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Forest Cover Changes in the Three-North Shelter Forest Region of China during 1990 to 2005

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ABSTRACT. The Three-North Shelter Forest Region (TNSFR) of China exhibits obvious forest cover changes that have been caused by numerous government-led afforestation and reforestation projects in recent decades. This study investigated the forest cover changes in the TNSFR during 1990-2005 based on a land cover dataset developed by the Chinese Academy of Science using remote sensing data and analyzed its relationship with meteorological change trends. The results indicated that the total forest area increased by 1.64 million ha (26.98 to 28.62 million ha) from 1990 to 2005. The composition of forest cover types of dense forest, shrubs, sparse forest and other forest remained approximately consistent over time, and the dominant cover type was dense forest. There was a uniform spatial distribution of forest cover change. The forest cover in North and Northeast China changed dramatically from 1990 to 2005, but the changes in Meng-Xin and on the Loess Plateau were not as extensive. The afforestation and reforestation projects made great strides toward increasing forest cover, whereas forest fires, forest harvesting and deforestation caused by urban and farm-land expansion led to decreases in forest cover. The annual average temperature and precipitation had clearly changed, and increased forest cover could slow down the rate of climate change to some extent in this region. Proper planning and implementation of afforestation and reforestation projects were essential to improving the natural conditions in the TNSFR. Information about the actual forest cover changes would help in the design of appropriate forestry policies and sustainable forest management strategies.

Keywords: forest cover change, deforestation, reforestation, Three-North Shelter Forest Region, climate change

1. Introduction

The Three-North Shelter Forest Region (TNSFR) of China once suffered from a degraded natural environment and frequent natural disasters (Cao, 2008; Wang et al., 2010; Zhao et al., 2013; Yuan et al., 2014). To address the immense environmental degradation and natural resource loss that occurred, the Chinese government implemented a large ecological restoration project known as the Three-North Shelter Forest Program (TNSFP) in 1978 (Moore and Russell, 1990). The TNSFP was the largest afforestation project in the world and was aimed at generating 35 million ha of forest between 1978 and 2050 (Wang et al., 2010). At present, the TNSFP has been implemented for more than 30 years, and the first stage has been completed. However, the condition of the natural eco-systems in the TNSFR remains dire (Cao et al., 2011), and the ecological value of the shelter forest is doubtful. Reforestation in these arid and semi-arid areas likely damaged the water balance and decreased soil moisture (Cao et al., 2009; Cao et al., 2010). Furthermore, the frequency of sand-dust storms in northern China followed a decreasing trend, with fluctuations from the 1950s to the 1990s, but the frequency of these storms increased greatly in 2000 and 2001 (Cao et al., 2010). Whether these sand-dust storms are related to the TNSFP cannot be confirmed. Land use change is the most important factor influencing environmental change, especially in terms of vegetation cover changes (Cao et al., 2010; Tong et al., 2012; Chen et al., 2013). Therefore, it is necessary to monitor the long-term forest cover changes in the TNSFR, which are the basic data used to analyze how forest cover changes influence environmental and hydrological cycles.

Remote Sensing (RS) has long been an effective means of monitoring land cover change, due to its ability to quickly collect information at a large regional scale, e.g. (Jia et al., 2012; Gong et al., 2013; Tang et al., 2013). Many land cover maps at global and regional scales have been produced in recent years using RS data (Hansen et al., 2000; Friedl et al.,

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2002; Gong et al., 2013; Jia et al., 2014b). However, these global land cover maps exhibit limited accuracy in China according to validation results (Ran et al., 2010). Furthermore, many efforts have been made to produce global and regional thematic forest cover maps, such as the MODIS Vegetation Continuous Fields (VCF) product (Hansen et al., 2003), the Japan Aerospace Exploration Agency (JAXA) forest cover map (Shimada et al., 2011), and the United Nations Educational Scientific and Cultural Organization (UNESCO) project for Reducing Emissions from Deforestation and Forest Degradation (Caplow et al., 2011). However, the VCF product suffers from low accuracy in certain regions of China (Liu et al., 2006), the JAXA forest map covers only one time period and cannot support long-term forest cover change analysis, and the other forest mapping projects have not provided forest cover maps for China. The Chinese Academy of Sciences (CAS) has developed a land cover map of China using Landsat Thematic Mapper (TM)/Enhanced Thematic Mapper plus (ETM+) data from the late 1980s, which have been confirmed as having satisfactory levels of accuracy in China (Liu et al., 2005a; Liu et al., 2010).

The extent of forest cover has clearly changed in the TNSFR. For example, Li and Zhou (2009) analyzed the land cover change patterns in the semiarid region of Northwest China, and Gao et al. (2006) revealed the land cover change characteristics of Northeast China. Afforestation and reforestation projects have been conducted to improve the environment in the TNSFR, and forest cover changes and spatial distributions are essential information for evaluating the effect of these projects. An assessment of forest cover change is urgently needed following the end of the first stage of the TNSFP. However, no academic literature has specifically analyzed forest cover change across the entire TNSFR.

This study investigates forest cover change in the TNSFR using a 1-km resolution percentage land cover dataset produced by the CAS from 1990 to 2005 and analyzes its relationship with two key meteorological change trends. First, this study provides an analysis of the detailed spatial and temporal variations of forest cover in the entire TNSFR using remote sensing data derived forest cover information, which is different from the government survey data and contains more comprehensive information. An analysis of the relationship between forest cover change and meteorological change reveals that increased forest cover can slow down the rate of climate change in this region and confirms the positive effect of increased forest cover, which contradicts some researchers' opinions that the afforestation project in this region may have worsened the environment. This study provides information about the objective forest cover change that can be useful in the design of appropriate forestry policies and sustainable forest management strategies.

2. Study Area

The TNSFR (Figure 1) covers approximately 4.069 million km^2, extending from 33º30' to 50º12' N and 73º26' to 127º50' E. It includes 551 counties in 13 provinces and autonomous regions, from Binxian in the Heilongjiang Province in the east to the Wuzibieli Mountains in the west; it covers a distance of 4,480 km from east to west and 560 to 1,460 km from south to north (Duan et al., 2011).

