

Development of quantitative methods for detecting climate contributions to boundary shifts in farming-pastoral ecotone of northern China

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Abstract: The quantitative effect of climate change on fragile regions has been a hot topic in the field of responses to climate change. Previous studies have qualitatively documented the impacts of climate change on boundary shifts in the farming-pastoral ecotone (FPE); however, the quantitative methods for detecting climate contributions remain relatively limited. Based on long-term data of meteorological stations and interpretations of land use since 1970, climate and land use boundaries of the 1970s, 1980s, 1990s and 2000s were delineated. To detect climate contributions to the FPE boundary shifts, we developed two quantitative methods to explore the spatial-temporal pattern of climate and land use boundary at the east-west (or south-north) (FishNet method) and transect directions (Digital Shoreline Analysis System, DSAS method). The results indicated that significant differences were exhibited in climate boundaries, land use boundaries, as well as climate contributions in different regions during different periods. The northwest FPE had smaller variations, while the northeast FPE had greater shifts. In the northwest part of the southeast fringe of the Greater Hinggan Mountains and the Inner Mongolian Plateau, the shifts of climate boundaries were significantly related to the land use boundaries. The climate contributions at an east-west direction ranged from 10.7% to 44.4%, and those at a south-north direction varied from 4.7% to 55.9%. The majority of the results from the DSAS were consistent with those from the FishNet. The DSAS method is more accurate and suitable for precise detection at a small scale, whereas the FishNet method is simple to conduct statistical analysis rapidly and directly at a large scale. Our research will be helpful to adapt to climate change, to develop the productive potential, as well as to protect the environment of the FPE in northern China.

Keywords: farming-pastoral ecotone (FPE) in northern China; climate change; land use; contribution; quantitative detection

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1 Introduction

The farming-pastoral ecotone (FPE), which is a transitional region between agricultural cultivation and pasture (Zhao and Li, 2009), is particularly susceptible to climate change and anthropogenic disturbances (Liu and Gao, 2008a). In this region, cropland and grassland are changed frequently over different spatial and temporal scales (Zhao *et al.*, 2002). In China, the FPE are mainly located in the South, Southwest and Northwest regions. As the most extensive spatial extent with fragile environment, the FPE in northern China has attracted the scholars who are interested in climate change and land use change, focusing on boundary fluctuation of the FPE.

From the delineation of the FPE boundary, various qualitative studies indicated that the climate and land use boundaries shifted at opposite directions (Liu and Gao, 2008b; Li and Pan, 2012). Some researchers also found that climate, policy and reclamation together dominated the processes of land use and land cover change, causing the fluctuations of boundaries (Ye and Fang, 2012), especially in Northeast China. A growing number of researchers have quantitatively investigated the influences of climate change and human activities on land use patterns (Shi and Shi, 2015). Models, like the Conversion of Land Use and its Effects Model (CLUE) (Gao and Yi, 2012) and Environment for Geoprocessing Objects Model (Dinamica EGO) (Deng and Zhan, 2004), are often combined with economic models to identify the contributions of natural and anthropogenic impacts on land use change and to project the future pattern in the FPE in northern China (Yang *et al.*, 2014). However, some problems including parameter acquisition, sophisticated operation, and inconsistent validation restricted the application of model analysis. Mathematical statistics such as logistic regression (Gao and Yi, 2012) and pearson correlation (Su *et al.*, 2015) can focus on the impacts of a specific climatic factor on land use change in the FPE in northern China. Previous studies focused on the impact analysis at point (Liu and Gao, 2008b; Gao and Liu, 2006) or polygon scales (Ye and Fang, 2013; Shi *et al.*, 2014). However, the methods for detecting quantitative contributions of climate change on boundary shift of the FPE in northern China are still unclear, particularly on line analysis of the boundary (Liu and Gao, 2008a; Liu and Gao, 2008b). Moreover, most of the previous analysis considered the study area as a whole region, which ignored the spatial heterogeneity in the contributions of climate change to the boundary shifts.

Based on the delineation of climate and land use boundaries of the FPE in northern China, we presented two methods to quantitatively measure the contributions of climate change to the boundary fluctuation at 1 km resolution across different periods and eco-regions, which can detect the impacts of climate change on the boundary fluctuation at the east-west and south-north directions as well as transect directions, respectively. In addition, we also conducted comparisons between the two methods, as well as the analysis of their advantages and limitations.

