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Vegetation restoration in Northern China: a contrasted picture

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Abstract:

China started a long-term effort to mitigate desertification and ensure the sustainability of its environment by implementing multiple large-scale national ecological restoration projects since 1978, but their success has been highly debated for a long time. Here, we estimated the change of vegetation fraction cover (VFC) in the Three-North Shelterbelt Project (TNSP) region over the past three decades based on the Normalized Difference Vegetation Index (NDVI) dataset from the Global Inventory Monitoring and Modeling System (GIMMS). We evaluate the national strategy of vegetation restoration in North China by comparing rainfall patterns, vegetation change, and national ecological restoration programs based on the Global Meteorological Forcing Dataset and the China Forestry Statistical Yearbooks. We find that the western, central, and eastern parts of the TNSP region exhibited a distinct increase in vegetation coverage. The western region had the highest increase of annual precipitation, but this did not result in the highest VFC increase. We infer that ecological restoration activities are the factor leading to the observed increase in VFC in the eastern and central region compared to the western region. The low survival rate of planted trees in the forest of the TNSP region indicates that it is necessary to improve the mode of vegetation restoration to obtain optimal returns and avoid excessive investment. The success of new strategies e.g. natural restoration and quasi-natural afforestation are promising as an alternative method. China's experiences in reforestation will be very beneficial for other countries to promote land degradation mitigation and vegetation improvement in the arid and semi-arid areas.

Keywords: Three-North Shelterbelt Project, reforestation, precipitation pattern, land degradation,

desertification

1 Introduction

Over 75% of the Earth's land area is already degraded, and over 90% could become degraded by 2050, with Africa and Asia being the most affected (Cherlet *et al.*, 2018). Vast areas of northeast Asia, particularly in China and Mongolia are under the threat of desertification and land degradation, and the situation is becoming even more challenging with climate change (Huang *et al.*, 2015). China has a long history of combating desertification and has been continuously fighting land degradation since the 1950s through various ecological restoration programs (Bryan *et al.*, 2018; Wang *et al.*, 2013). To mitigate land degradation in China, the government launched a series of national ecological restoration projects, such as the Three-North Shelterbelt Project (TNSP, 1979 – present), the Grain to Green Project (GGP, 1999–present), and the Beijing and Tianjin Sandstorm Source Control Project (BTSSCP, 2001–present) (Bryan *et al.*, 2018). The TNSP aims at planting shelterbelt forests in arid and semi-arid areas located in North China and is scheduled to continue until 2050. It is the most extensive and longest-running afforestation plan in the history of the world. The goal of the GGP is to convert farmland into forestland and grassland and is being implemented locally throughout most of China. The BTSSCP aims at preventing sand and dust storms through vegetation restoration in northeastern China. Many tree species including *Populus alba*, *Pinus sylvestris* var. *Mongolica*, *Salix matsudana*, and *Ulmus pumila*, which all have a high tolerance to drought, cold, soil infertility, and soil salinity, have been introduced in sandy areas to prevent sand and dust storms and the migration of sand dunes towards human habitations. At the end of 2014, national monitoring of desertification showed that the area impacted by desertification in China had decreased from 2.64 million to 2.61 million km^2 over the past ten years (Cheng *et al.*, 2016; State Forestry Administration of China, 2015).

As a result of these nationwide afforestation projects, the forest fraction coverage in China has increased from 12% in the 1970s to 22% in 2013. In the TNSP region, forested land fraction went from 5% in 1977 to 12% in 2013 (State Forestry Administrator, 2017). By the end of 2013, the total area that had been afforested in China approached 3 million km^2, which is equivalent to ten times the surface of Italy (Fig. 1). However, only 0.69 million km^2 of the planted area actually remained under forest cover by 2013 (State Forestry Administrator, 2017). This situation might be caused by the high tree mortality in the harsh environment of the degraded areas of North China. The economic loss associated with these 'lost plantations' is very high and the controversy has intensified as to whether the existing afforestation policies and methods should continue to be applied in semi-arid and arid areas in Northern China (Cao *et al.*, 2010; Chen *et al.*, 2015; Tan & Li, 2015; Wang *et al.*, 2010; Yang *et al.*, 2010).

