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Do afforestation projects increase core forests? Evidence from the Chinese Loess Plateau

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A B S T R A C T

The spatial pattern of forests impacts on biodiversity, stability and sustainability of forest ecosystems. Afforestation and reforestation projects have massively increased forested areas on the Chinese Loess Plateau, however, the spatial pattern of the new and old forests, as well as their interaction, remains unknown. Here we study the spatiotemporal dynamics of old and new forests for the period 2001–2016, and found that 84.21% of the old forests existed throughout the study period. Moreover, core forests (defined as a forest area which is surrounded by other forest areas) significantly increased (2585 km\textsuperscript{2} yr\textsuperscript{-1}, in total 39, 597 km\textsuperscript{2}). Two ecological restoration projects have left clear footprints on the forest landscape of the Loess Plateau: (1) The Natural Forest Conservation Project, aiming at expanding old forest, has resulted in the establishment of considerable areas of new forest surrounding old forest. Consequently, this has promoted new core forest areas to emerge. (2) The Grain for Green Project has mainly caused a fragmented landscape of forest islets which gradually connect to core forest areas. The general increase in core forest areas can be considered an ecological improvement, and the assessment method presented here may guide stakeholders in measuring the success of forest restoration activities that goes beyond a classical quantification of forest cover.

1. Introduction

The world’s forests are experiencing permanent change (FAO, 2016; Aleman et al., 2018; Endreny, 2018). While farmland expansion, urbanization, and increasing demand for wood products lead to continued deforestation and forest degradation, afforestation and reforestation projects are being established worldwide (Chazdon, 2008; Meyfroidt and Lambin, 2009; Tong et al., 2018). These dynamic processes of forest gains and losses often happen simultaneously or successively in the same areas and do not only affect the overall forest area but also the spatial distribution of trees and forest patches (Skole and Tucker, 1993; Wickham et al., 2008; Taubert et al., 2018). The ability of forests to provide ecosystem services is closely related to the spatial distribution of trees, since larger areas of connected and compacted patches of trees, are able to guarantee a stable ecosystem, high biodiversity and forest health (Zhang et al., 2009; Didham and Ewers, 2012). Hence, the creation and conservation of core forest areas, defined here as forests surrounded by more forested areas (Anderson et al., 2013; Abrahams et al., 2015), should be emphasized in the fields of forest management, nature conservation and preservation (Azevedo et al., 2014; Abrahams et al., 2015).

Based on the Island Biogeography theory (Macarthur et al., 1967), large forest reserves have relatively higher species richness, and are less endangered of losing species as compared with small forest reserves (Laurance, 2008). However, a large forest patch is not necessarily uniform in providing the same amount of ecosystem services, and forest edge areas bordering other landscapes are typically less resistant to external stressors (Baker et al., 2016a; Hebert-Dufresne et al., 2018). This is related to a variety of factors such as increased predation risk (Dodonov et al., 2017), modified microclimate (Baker et al., 2016b; Schmidt et al., 2017), and increased human activities (Weathers et al., 2001). Moreover, the competition between species is higher at edges as...
compared with core areas (Harper et al., 2005; Numata et al., 2017). Large and compact forests contain core areas where “edge effects” do not apply, and these core areas are the most widely used indicator to assess the general quality of the spatial pattern of a forest (Riitters and Wickham, 2012; Riitters et al., 2016).