2 Data and methods

2.1 Study area

The FPE in northern China, including the southeast fringe of the Greater Hinggan Mountains, the southern fringe of the Inner Mongolian Plateau, and the northern Loess Plateau, as well as a part of the Hexi Corridor, lies between 102°40'E–126°14'E and 34°16'N–48°57'N. It

covers an area of about $61.4\times10^4\text{ km}^2$, and is located in ten provincial regions including Inner Mongolia, Ningxia, Heilongjiang, Jilin, Liaoning, Hebei, Beijing, Shanxi, Shaanxi and Gansu. In the study area, the annual mean temperature ranges from 0 to 10°C, and the mean annual precipitation is between 300 mm and 500 mm. The elevations in most of the study area are over 1000 m. The cropland, grassland and forest are demonstrated staggered distribution. The major land use type is grassland in the northwest FPE, while cropland is predominant in the southeast FPE. The vegetation is typical dry steppe, varying from forest-steppe to steppe and desert steppe. Moreover, due to the rapid increase of economy and population in the southeast FPE during the past 40 years, extensive lands were reclaimed. Consequently, the boundaries were significantly disturbed by human activities in this region. Because different natural and human factors dominated in different regions of the FPE in northern China, four eco-regions are divided to obtain specific results of the climate contributions to the FPE boundary shifts. Based on the division of Huang *et al.* (2010), we buffered the eco-regions as far as totally covering the whole FPE. The four eco-regions in the study area were created, including the restricted cultivation and water conservation region in the southeast fringe of the Greater Hinggan Mountains (region 1), the agricultural-forestry-pastoral production region in the southeast fringe of the Inner Mongolian Plateau (region 2), the farming-pastoral and soil-water conservation region in northern Loess Plateau (region 3), and the arid desert-oasis cultivation region in the Hexi Corridor (region 4) (Figure 1 and Table 1). Then, the 400 mm isotype was further used to divide the four eco-regions into the northwest (NW) and southeast (SE) parts (Figure 1 and Table 1).

Table 1 Ecological function regions in the FPE of northern China

Regions	Ecological function regions	Primary ecological functions
Northwest part of region 1 (NW-1)	The restricted cultivation and water conservation region in the southeast fringe of the Greater Hinggan Mountains	Agricultural-pastoral production, forestry-fruit production, and ecological tourism
Southeast part of region 1 (SE-1)		
Northwest part of region 2 (NW-2)	The agricultural-forestry-pastoral and ecological production region in the southeast fringe of the Inner Mongolian Plateau	Agricultural-pastoral production, and desertification mitigation
Southeast part of region 2 (SE-2)		
Northwest part of region 3 (NW-3)	The farming-pastoral and soil-water conservation region in northern Loess Plateau	Soil-water conservation, and agricultural-forestry production
Southeast part of region 3 (SE-3)		
Northwest part of region 4 (NW-4)	The arid desert-oasis cultivation region in the Hexi Corridor	Desertification mitigation, and agricultural production
Southeast part of region 4 (SE-4)		

2.2 Data

2.2.1 Climate data

The daily temperature and precipitation data (1970–2010) were from 197 national meteorological stations. ANUSPLIN was employed to obtain raster datasets of climate variables at a 1 km resolution. The daily temperature dataset was represented by the homogenized daily temperature series for China with the Multiple Analysis of Series for Homogenization (MASH), which can remove systematic bias from time and instruments of observation (Li and Yan, 2009).

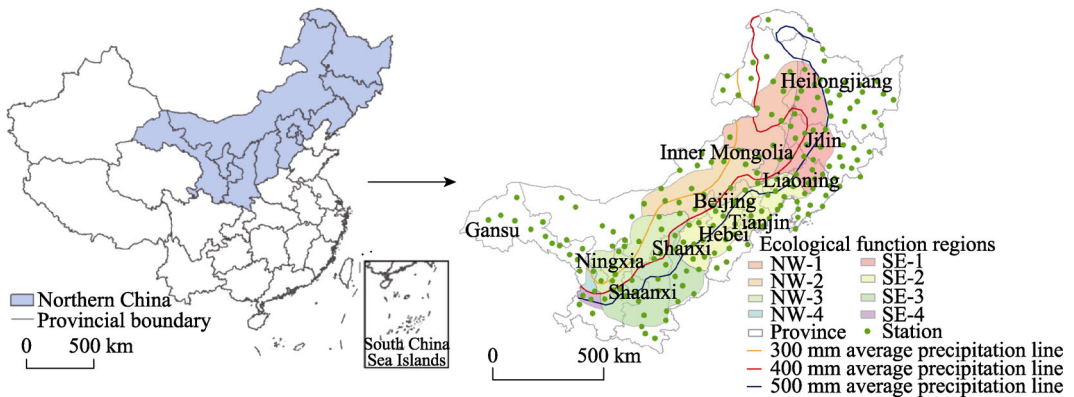


Figure 1 The distributions of ecological function regions and isohyets in the FPE of northern China

2.2.2 Land use data

We obtained the time-series dataset of 1 km² area percentage land use data (1970s, 1980s, 1990s and 2000s) from the National Land Cover Dataset (NLCD) (Liu *et al.*, 2003; Liu *et al.*, 2005a; Liu *et al.*, 2010) to investigate the dramatic changes during the past 40 years, which were based on the interpretation of Landsat TM/ETM/MSS, CBERS-1 and CBERS-2. The land use category included cropland, grassland, forest, water body, built-up land and unused land in the NLCD (Liu *et al.*, 2005b; Zhang *et al.*, 2012).

