses about dynamics of potential dust source regions are useful for understanding the effects of human activities on the fragile ecosystem in the extremely arid zone and also provide scientific evidence for the rational land development in the future. This paper therefore selected the Tarim Basin, NW China, as a representative study area to reveal spatiotemporal dynamics of land cover and their impacts on potential dust source regions. The results showed that farmland, desert and forest increased by 28.63, 0.64 and 29.27%, while grassland decreased by 10.29% during 1990–2010. The largest reclamation, grassland loss and desertification were 639.17×10^3, 2350.42×10^3 and 1605.86×10^3 ha during 1995–2000. The relationship between reclamation and grassland loss was a positive correlation, while a highly positive correlation was 0.993 between the desertification and grassland loss at different stages. The most serious dust source region was the desertification during 1990–2010 (1614.58 thousand ha), and the serious region was stable desert (40,631.21 thousand ha). The area of the medium and low dust source region was 499.08×10^3 and 2667.27×10^3 ha. Dramatic reclamation resulted in the desertification by destroying natural vegetation and breaking the balance of water allocation in various regions.

Keywords Spatiotemporal dynamics · Dust sources · Human activities · Tarim Basin

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Introduction

Dust storms frequently occur in the arid and semiarid zones of the world (Al-Dousari et al. 2013). Dust and dust storms have deeply affected the air quality and habitat environment and caused a series of disasters (Batjargal et al. 2006). A series of factors causing dust storms are wind, rainfall, deforestation, drought and land cover changes (Al-Hurban 2013). Generally, two critical factors impact the formation of dust storms, namely wind and dust sources (Davara and de la Cruz 2004). The former provides power for dust storms, while the latter provides dust particles. The formation of dust particles, desertification and dust storms is seriously affected by climate change and human activities

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(Wang et al. 2012). Drivers affecting the dust storm are wind erosion and other climatic factors, while its main cause is the destruction of vegetation caused by human activities (Sabit and Imin 2011). Therefore, human activity is the main factor affecting dust source regions and storms by altering land cover types and their soil physical characteristics.

Regarding researches on the dust storms, many scholars analyzed dust storms assessment (Liu et al. 2012b), effects of dust on vegetation growth (Abuduwaili et al. 2015), dust storms identification based on remote sensing (Kaskaoutis et al. 2011), temporal changes analysis of dust storms using remote sensing (Huang et al. 2007; Samadi et al. 2014; Shahraiyni et al. 2015), classification of dust days (Sorek-Hamera et al. 2012), effects on global climate change (Yang et al. 2008), dust storms disaster (Fan et al. 2007) and ecological impacts (Abuduwaili et al. 2010), socioeconomic impacts on dust storms (Ai and Polenske 2008) and relationship between vegetation coverage and dust storms (Betz et al. 2015). Additionally, many researchers analyzed the relationship between the agricultural soil texture, land degradation and wind erosions (Houyou et al. 2014; Gao et al. 2015; Colazo and Buschiazzo 2015). Because dust sources are mainly affected by land cover types and their dynamics, numerous scholars analyzed the relationship between vegetation coverage and frequency of dust storms as well as the desertification (Jafari and Bakhshandehmehr 2013; Izzo et al. 2013; Fleskens and Stringer 2014; Miao et al. 2015). However, rare scholars considered researches about potential dust source regions by analyzing spatiotemporal variations of vegetation coverage and land cover types. The response of generated dust to various land cover types (forest, meadow and cropland) has been studied by in situ experiments (Wang and Jia 2013; Wang et al. 2013; Hahnenberger and Nicoll 2014). These researches have all illustrated various influences of land cover types on dust sources. Although desertification and its influencing factors have been already studied, the extraction and analysis of dust source regions at the regional scale are rarely proposed in previous researches (Bhattachan et al. 2012). However, dust source regions are critical for the formation of dust storms. Thus, this paper mainly studied on the changes in the underlying surface and potential dust source regions caused by human activities.

The Taklimakan Desert, the world's second largest desert and the largest shifting desert, is located in the Tarim Basin and is a major source of dust storms in China. The particular climate and geographical location result in a fragile ecosystem in the Tarim Basin. Distribution of the oasis is along the Tarim River and its branches, which constitutes an important green barrier to isolate deserts (Liu et al. 2012a). In recent decades, the severe reclamation and cotton cultivation caused by the rapid economic development resulted in drastic reduction of natural vegetation coverage. Severe dust storms happened in the Tarim Basin destroyed large areas of crops and caused casualties of local residents and damages on the economic development (Chen and Zhu 2000). Dust not only affects the photosynthesis and growth of crops (Abuduwaili et al. 2015), but also affects human health by carrying toxic substances, bacteria and viruses (Hu et al. 2001). Additionally, the severe dust storms from the Tarim Basin can also reach eastern China, Korea Peninsula, Japan, the Pacific and western coast of North America (Duce et al. 1980; Zhao et al. 2013). Gao and Washington (2010) analyzed delivery trajectories of dust originating from the Tarim Basin. However, researches regarding origin places of dust were rarely reported. What are details of land cover changes in the past two decades? Where would be a potential source of dust? Therefore, two main objectives of this paper were to: (1) reveal spatiotemporal dynamics of land cover types during 1990–2010 and (2) analyze potential dust source regions and their macroscopic changes in time and space.