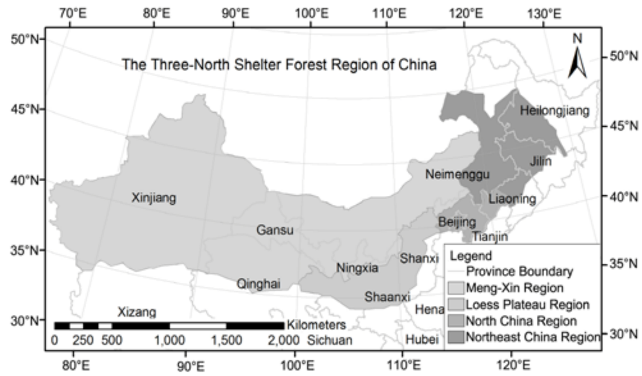

Figure 1. Location of the Three-North Shelter Forest region of China.

Arid and semi-arid regions account for two-thirds of the TNSFR, and the precipitation decreases from east to west and south to north. In the southeastern Ili river region of the Xinjiang Uygur Autonomous Region and the Datong River areas of Qinghai Province, the annual average precipitation is greater than 400 mm. The annual average precipitation is less than 200 mm in western Erenhot, Urad Qianqi, the Helan Mountains, and the northwestern Qilian Mountains. The average annual precipitation is less than 100 mm in the Tengger Desert, the Badain Jaran Desert in southern Xinjiang, and in the Qaidam Basin, and most of these regions have an average precipitation between 20 and 50 mm, representing the driest places in China (Duan et al., 2011). The temperature varies greatly across the region; the annual average temperature varies from -2 °C in the northeast to 14 °C in the southern part of the TNSFR, with a mean temperature ranging between 2 and 8°C in most areas. According to the natural features, such as the topography, climate, soil and water resources, and the ecological environment construction requirement, the TNSFR can be divided into four sub-regions (Figure 1): Meng-Xin, Loess Plateau, North China and Northeast China.

3. Data and Methods

The 1-km resolution percentage land cover data developed by the CAS (Liu et al., 2005a; Liu et al., 2010) was selected for the forest cover change analysis in this study. This dataset was selected for the following reasons: (1) it had high classification accuracy; (2) the area percentage data could provide more detailed forest cover information because they contained the percentage forest cover for each pixel, which was preferable to the typical mixed pixel in a 1-km spatial resolution; and (3) the spatial resolution was suitable for most land surface process models, which usually operated at the scale of kilometers rather than tens of meters.

The CAS percentage land cover dataset was based on Landsat TM/ETM+ data for the entire country. After data enhancement using linear contrast stretching and histogram equalization, the Landsat TM/ETM+ data were geo-referenced to a common ALBERS equal area coordinate system; next, visual interpretation was used to identify the land cover types on a computer screen based on an understanding of the spectral reflectance and structure of each object, as well as other information (Liu et al., 2005a). The minimum area considered for classification was 0.25 ha. A hierarchical classification system of 25 land cover classes was applied to the interprettation of the Landsat data, which were further grouped into six aggregated classes of land cover: croplands, woodlands, grasslands, water bodies, unused land and built-up areas (Liu et al., 2003). The term "forest" in this study referred to land that contained growing trees, including arbors, shrubs and bamboo used for forestry; four sub-classes were also identified, including dense forest, shrubs, sparse forest and other forest (Table 1). Other forest referred to land that was covered with tea gardens, orchids, and imamture forests. Different forest types had different spectral reflectance and texture characteristics in the remote sensing images, which are described as follows (Deng et al., 2010). Dense forest had distinct spectral and textural characteristics, such as a patch or belt pattern; broad-leaf forest had a bright red color, conifer forest had a dark red color that was even and had a lighter tone; there was a clear boundary with grassland and cropland, but there was an ambiguous boundary with shrubs; however, they could be distinguished by texture. Shrubs appeared as a light red color, with dispersed bright red spots in some cases because of the existence of scattered trees; they also exhibited a rough texture. Sparse forests were always light red in color, with dispersed bright red spots and an uneven and dark tone. Orchards in the other forest category were bright red in color, scattering on cropland or around residential land, whereas regenerated forest land exhibited a cyan or gray color and was mixed with shrubs or open forest. These classification results were converted into 1-km resolution percentage land cover data without destroying the acreage information by using an area percentage data model (APDM); this process included three steps (Deng et al., 2010; Liu et al., 2010): first, a standard grid frame with a vector format was built, and each grid cell of 1 km × 1 km was identified with a unique identity (ID) number; second, a frame was used to intersect the classifycation results to group the input information for each cell; and finally, a summary of the area percentages for each cell was provided and grouped by class.

The CAS dataset includes time series data for four periods: a) the late 1980s, including Landsat data acquired from 1986 to 1989 (1990 data); b) the mid-1990s, including Landsat data acquired from 1995 and 1996 (1995 data); c) the late 1990s, including Landsat data acquired from 1999 and 2000 (2000 data); and d) the mid-2000s, including Landsat data acquired from 2004 and 2005 (2005 data). Classification accuracy is the basis for assessing classification results, and high quality land cover classification is essential for change analysis (Olofsson et al., 2013; Jia et al., 2014a). Field surveys and random sample checks revealed that the overall interpretation accuracies for land cover classification in this study were 92.9, 98.4, 97.5 and 95.0% for the 1990, 1995, 2000 and 2005 data, respectively (Liu et al., 2005b; Liu et al., 2010). The 1-km resolution percentage land cover data from the APDM demonstrated the retention of high levels of accuracy from the original land cover map produced from the Landsat TM/ETM+ data; therefore, it had been used for land cover change analysis (Liu et al., 2005a; Deng et al., 2010).

Table 1. Class Types in CAS Land Cover Dataset for Forest Cover Changes Analysis in This Study

Class type	Descriptions
Dense forest	Natural or planted forests with canopy cover greater than 30%
Shrub	Lands covered by trees less than 2 m high, the canopy cover > 40%
Sparse forest	Lands covered by trees with canopy cover between 10–30%
Others	Lands such as tea-garden, orchards, groves and nurseries

In this study, forest cover referred to the woodland class in the CAS land cover dataset, which includes dense forest, shrubs, sparse forest and other. The forest cover change between the two periods was obtained by subtracting the value of the forest cover between the two periods. The pixel value in each grid indicates the fraction of forest cover, e.g., 10% indicates 10% of the grid area (1 km^2), which is 0.1 km^2.