2.3 Method

2.3.1 Delineation of boundaries based on climate and land use data

Recent works have presented various indices to define the spatial extent of the FPE in northern China. There are two types of indices usually used to delineate the FPE boundary, including climate index and land use index.

For the definition of climate boundary, Zhu *et al.* (1984) considered that the mean annual precipitation in the FPE varies between 300 and 500 mm. Based on the location of the south fringe of the Inner Mongolian Plateau and the Great Wall, Zhao *et al.* (2002) selected the mean annual precipitation between 300 and 450 mm, the precipitation variability between 15% and 30%, and the aridity index between 1 and 2 to delineate the spatial extent of the FPE. Similarly, Liu and Gao (2008b) modified the scope from Zhao *et al.* (2002) with the precipitation variability (between 15% and 30%) and acidity index (between 0.2 and 0.5). Furthermore, they set the 400 mm isotype as the central line, and used the 300 mm and 450 mm isotypes to modify the northwest and southeast boundaries, respectively. Based on the previous research, we defined the climate boundary as follows: (i) the precipitation variability varies from 15% to 30% (Liu and Gao, 2008b); (ii) the acidity index varies from 0.2 to 0.5 (Liu and Gao, 2008b); (iii) the 400 mm, 300 mm and 500 mm isotypes are set as the central line, northwest boundary and southeast boundary, respectively. The isotypes with an interval of 50 mm from 300 mm to 500 mm were used to connect the northwest and southeast boundaries to complete closed boundaries. For a given part of the boundary during different periods, the same isotypes were used to make fair comparison.

For the definition of land use, Ye and Fang (2012) considered that the area-percentage of cropland should be higher than 15% in the FPE. Wang and Shi (1988) chose the area-

percentage of cropland (between 15% and 35%) and grassland (between 35% and 75%) to define the FPE of Inner Mongolia. Actually, the cropland proportion for the whole FPE should be higher than those in Inner Mongolia. Wu and Guo (1994) presented that the proportion for cropland, grassland and forest should be 1:0.5:1.5 in the FPE. Therefore, we defined land use boundary as follows: (i) both the area-percentages of cropland and grassland should be greater than 15% in each 1 km×1 km grid; and (ii) the spatial extent should be contiguous distribution and also be contained in the four eco-regions.

2.3.2 Detection of the boundary shifts at the east-west and south-north directions

This method could distinguish the boundary shift at the east-west and south-north directions with the FishNet operation in ArcGIS. The 1 km×1 km fishnet was created to entirely cover the largest scope of the FPE over the four periods, the shift distances and directions for both of the climate and land use boundaries on each fishnet line were computed at two directions in each period. When a fishnet line crossed the boundaries during former period and latter period from east to west (or from south to north), the direction was coded as 1. The direction was set as -1 if it crossed boundaries from the opposite directions. The direction was coded as 0 for the boundaries of the same period crossed by a fishnet line. The distance signed with direction could be computed by the equation (1),

$$D_{fp-lp} = L_{fp-lp} \times \text{Direction} \quad (1)$$

where fp is the former period, lp is the latter one; L_{fp-lp} represents the length of fishnet line; Direction represents the shift direction of boundaries; D_{fp-lp} represents the distance with direction sign. The L_{fp-lp} was used to compute the maximum, minimum, median, as well as the mean of the shift distance for climate and land use boundaries, and the D_{fp-lp} was used to examine the shift ranges and correlations between climate and land use boundaries.

2.3.3 Detection of the boundary shifts at the transect direction

A baseline was created according to the buffer of the innermost boundary, and then transects were casted perpendicularly to the baseline with an interval of 1 km and intersected the boundaries during different periods using the Digital Shoreline Analysis System (DSAS method) (Wang *et al.*, 2014; Jayson *et al.*, 2013). The distance (D_p) from the baseline to the intersect point of each boundary was computed. The shift distance and direction of climate and land use boundaries could be computed according to the equation (2),

$$D_{fp-lp} = D_{lp} - D_{fp} \quad (2)$$

where D_{fp} represents the distance between the boundary in the former period and the baseline, D_{lp} represents the distance between the latter boundary and the baseline, D_{fp-lp} represents the distance between the former and latter boundaries marked with direction. The absolute values of D_{fp-lp} can be used to compute the maximum, minimum, median, as well as the mean of the shift distance for climate and land use boundaries. The D_{fp-lp} was subsequently used to examine the shift ranges and correlations between climate and land use boundaries.