Materials and methods

Study area

As the largest endorheic basin, Tarim Basin (area: about 5.3×10^5 km^2) is approximately located in the south of Xinjiang Uygur Autonomous Region, NW China, with the latitude of 37°–42°N and longitude of 73°–94°E. The terrain is higher in western, while it is lower in the eastern Tarim Basin. The center of Tarim Basin is the Taklimakan Desert, which is the second largest desert in the world (Sun et al. 2010). Surrounding the Taklimakan Desert, there are numerous mountains in western, northern and southern regions (Fig. 1). This paper selected the regions with the elevation of less than 2500 m as study area because it is consistent with the boundary of dust storms from in situ observations at meteorological stations (Wang and Jia 2013). The main soil types distributed in the Tarim Basin are the blown desert, meadow, salt and eolian soil (Zhang and Zhang 2012). Study area is a major cotton cultivation region in China. The annual precipitation approximately ranges from 15 to 70 mm, while the annual evaporation is above 2600 mm (Zhang and Zhang 2012). The average wind speed is about 2.4 m/s (Li et al. 2008). Both eastern and southeastern parts of Tarim Basin are affected by the northeasterly airflow, while the western and northern parts of Tarim Basin are affected by the

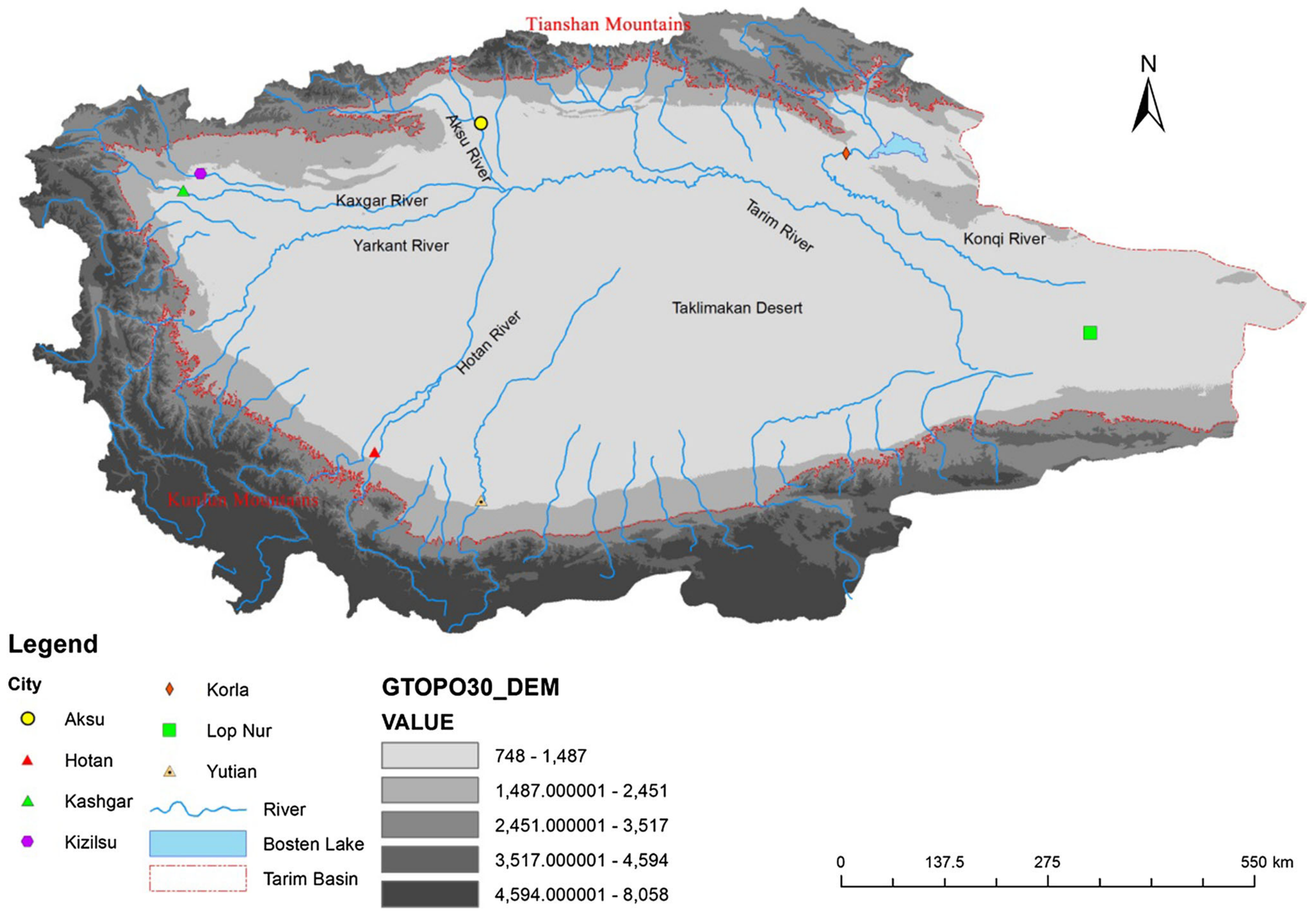

Fig. 1 Location map of the study area

westerly, northwesterly and northerly airflow (Wang and Jia 2013). The annual frequency of sandstorm increases during 1997–2007, and the seasonal frequency is the highest in spring (Xue et al. 2009).