The Loess Plateau (LP) in central North China is regarded as the cradle of the ancient Chinese civilization (Liu, 1985; Liu et al., 1996). Intensive land use over thousands of years has led to severe vegetation degradation, soil erosion and water loss (Chen et al., 2008; Zhao et al., 2013). Forests were reported to cover < 10% of the LP at the turn of the new millennium (Cai, 2002), and were mainly located in mountainous areas. These relict forest areas are of high ecological value, and 22 national and 66 provincial Wildlife and Forest Reserves are located within these forests (Fig. 1), providing shelters for numerous rare plants and animals (Li et al., 2013). Since the end of the last century, the Chinese government has launched a series of ecological restoration projects, such as the ‘Natural Forest Conservation Project’ (NFCP, since 2000) (Zhang et al., 2000) and the ‘Grain for Green Project’ (GGP, since 1999) (Delang and Yuan, 2015), aiming to improve China’s eroded landscapes (Feng et al., 2016). In the case of the LP, the natural forests (including old-growth and secondary forests) have been protected and conserved, and large-scale afforestation projects have been implemented for the entire area (Deng et al., 2014). However, the human population and urbanization rate continues to increase rapidly (Gao et al., 2015; Yang et al., 2016; Wang et al., 2018a), putting continued pressure on the forest resources. Although forested areas of the Loess Plateau increased massively during the recent 15 years (Wang et al., 2018a, Wang et al., 2018b), it remains unknown if the new forest areas are able to form new core areas in conjunction with old forests, or if this massive afforestation conceals a loss or fragmentation of pristine old forest areas. To assess temporal change in forest spatial patterns from the use of Earth observation (EO) technology, a bi-temporal approach is often applied, in which imagery from two different time steps are commonly compared (Li et al., 2009; Reddy et al., 2013; Zhang et al., 2017). However, EO time series data can improve our understanding of ongoing change processes (Schulz et al., 2017). Especially planted forests are characterized by a high temporal dynamics and do not develop continuously over time and space, since successful growth depends largely on management/survival rate. Moreover, the trajectory of the development of new core forest areas, emerging between new forests and old forests (see section 2.1 for details) cannot be fully inferred by comparing images of two time steps. Dense temporal data/information is needed to adequately capture forest dynamics and transformation that start with several new forest islets growing into larger forest patches that may be part of edges of old forests and ultimately lead to new core areas (Gergel and Turner, 2017).

The aim of this study is to assess and quantify spatial patterns of forest dynamics on the Loess Plateau following massive reforestation/afforestation projects. For a project implementation to be deemed successful, two requirements have to be fulfilled: 1. Due to their high ecological value, old forests need to be preserved. 2. New forests must expand around old forests building new core areas.

Here we apply the Morphological Spatial Pattern Analysis (MSPA) on dense EO time series and study the temporal development of forest spatial patterns on the Loess Plateau in relation to above mentioned requirements.

2. Materials and methods

2.1. How old forests and new forests build cores

The theory of the interaction between old and new forests leading to new core forest or preservation of old core areas is illustrated in Fig. 2. A variety of realizations of afforestation and reforestation can happen but only one example (Fig. 2c4) shows the optimum situation: the old forests remain stable and the new forests extend compactly around the old forests, building new core areas. The conservation of old forests has the highest priority, but only one example in Fig. 2b shows this...
situation (Fig. 2b4). However, also the location of the new forests is of high importance for establishing new core forest, and none of the examples in Fig. 2b show a situation where new forests have increased the core areas. Fig. 2c1-4 shows improved distribution of new forests around old forests for establishing new core forest, yet, only two of the examples (Fig. 2c3, 4) show a spatial distribution of new forest areas resulting in an increase in core area. These examples show that it is necessary to analyze both the continuity of old forests and its spatial relationship to new forests to identify the establishment of new core areas (Bergès et al., 2016).

2.2. Study area

The Loess Plateau (33°41′–41°16′N, 100°52′–114°33′E) is located in North China (Fig. 1), and extends approximately over 1,000 km from east to west, and 700 km long from north to south, spanning a total area approximately $6.4 \times 10^5$ km$^2$. The surface of the plateau is covered by continuous loess on hills, basins, and alluvial plains of different elevation, with the loess varying between 100 and 300 m in thickness. The loess was geologically transported from the northwestern Gobi desert by wind and has accumulated on the Loess Plateau since the beginning of the Quaternary. The region lies in the semi-humid and semi-arid transitional climate zone and has an annual average temperature of 4.3 °C in the northwestern region and 14.3 °C in the southeastern region. Rainfall is highly variable both spatially and temporally, with an annual average ranging from 200 to 800 mm, increasing from northwest to southeast, concentrating mostly during the summer months. Frequent storms, steep landforms, low vegetation coverage and highly erodible loessial soil have led the Loess Plateau to be one of the most severely eroded regions globally (Zhu, 1995; Wang et al., 2006).