2.3.4 Calculation of the climate contributions to boundary shifts

The shift distances (D_{fp-lp}) of the climate and land use boundaries at the east-west, south-north and transect directions in each eco-region were calculated using both methods of the FishNet and DSAS. The correlation coefficient (r^2) and significance (p) were calculated according to the shift distances of the climate and land use boundaries. To explore how

much of land use boundary shifts can be explained by climate change, we selected the datasets with significantly positive correlations ($p < 0.05$, $r > 0$) between climate and land use boundaries shifts, and selected the coefficient (r^2) to demonstrate the contributions of climate change to the FPE boundary shifts.

3 Results and discussion

We used the FishNet and DSAS methods to detect the spatial-temporal pattern changes of the FPE boundaries based on the data of climate and land use. Quantitative detection of the climate contributions to the FPE boundary shifts was then conducted using these two methods.

3.1 Spatial-temporal pattern changes of the FPE boundaries detected by the FishNet method

3.1.1 Climate boundary

The greatest change of climate boundary shifted eastward in SE-2 region from the 1990s to the 2000s with 278.54 km at the east-west direction (Figures 2a, 2c and 2e). Extensive shifts existed in region 1, NW-2 and SE-3 regions. For example, during the 1990s–2000s, the FPE boundaries in NW-1 and NW-2 regions significantly moved eastward with the median shift distances of 91.88 km and 78.76 km, while it moved westward with 72.02 km in the SE-3 region. In contrast, the FPE boundaries in region 4 varied more slightly with the median distances less than 10 km.

The largest change of climate boundary shifted southward with 271.25 km at the south-north direction in NW-1 region from the 1970s to the 1980s (Figures 2b, 2d and 2f). The climate boundaries in the southeast (SE) part experienced greater shifts than those in the northwest (NW) part. More extensive changes of the FPE boundaries can be detected in region 1, SE-2 and SE-3 regions, while the boundaries in NW-4 region continuously moved northward with slight changes. As an increase of precipitation in Northeast China during the 1980s, the FPE boundaries in region 1, NW-3 and SE-2 regions shifted southward during the 1970s–1980s. The median shift distances of the NW and the SE parts in region 1 were 97.28 km and 84.93 km, respectively. After that period, the climate boundaries gradually moved northward with a decrease of precipitation.

3.1.2 Land use boundary

The land use boundary shifted eastward with 140.39 km at the east-west direction in SE-2 region during the 1970s–1980s, which was the most extensive shift in the whole FPE area during the study periods (Figures 2a, 2c and 2e). Similarly, extensive shifts of the land use boundaries were found in region 1 and region 2. During the 1980s–1990s, the boundary in NW-1 region mainly experienced westward moving with a median distance of 32.34 km, while boundaries moved slightly in region 4, with the median distances lower than 7 km. However, for the whole FPE boundaries, there were no significant differences between the SE and NW parts due to the boundary fluctuations.

At the south-north direction, the largest change of land use boundary shifting northward with 149.82 km was observed in NW-2 region during the 1970s–1980s (Figures 2b, 2d and 2f). Boundaries shifts in region 1 were more extensive than those in the others. A significant northward moving was detected in SE-1 region during the 1990s–2000s, with a median dis-

tance of 46.07 km. The boundaries in regions 2, 3 and 4 experienced minor shifts, of which median distances were lower than 10 km with the exception of those in NW-4 region with 10.82 km during the 1980s–1990s.