In this study, we aim at evaluating China vegetation restoration strategy by untangling the influences of large-scale national ecological restoration projects and climate on vegetation changes in North China over the past three decades. The following questions are addressed: 1) What is the change of vegetation fraction cover (VFC) in the TNSP region from 1981 to 2013? 2) What is the combined effect of the large-scale ecological restoration projects and climate change on vegetation change in the TNSP region? 3) Finally, we propose alternative approaches to promote vegetation restoration that may be adopted in dryland ecosystems.

2 Methods and materials

2.1 Study area

In this study, we mainly focus on the TNSP area, because commercial logging is minimal there. The region of the TNSP covers 551 Chinese countries in 13 provinces located in the northwestern, north and northeastern parts of China (Fig. 2). The TNSP has a total area of 4.07 million km^2, which covers about 42% of the national land surface (Qiu *et al.*, 2017). The TNSP region mainly includes hyper-arid, arid, semi-arid, dry sub-humid, and humid climates based on the aridity index (AI), which is the 30-year averaged ratio (*P*/*PET*) of the annual precipitation (*P*) and the annual potential evapotranspiration (*PET*) based on long-term climate data (Cherlet *et al.*, 2018). The vegetation restoration region is mainly located in the arid, semi-arid, and dry sub-humid areas(Zhang *et al.*, 2018).

2.2 Data source

This study uses the third generation GIMMS NDVI3g dataset from NOAA's Advanced Very High Resolution Radiometer (AVHRR) sensors. This dataset is the semi-monthly, 8 km (1/12-degree) resolution global NDVI product available from July 1981 to December 2013. The dataset is accessible on NASA's website at: https://nex.nasa.gov/nex/projects/1349/wiki/general_data_description_and_access/. The precipitation data comes from the Global Meteorological Forcing Dataset provided by the Terrestrial Hydrology Research group at Princeton University (Sheffield *et al.*, 2006). This dataset provides daily rainfall at 0.25-degree resolution globally for 1948-2010. It is available online free of charge (http://hydrology.princeton.edu/data.pgf.php). Details on the area reforested yearly from 1949 to 2016, the total area of plantations, and the forest fraction coverage for China and the TNSP region are all available in the latest China Forestry Statistical Yearbook 2016 (State Forestry Administrator, 2017).

2.3 Statistical analyses

The maximum annual NDVI of every pixel was extracted from the global GIMMS NDVI3g data set between 1981 and 2013. A dimidiate pixel model was chosen to estimate vegetation fraction cover F_c from NDVI values as shown in eq. (1).

$$F_c = \frac{NDVI - NDVI_S}{NDVI_V - NDVI_S} \quad (1)$$

where $NDVI_v$ and $NDVI_s$ are the NDVI values of fully vegetated areas and bare land, respectively. Combined with NDVI statistics, $NDVI_{veg}$ and $NDVI_{soil}$ were selected as the maximum and minimum values of remote sensing images. $NDVI_{min}$ value is taken as the value of 5% on the *NDVI* frequency cumulative table, and $NDVI_{max}$ value is taken as the value of 95% on the *NDVI* frequency cumulative table. For large areas covered by various land cover types (from bare soil to complete vegetation cover), the distribution of *NDVI* frequency could be considered as a normal distribution. $NDVI_{soil}$ is considered as 0.05, and $NDVI_{veg}$ is taken to be 0.95 (Xiao & Moody, 2005).

The trends in vegetation fraction cover during 1981-2013 was captured by estimating the slope of the time series of the maximum annual vegetation cover at pixel-scale based on the linear regression analysis. The change of vegetation cover between 1981-2013 was estimated by the product of the slope and time span (33 years).

The mean annual precipitation was extracted from daily rainfall in the Global Meteorological Forcing Dataset. The trend of annual precipitation during 1981-2010 was estimated by the slope of the linear regression for the time series of the annual precipitation at pixel-scale based on the linear regression analysis.