Data sources

Gridded land cover data in 1990, 1995, 2000 and 2005 were acquired from Data Sharing Infrastructure of Earth System Science in China (http://www.geodata.cn/Portal/index.jsp). These land cover data with the spatial resolution of 30 m were all acquired based on Landsat remotely sensed images. A series of Landsat-5 Thematic Mapper (TM) remotely sensed images covering study area with spatial resolution of 30 m were also acquired from the US Geological Survey. Additionally, Chinese HJ/CCD remotely sensed images in 2010 were acquired from China Centre for Resources Satellite Data and Application (CRESDA) and were also acquired to supplement missing of Landsat-5 TM images and construct time series of remote sensing images. Chinese HJ satellites belong to small satellite constellation with the high temporal resolution of 2 days and the spatial resolution of 30 m, and the detailed description of Chinese HJ/CCD can be found from Liu et al. (2014). The land cover map within 2014 (http://chinageoss.org/dsp/sciencedata/sciencedata_view.action?dataId=5fa048d5-5746-406c-83e3-5348585b4804) was also obtained from the Center for Earth System Science, Tsinghua University (http://data.ess.tsinghua.edu.cn/data/temp/OBOR/). Although the low spatial resolution is 250 m, land cover data within 2014 can be also used to reveal the relationship between frequencies of spring sandstorm and major types of land cover change. Land cover sampling data within 2010 were also collected using the handheld GPS. The data about the frequency of spring sandstorm outbreak during 1990–2014 were acquired from relevant literature (Ablikim and Aji 2011; Li et al. 2012a; Ma et al. 2016). These studies calculated and showed the average frequency of sandstorm according to 15 weather stations around the Taklimakan Desert and a station in the center of the Taklimakan Desert. Visual field observations about sand-transporting capacity of various land cover types during 2008–2014 were acquired. During these campaigns, interviews and questionnaires from local residents were also implemented. In addition, many results about the sand-transporting capacity of various land cover types were also obtained from relevant field experiments, reports and literature.

Preprocessing and classification

We performed the geometric rectification on HJ/CCD images based on corresponding Landsat TM images using the ENVI 5.0 software. A total of 50 ground control points (GCPs) were used to correct HJ/CCD images combined with a second-order polynomial fit. The root-mean-square error (RMSE) for all HJ/CCD images was all less than 0.5 pixels. After geometric rectification, the radiometric calibration was employed to transform digital number (DN) of Landsat and HJ/CCD images into radiance using gain and offset parameters of these images. Then, we performed the atmospheric correction to acquire the surface reflectance using a FLAASH model within ENVI software, which is based on the MODTRAN4+ radiative transfer model.

According to the classification criteria of the State Bureau of Land Administration and Chinese Academy of Sciences (Liu et al. 2005, 2015), the land cover types were divided into seven categories, including farmland, forest, grassland, water body, built-up land and desert. Land cover sampling and high spatial resolution from Google Earth were all used to generate regions of interested (ROI) for land cover classification. Then, a support vector machine (SVM) method combined with visual interpretation method was used to extract the land cover types. The overall accuracies of classification and Kappa coefficients were all greater than 86.1% and 0.85 based on field-observed land cover samples using GPS.

Methodology

This paper illustrated the procedure for revealing spatiotemporal dynamics of land cover types and potential dust source regions in the Tarim Basin (Fig. 2). Firstly, spatial and temporal dynamics of land cover were identified based on land cover maps during 1990–2010 by

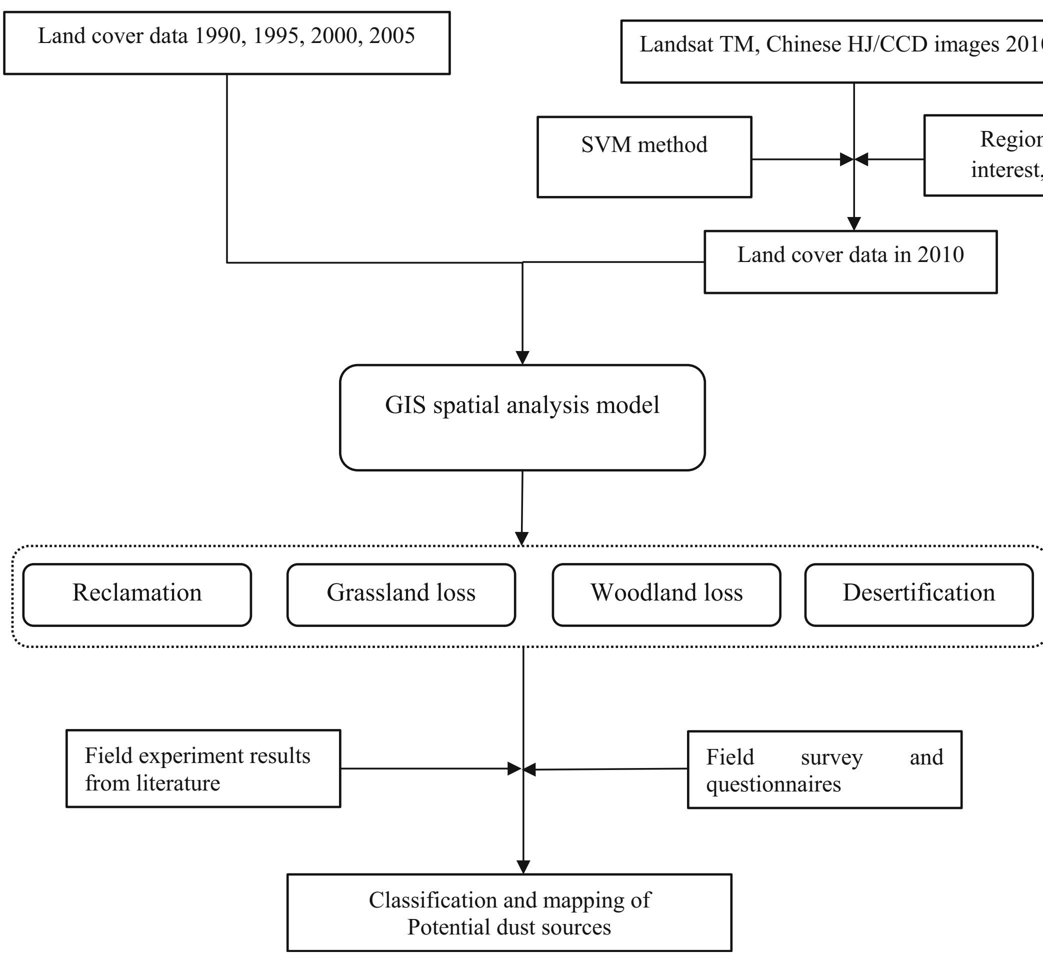

Fig. 2 Flow chart of the paper

Table 1 Temporal changes in area of land cover types (10^3 ha)

	1990	1995	2000	2005	2010
Farmland	2447.42	2448.38	2667.27	3043.61	3148.07
Forest	859.64	858.55	1173.39	1135.04	1111.25
Grassland	12,858.61	12,857.67	11,787.15	11,547.76	11,535.58
Desert	42,119.61	42,116.90	42,511.80	42,434.60	42,388.11

employing a GIS spatial analysis model. Then potential dust source regions were analyzed according to land cover changes associated with field observations, questionnaires, related reports and literature.