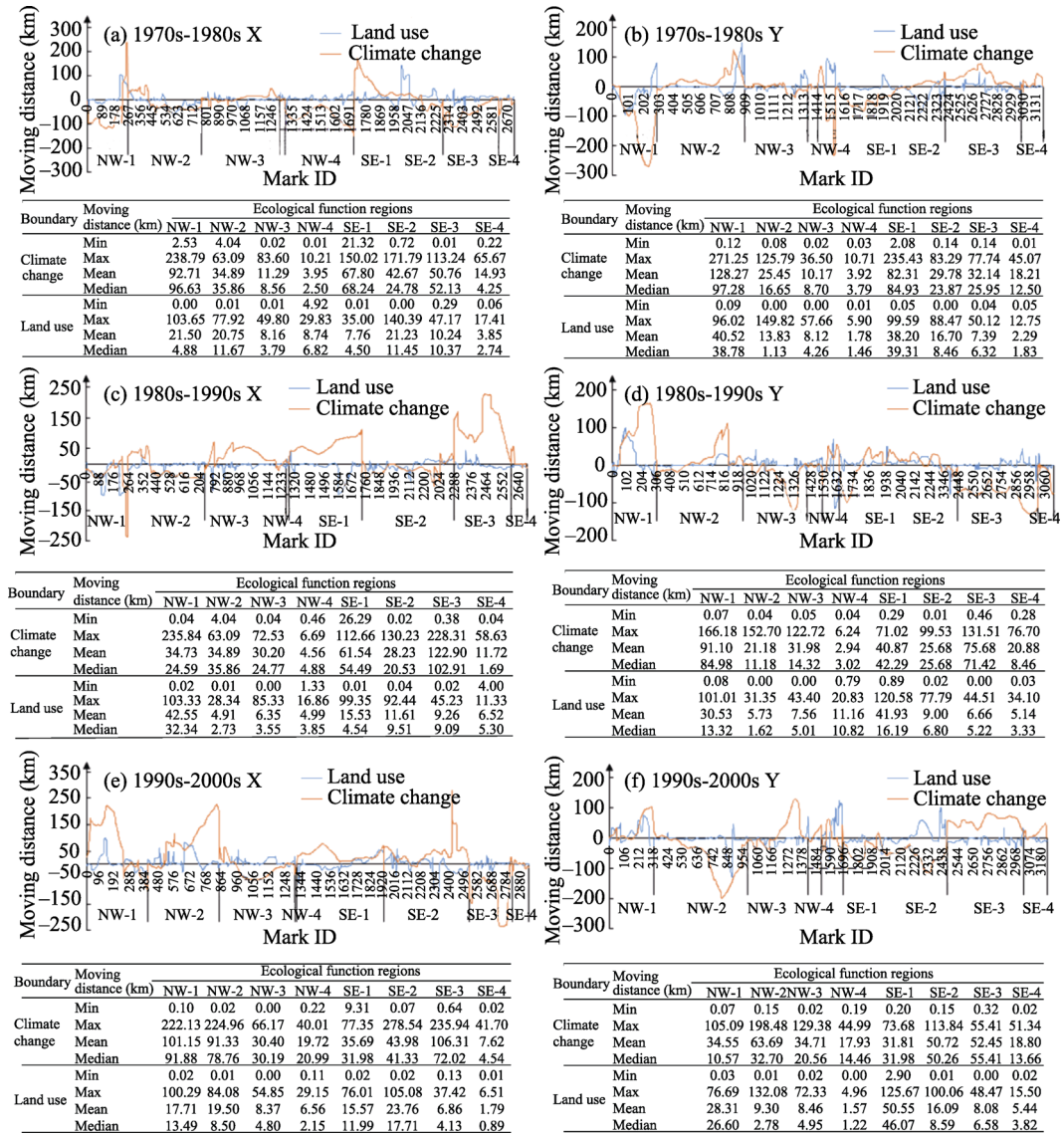


Figure 2 Changes of climate and land use boundaries detected by the FishNet method

3.2 Spatial-temporal pattern changes of the FPE boundaries detected by the DSAS method

3.2.1 Climate boundary

The climate boundaries experienced more extensive shifts than land use boundaries. The largest change of climate boundary was observed in SE-1 region during the 1970s–1980s, which shifted southward with 299.09 km (Figures 3a, 3c and 3e). Similarly, we found considerable shifts in regions 1 and 2 detected by the FishNet. The most extensive shift was

detected during the 1970s–1980s in SE-1 region, which shifted westward with the median shift distance of 103.75 km. On the contrary, boundaries in region 4 experienced slight fluctuations, most of medians of shift distances were lower than 5 km, except for those in the NW-4 region during the 1990s–2000s (16.71 km). For boundary fluctuations of the whole FPE, the greater changes were observed in the SE part than those in the NW part.

3.2.2 Land use boundary

The largest change of land use boundary was observed with a shift of 217.79 km moving northeastward in SE-1 region from the 1990s to the 2000s (Figures 3b, 3d and 3f). The highest median was found in NW-1 region, which was 28.89 km shifted northwestward during the 1980s–1990s. Similar to the results from the FishNet, there were no significant shifts in regions 2, 3 and 4. The medians of shift distances in region 4 were lower than 10 km except for that in the NW-4 region during the 1980s–1990s (12.39 km).