3 Results and Discussion

3.1 Precipitation trend

Northern China has been the focus of afforestation initiatives to reduce the surface area of degraded land and protect local soils and water resources since the end of 1970s. The mean annual precipitation in most of the region is lower than 400 mm. Due to differences in precipitation amount, the western, central, and eastern parts of the TNSP exhibit very distinctive climate types: arid and hyper-arid zone in the west, semi-arid and arid zone in the center, and dry sub-humid and semi-arid zone in the east (corresponding to the three green rectangles in Fig. 3a, as shown in Table 1). Records of annual precipitation in the three regions indicate different trends over the past three decades: increasing in the west, slightly decreasing in the central part, and sharply decreasing in the east, with some areas experiencing a reduction rate of up to 5.5 mm y^{-1} (Fig. 3b).

3.2 Vegetation change

After the initiation of the TNSP, vegetation cover in Northern China increased from 41% in 1981(Fig. 4a) to 45% in 2013 (Fig. 4b). Under the assumption that the increase in vegetation cover was all due to newly planted trees, the estimated 4% increase in forest area from 1981 to 2013 corresponds to 0.16 million km^2 of reforested land. The western, central, and eastern parts of the TNSP have experienced a significant increase ($p < 0.05$) in vegetation cover (Fig. 4c). According to the China Forestry Statistical Yearbook, the cumulative afforested area between 1979 and 2013 is about 0.35 million km^2 in the TNSP area, as shown in Fig. 1 (State Forestry Administrator, 2017). Therefore, the actual survival rate of planted trees into forest in the TNSP area is less than 45%. In recent research, the overall survival rate of trees planted during afforestation projects has been reported to only 15% across arid and semiarid Northern China since 1949 (Cao, 2008). Such a low survival rate suggests that the current afforestation strategies need to be considerably improved.

3.3 Effect of vegetation restoration and climate

Comparatively speaking, the afforestation in the central area was the most successful, since the vegetation cover there increased from 31.6% in 1999 to 59.6% in 2013 (Chen *et al.*, 2015). As shown in Table 1, the effects of vegetation restoration in the three regions suggest the following pattern:

central > eastern > western,

while the trends in annual precipitation in the three regions is the following:

western > central > eastern,

Within the TNSP area, increase of vegetation cover was more effective in the central part than in the eastern and western areas. Indeed, water is the limiting environmental factor for vegetation establishment in arid areas, but we find that the western region experienced the smallest VFC increase despite having the highest increase in annual precipitation. While only the TNSP was implemented in the western region, the eastern and central regions had both another national ecological engineering project ongoing at the same time (Table 1, BTSSCP and GGP, respectively). We infer that ecological restoration and protection activities are one of the factors leading to the observed increase in vegetation coverage.

Although national ecological restoration projects are beneficial for improving vegetation coverage in North China, the low survival rate of planted tree estimated in Section 3.2 indicates that there is a need for governmental agencies to select an appropriate method of vegetation restoration that is adapted to the local climate and topography in order to obtain optimal returns and avoid excessive investment.

3.4 Natural restoration and quasi-natural afforestation

Natural restoration and quasi-natural afforestation are two alternative strategies to high-density afforestation. Natural ecosystems are considered to be resilient and self-healing after the disturbance caused by human activities is reduced. Although the gradual process of natural restoration takes time, the slow restoration process also provides many long-term ecosystem services (Liu *et al.*, 2018). As an example, elm (*Ulmus pumila*) open canopy woodland is endemic in the sandy areas of North China. Elm open canopy woodlands represent a natural vegetation transition from forests in eastern China with high precipitation, to low-rainfall grasslands in the west. Thus, it is a reasonable choice to restore degraded land in Otindag and Korqin, where annual precipitation averages 300 to 400 mm, to open canopy woodland using sparse elm forests. While natural restoration is often the best way to ensure that adapted species repopulate the area, its performance can be limited on moderately degraded sites.

