



Rapid afforestation on the Loess Plateau: a compacted process for the pre-existing forest landscape patches

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SUMMARY: *In the past couple of decades, large - scale greening undertakings have been implemented across the Loess Plateau, bringing about notable improvements in regional vegetation cover. Besides afforestation, there have also been remarkable alterations in the spatial structure of forests. For a more in - depth understanding of afforestation processes, characterizing the dynamics of forests' spatial structure is essential. We set the goal to characterize the dynamics of forest spatial structure in the course of afforestation and describe the spatiotemporal distribution of forest landscape across the Loess Plateau. Landscape metrics showing the complexity of shape, patch aggregation, and fragmentation were computed, sorted, and contrasted to find the dominant spatial pattern of forest patches. An analysis of the spatiotemporal distribution of the dominant spatial pattern and its transitions was performed, with emphasis on areas where forest cover expanded from low to high. The results demonstrate that when forest cover occupies a relatively small space, landscape configuration becomes the dominant spatial pattern in a kind of random way. As forest patches get bigger, the spatial pattern rapidly heads towards an aggregated state. So, aggregation was the most common forest spatial structure across the Loess Plateau from 2001 to 2022. The widespread trend of afforestation on the Loess Plateau shows a rapid increase in forest compactness, meaning that human - led efforts have mainly aimed at expanding forest cover over pre - existing patches.*

KEYWORDS: *landscape configuration; forest spatial structure; afforestation; The Loess Plateau*

1 Introduction

The concept of landscape is often mentioned when talking about the restoration of the forest, as it correlates well with the important concepts like spatial and temporal scales, forest patterns, and processes (Mansourian 2021; Mayer et al. 2016) which are central to the very notion of forest restoration. It is specifically clear within the scope of the Sustainable Development Goals (SDGs), assumed by all UN member states in 2015 (Griggs et al. 2014; Haliscilik and Soytaş 2019). Forest landscapes are directly connected with ecological processes and ecosystem services; therefore, analyzing their dynamics is one of the key steps to learn about ecological processes of the region and its overall effects (Haines-Young and

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Chopping 1996; Pfeifer *et al.* 2017).

The Loess Plateau, formerly seen as a rather ecologically vulnerable area with a critical situation of soil erosion, has experienced significant environmental change since the introduction of China Grain to Green Programme (GTGP) in 1999 (Chen *et al.* 2015; Wang *et al.* 2018). Due to this mass afforestation project, the amount of vegetation cover and forest land was expanded to a significant extent leading to massive forest restoration. The program has given significant effects to landscape structure, which in turn have been associated with effects on the climate of the region (Li *et al.*, 2019; Tian *et al.* 2022), hydrology (Lu *et al.* 2015; Yan *et al.* 2019), ecological conditions (Wu *et al.* 2019; Wang *et al.* 2016), soil quality (Chang *et al.* 2011), water resources (Feng *et al.* 2016; Wang *et al.* In terms of the landscape, studies have focused on the shifts in the composition of the landscape, e.g. the area of forests or biomass. But again, with further growth in forest cover, the spatial structure (i.e. form and pattern) of forested scenery is undergoing change as well. There has been growing evidence that ecological effectiveness of plantations is closely associated with spatial structure (César *et al.* 2020; Chen *et al.* 2023; Y Li *et al.* 2021). The achievement of the long-term ecological sustainability and the high cost of investment payback of the GTGP is a significant challenge (Chen *et al.* 2015; Liu *et al.* 2008). One of the questions that are yet to be answered is how alterations in the structure of the forest lead to ecological consequences on the Loess Plateau—an aspect that has not been fully addressed in the literature available on the same.

Landscape configuration may be described as the spatial positioning and structuring of the landscape elements i.e. the way the landscape elements are distributed and patterned in space (Gao *et al.* 2023; Wen *et al.* 2023). Patch-based landscape measures are usually used to describe and measure this spatial structure (Gustafson 1998; Haines-Young and Chopping 1996; McGarigal 1995). Scholars have observed that the connection between spatial structure and ecological processes is usually complicated and not well comprehended, and those should be examined in detail and interpolated with sensitivity (Gustafson 2019). The environmental impact of forest spatial structure has become the interest of Loess Plateau, and fragmentation has become the most widely discussed component of it (Fahrig 2017; Gu *et al.* 2021; Lei *et al.* 2024; Yu Li *et al.* 2021; Xie *et al.* 2017). Fragmentation is a rather significant spatial characteristic, which is interconnected with forest functioning and ecosystem integrity (Korosuo *et al.* 2014; Ma *et al.* 2023). Nevertheless, other than fragmentation, there is little and partial knowledge of the forest spatial structure in afforestation process. This gap could not allow deeper understanding of how the spatial pattern of local forests affects the ecological outcomes in this region.