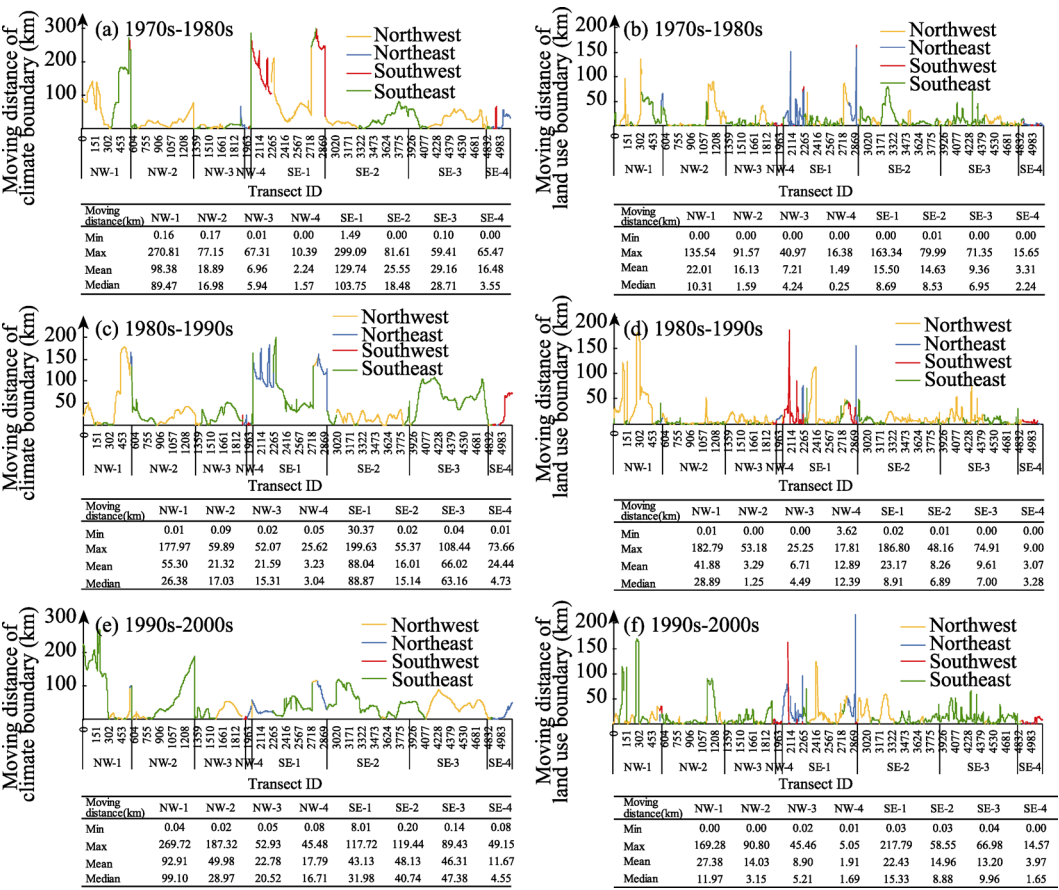


Figure 3 Changes of climate and land use boundaries detected by the DSAS method

3.3 Quantitative detection of the climate contributions to the FPE boundary shifts using the FishNet method

The climate contributions to the FPE boundary shifts significantly varied among regions and periods detected by the FishNet method (Table 2).

Table 2 The quantitative detection of climate change effects on the boundary fluctuation in the FPE of northern China

Regions	Periods	X direction		Y direction		Transect direction	
		Sample numbers	r^2	Sample numbers	r^2	Sample numbers	r^2
NW-1	1970s–1980s	261	0.444	—	—	580	0.027
	1980s–1990s	255	0.107	—	—	—	—
	1990s–2000s	411	0.202	331	0.047	580	0.011
NW-2	1970s–1980s	473	0.209	655	0.088	755	0.168
	1980s–1990s	—	—	726	0.559	—	—
	1990s–2000s	—	—	697	0.104	755	0.043
NW-3	1970s–1980s	—	—	—	—	—	—
	1980s–1990s	—	—	457	0.082	612	0.043
	1990s–2000s	—	—	—	—	—	—
NW-4	1970s–1980s	—	—	77	0.052	73	0.153
	1980s–1990s	—	—	—	—	—	—
	1990s–2000s	—	—	—	—	—	—
SE-1	1970s–1980s	—	—	—	—	—	—
	1980s–1990s	—	—	—	—	—	—
	1990s–2000s	—	—	—	—	891	0.015
SE-2	1970s–1980s	—	—	—	—	—	—
	1980s–1990s	567	0.040	—	—	985	0.032
	1990s–2000s	—	—	—	—	—	—
SE-3	1970s–1980s	357	0.201	568	0.227	932	0.099
	1980s–1990s	—	—	—	—	—	—
	1990s–2000s	—	—	—	—	932	0.019
SE-4	1970s–1980s	—	—	—	—	—	—
	1980s–1990s	—	—	—	—	—	—
	1990s–2000s	—	—	—	—	—	—