The intrinsic spatial patterns of vegetation in semi-arid and arid areas were not considered in past afforestation practices. In fact, patching and striping are common features of vegetation patterns in many semi-arid regions, including parts of Africa, Australia, and Asia (Klausmeier, 1999). A new quasi-natural method of vegetation restoration in semi-arid, arid, and hyper-arid areas which is aimed at establishing shelterbelts with low vegetation coverage (quasi-natural restoration) has been proven to be effective for improving windbreak and sand fixation in Northern China (Yang *et al.*, 2015). The new method proposes a comprehensive shelterbelt system that mixes trees, shrubs, and grass. This method is more appropriate for dryland ecosystems where trees cover 15~25% of the area, and the remaining 75~85% is comprised of shrubs and grass. This new method leads to vegetation restoration at a faster pace than natural restoration.

3.5 Vegetation restoration strategy

Afforestation is a reasonable vegetation restoration strategy in deforested landscapes, but it can be catastrophic when implemented in formerly treeless regions in arid and semi-arid areas with a mean annual precipitation of less than 400 mm (Bond, 2016; Veldman *et al.*, 2015). The silvicultural experience of the TNSP implies tradeoffs between vegetation carrying capacity and the extent and type of the afforestation project (Chen *et al.*, 2015; Feng *et al.*, 2016). In the early stages of China's national afforestation effort, afforestation projects were mainly focused on increasing vegetation coverage as quickly as possible in order to decrease wind erosion. The high-density afforestation method used in the TNSP consumed large amounts of available soil moisture. Furthermore, it led to more water scarcity as trees matured and their water needs increased. Consequently, 'diebacks' occurred in a number of locations and gradually extended to other afforested areas (Wang *et al.*, 2010; Zhang *et al.*, 2012). For example, *Pinus sylvestris* var. *Mongolica* plantations as a shelterbelt, which were introduced into Korqin's sandy land located in the eastern part of the TNSP region in the 1950s, proceeded to decline and die by the 1990s due to soil moisture scarcity (Zheng *et al.*, 2012). The mean annual precipitation in most regions implementing the TNSP is lower than 400 mm. The high-density plantations can severely compromise local ecosystems, especially the water balance. Therefore, there is an urgent need to recognize that large-scale, high-density afforestation should not be implemented in semi-arid and arid areas where annual mean precipitation is below 400 mm.

Different vegetation restoration strategies should be adopted in different climatic region. Three different modes of vegetation restoration for afforested shelterbelt in semi-arid, arid and hyper-arid area in North China are proposed, with an emphasis on the use of local plant species (Fig.5): it is suggested that tree canopy density should be kept at 0.15, shrub fraction cover kept at 25%, and mixed tree and shrub forest fraction kept at 25% in semi-arid areas. Tree canopy density should be kept at 0.1, shrub fraction cover at 20%, and mixed tree and shrub forest fraction at 15% in arid areas, and tree canopy density at 0.1, shrub fraction cover at 15%, and mixed tree and shrub forest fraction at 10% in hyper-arid areas (Yang et al., 2015). More importantly, no attempt should be made to implement planting programs in naturally treeless areas.

4 Conclusions

The last 60 years of afforestation history in China have provided many examples of successes and failures, allowing the community to better understand where should be afforested and what the best afforestation strategy is for each of them. There is no unique afforestation method that will work for all types of degraded lands. The right afforestation technique should therefore be selected by taking into account the local climate and environment. In the past several decades, Chinese practices have contributed to progress towards ecological restoration in Northern China(Chen *et al.*, 2019; Zhu *et al.*, 2019), and the experience gained there will be beneficial to help other countries facing similar threats of desertification.

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Notes

The authors declare no competing financial interest.

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Table 1: Vegetation restoration effects in three different climate types

Region	Western	Central	Eastern
Climate type	Arid and hyper-arid	Semi-arid and arid	Dry sub-humid and semi-arid
Vegetation increase	High	Highest	Higher
Multiyear average precipitation	100-400 mm y^{-1}	200-600 mm y^{-1}	400-900 mm y^{-1}
Ecological projects *	TNSP	TNSP + GGP	TNSP + BTSSCP

*TNSP: Three-North Shelterbelt Project (TNSP, 1979 – present), GGP: Grain to Green Project (GGP, 1999–present), and Beijing and Tianjin Sandstorm Source Control Project (BTSSCP, 2001–present).