Furthermore, the meteorological data consisted of the annual average temperature and precipitation values from 1988 to 2007 at 201 weather stations with completed observation records that were distributed throughout the TNSFR; they were obtained for the analysis of the relationship between forest cover change and meteorological change trends. The meteorological data were provided by the National Meteorological Bureau of China. A linear regression was used to simulate the meteorological change at each station during the study period. A least squares method was used to estimate the temporal trends in this study (Equation 1), as follows:

$$\Theta_{slope} = \frac{n \times \sum_{i=1}^{n} i \times MF_i - \sum_{i=1}^{n} i \sum_{i=1}^{n} MF_i}{n \times \sum_{i=1}^{n} i^2 - \left(\sum_{i=1}^{n} i \right)^2} \tag{1}$$

where Θ_{slope} is the slope of the meteorological factor trend line, n is the number of simulated years (n = 20 years in this study), i is the ordinal number for the year, and MF_i is the meteorological factor value of the i-th year (MF refers to temperature and precipitation in this study). The Θ_{slope} reflects the meteorological trend during the study period, with $\Theta_{slope} > 0$ indicating an increase in the meteorological factor during the study period, $\Theta_{slope} < 0$ indicating a meteorological factor decrease, and $\Theta_{slope} = 0$ indicating that a meteorological factor remained constant during the study period. The meteorological change trends at each station were mapped for the TNSFR using the latitude and longitude of each station; then, the relationship between the meteorological trends and forest cover change was qualitatively analyzed because there were only four periods of forest cover data instead of continuous data.

4. Results

The forest cover areas were 26.98, 27.35, 26.72 and 28.62 million ha in the TNSFR of China in 1990, 1995, 2000 and 2005, respectively (Table 2). The total forest area increased by 1.64 million ha from 1990 to 2005, accounting for 6.1% of the total forest area in 1990. The forest cover in the TNSFR had an approximately consistent composition of dense forest, shrubs, sparse forest and other forest over time (Table 2). The dense forest type is the dominant type and accounts for approximately 50% of the forest cover. Shrubs, sparse forest and other forest comprise a smaller share, especially the other forest type, which only accounts for approximately 2%. Shrubs and sparse forest account for approximately 32 and 16% of the forest cover, respectively.

The spatial distribution of the forest cover is not uniform across the TNSFR (Figure 2). Northeast China has the largest area of forest cover, which comprises approximately one-third of the total forest cover. North China has the smallest forest cover area but the highest percentage of forest cover at approximately 35%. Meng-Xin has the largest land area and the lowest percentage of forest cover. The Loess Plateau has a similar amount of forest cover to that of Northeast China. Furthermore, there are various composition structures of dense forest, shrubs, sparse forest and other forest in the four subregions, but the composition structure in each region is primarily consistent (Table 2). In Meng-Xin, the proportions of dense forest and shrub are quite similar, and these two types account for approximately 85% of the total forest cover. The proportion of sparse forest is third largest, and other forests are only present in small amounts. Shrub is the dominant forest type on the Loess plateau, accounting for approximately 50% of the total forest cover. The proportion of dense forest is nearly equivalent to that of sparse forest, and other forest only occupies a small portion of the region. The main reason that shrubs are so common in Meng-Xin and on the Loess Plateau is that these two regions are classified as arid and semi-arid. Water is the limiting factor in these conditions, creating suitable habitat for shrubs. In North China, dense forest accounts for approximately 50% of the total forest cover, whereas the proportions of shrubs, sparse and other forest types decrease successively. Dense forest has dominated the forest cover in Northeast China over time, which comprises more than 70% of the total forest cover area. The proportion of sparse forest is slightly lower than that of shrub, which accounts for approximately 16% of the total forest area in Northeast China. The main reason that dense forest dominates the forest cover in North and Northeast China is because water conditions have improved compared to Meng-Xin and the Loess Plateau.

From 1990 to 2005, there was a persistent increasing trend in the total forest cover across the TNSFR in China, except for the timeframe from 1995 to 2000. The decrease in total forest cover from 1995 to 2000 was mainly caused by an obvious shrinking of the sparse forest type, whereas the dense forest and shrub types continued to increase. The change in the other forests type was not significant. However, the temporal forest cover changes in the four sub-regions were quite different. In Meng-Xin, the total forest cover exhibited a persistent increasing trend from 1990 to 2005, and the total forest area increased by 0.39 million ha between 1990 and 2005, accounting for 5.6% of the total forest area in 1990. There was a decrease from 1990 to 1995 and a continuous increase from 1995 to 2005 on the Loess Plateau, whereas there was a total increase of 0.1 million ha from 1990 to 2005. For the North China region, the forest cover change was unstable; the forest cover increased from 1990 to 1995 and from 2000 to 2005 but decreased from 1995 to 2000. There was a persistent decrease in forest cover from 1990 to 2000 in Northeast China and a sharp increase from 2000 to 2005, leading to an overall increase of 0.82 million ha in forest cover from 1990 to 2005. The main cause of forest cover loss from 1995 to 2000 is excessive deforestation for farmland expansion and timber and forest degradation from deforestation (Li et al., 2013). Until 1999, deforestation of natural forests was forbidden by the Chinese government; the forest loss trend was controlled and forest restoration began, which was also exhibited by the forest cover increases from 2000 to 2005 in this study.

The spatial distribution of forest cover change in the TNSFR from 1990 to 2005 is shown in Figure 3. Generally speaking, most of the regions exhibited increases in forest cover from 1990 to 2005, whereas a small number of regions exhibited decreases, mostly in Northeast China (Figure 3). The forest cover did not change greatly, with the overall trends mainly falling between -10% and 10%. Forest cover percentage changes of more than 50% were mainly distributed along the boundaries of Meng-Xin and Northeast China. The forest cover changes varied greatly at various times. From 1990 to 1995, most parts of Meng-Xin, the Loss Plateau and Northeast China showed slight increases with a small number of decreases, whereas there was an obvious increase in forest cover in North China. In contrast, most regions exhibited a slight decreasing trend in forest cover from 1995 to 2000, especially in North China, which exhibitted a visible decrease. From 2000 to 2005, the forest cover increased slightly in most regions, and examples of decreases were extremely rare. Farther away, the forest cover increases were obvious along the boundaries of Meng-Xin and Northeast China, as well as along the boundaries of North and Northeast China.