Results and analysis

Spatiotemporal dynamics of land cover

Table 1 shows that temporal changes in four major land cover types. During 1990–2010, farmland increased by 28.63%, while grassland decreased by 10.29%. Desert and forest increased by 0.64 and 29.27%, respectively. However, both desert and forest had a decline trend from 2000 to 2010. The decline rate of desert and forest was 0.29 and 5.30% during 2000–2010. The dramatic decline of grassland was occurred in the period between 1995 and 2000 with a percentage of 8.33%. During 1995–2000, forest and desert increased most dramatically with a percentage of 36.67 and 0.94%. The increase in forest during 1995–2000 was mainly caused by the Grain for Green project (Liu et al. 2015) and Three-North Shelterbelt project (Li et al. 2012b).

Spatiotemporal dynamics of reclamation, desertification and grassland loss

During 1995–2000, the area of reclamation was the largest (639.17 thousand ha), followed by the period of 2000–2005 with area of 389.79 thousand ha (Table 2). The decline of reclamation from 1995 to 2010 was affected by the state policies about reclamation limitation (Lv and Liu 2009). According to spatial distribution of reclamation in the Tarim Basin, reclamation in different periods was mainly located in the north and southwest of study area. The spatial distribution of reclamation is nearby the original farmland.

The largest grassland loss was occurred in the period of 1995–2000 with the area of 2350.42 thousand ha. The transformation of grassland mainly tended to be desert and farmland. Since 2000, the trend of grassland loss has been reduced due to local residents' behaviors caused by some policies such as the Grain for Green project (Cao et al. 2011). The similar decline trend of reclamation and grassland loss revealed a positive correlation between them. The Pearson correlation coefficient between reclamation and grassland loss at different stages was 0.87. In this paper, desertification is defined as a land cover change type, transforming from non-desert into desert coverage. The largest area of desertification was also occurred during 1995–2000 (1605.86 thousand ha), and then desertification decreased from 2000 to 2010. Desertification during 1995–2000 was mainly from grassland loss according to the almost consistent distribution of desertification and grassland in Fig. 3b, c. There was a positive correlation at the 0.01 levels (bilateral) between desertification and grassland loss at different stages, and the Pearson correlation coefficient was 0.993.

Table 2 Temporal changes in reclamation, grassland and desertification (10^3 ha)

	Reclamation	Grassland loss	Desertification
1990–1995	143.47	418.26	324.73
1995–2000	639.17	2350.42	1605.86
2000–2005	389.79	289.32	9.12
2005–2010	122.07	82.33	0.12

As an important land cover type, natural grassland is a critical shelter limiting desertification. Thus, we revealed the spatial and temporal dynamics of grassland loss between 1990 and 2010 (Fig. 4). The total area of grassland converted into farmland, desert and forest was 746.86×10^3, 1251.82×10^3 and 381.21×10^3 ha, respectively, between 1990 and 2010. Numerous grassland patches were converted into desert and farmland, leading to land cover type with a high sand-fixing ability into those with the lower ability. These transformations between 1990 and 2010 also provide scientific evidence for assessing potential dust source regions. Converted into farmland type was mainly located in regions nearby rivers and other water sources, while the converted into forest type was mainly nearby river channels. Converted into desert type was mainly located in southwestern and northeastern Tarim Basin caused by the dramatic reclamation. Tarim River catchment is also located in the study area and provides water for irrigated agriculture. However, excessive land reclamation and cotton cultivation in the upstream and midstream resulted in an increase in agricultural water while a drop of water volume and vegetation recession in the lower reaches of the Tarim River (Liu et al. 2012a). Then groundwater in the lower reaches of Tarim River dropped from 3 m in the 1950s to 12 m in the 2000s (Wang et al. 2002). Meanwhile, existing electromechanical wells in 2008 were about 1129 in the study area, while about 5618 electromechanical wells will be constructed during 2008–2010 (Shi 2008). In addition, Deng (2010) also pointed out that a large-scale, over-exploitation of groundwater for irrigation can eventually result in depletion of water resource. Li (2014) found that ground water in the Bachu County (northwestern study area) decreased by 1–1.5 m within 2009 due to agricultural irrigation.

Discussions

Ecological theory of potential dust source regions

Although no experiments were used to analyze sand-transporting quantity of different land cover types, adequate field observations during 2008–2014 at regional scale are also credible data and provide spatial and temporal information for analyzing the phenomena of desertification and the formation of dust source regions. In addition, feedbacks of interviews and questionnaires from local residents also provided empirical knowledge. Finally, long-term observations, cited experiment data and questionnaires all consistently reflect effects of land cover and change on dust sources formation.