Figure legends

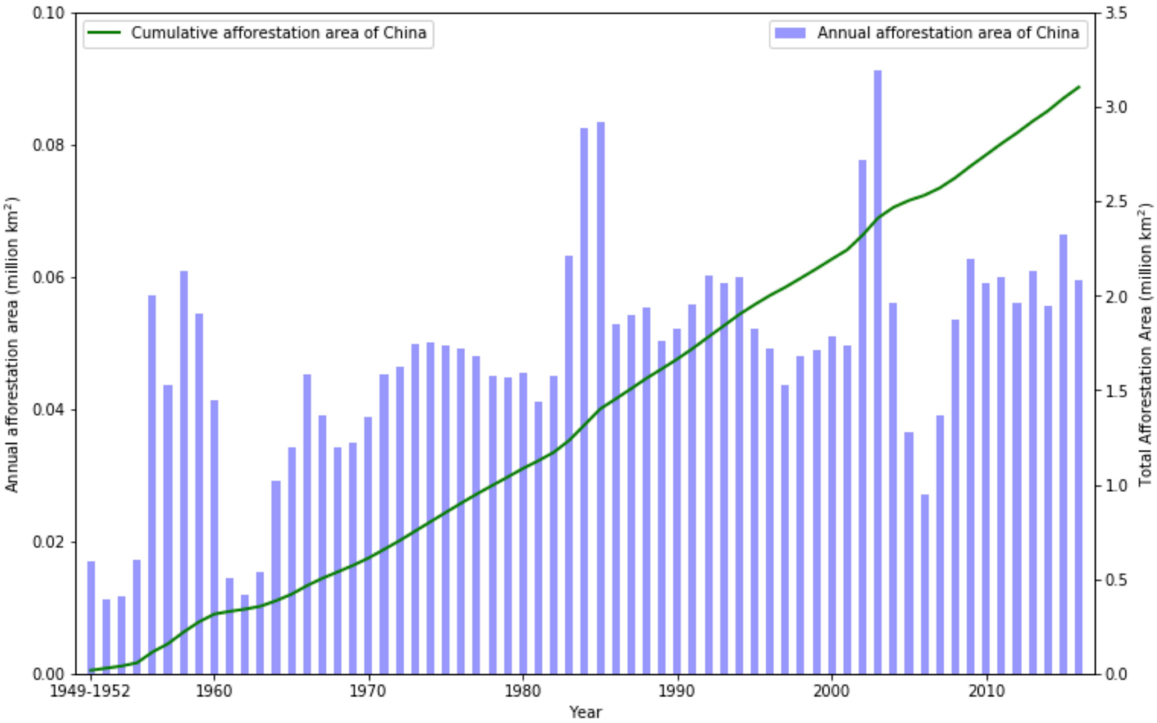
Figure 1 The total and annual afforested areas in China (1949-2013). *Data source:* China Forestry Statistical Yearbook 2017

Figure 2 Location of the "Three North Shelterbelt Program" area and climatic zones in China

Figure 3 Mean annual precipitation and trend of annual precipitation in the region of TNSP located in North China: **a)** Mean annual precipitation. **b)** The trend of annual precipitation from the Global Meteorological Forcing Dataset between 1981 and 2010 estimated as the slope of the linear regression of the time series of the annual precipitation data at each pixel. The precipitation data comes from a reanalysis dataset provided by the Terrestrial Hydrology Research group at Princeton University (http://hydrology.princeton.edu/data.pgf.php)

Figure 4 Change in vegetation cover in the region of TNSP located in North China: vegetation cover increased while annual precipitation decreased in northeastern China (the right green rectangle). **a)** Vegetation cover fraction estimated from the AVHRR NDVI3g satellite dataset in 1981, **b)** Vegetation cover fraction estimated from the AVHRR NDVI3g satellite dataset in 2013. **c)** Change of annual maximum vegetation cover fraction between 1981-2013 estimated as the product of overall time span (33 years) and the slope of the trend of the maximum annual vegetation cover fraction, based on the linear regression analysis. The satellite data used here is available from NASA at https://nex.nasa.gov/nex/projects/1349/wiki/general_data_description_and_access/