The spatial distribution of the meteorological change trends including temperature and precipitation in the TNSFR of China from 1988 to 2007, are shown in Figure 4. Nearly all of the stations indicate an increasing temperature trend, and most stations indicate decreasing precipitation trends, except for some slightly increasing trends in the western part of the TNSFR. These phenomena are consistent with large scale climate change, which predicts a warming and drying trend in this re-

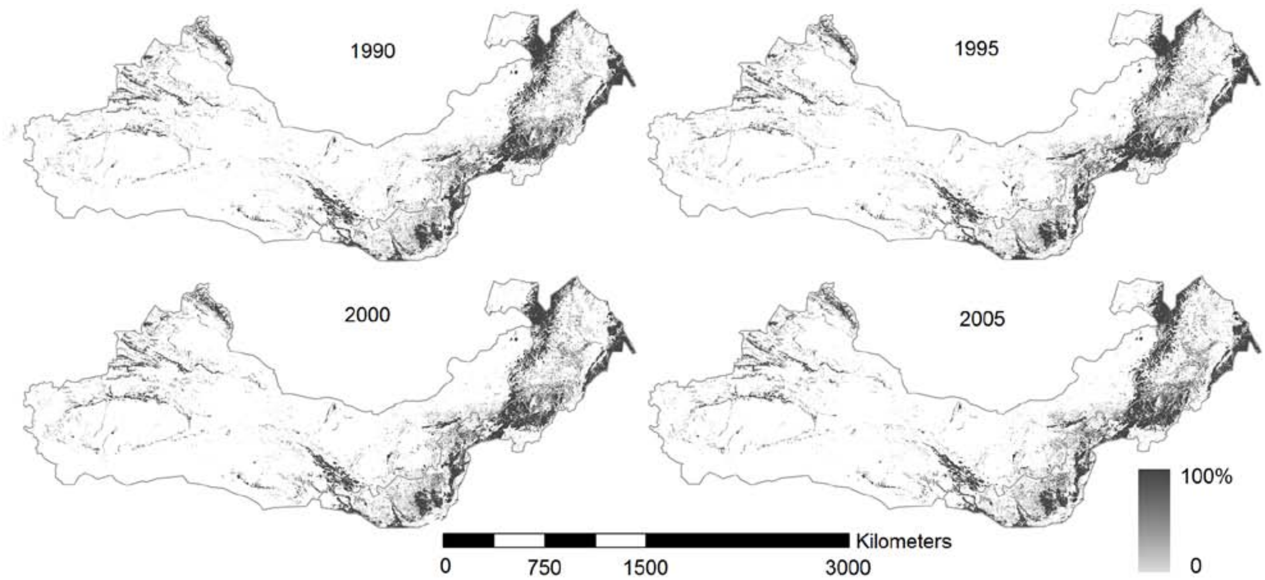

Figure 2. Spatial patterns of the forest cover identified by the 1-km area percentage land cover data in the Three-North Shelter Forest region of China.

Table 2. Forest Area of the Three-North Shelter Forest Region of China in 1990, 1995, 2000, and 2005 (in million ha)

Region	Year	Total area	Dense forest	Shrub	Sparse forest	Other forest
Meng-Xin region	1990	6.96	2.96	2.68	1.24	0.09
	1995	7.04	3.04	2.53	1.38	0.10
	2000	7.20	2.91	2.90	1.29	0.11
	2005	7.35	3.14	2.78	1.25	0.18
Loess Plateau region	1990	5.72	1.49	2.86	1.24	0.12
	1995	5.49	1.42	2.67	1.27	0.13
	2000	5.71	1.48	2.85	1.25	0.14
	2005	5.82	1.50	2.88	1.19	0.25
North China region	1990	4.70	2.42	1.39	0.77	0.12
	1995	5.37	2.27	1.71	1.18	0.21
	2000	4.62	2.42	1.38	0.67	0.15
	2005	5.02	2.70	1.62	0.53	0.17
Northeast China region	1990	9.60	6.73	1.48	1.03	0.37
	1995	9.45	6.58	1.60	1.18	0.09
	2000	9.19	6.64	1.48	1.01	0.06
	2005	10.42	8.05	1.72	0.61	0.05
Total	1990	26.98	13.60	8.40	4.28	0.69
	1995	27.35	13.31	8.51	4.99	0.53
	2000	26.72	13.43	8.61	4.22	0.46
	2005	28.62	15.38	9.01	3.57	0.66

gion. The average change rates of the 201 stations from 1988 to 2007 are 0.054 °C/year and -1.905 mm/year for temperature and precipitation, respectively. However, the change rates in temperature and precipitation exhibit a very different spatial distribution. The rate of increase in the temperatures in Northeast and North China are usually lower than in the Meng-Xin and Loess Plateau, whereas the rates of decrease in Northeast China are higher than in other regions.

When the meteorological change trends are compared with the forest cover changes (Figures 2, 3 and 4), it is clear that the regions with more forest coverage and forest cover increases have slower rates of temperature increases, e.g., in Northeast, North China and northwestern Meng-Xin, there were even three stations with temperature decrease trends. Forest have a cooling effect on the atmosphere, and increased forest cover can slow down the rate of temperature increase the TNSFR in China. As for precipitation, broader forest distribution and increased forest cover can slow down the rate of