As a factor of dust storms, dust source regions provide the material sources for dust storms. Dust sources are generally affected by land cover changes by altering the compaction of surface soil and vegetation coverage. In the Taklimakan Desert, fine and extremely fine sand occupy about 70–80% of particles (Gao et al. 2002) with the average particle size of 0.01–0.1 mm (He and Zhao 1997). Additionally, both low vegetation coverage of cotton fields, rare precipitation and lack of irrigation in spring result in the decline of soil moisture. Dry surface soil of cropland is therefore one dust source with a large amount of particle (<0.063 mm) (Zhang et al. 2007). Land cover changes affected abilities of sand-transporting between arable land and natural vegetation coverage by altering the loose topsoil. Based on existing ecological knowledge, dust sources were finally acquired associated with multi-temporal remote sensing images. Despite the lack of large-scale field observations, this method has fast and advanced traits on the classification of dust source regions. The classification is basically consistent with the actual conditions and can be a scientific evidence for decision making.

Therefore, desertification, reclamation and grassland loss all affected changes in underlying surface and surface particles. The dramatic decline in grassland was caused by reclamation and desertification. The response of dust source regions to changes in various land cover types varies over the time. Three categories of data mentioned above can be used as priori knowledge because they have been recognized by many scientists and local residents. Because these priori data have ecological significance, classification coupling remote sensing images with ecological knowledge can make results more credible. Thus, we also analyzed differences of dust source regions based on various underlying surface types and their dynamics. Fallow and recently reclaimed arable lands are both prone to dust without shelterbelt. The probability of orchard lands substantially reduced compared to arable land due to increasingly stable vegetation coverage. However, natural grassland areas have formatted an approximate closed natural coverage to reverse desertification and to reduce dust storms. Roels et al. (2001) had the consistent result based on detailed in situ observations. Thus, changes in desert, farmland, woodland and grassland are all critical types of land cover change for generating dust. In particular, the decreasing vegetation coverage in degraded grasslands can increase the occurrence of dust storms by reducing the roughness of the land surface (Wang et al. 2004a). Additionally, frequencies of spring sandstorm outbreak within four periods (1990–1995, 1995–2000, 2000–2005, 2005–2010 and 2010–2014) were related to three major types of land cover change, namely reclamation, grassland loss and desertification. The Pearson correlation coefficient between dust storm frequency and reclamation, grassland loss and desertification was 0.947, 0.951 and 0.941, respectively. The relationship showed that dust storm frequency is positive against reclamation, grassland loss and desertification from 1990 to 2010 in the Tarim Basin. These findings are also consistent with the results from Chen and Zhou (2010).

Extraction of potential dust source regions

Thereby, the classification criteria of dust source regions are proposed based on the ecological significance summarized from long-term field observations, questionnaires and relevant literature (Zhao et al. 2011; Betz et al. 2015). Desertification caused by human activities broke the balance between desert and natural vegetation (Betz et al. 2015). Generally, transformations into desert regions were close to human settlements and locations with human activities (Zhao et al. 2011). Currently, the degraded grassland and the edge between oasis and desert are key areas of sandstorm prevention in China (Meng and Jiang 2002). This type is therefore considered as the most serious dust source region. Stable desert is mainly affected by natural factors, and it is also a serious region for dust formation. The loose surface of