Figure 5 Different methods of vegetation restoration adapted to the different climate types in Northern China: (a) *Populus tremula* in the Korqin sandy land (semi-arid); (b) *Artemisia ordosica* in the Mu Us sandy land (arid); (c) *Haloxylon ammodendron* in the Badain Jaran Desert (hyper-arid)



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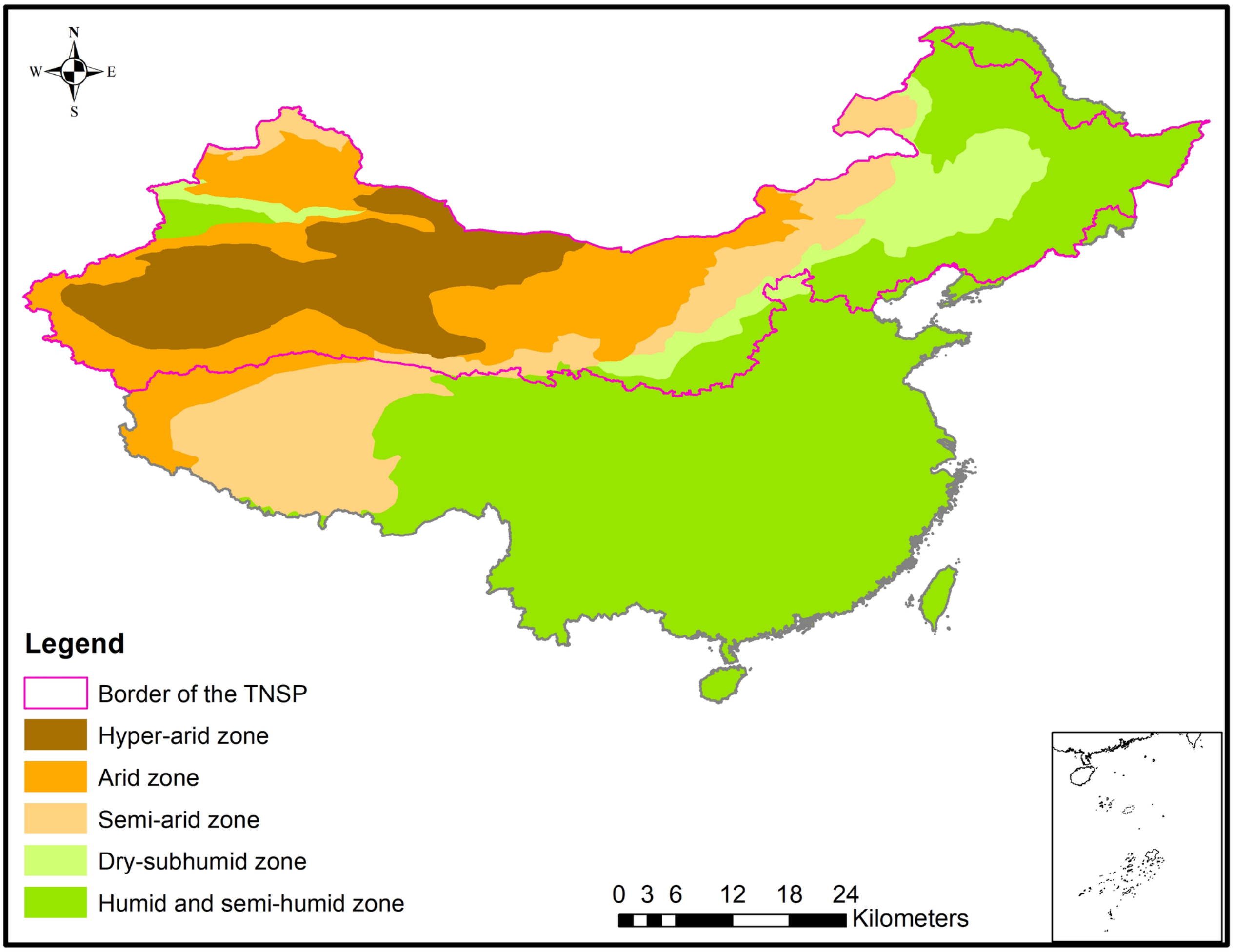