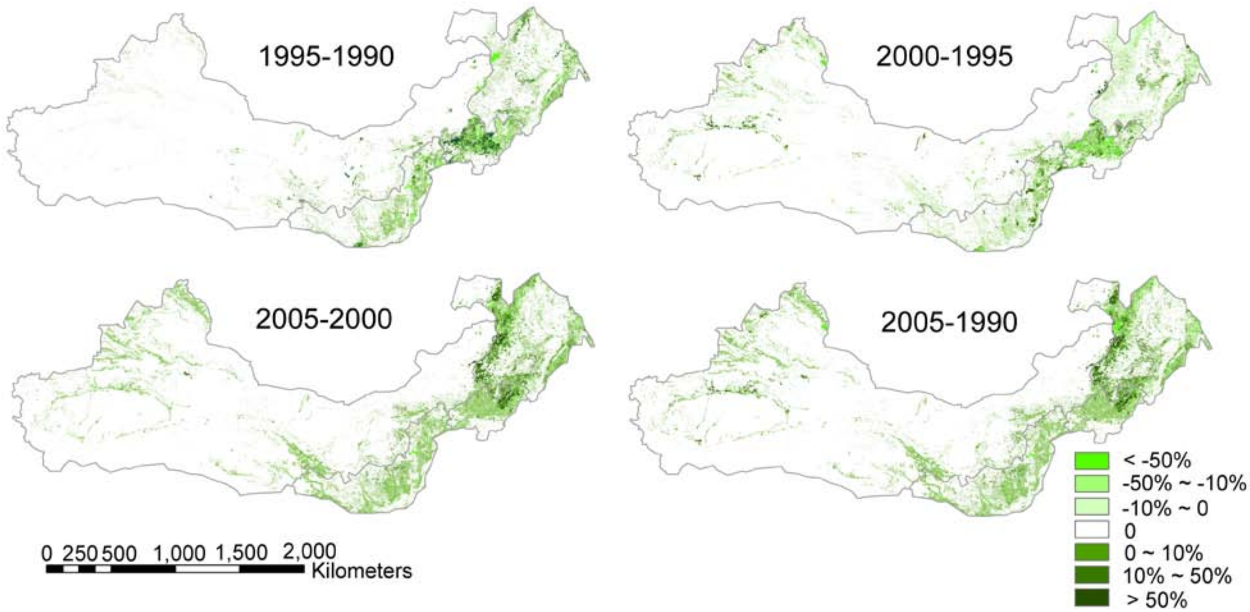

Figure 3. Spatial patterns of forest cover change from 1990 to 2005 in the Three-North Forest region of China (units: percentage).

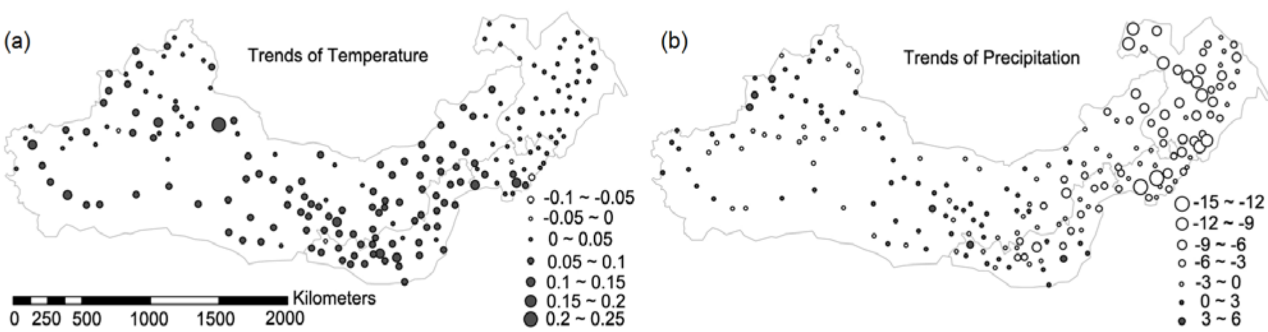

Figure 4. Spatial patterns of annul average temperature (a) and precipitation (b) change trends from 1988 to 2007 in the Three-North Forest region of China.

the TNSFR in China. As for precipitation, broader forest distribution and increased forest cover can slow down the rate of precipitation decrease or even change the precipitation trend in most regions, e.g., North China, the Loess Plateau and Meng-Xin. These results show that increased forest cover is benefit to precipitation increases. Although the increased forest cover in the TNSFR cannot change the large-scale climate change trends, it can slow down the rate of climate change to some extent.

5. Discussion

This study evaluated detailed spatial and temporal forest cover change information in the entire TNSFR, which urgently needed an assessment of afforestation and reforestation projects. No academic literature, especially of detailed forest cover change across the entire TNSFR, was found for this region, with the exception of some small regional land cover change analysis (Gao et al., 2006; Li and Zhou, 2009); therefore, this study provided comprehensive and objective spatio-temporal forest cover change information. The results indicated that the forest cover in the TNSFR was 6.63, 6.72, 6.57, and 7.03% in 1990, 1995, 2000 and 2005, respectively. Nevertheless, the government survey data indicated that the forest cover in the TNSFR reached 10.51% at the end of 2007 (Li, 2009). Although the forest cover has followed an increasing trend, government survey data seems to be somewhat higher than the RS survey data. The gap might be due to differences in the survey method, e.g., RS data can offer detailed detection of forest gaps while neglecting smaller independent forest stands; furthermore, RS data are strongly related to the acquisition time, and forest management can lead to temporary forest cover loss in the RS data, thereby leading to less forest area than is reflected by official data.

The TNSFR has a fragile ecology, and the forest is mainly affected by human activity. Many afforestation and reforestation projects have been implemented by the Chinese govern-in this region to increase the proportion of forest cover. Ex-

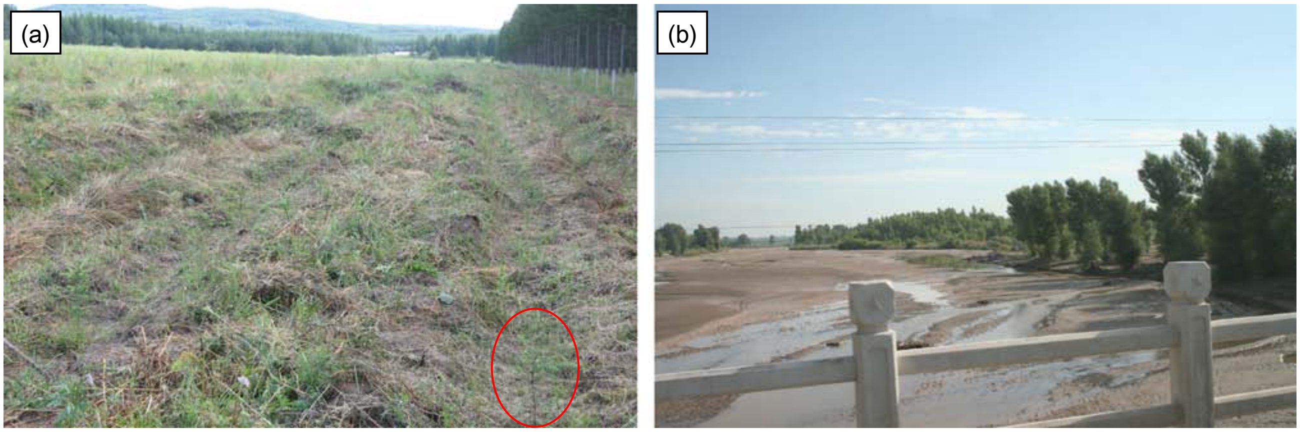

Figure 5. Field survey photos taken in North China (a) and Northwest China regions (b).