2.3. Conceptual approach

Firstly, we introduce the terms of old forests (forest areas already present in 2001), new forests (not present in 2001), and core forest (a forest area surrounded by forests) in relation to our study. Since our study operates at a scale where the smallest unit size is 250 m × 250 m, an area qualifies for being classified as forest if a majority of a 0.0625 km$^2$ pixel is covered by adult trees (Wang et al., 2018b). Consequently, the smallest possible forest area with a core in our study consists of a 750 m × 750 m (0.5625 km$^2$) area. Within these 0.5625 km$^2$, 0.0625 km$^2$ (the middle pixel) can be considered as core forests (Fig. 2a), whereas the remaining areas are classified as edges. Old forests are typically relicts of old-growth or secondary forests hosting large numbers of forest or wildlife reserves (Fig. 1). We validated the assumption that forests present in 2001 can be considered as ‘old forests’ with 6000 random points selected in old forest areas that were compared with in the 1:1 million Chinese Vegetation Map, which is based on field surveys from the 1970 s to the 1980 s. We found that 92% of the points that we classified as old forests were already forests in this map (Fig. S1).

Secondly, to test for continuity of old forests and the spatial distribution of new forests in relation to core forest areas, we classified the study area in (I) continuous forest areas (CF), (II) dynamic forest areas (DF) and (III) non-forest (NF) (section 2.5). We then applied a spatial pattern analysis on CF and DF to classify the forest areas in core forests and edges (and other types) at annual scale (section 2.6). Furthermore, assuming that new forests impact on the general pattern of forest areas (also creating new core areas by extending CF), we assessed temporal changes in core forest areas both for CF and DF (section 2.6). Finally, we compared the areas of core forests of the beginning year 2001 and the last year 2016 to obtain the area and spatial pattern change of core forests.
2.4. Annual forest/non-forest data and forest definition

We applied a recently produced forest/non-forest data set that is available at an annual basis for the entire Loess Plateau for the period 2001–2016 (Wang et al., 2018b). The data set is based on MODIS satellite data at a 250 m spatial resolution and uses a field data trained Random Forest classifier resulting in a high accuracy (96%) forest/non-forest classification map. For the forest field plot used to train the model, the average height of trees was 9 ± 3 m, and the average canopy density was 66 ± 18% (Wang et al., 2018b).

2.5. Classifying forest areas

The study area was classified into CF, DF and NF (Fig. 3) based on the temporal changes in the spatial distribution of old and new forest areas (Fig. 3a1-3). Areas in the CF class remain forested over the entire study period. The survival rate of old forests was assessed by comparing the area of CF to the total forest area in 2001. DF areas are defined by a change from non-forest to forest (or vice versa) at least once during the period of analysis, representing areas of forest gain and loss. NF areas are without forest in any classifications over the full period (Fig. 3b). Assuming that DF change around CF, we calculated the nearest Euclidean distance (NED) from DF to CF (Fig. 3b).

2.6. Dynamics of core forest areas

To quantify the annual extent of core forest areas and their surroundings (e.g. isolated forest areas, forest edges, branches and bridges) we applied the Morphological Spatial Pattern Analysis (MSPA) (Soille and Vogt, 2009) which is a segmentation technique developed to identify spatial patterns of connected features. MSPA is based on morphological image processing techniques, and allows an automated per-pixel classification, describing the geometry, spatial pattern, and connectivity of objects. This method uses binary input images (consisting of foreground and background), according to the presence or absence of a category (in our case forest/non-forest). The foreground areas are further classified into morphological elements describing the connective structure of the image components. If derived from a forest landscape, these classified elements (illustrated in Fig. 4 and explained in Table 1), typically have an ecological meaning that is in most cases related with core forest areas and their surroundings. From this, we are not only able to test if a forest area quantified as a core forest at a specific point in time, but can also monitor the temporal dynamics of new forests that typically start as an islet (isolated forest area which is too small for being a core) or branch (extending core forests), and ideally develop into a bridge (connecting core forests), edge (surrounding core forests) and finally a core forest (Fig. 4). Finally, several metrics serve as a measure to quantify the fragmentation of core forest areas (perforation, loop), which are ideally to be reduced over time by the implementation of successful forest protection projects.
If analyzed at annual scale, these landscape element metrics are thus supposed to provide an ecologically meaningful quantification of the development of afforestation and reforestation (new forests) in relation to old forests and core forests. The detection of edges needs to be parametrized, and here we chose 250 m as the smallest possible size (corresponding to the size of a MODIS pixel). This is important, since it implies that no identified feature can be smaller than 250 m × 250 m (0.0625 km²).

The MSPA segmentation was carried out using the software GUIDOS, freely available from the EC-JRC Forest Action website (Vogt and Riitters, 2017).