During the afforestation of the Loess Plateau, we suggest that forest patches tend to evolve based on the three intuitively growth forms including: area-aggregating, edge-expanding and patch-adding. These are the spatial configurations of aggregation, shape complexity and fragmentation respectively. Within this framework, the contents of this study are to characterize the spatial features of forest patch on Loess Plateau by: (1) identifying the spatial forms of forest patches to intuitively express forest development; (2) describing the change of the spatial forms of forest configurations throughout the process of forest area expansion; (3) summarizing the spatiotemporal changes in forest landscape forms in the period of 2001-2022.

2 Materials and Methods

2.1 Study Area

The Loess Plateau developed in the upper and the middle of the Yellow River in China, in the latitude ranges within the 34° N to 42° N and a longitude between the 105° E and 117° E. It is a land region of around 640,000 km² with around 12.5 percent of total land area of China. It is a large area that includes several provinces, such as Inner Mongolia, Shanxi, Ningxia, Shaanxi, Gansu, and some areas of Henan (Figure 1). The annual precipitation varies between 200 and 700 mm and the average annual temperatures are in a range of 6° C to 14° C, which makes the Plateau semi-humid and semi-arid (Li et al. 2012; Zhang et al. 2015).

The GTGP represents one of the biggest ecological restoration projects in the whole world (Liu et al. 2008; Wang et al. 2016), a massive experiment in the restoration of vegetation on the Loess Plateau on the large scale. This significant success has been handsomely captured by different remote sensing data. As an example, Fractional Vegetation Cover (FVC) rose on average by 0.42 percent per year now, and the maximum annual Fractional Vegetation Cover (FVC) has climbed by 20% between 2000 and 2023 with the data of MODIS (Gou et al. 2024). Likewise, the Landsat data show a growth in forest cover since in 1990, it was 7,477.45 km² and in 2020, it has reached 9,074.91 km² (Lyu et al. 2023). A different study that combined Landsat and PALSAR images indicated that the forest area increased by nearly 15,000 km² over 2007-2017 (Zhou et al. 2019).