cept for the well-known TNSFP project, there are also many afforestation and reforestation projects that affect this region, such as the National Natural Forest Protection Project (Zhang et al., 2006), the Sandstorm Source Control Project of Beijing and Tianjin (Xu et al., 2011) and the Grain for Green Project (Cao et al., 2009). The National Natural Forest Protection Project began in 1998 and promotes forest management activities to prevent forest destruction and further deterioration (Li, 2004); these goals are mostly relevant to the TNSFR, where the main effort is to protect natural forest and to reforest arable areas. The Sand-storm Source Control Project of Beijing and Tianjin began in 2001 and mainly focuses on North China; it has made a great effort to increase forest cover in North China. The Grain for Green Project began in 1999 and was designed to restore fragile ecosystems that had been damaged by unsustainable farming and grazing; its main effort has been to protect forests and to reforest cultivated land. These afforestation and reforestation projects and policies have made great progress toward increasing the forest cover in the TNSFR. Take the southern Inner Mongolia Grassland as an example: there were huge areas that were converted from cropland to forest from 2000 to 2005 (Figure 3), which were mainly converted due to the implementation of reforestation projects (Deng et al., 2010).

The increased demand for grain from socio-economic development and population growth has become the main reason for forest cover decreases in the TNSFR, especially in the 1990s and in Northeast China (Figure 3). Deforestation has been primarily caused by the expansion of agricultural practices, the need for timber and urban expansion (Liu et al., 2005a). Furthermore, inappropriate forest management following deforestation is also responsible for forest cover loss (Deng et al., 2010). Forest management can lead to temporary forest cover loss in land cover data produced from RS data; this is also why the forest cover area from the RS data may vary from government survey data (Figure 5A). Figure 5A is a field survey in North China, where the mature trees were harvested for timber and saplings (see the red oval in Figure 5A) were planted; this region would be classified as other land types when using RS data. Forest fire is another source of forest cover loss in the TNSFR and is an important factor in Northeast China (Lv et al., 2006). Forest fires not only directly reduce the forest area but also cause serious damage to the forest environment, resulting in imbalanced forest ecosystems and decreased forest biomass. Therefore, forest fires are a serious natural disaster in terms of forest cover loss. Furthermore, the limited availability of water in the arid and semiarid Meng-Xin and Loess Plateau was an important factor limiting forest cover area increases. When precipitation in these regions is lower than the potential evaporation, the surface soil moisture typically cannot sustain forest vegetation, leading to dead trees and lost forest cover and even accelerating environmental deterioration (Cao et al., 2010). Furthermore, when the forest cover area is smaller than the original Landsat TM/ETM+ pixel size, the forest cover will not be recognized, leading to lower forest area estimates in the land cover results.

Forest has the effect of slowing down climate change rates and improving the environment in the TNSFR; these improvements result mainly from the ability of forest to intercept precipitation, maintain water sources and increase evaporation, thereby cooling the atmosphere and increasing precipitation. However, some research has also found that afforestation and reforestation projects may worsen the already fragile environment in this region (Cao et al., 2009; Cao et al., 2010). This study finds that increased forest cover can slow down the rate of climate change and improve the environment at a large scale during the study period. This study confirms the positive effect of afforestation and reforestation projects in the TNSFR, and the appropriate implementation of these projects is encouraged.

The ecological environment in the TNSFR is fragile and easily damaged. Therefore, proper planning and implementation of afforestation and reforestation projects are essential to improving the natural environment in the future. Sustainable forest management is the optimal way to keep the forest healthy and to steadily increase the forest cover area. Sustainable forest management seeks to maintain forest biodiversity, productivity and the regeneration capacity while not causing damage to the ecological, economic and social functions of the forest. In addition, the selection of suitable tree species and planting locations according to local conditions increases the chance of success, because planting the wrong tree species can lead to tree death while depleting the soil water and exacerbating environmental degradation (Cao et al., 2010). In the arid region, for example, trees should only be planted in regions that have enough water to support tree growth, which increases the likelihood that a tree will survive (Figure 5B). Figure 5B is a field survey in Northwest China, in which trees planted near the stream grow healthy and improve the nearby environment.

6. Conclusions

The 1-km spatial resolution percentage land cover dataset developed by the CAS is used to investigate forest cover changes in the Three-North Shelter Forest region of China from 1990 to 2005. From 1990 to 2005, the total forest cover area increased by 1.64 million ha, with a slight area decrease from 1995 to 2000 and an obvious area increase from 2000 to 2005. The composition of forest cover types remained approximately consistent over time and was comprised of dense forest, shrubs, sparse forest and other forest, with dense forest being the dominant type. The spatial distribution of forest cover change was not uniform. North and Northeast China underwent major forest cover change from 1990 to 2005, whereas forest cover change in Meng-Xin and on the Loess Plateau was not as pronounced. The implementation of numerous afforestation and reforestation projects by the Chinese government played an important role in forest cover increases, whereas deforestation for urban areas and farm-land, forest harvesting, forest fires and harsh natural conditions were responsible for forest cover decreases. The relationship between forest cover change and meteorological change trends indicated that increased forest cover could slow down the rate of change of the annual average temperature and precipitation and could improve the environment. Therefore, proper planning and implementation of afforestation and reforestation projects is needed to improve the natural conditions of these fragile ecological regions. An understanding of forest cover changes will help with the design of appropriate forestry policies and sustainable forest management strategies, which represent the future objecttives of this study.