2.7. Drivers of core forests dynamics

To understand the drivers of core forests dynamics, we investigated the climatic factors and ecological restoration investments, which together represent the main drivers from natural and human influence, respectively. Climatic factors included annual mean temperature and annual precipitation from 2001 to 2016, calculated based on daily data acquired from the National Meteorological Information Center of China (http://data.cma.cn). The daily meteorological dataset includes 109 meteorological stations, which were selected according to the standards of the European Climate Assessment. These meteorological stations were spatially well distributed across the LP (Fig S2). Using the ANUSPLIN program, the point climate data passing the continuity test (i.e., data quality check to make sure the data contain consecutive months in the correct sequence) were interpolated with an algorithm using the thin-plate smoothing spline method (Hutchinson, 2004). Annual ecological restoration investments from 2001 to 2016 were acquired from the Chinese Forestry Statistical Yearbook at the county scale, and annual cumulative ecological restoration investments were calculated. Ecological restoration investments were measured in areas of afforestation and forest conservation.

The space–time heterogeneities for annual mean temperature, annual precipitation and cumulative ecological restoration investments from 2001 to 2016 were analyzed at the regional and county scale by comparing the change trends for these factors. To understand impacts from changes in climatic factors on the Loess Plateau, the change trends for annual mean temperature and annual precipitation from 2001 to 2016 were also analyzed per pixel by using a linear regression. Annual precipitation/mean temperature increase/decrease were defined as the change trend larger/less than 0.

Fig. 4. Illustration of MSPA applied on a forest/non-forest image, which is classified into core forest and forest areas of various other sub-classes. Also non-forest areas are classified in relation to their locations to core forests. In our analysis, the squares correspond to 250 m × 250 m areas, which equals to smallest possible aerial unit detectable. See Table 1 for a detailed description of the types.

Table 1
The output types of MSPA. Areas correspond 250 m × 250 m squares.

<table>
<thead>
<tr>
<th>MSPA type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forest</td>
<td></td>
</tr>
<tr>
<td>Core</td>
<td>Core forests are surrounded by other forest types.</td>
</tr>
<tr>
<td>Edge</td>
<td>Typically surrounding core forests, separating them from non-forest areas.</td>
</tr>
<tr>
<td>Perforation</td>
<td>Similar to edges, but within larger core forest areas, perforation areas surround non-forest areas that lay within core forests (e.g., glades).</td>
</tr>
<tr>
<td>Bridge</td>
<td>Bridges connect core forests that are disconnected by non-forests.</td>
</tr>
<tr>
<td>Loop</td>
<td>Similar to bridges, but occurring within core forest areas where loops connect core areas that are interrupted by glades.</td>
</tr>
<tr>
<td>Branch</td>
<td>Areas extending core forests but without being directly connected.</td>
</tr>
<tr>
<td>Islet</td>
<td>Isolated forest areas too small to be a core forest.</td>
</tr>
<tr>
<td>Non-forest</td>
<td></td>
</tr>
<tr>
<td>Core Opening</td>
<td>Non-forest within core forests, surround by Perforation areas (typically glades).</td>
</tr>
<tr>
<td>Border Opening</td>
<td>Non-forest surrounded by an Edge, Loop, Branch, or Bridge.</td>
</tr>
<tr>
<td>Background</td>
<td>Includes the remaining non-forest areas.</td>
</tr>
</tbody>
</table>
3. Results

3.1. Change in forest areas and environmental factors

The forested areas in the study region increased considerably from 2001 to 2016 (3,498 km² yr⁻¹, \( p < 0.001 \)) (Fig. S2a) (Wang et al., 2018b). Out of the forested area in 2001, 84.2% were classified as CF (i.e. forest over the entire study period). DF was closely related with CF in the spatial domain (Fig. 5), with a mean NED from DF to CF of 5.86 km, and 53.49% of all DF being located within 2.5 km distance to the boundary of CF.

Cumulative ecological restoration investments considerably increased from 2001 to 2016 (9 × 10⁵ km² yr⁻¹, \( p < 0.001 \)) (Fig. S3b). Mean annual temperature and annual precipitation on the Loess Plateau...
slightly increased from 2001 to 2016 without significant trends (Fig. S3c, d) \( (p > 0.05). \) As compared to the mean annual temperature and annual precipitation, cumulative ecological restoration investments showed the highest correlation with forest area increase (Fig. S4). Furthermore, no strong impact of mean annual precipitation/temperature, trends in annual precipitation/temperature, and mean annual precipitation/temperature for areas with precipitation/temperature increase on CF and DF was found (Fig. 6). Within CF and DF areas, annual precipitation was mostly higher than 400 mm but less than 400 mm in NF (Fig. 6a). Annual precipitation had an increasing trend in 50.77% of CF and 68.36% of DF areas (Table S1), and the increase in precipitation was primarily in areas with mean annual precipitation larger than 400 mm for CF and DF (Fig. 6c).