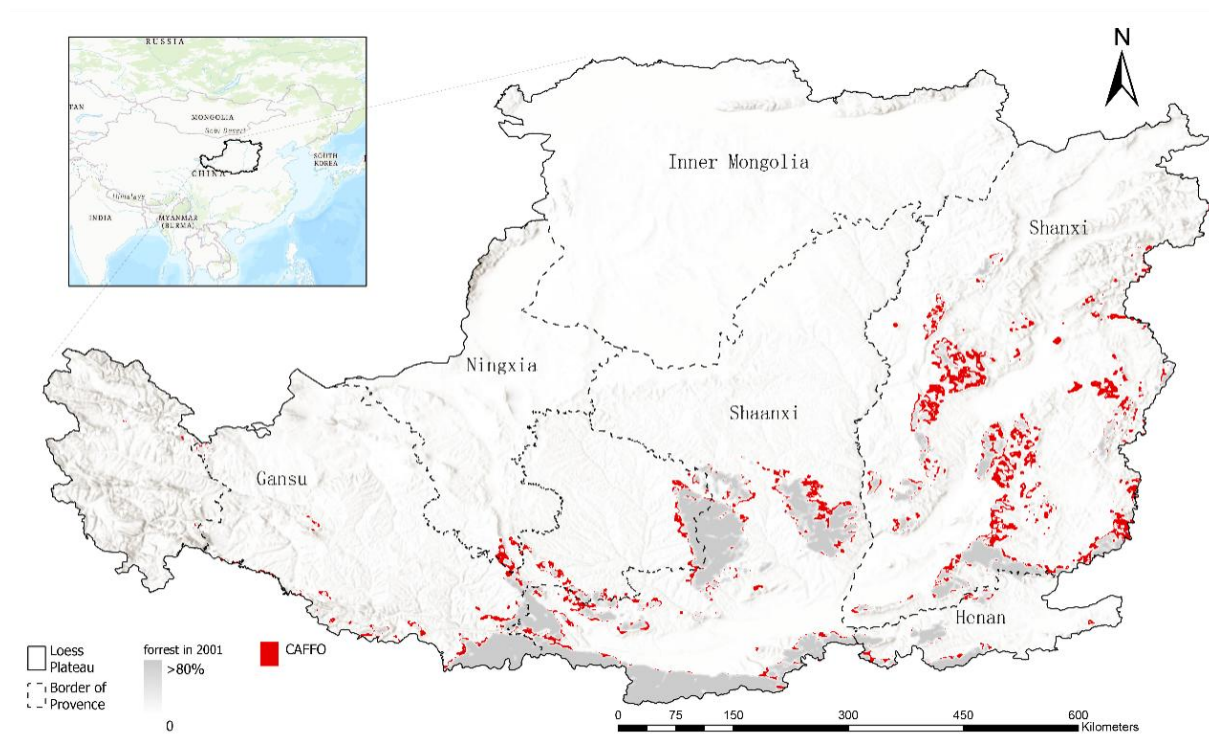


Figure 1: Geographic extent and location of the Loess Plateau

2.2 Data Preparation

The forest landscape on the Loess Plateau in the study were derived from the Land Cover Type (MCD12Q1) Version 6.1 data product, of which the land cover type derived from International Geosphere Biosphere Programme (IGBP) were selected with a spatial resolution

of 500m in 2001 to 2022. In this dataset, values 1-5 represent the landscape types at the raster pixel locations of Evergreen needle leaf forest, Evergreen broadleaf forest, Deciduous needle leaf forest, Deciduous broadleaf forest and Mixed forests, respectively, which were uniformly treated as forested landscapes without distinction in the study. This data is easily accessible from the Google earth engine platform, see “https://developers.google.com/earth-engine/datasets/catalog/MODIS_061_MCD12Q1# citations”.

The vector data of provincial administrative units used in the study were obtained from the National Geographic Information Public Service Platform, “<https://cloudcenter.tianditu.gov.cn/dataSource>”. Vector data on the extent of the Loess Plateau used in the study were obtained from the Resource and Environment Science Data Platform (RESDP), “<https://www.resdc.cn/Default.aspx>”.

2.3 Methods

2.3.1 Moving Window

Moving windows are widely used spatial statistical units in landscape pattern analysis. Based on the assumption that ecological processes at a specific location are influenced by the surrounding landscape pattern, we applied a moving window approach to estimate forest landscape characteristics. In particular, a 9×9 pixel window (equal to 20.25 km² in the modis dataset) was employed and the window had the center of each focusing pixel. This methodology allowed estimating the spatial structure of forested landscapes on a per-pixel basis, as well as provided the possibility to study the dynamic of the landscapes as it is observed between 2001 and 2022 in-depth.

2.3.2 Landscape Metrics for Forest Spatial Configuration

A commonly known approach, which quantifies the spatially based features of ground cover in patch data, is the landscape metric. In landscape ecology a boundary is normally known as a forest patch which consists of either individual pixels or a group of pixels. Total Class Area (CA) index is an important index of measuring the area of forest patches in a moving window. The spatial patterns of forest development were tested out in greening process on the Loess plateau, based on three types of forest patch development such as agglomeration, expansion of edges, and inclusion of patches. The main features of these processes are Aggregation Index (AI), Shape Index (SI), and Number of Patches (NP). The AI quantifies the degree of patch clustering within a given area; the SI, a fundamental measure of shape complexity, is influenced by edge growth, which we propose directly affects shape complexity; and the NP represents the total number of patches, indicating the fragmentation of the landscape. The key calculations for these indices are provided in the table (Table 1).

Table 1: Landscape metric calculated in the study

	name	calculation	description
1	Total Class Area (CA)	$CA = \sum_{j=1}^n a_{ij} \left(\frac{1}{10000} \right)$	CA approaches 0 as the patch type becomes increasing rare in the landscape.
2	Shape index (SI)	$SI = \frac{0.25P_{ij}}{\sqrt{a_{ij}}}$	SHAPE ≤ 1 , without limit. SHAPE=1 when the patch is square and increases without limit as patch shape becomes more irregular.
3	Number of Patches (NP)	$NP = n_i$	NP ≥ 1 , without limit. NP=1 when the landscape contains only one patch of the corresponding patch type; that is, when the class consists of a single patch.
4	Aggregation Index (AI)	$AI = \left[\frac{g_{ii}}{\text{MAX} \rightarrow g_{ii}} \right] (100)$	$1 \leq AI \leq 100$ Given any P_i , AI equals 0 when the focal patch type is maximally disaggregated (i.e., when there are no like adjacencies); AI increases as the focal patch type is increasingly aggregated and equals 100 when the patch type is maximally aggregated into a single, compact patch.

2.3.3 Defining the Forest Dominant Spatial Pattern

In this study, we define the forest Dominant Spatial Pattern (DSP) as the most prominent configuration characteristic, determined by comparing the index calculation results presented in Table 1. Specifically, each pixel is evaluated to yield three index values: SI, AI, and NP, which are then categorized into five levels. If the SI is graded at the highest level, the DSP on the pixel is classified as SHAPE, indicating that the shape complexity is the most notable feature, surpassing both AI and NP. Similarly, when the AI achieves the highest level, the DSP is classified as AGGR, and when the NP is highest, the DSP is classified as FRAG. If no index exceeds the others, the DSP is classified as MIX.