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References

Cao, S.X. (2008). Why large-scale afforestation efforts in China have failed to solve the desertification problem. *Environ. Sci. Technol.*, 42(6), 1826-1831. http://dx.doi.org/10.1021/es0870597

Cao, S.X., Chen, L., Shankman, D., Wang, C.M., Wang, X.B., and Zhang, H. (2011). Excessive reliance on afforestation in China's arid and semi-arid regions: Lessons in ecological restoration. *Earth-Sci. Rev.*, 104(4), 240-245. http://dx.doi.org/10.1016/j.earscirev.2010.11.002

Cao, S.X., Chen, L., and Yu, X.X. (2009). Impact of China's Grain for Green Project on the landscape of vulnerable arid and semiarid agricultural regions: A case study in northern Shaanxi Province. *J. Appl. Ecol.*, 46(3), 536-543. http://dx.doi.org/10.1111/j.1365-2664.2008.01605.x

Cao, S.X., Tian, T., Chen, L., Dong, X.B., Yu, X.X., and Wang, G.S. (2010). Damage caused to the environment by reforestation policies in arid and semi-arid areas of China. *Ambio*, 39(4), 279-283. http://dx.doi.org/10.1007/s13280-010-0038-z

Caplow, S., Jagger, P., Lawlor, K., and Sills, E. (2011). Evaluating land use and livelihood impacts of early forest carbon projects: Lessons for learning about REDD. *Environ. Sci. & Policy*, 14(2), 152-167. http://dx.doi.org/10.1016/j.envsci.2010.10.003

Chen, Y., Cheng, S.Y., Liu, L., Guo, X.R., Wang, Z., Qin, C.H., Hao, R.X., Lu, J., and Gao, J.J. (2013). Assessing the effects of land use changes on non-point source pollution reduction for the Three Gorges Watershed using the SWAT model. *J. Environ. Inf.*, 22(1), 13-26. http://dx.doi.org/10.3808/jei.201300242

Deng, X.Z., Jiang, Q.O., Su, H.B., and Wu, F. (2010). Trace forest conversions in Northeast China with a 1-km area percentage data model. *J. Appl. Remote Sens.*, 4(1), 041893. http://dx.doi.org/10.1117/1.3491193

Duan, H.C., Yan, C.Z., Tsunekawa, A., Song, X., Li, S., and Xie, J.L. (2011). Assessing vegetation dynamics in the Three-North Shelter Forest Region of China using AVHRR NDVI data. *Environ. Earth Sci.*, 64(4), 1011-1020. http://dx.doi.org/10.1007/s12665-011-0919-x

Friedl, M.A., McIver, D.K., Hodges, J.C.F., Zhang, X.Y., Muchoney, D., Strahler, A.H., Woodcock, C.E., Gopal, S., Schneider, A., Cooper, A., Baccini, A., Gao, F., and Schaaf, C. (2002). Global land cover mapping from MODIS: Algorithms and early results. *Remote Sens. Environ.*, 83(1-2), 287-302. http://dx.doi.org/10.1016/S0034-4257(02)00078-0

Gao, J., Liu, Y.S., and Chen, Y.F. (2006). Land cover changes during agrarian restructuring in Northeast China. *Appl. Geogr.*, 26(3-4), 312-322. http://dx.doi.org/10.1016/j.apgeog.2006.09.001

Gong, P., Wang, J., Yu, L., Zhao, Y.C., Zhao, Y.Y., Liang, L., Niu, Z.G., Huang, X.M., Fu, H.H., Liu, S., Li, C.C., Li, X.Y., Fu, W., Liu, C.X., Xu, Y., Wang, X.Y., Cheng, Q., Hu, L.Y., Yao, W.B., Zhang, H., Zhu, P., Zhao, Z.Y., Zhang, H.Y., Zheng, Y.M., Ji, L.Y., Zhang, Y.W., Chen, H., Yan, A., Guo, J.H., Wang, L., Liu, X.J., Shi, T.T., Zhu, M.H., Chen, Y.L., Yang, G.W., Tang, P., Xu, B., Giri, C., Clinton, N., Zhu, Z.L., Chen, J., and Chen, J. (2013). Finer resolution observation and monitoring of global land cover: first mapping results with Landsat TM and ETM+ data. *Int. J. Remote Sens.*, 34(7), 2607-2654. http://dx.doi.org/10.1080/01431161.2012.748992

Hansen, M.C., DeFries, R.S., Townshend, J.R.G., Carroll, M., Dimiceli, C., and Sohlberg, R.A. (2003). Global percent tree cover at a spatial resolution of 500 meters: First results of the MODIS vegetation continuous fields algorithm. *Earth Interact.*, 7(1), 1-15. http://dx.doi.org/10.1175/1087-3562(2003)007<0001:GPTCAA>2.0CO;2

Hansen, M.C., Defries, R.S., Townshend, J.R.G., and Sohlberg, R. (2000). Global land cover classification at 1 km spatial resolution using a classification tree approach. *Int. J. Remote Sens.*, 21(6-7), 1331-1364. http://dx.doi.org/10.1080/014311600210209

Jia, K., Li, Q.Z., Tian, Y.C., Wu, B.F., Zhang, F.F., and Meng, J.H. (2012). Crop classification using multi-configuration SAR data in the North China Plain. *Int. J. Remote Sens.*, 33(1), 170-183. http://dx.doi.org/10.1080/01431161.2011.587844

Jia, K., Liang, S., Wei, X.Q., Zhang, L., Yao, Y.J., and Gao, S. (2014 a). Automatic land-cover update approach integrating iterative training sample selection and a Markov Random Field model. *Remote Sens. Lett.*, 5(2), 148-156. http://dx.doi.org/10.1080/2150704X.2014.889862

Jia, K., Wei, X.Q., Gu, X.F., Yao, Y.J., Xie, X.H., and Li, B. (2014b). Land cover classification using Landsat 8 Operational Land Imager data in Beijing, China. *Geocarto Int.*, http://dx.doi.org/10.1080/10106049.2014.894586

Li, B.L., and Zhou, Q.M. (2009). Spatial pattern of land cover change in China's semiarid environment. *J. Arid Land*, 1(1), 16-25. http://dx.doi.org/10.3724/sp.j.1227.00016

Li, J. (2009). The development of China's forestry ecological engineering from the construction of the Three-North Shelter. *For. China*, 9, 38-39.