3.2. Dynamics in core forest areas

Together with the forested areas, all the MSPA foreground types significantly increased from 2001 to 2016 (Core, Perforation, Edge, Loop, Branch, Opening, Core Opening: \( p < 0.001, \) Islet: \( p < 0.05 \) and Bridge: \( p < 0.01 \)). Core areas showed the highest increase with 2,585 km\(^2\) yr\(^{-1}\) (Fig. 7a).

In the CF areas, the Core class significantly increased \( (p < 0.001), \) while the other six MSPA forest types significantly decreased (Islet: \( p < 0.1, \) Perforation, Edge, Loop and Bridge: \( p < 0.001, \) and Branch: \( p < 0.05) \) (Fig. 7b). This reflects the transformation of the different forest MSPA types into core areas, and in particular areas classified as Edge were transformed into Cores. In the DF areas, all forest and two non-forest MSPA types significantly increased (Core, Perforation, Edge, Loop, Bridge, Branch: \( p < 0.001, \) Islet: \( p < 0.1) \) (Fig. 7c), indicating that non-forest areas (Background) were changing to forests.

Two dominating but different spatial processes were observed during the study period (Fig. 8 and Fig. S5); (1) new forests increased at the edges of old forests, extending the existing forest patches (Fig. 8, left column, A), and (2) new forests emerged without being connected to old forests. Here the new forests started as small patches (Islets), which were then transformed into Cores, Edges, Bridges or Loops (Fig. 8, right column, B).

3.3. Changes in core forests (2001–2016)

In 2001, core forests covered 5.30% of the study area, of which 98.98% (5.24% of the study area) remained unchanged in 2016. Moreover, an increase in core forest areas of 6.39% was observed from 2001 to 2016, mainly emerging from areas classified as Background (63.01%) and Edge (15.74%), showing that most of the core forests transformed from non-forest areas (Background). Losses of existing core forests accounted for 0.54% of the study area and were primarily transformed into Perforation (38.09% of the core forest loss) and Edge (30.77%) areas in 2016 (Fig. 9, Table 2).

4. Discussion

4.1. Ecological restoration projects create new core forests

Our study found an increase in core forest areas on the Loess Plateau from 2001 to 2016, which is a sign for improved forest quality following a period of ecological restoration projects. Even though precipitation is regarded the main factor affecting forest distribution for the Loess Plateau (Zhu, 1995), annual precipitation from 2001 to 2016 did not show significant changes and no differences in precipitation trends were found in unchanged dynamic forest areas (Fig. 6b). On the other hand, the ecological restoration projects were implemented all over the Loess Plateau involving large investments and seemingly contributed to a forest increase for more than half of the counties on the Loess Plateau (Fig. S3, S4). In response to decades of deforestation, two major projects, namely the Natural Forest Conservation Project (NFCP) and the Grain for Green Project (GGP) have been implemented. The former aims at protecting the natural old forests, which are relict forests (Zhang et al., 2000), and the latter targets on converting croplands (which are typically fragmented) on sloping hills into forests (Delang and Yuan, 2015). Our results support that the effects of both projects can be observed: (1) the extension of old forests creating new core areas, and (2) the appearance of new forest patches first leading to fragmented forest landscapes that gradually transform into larger forest areas. These findings are consistent with the results from local studies on the LP, such as a case study in the region of Ansai reporting an increased number of small forest patches (Zhou et al., 2012), and conservation policies aiming at protecting the forest in the giant panda habitat (Li et al., 2013). Furthermore, we found a considerable increase in core forests extending old forests (that is, in CF regions), and only few isolated patches transformed into core areas implying that the NFCP have played a more pronounced role in promoting changes towards increased forest quality.