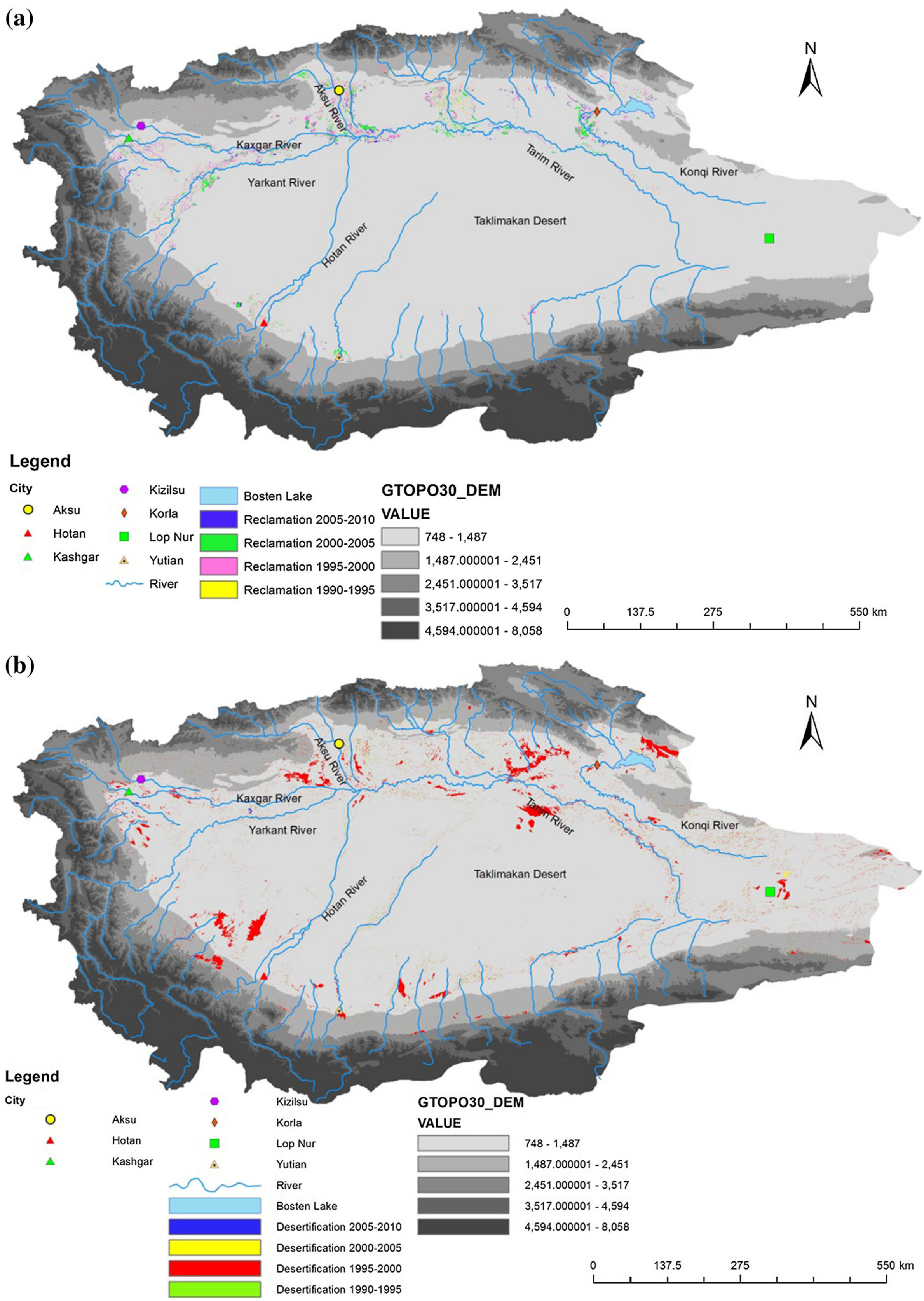

Fig. 3 **a** Spatial distribution of reclamation, **b** desertification and **c** grassland loss in the period of 1990–1995; 1995–2000; 2000–2005; 2005–2010

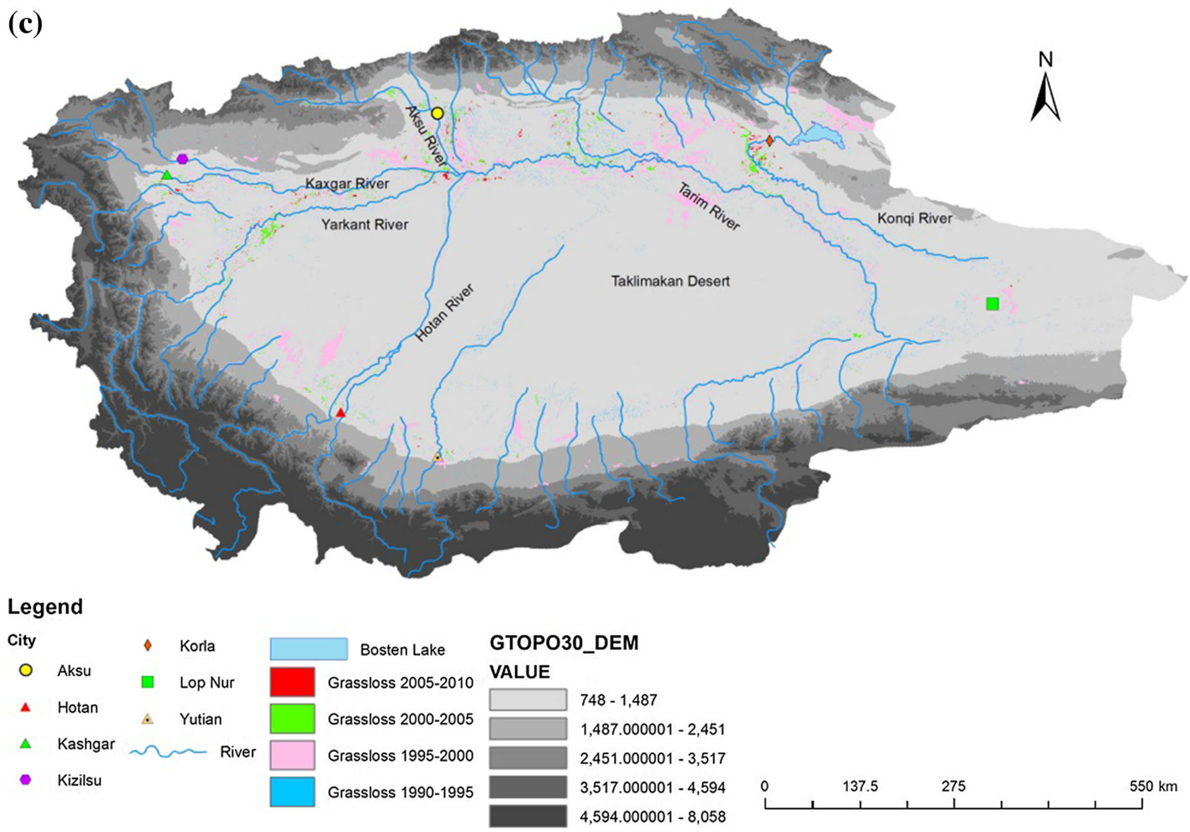

Fig. 3 continued

farmland is another potential source of dust caused by corresponding cultivations (Wang et al. 2004b). As the major cultivated crop in the study area, cotton is generally cultivated in early April with relatively scarce cotton coverage. However, wind speed and frequency is larger during March–May than the other months, which providing a power-driven factor for dust storms. Compared to old farmland, recent reclamation is more likely to be dust source region due to lack of shelterbelt protection. The recent reclamation was mainly transferred from natural grassland and resulted in decline of natural wind barrier. The recent reclamation from 2000 is therefore considered as the medium dust source region because fine-grained particles from the recent reclamation without shelterbelts are easily blown (Sabit and Imin 2011; Wang and Jia 2013). Finally, the other farmland types are defined as the low dust source region because these farmlands are well managed with perfect irrigation facilities and shelterbelts (Table 3).

According to the classification criteria, we acquired the spatial pattern of the potential dust source regions by employing the spatial analysis model (Fig. 5). The area of the most serious dust source region was about 1614.58 thousand ha, and the area of serious dust source region was 40,631.21 thousand ha. Therefore, these regions should be key focus of dust governance. The area of the medium serious dust source region and low serious dust source region was 499.08 thousand and 2667.27 thousand ha.