Li, W.H. (2004). Degradation and restoration of forest ecosystems in China. *For. Ecol. Manage.*, 201(1), 33-41. http://dx.doi.org/10.1016/j.foreco.2004.06.010

Li, X.F., Su, L., Zhang, J.X., Zhang, Z.X., Liu, L.M., and Liu, X.F. (2013). Spatiotemporal variation characteristics and influencing factors of protection forests after their 30 years construction in Northwest Shanxi Province of China. *Chin. J. Ecol.*, 32(9),2382-2389.

Liu, J.Y., Liu, M.L., Tian, H.Q., Zhuang, D.F., Zhang, Z.X., Zhang, W., Tang, X.M., and Deng, X.Z. (2005a). Spatial and temporal patterns of China's cropland during 1990-2000: An analysis based on Landsat TM data. *Remote Sens. Environ.*, 98(4), 442-456. http://dx.doi.org/10.1016/j.rse.2005.08.012

Liu, J.Y., Liu, M.L., Zhuang, D.F., Zhang, Z.X., and Deng, X.Z. (2003). Study on spatial pattern of land-use change in China during 1995-2000. *Sci. China Ser. D (Earth Sci.)*, 46(4), 373- 384.

Liu, J.Y., Zhan, J.Y., and Deng, X.Z. (2005b). Spatio-temporal patterns and driving forces of urban land expansion in China during the economic reform era. *Ambio*, 34(6), 450-455. http://dx.doi.org/10.1579/0044-7447-34.6.450

Liu, J.Y., Zhang, Z.X., Xu, X.L., Kuang, W.H., Zhou, W.C., Zhang, S.W., Li, R.D., Yan, C.Z., Yu, D.S., Wu, S.X., and Nan, J. (2010). Spatial patterns and driving forces of land use change in China during the early 21st century. *J. Geogr. Sci.*, 20(4), 483- 494. http://dx.doi.org/10.1007/s11442-010-0483-4

Liu, R.G., Liang, S.L., Liu, J.Y., and Zhuang, D.F. (2006). Continuous tree distribution in China: A comparison of two estimates from Moderate-Resolution Imaging Spectroradiometer and Landsat data. *J. Geophys. Res. (D Atmos.) (1984-2012)*, 111(D8), D08101. http://dx.doi.org/10.1029/2005JD006039

Lv, A.F., Tian, H.Q., Liu, M.L., Liu, J.Y., and Melillo, J.M. (2006). Spatial and temporal patterns of carbon emissions from forest fires in China from 1950 to 2000. *J. Geophys. Res. (D Atmos.) (1984-2012)*, 111(D5), D05313. http://dx.doi.org/10.1029/2005JD006198

Moore, R., and Russell, R. (1990). The 'Three Norths' forest protecttion system - China. *Agrofor. Syst.*, 10, 71-88. http://dx.doi.org/10.1007/BF00118728

Olofsson, P., Foody, G.M., Stehman, S.V., and Woodcock, C.E. (2013). Making better use of accuracy data in land change studies: Estimating accuracy and area and quantifying uncertainty using stratified estimation. *Remote Sens. Environ.*, 129(1), 122-131. http://dx.doi.org/10.1016/j.rse.2012.10.031

Ran, Y.H., Li, X., and Lu, L. (2010). Evaluation of four remote sensing based land cover products over China. *Int. J. Remote Sens.*, 31(2), 391-401. http://dx.doi.org/10.1080/01431160902893451

Shimada, M., Isoguchi, O., Motooka, T., Shiraishi, T., Mukaida, A., Okumura, H., Otaki, T., and Itoh, T. (2011). Generation of 10m resolution PALSAR and JERS-SAR mosaic and forest/non- forest maps for forest carbon tracking, *Proc. of 2011 IEEE International Geoscience and Remote Sensing Symposium*, Vancou- ver, Canada, pp. 3510-3513. http://dx.doi.org/10.1109/IGARSS.2011.6049978

Tang, X.M., Zhang, G., Zhu, X.Y., Pan, H.B., Jiang, Y.H., Zhou, P., and Wang, X. (2013). Triple linear-array image geometry model of ZiYuan-3 surveying satellite and its validation. *Int. J. Image Data Fusion*, 4(1), 33-51. http://dx.doi.org/10.1080/19479832.2012.734340

Tong, S.T.Y., Sun, Y., and Yang, Y.J. (2012). Generating a future land use change scenario with a modified population-coupled Mar- kov Cellular Automata model. *J. Environ. Inf.*, 19(2), 108-119. http://dx.doi.org/10.3808/jei.201200213.

Wang, X.M., Zhang, C.X., Hasi, E., and Dong, Z.B. (2010). Has the Three Norths Forest Shelterbelt Program solved the desertification and dust storm problems in arid and semiarid China? *J. Arid Environ.*, 74(1), 13-22. http://dx.doi.org/10.1016/j.jaridenv2009.08.001

Xu, X.G., Duan, X.F., Sun, H.Q., and Sun, Q.A. (2011). Green space changes and planning in the capital region of China. *Environ. Manage.*, 47(3), 456-467. http://dx.doi.org/10.1007/s00267-011-9626-3

Yuan, W.P., Li, X.L., Liang, S., Cui, X.F., Dong, W.J., Liu, S.G., Xia, J.Z., Chen, Y., Liu, D., and Zhu, W.Q. (2014). Characterization of locations and extents of afforestation from the Grain for Green Project in China. *Remote Sens. Lett.*, 5(3), 221-229. http://dx.doi.org/10.1080/2150704X.2014.894655

Zhang, Y.F., Tachibana, S., and Nagata, S. (2006). Impact of socioeconomic factors on the changes in forest areas in China. *For. Policy Econ.*, 9(1), 63-76. http://dx.doi.org/10.1016/j.forpol.2005.02.005

Zhao, S.H., Wang, Q., Zhang, F., Yao, Y.J., Qin, Q.M., You, L., Li, J.P., Li, Z.J., Wu, Y.T., Liu, S.H., and Li, Y. (2013). Drought mapping using two shortwave infrared water indices with MODIS data under vegetated season. *J. Environ. Inf.*, 21(2), 102- 111. http://dx.doi.org/10.3808/jei.201300237