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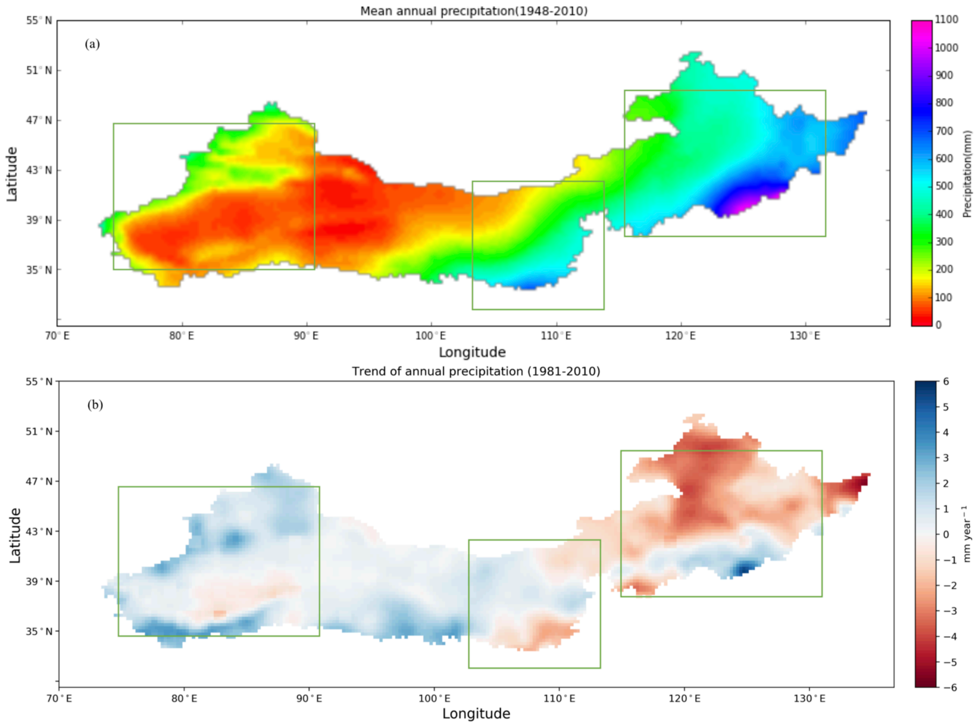