Relationship between desertification and reclamation

Reclamation implemented by the local government and military corps undermines land cover, causing damage to a large area of grassland and natural forest. Reclamation caused changes in the underlying surface and directly affected the desertification process. Driven by economic stimulus, new reclaimed arable land was used for cotton cultivation. Increasing agricultural irrigation demands of cotton and other crops also led to an uneven distribution between agricultural and ecological water allocations (Feng et al. 2005). Decreases in the ecological water and groundwater level caused decay and death of natural

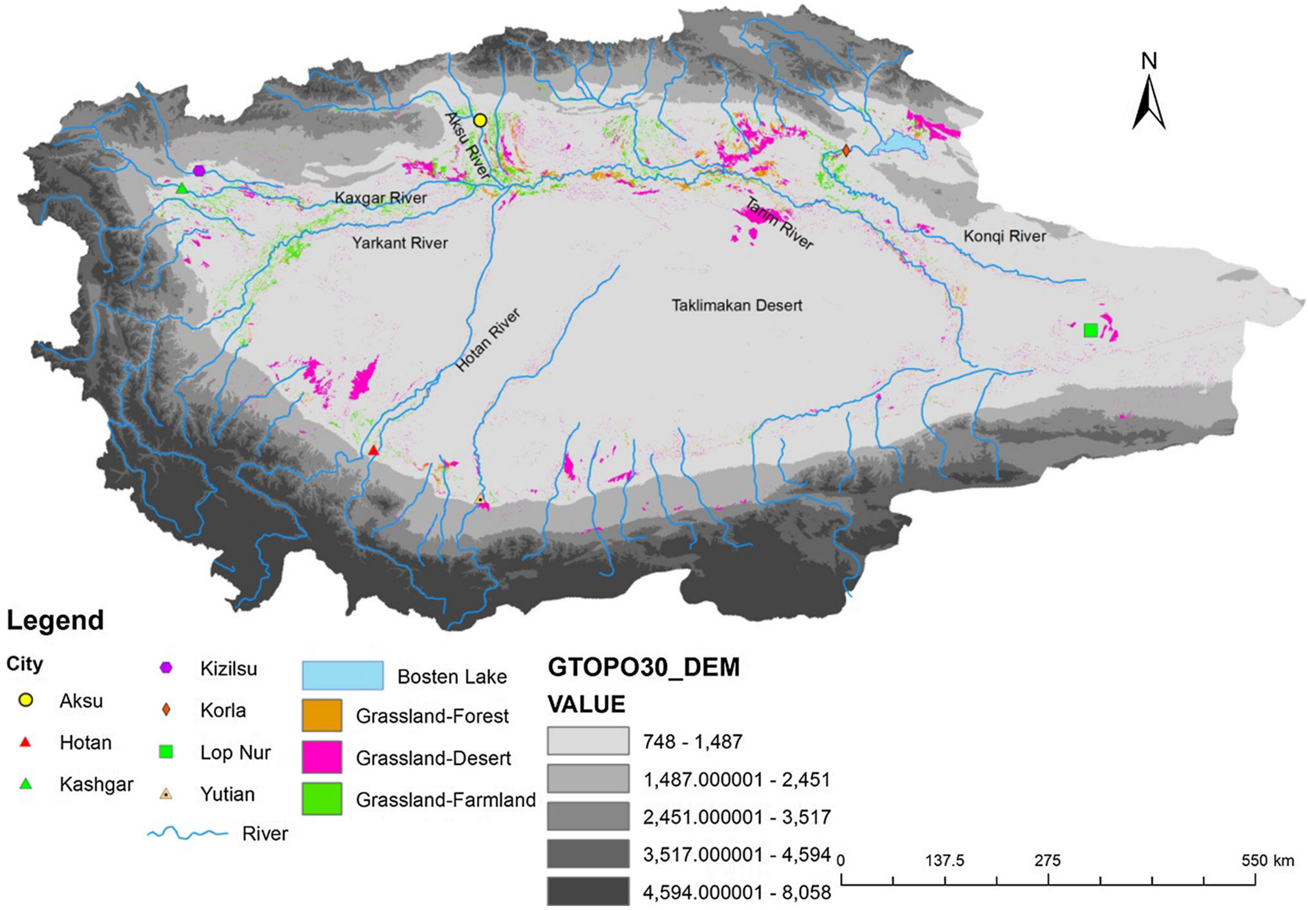

Fig. 4 Spatial and temporal dynamics of grassland loss during 1990–2010

Table 3 Classification criteria of dust source regions

Category	Definition
Most serious dust source region	Desertification in the desert oasis ecotone, during 1990–2010
Serious dust source region	Stable desert type during 1990–2010
Medium dust source region	Recent reclamation since 2000
Low dust source region	The other farmland types

vegetation in the lower reaches of Tarim River (Aishan et al. 2013). Thus, desertification was mainly driven by anthropogenic reclamation in the study area.