In different eco-regions of the FPE, climate had pronounced impacts on the FPE boundary fluctuations in NW-1 region, with the contributions from 10.7% to 44.4% at the east-west direction, while the climate contribution at the south-north direction was only 4.7% during the 1990s–2000s. In region 2, climate change significantly influenced boundary fluctuations in the NW part with climate contributions from 8.8% to 55.9% at the south-north direction in the three periods. However, the boundary during the 1970s–1980s was only largely driven by climate change with a contribution of 20.9% at the east-west direction. In addition, climate change hardly impacted the boundaries in the SE part; only 4.0% of the climate contribution was detected at the east-west direction during the 1980s–1990s. In region 3, the climate contribution was 8.2% at the south-north direction during the 1980s–1990s in the NW part. On the contrary, remarkable climate impacts with contributions of 20.1% and 22.7% were observed in both directions during the 1970s–1980s. The climate contributions were also very low in region 4, in which climate change only significantly drove the boundary shift with a contribution of 5.2% in the NW part at the south-north direction during the 1970s–1980s.

During different periods, climate change had different contributions to the FPE boundary shifts. The climate contributions in NW-1, NW-2 and SE-3 regions varied from 20.1% to 44.4% at the east-west direction in the 1970s–1980s. Meanwhile, the contributions of cli-

mate change in NW-2, NW-4 and SE-3 regions varied from 5.2% to 22.7% at the south-north direction. During the 1980s–1990s, the contributions of climate change in NW-1 and SE-2 regions were between 4.0% and 10.7% at the east-west direction, while the contributions of climate change in NW-2 and NW-3 regions ranged from 8.2% to 55.9% at the south-north direction. During the 1990s–2000s, climate significantly influenced the NW-1 and NW-2 regions. The contribution of climate change in NW-1 region got up to 20.2% at the east-west direction during this period, and the contributions in NW-1 and NW-2 regions at the south-north direction were 4.7% and 10.4%, respectively.

Detected by the FishNet method, the greatest climate contribution was 44.4% in NW-1 region at the east-west direction during the 1970s–1980s. In addition, it was 55.9% at the south-north direction in NW-2 region during the 1980s–1990s. Higher contributions of climate change were concentrated in NW-1 and NW-2 regions, which were between 10.7% and 44.4% at the east-west direction and ranging from 4.7% to 55.9% at the south-north direction. The results indicated that the FPE boundary changes were largely driven by climate in Northeast China.

3.4 Quantitative detection of the climate contributions to the FPE boundary shifts using the DSAS method

The climate contributions in different regions and periods detected by the DSAS method were similar to those detected by the FishNet method (Table 2).

The FPE boundaries in regions 1 and 2 were considerably shaped by climate change. The contributions during the 1970s–1980s and 1990s–2000s in NW-1 region were 2.7% and 1.1%, respectively. Furthermore, the climate contribution during the 1990s–2000s in SE-1 region was 1.5%. For NW-2 region, the climate contributions to land use boundaries were 16.8% and 4.3% during the 1970s–1980s and 1990s–2000s, respectively. It was 3.2% in SE-2 region during 1980s–1990s. Significant impacts of climate on the FPE boundaries were limited in regions 3 and 4. The contributions in SE-3 region were higher than those in NW-3 region. The contributions were 9.9% and 1.9% in SE-3 region during the 1970s–1980s and 1990s–2000s, respectively. The climate contribution in NW-3 region was 4.3% during the 1980s–1990s. However, the climate contribution in the NW-4 region was 15.3% during the 1970s–1980s.

Climate had pronounced influences on land use boundaries during the 1970s to the 1980s. The climate contributions in the NW part ranged from 2.7% to 16.8%, which were slightly higher than those in the SE part. During the 1980s–1990s, the climate contributions exhibited lower values than those in the 1970s–1980s, which varied from 3.2% to 4.3%. From the 1990s to the 2000s, land use boundaries in region 1, NW-2 and SE-3 regions were all influenced by climate, in which the climate contributions were between 1.1% and 4.3%.

Using the DSAS method, the largest contribution with 16.8% was observed in NW-2 region during the 1970s–1980s. Higher contributions existed in NW-1, NW-2, NW-4 and SE-3 regions during the 1970s–1980s.