4.2. Quantification of dynamics in forest spatial patterns

Our study presents a quantification of dynamics in forest spatial patterns and the interaction between new and old forests by the use of Morphological Spatial Pattern Analysis (MSPA). This assessment going beyond forest cover change is important, since afforestation may cause a general increase of forested areas which conceals a loss or increased fragmentation of old forests (Kozak et al., 2018). It is therefore pivotal.
to assess the spatial distribution of new forests by mapping and quantifying spatial patterns and connectivity of forest patches. Connection and aggregation are considered better than separation in relation to forest functionality (van Toor et al., 2018) and stability (Echeverría et al., 2006). Furthermore, old forests have a higher ecological value than newly planted forests such as storing carbon and providing habitats (Gómez-Pompa et al., 1972; Zhou et al., 2006; Barlow et al., 2007; Wingfield et al., 2015).

Our method is reproducible due to several reasons. First, the separation between old and new forests is simple, and can be applied on two or multiple temporal data sets to assess the continuity of old forests and the spatial relationship between old and new forests. Second, the MSPA approach used to obtain forests spatial patterns is robust, freely available and has been used in numerous studies (Vogt et al., 2007; Soille and Vogt, 2009; Rosot et al., 2018). Moreover, compared to traditional assessments on landscape fragmentation (McGarigal and Marks, 1995), which provide numbers and statistics for the entire study area, the MSPA provides the results as a spatial pattern that can be further interpreted in the relevant context (Vogt et al., 2007; Vogt et al., 2009). Since deforestation, afforestation and reforestation are topics of global significance, our approach provides a way to assess their footprints in the forest landscapes from a biological conservation perspective at a large scale.

Fig. 8. Spatial pattern of MSPA types on LP and close-ups in 2001, 2006, 2011 and 2016. The close-ups of location A are shown in the left column, and location B are shown in the right column.
4.3. Uncertainties

The spatial units of the analysis may introduce uncertainties related to forest types. The threshold setting for edges impacts on the results (O’Neill et al., 1996), however, there is no consensus on the choice of the correct extent of edges, which defines the size of core areas and also varies among different forest types (Wuyts et al., 2009). The extent of edges in literature ranges from a few meters up to 250 m (Bergès et al., 2016). Here, we were constrained by the spatial resolution of the forest data, which was 250 m × 250 m. Indeed, this rather coarse resolution also limits the local applicability of this study, since forest plantations do not always extend over this scale and in particular the classification of several of the MSPA forest types (e.g. bridges, branches and loops) would benefit from a higher spatial resolution. However, since annual forest/non-forest time series data is necessary to analyze dynamics in forest spatial patterns, it is challenging to conduct such analysis using higher spatial resolution Earth observation data (e.g. Landsat imagery) from which annual forest/non-forest classifications are not currently available. However, even though the defined edge size may affect the MSPA change trend, larger edge units (500 m, 750 m and 1000 m) showed consistency for different MSPA forest types in our study (Fig. S6).

The forest/non-forest data used as input cannot adequately distinguish old and new forests, which are substantially different in height, age, and species diversity. The annual forest data inferred from satellite time series data was trained by stable field plots (located in old forests). This implies that the growth characteristics of new forests are comparable to old forests, which does however not necessarily apply to structure or species diversity which are important for ecosystem health.

Drivers of core forests dynamics were analyzed at the regional and county scales. To investigate drivers for core forests dynamics specifically, further field work including information on when and where the ecological restoration took place and different systemic ecosystem outcomes (diversity, forest cover) can help to understand the change in cover/diversity dependency on multiple controllable drivers. Furthermore, the uncertainty-sensitivity-complexity of the model/data considering variable interactions also needs to be taken into account, and Global Sensitivity and Uncertainty Analysis (GSUA) offers a good choice for future studies (Convertino et al., 2014; Saltelli et al., 2008).

4.4. Conclusions

Our study quantified spatial forest pattern dynamics in relation to large scale afforestation and restoration projects on the Loess Plateau by the use of Morphological Spatial Pattern Analysis (MSPA). Here our study goes beyond the commonly used assessment of forest cover dynamics, and breaks forested areas down into different types of forests, reflecting their spatial distribution and connectivity. The two major ecological restoration measures (GGP and NFCP) have left clear footprints on the forest landscape: The conversion of farmlands into forests has created various small islands of forest patches, and the extension of old forests has increased their spatial coverage and created new core areas. The proposed method has proven to be suitable for monitoring the effects, and we suggest that forests spatial pattern analysis could be included as a complementary information to classical forest/non-forest classification in assessing the effectiveness of ecological restoration projects.

CRediT authorship contribution statement

Yuhang Wang: Conceptualization, Methodology, Software, Writing - original draft, Writing - review & editing. Martin Brandt:

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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