Advantages and disadvantages

According to reported news in recent years, frequency and scale of dust storms events were both tend to increase in the residential regions and reclamation districts (Zong 2015). Then we found that dust storms were severe in reclamation areas because fluffy soil on the surface of arable land provides a potential dust source during field campaigns. Additionally, according to the questionnaire and interview data from local residents aged above 45, virgin forests and wildlife disappeared, while dust storms gradually increased. At two decades temporal scale, climate change effects have no such huge effects and are less than large-scale reclamations. Thus, reclamations caused by human activities led to more changes in underlying surfaces and formed dust sources. We acquired natural and human-generated dust source regions by analyzing land cover changes during 1990–2010. The human-generated dust source region caused by intensive reclamations in the non-growing season can be considered a more severe sandstorm source because reclamations altered the surface roughness and soil particle diameter by decreasing vegetation

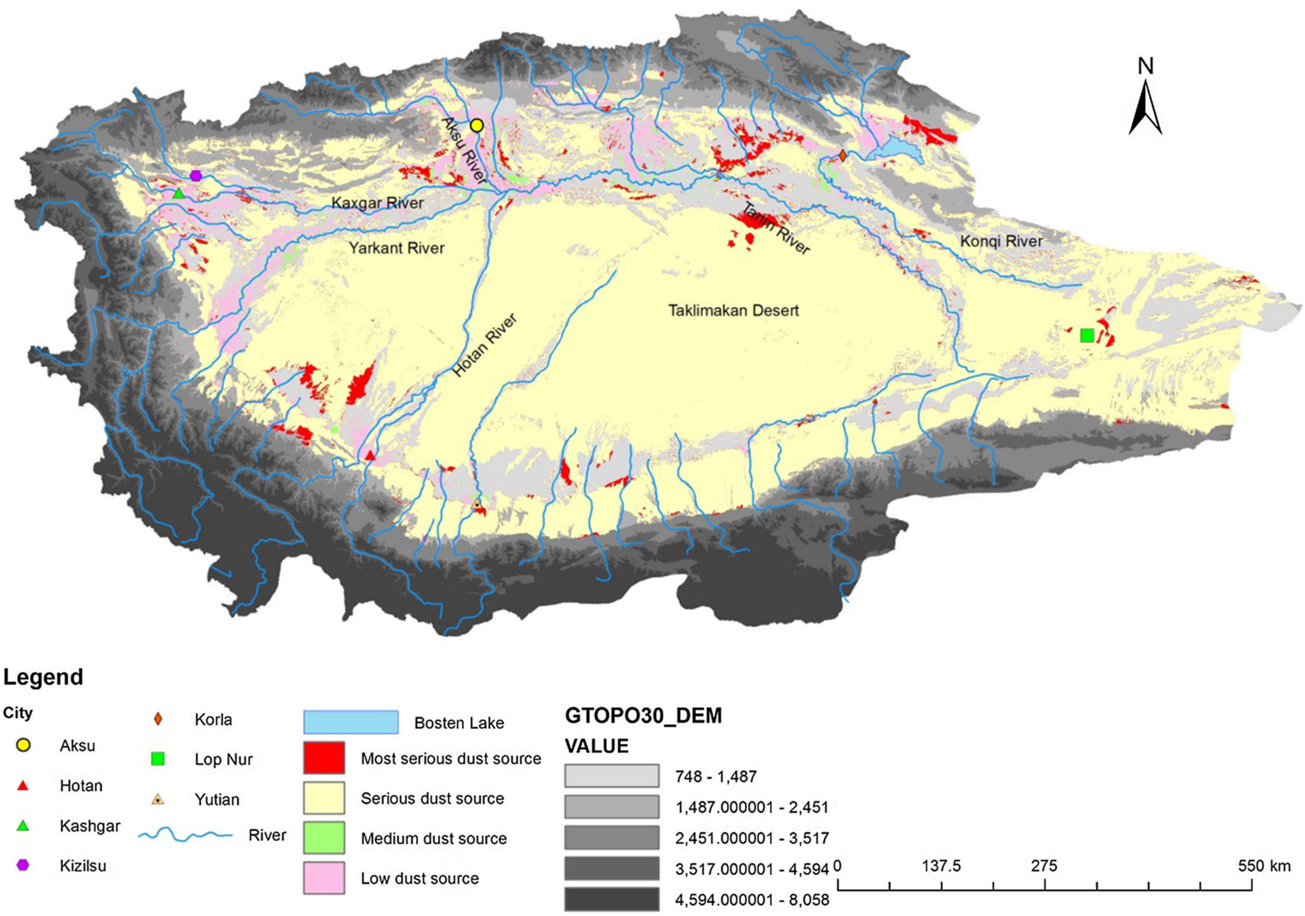

Fig. 5 Spatial distribution of potential dust source regions in the Tarim Basin

coverage (Mei et al. 2004). Therefore, shelterbelts should be configured for the recent reclamation to isolate the possibility of dust storms formation. Thus, these findings verified the accurateness of potential dust source regions estimation.

By means of remote sensing and GIS approaches, we acquired spatial and temporal dynamics of underlying surfaces of Tarim Basin during 1990–2010. Furthermore, changes in underlying surfaces resulted in tightness of soil. Then according to the result from field-level experiments, we classified processes of land cover changes to acquire the potential distribution of dust source regions at the regional scale. This method accurately illustrates the distribution of dust source regions and provides scientific evidence for relevant sectors to make decisions.

However, the shortcoming of this article is lack of quantitative data about natural factors, thereby weakening the quantitative analysis. Thus, numerous indicators such as surface drought index, wind speed, air temperature, relative humidity and air pressure gradient can be also added into this classification system for a higher accuracy in the future.

Conclusions

The spatiotemporal dynamics of land cover in the Tarim Basin was acquired based on multi-temporal remote sensing images and the spatial analysis model. The dust storm frequency positively correlated to reclamation, grassland loss and desertification with the Pearson correlation of 0.947, 0.951 and 0.941, respectively. These findings associated with long-term observations, cited experiment data and questionnaires provided the robust ecological significance and classification criteria for dust source regions extraction. Then, five types of potential dust source regions (the most serious, serious, medium and low dust source regions) were mapped. The spatial distributions of potential dust source regions are all seriously affected by land cover changes. Spatially explicit distribution of potential dust source regions based on remote sensing and field observations fully revealed the spatial heterogeneity of potential dust source regions at a regional scale. The research provided implications on environment protecting, reclamation restricting and desertification controlling in the future. The results in this paper are also robust, and the method can be also applied in the related researches in the other regions.

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