3.5 Discussion

3.5.1 Compared with the results from previous research

Several studies showed that climate warming had caused cropland expansion in Northeast China since the 1980s (Ye *et al.*, 2012; Liu *et al.*, 2009; Wang *et al.*, 2009), which fitted well

with the obvious climate contributions in NW-1 and NW-2 regions in our study. Liu *et al.* (2011) found that the FPE boundary in the SE part of Northeast China was influenced by human activities from 1986 to 2000, and cropland in this region showed a predominant expansion to the west, which was in accordance with the results of insignificant climate impacts on the FPE shifts in SE-1 region during the former two periods. This conclusion was similar to the results in SE-1 region in our study. Furthermore, the implement of the Green for Grain Project and Grazing Prohibition policy affected the boundary shifts in the northwest FPE since 1999, which was in accordance with the insignificant impacts of climate on the FPE boundaries in NW-3 and NW-4 regions during the 1990s–2000s (Lu *et al.*, 2013). Zuo *et al.* (2014) showed that the land use in western China has been dominated by human activities and policies since the 1980s. This result was also consistent with the insignificant contributions of climate in region 4 since the 1980s, which was located in the northwest of China. Thus, anthropogenic disturbance was also one of the primary drivers of boundary shifts in the FPE of northern China (Yang *et al.*, 2014; Liu *et al.*, 2014).

3.5.2 Comparison of the two methods of FishNet and DSAS

Most of the spatial-temporal pattern of boundary shifts detected by the methods of FishNet and DSAS had good consistence with each other. The changes of climate boundaries were at larger extent than those of land use boundaries using both methods. The greatest shifts were detected in region 1 and the smallest shifts were shown in region 4 over the three periods. The mean values and medians of shift distances in most of regions were close to the minimum, suggesting smaller changes of boundaries in these regions. The shift directions of the boundaries based on climate and land use were similar in most of the regions. For example, the shift directions of climate boundaries in regions 2 and 3, as well as land use boundaries in SE-2 and SE-3 regions were coincident detected by the methods of FishNet and DSAS. However, some inconsistencies also existed in some regions. Compared with the FishNet method, the DSAS method is closer to the facts of the detection of directions and distances for the FPE shifts.

Using the two methods, climate contributions to the FPE boundary shifts varied among regions during the study periods, and the results detected by the FishNet and DSAS methods were approximately coincident. For example, during the 1970s–1980s, the climate contributions detected by the FishNet in NW-2 region at the east-west and south-north directions were 20.9% and 8.8%, respectively, and the contribution was 16.8% from the DSAS method. Another example was in SE-3 region during the 1970s–1980s. The contributions were 20.1% and 22.7% at the east-west and south-north directions detected by the FishNet method, whereas the result from DSAS was 9.9%. However, differences were also investigated from the two methods. For instance, during the 1980s–1990s, the climate contribution at the south-north direction was 55.9% in NW-2 region, but the correlation of the shifts based on climate and land use boundaries detected from the DSAS method was not significant in this region.

Overall, the FishNet method distinctly demonstrates the climate impacts on the FPE boundary at the east-west and south-north directions, which is simple but not as accurate as the DSAS method. Therefore, this method can be employed to directly analyze the boundary changes at large scales, if it is not necessary to achieve strict requirement of accuracy. On the contrary, the DSAS method can precisely show the climate contributions to boundary shifts at the transect direction, but it is noted that the results are easily affected by the base-

line. This method is especially suitable to detect the boundary changes at a small scale. Both of the two methods are primarily influenced by extreme values, and the uncertainties are relatively large in the junctures of eco-regions.

4 Conclusions

The FPE boundary fluctuations were not only driven by climate change, but also affected by human activities in northern China. We presented the FishNet method and DSAS method to quantitatively investigate the climate contributions to the boundary shifts at the scale of 1 km resolution. The results will be helpful for understanding the climate change impacts on fragile regions, and also for determining adaptation measures that should be adopted.

Due to the large area of the FPE in northern China and complicated natural environment of different eco-regions, the boundary shifts have great differences among regions during different periods. We detected these differences in the shifts of climate and land use boundaries using the methods of FishNet and DSAS. The greatest fluctuations were detected in region 1, whereas region 4 had the smallest shifts. Good spatial coupling relationships between the shifts of climate and land use boundaries were detected in the NW-1 and NW-2 regions. Climate contributions of these regions varied from 10.7% to 44.4% at the east-west direction, as well as from 4.7% to 55.9% at the south-north direction detected by the FishNet method. The climate contributions in these regions were between 1.1% and 16.8% detected by the DSAS method. During the study periods, relationship between the shifts of climate boundaries and land use boundaries was not significant in region 4, suggesting that climate change was not the main driving force of the FPE boundary shifts.

Therefore, the conclusions of the detection from the FishNet method and DSAS method had good consistence. The DSAS method is more accurate than the FishNet method, which is a proper one to detect precise changes at a smaller scale. However, the FishNet method is simple to operate, and is suitable to conduct statistical analysis rapidly and directly at a larger scale.

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