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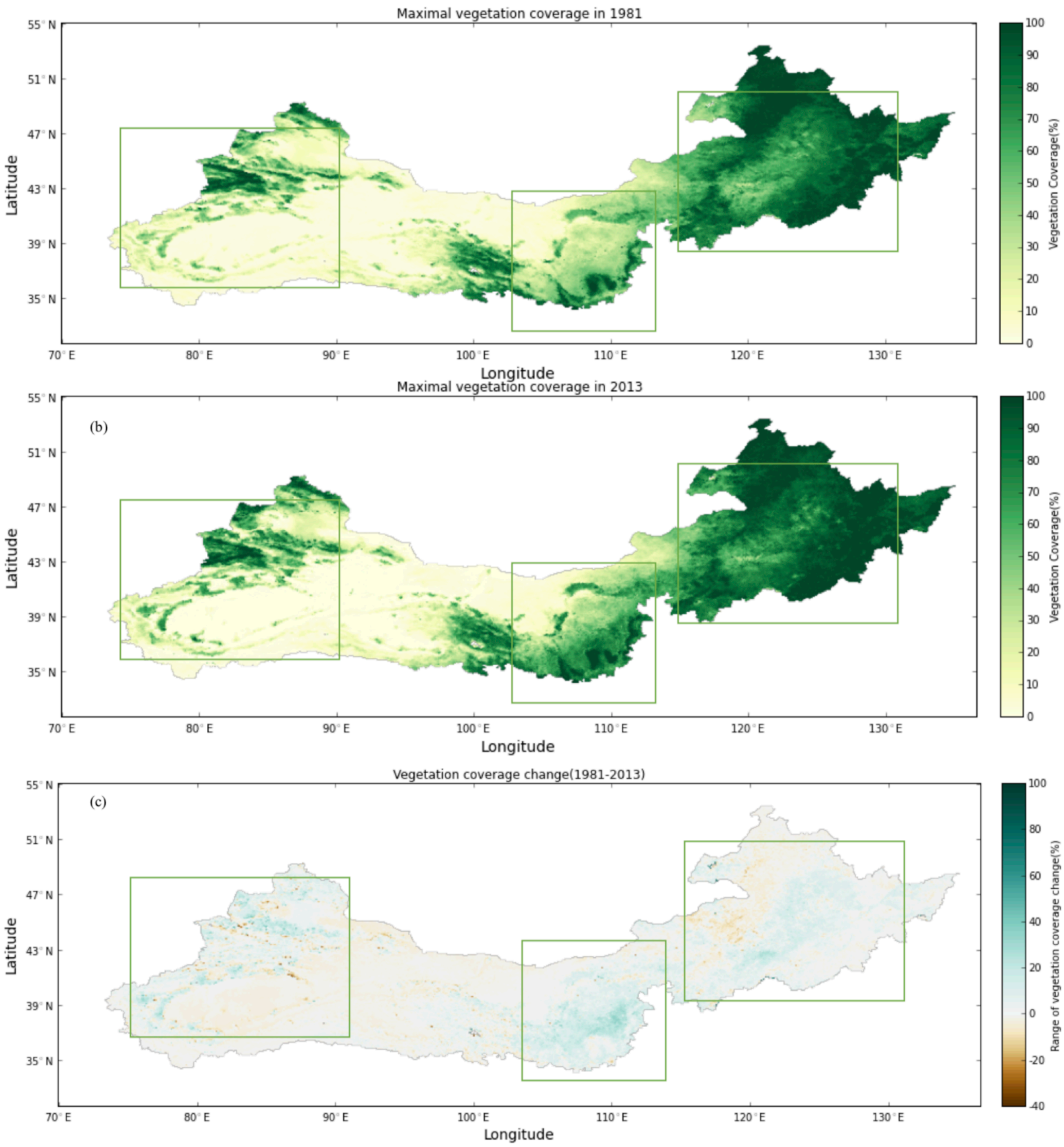

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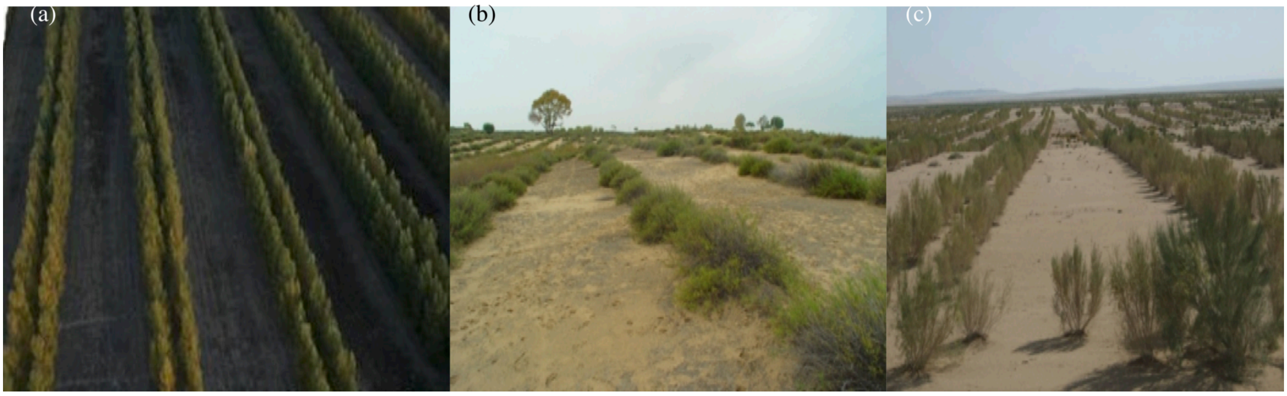

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