In theory SI is 1 to a 2-D patch with a square shape, and this number only tends to infinity as the shape becomes more infiltrated. In the moving window case however, the maximum SI value is achieved when the patch is in the form of a checkerboard. The highest fragmentation is a checkerboard and it takes NP value of 40. The AI has a value in the range of 0 to 100 with a maximum of 100, which will be achieved when the patch is fully aggregated into a single and compact unit. These indices have five levels into which thresholds established can be seen at 20, 40, 60 and 80 percent points in their levels respectively.

2.3.4 Analysis of the Evolution of Forest Spatial Patterns

As forest patch size increases, the landscape spatial pattern evolves. To better describe and analyze the evolution of the DSP, we categorized the CA based on the percentage of forested landscapes relative to the total area, using thresholds at 10%, 20%, 40%, 60%, and 80%. These categories were labeled as $CA \leq 10\%$, $10\% < CA \leq 20\%$, $20\% < CA \leq 40\%$, $40\% < CA \leq 60\%$, $60\% < CA \leq 80\%$, and $80\% < CA$. The DSP was recorded to each level of CA. The DSPs different in the following year (Trans-out) and the Trans -in DSP different in comparison to the previous year were also monitored. The number of DSP conversions through time as well as the details of the last change were also recorded and evaluated with respect to each pixel.

To reduce the role of native forests in the analysis and have a clear idea of the dependence between the DSP of forest landscapes and their areas increase, we have extracted the pixels where the CA has changed between the level CA 10 \leq 1 and the level CA 40 \leq 60. This CA development was to be termed as the Complete Afforestation Process (CAFFO). In the selected case of the Loess Plateau between 2001 and 2022 we have recorded the occurrence or absence of CAFFO per pixel, when and in which type of DSP it occurred, and the DSP conversions. This data was to be examined in the change of forest DSP throughout the forest growth process.

DSP conversion characteristics analysis during the CAFFO process showed that in case CA under the level of 40% $<$ CA 60% (ca. 8 -12 km²), there are high chances of further forest area development or DSP alteration. Also, in case CA is above this level but the appropriate DSP is not AGGR, then the spatial pattern is still vulnerable to alteration. These two situations were termed as the Unstable State of forest landscape spatial structure, which were applied in mapping the whole of Loess Plateau region.

3 Results

3.1 Forest Spatial Pattern Evolution in the Afforestation Process

According to the CA growth, the CAFFO areas have been discovered and their location has been mapped in Figure 1 which occupies about 14,708.5 km². They are mainly found in provinces of Shanxi, Shaanxi and Gansu with some relatively minor regions being found in Qinghai and Inner Mongolia. The various spatial patterns (DSPs) of forest landscape at the onset of CAFFO were shared fairly even, with SHAPE, AGGR and MIX making up 34.14, 36.75, and 29.11 per cent of the land cover, respectively. Nevertheless, at the end of CAFFO the AGGR pattern had done so to an overwhelming majority by 99.84% (Table 2, Figure 2).

The transitions of DSP during the CAFFO process were systematically analyzed. Notably, over 90% of CAFFO trajectories involved no more than three DSP conversions. Due to the near-universal dominance of AGGR at the end of CAFFO (Figure 2a), this final stage does not effectively reveal the full dynamics of DSP transitions throughout the process. Therefore, to better characterize the distribution of conversions, the final transition was excluded from the analysis. Under this condition, MIX emerged as the most common Trans-in pattern, with 49,680 recorded instances during 2001–2022, followed by SHAPE and then AGGR (Figure 2a).

Table 2: Area of DSPs across CA levels during the CAFFO process.

	CA \leq 10%		10% $<$ CA \leq 20%		20% $<$ CA \leq 40%		40% $<$ CA \leq 60%	
	area	%	area	%	area	%	area	%
SHAPE	11780.5	34.14	2352.75	10.39	6.5	0.03	0	0.00
AGGR	12681.25	36.75	15602	68.93	20234.25	94.57	21110	99.84
FRAG	1.75	0.01	13	0.06	26	0.12	1.25	0.01
MIX	10046.5	29.11	4666.25	20.62	1128.5	5.27	32.25	0.15

The evolution of forest DSP during the CAFFO process can be summarized as follows: when the forested area is relatively small, the DSP types—SHAPE, AGGR, and MIX—are distributed in approximately equal proportions. As the forest area expands, DSP transitions become more frequent, with a slight tendency toward conversion to MIX. Once the forest area reaches the 40% $<$ CA \leq 60% level, the AGGR pattern becomes overwhelmingly dominant.

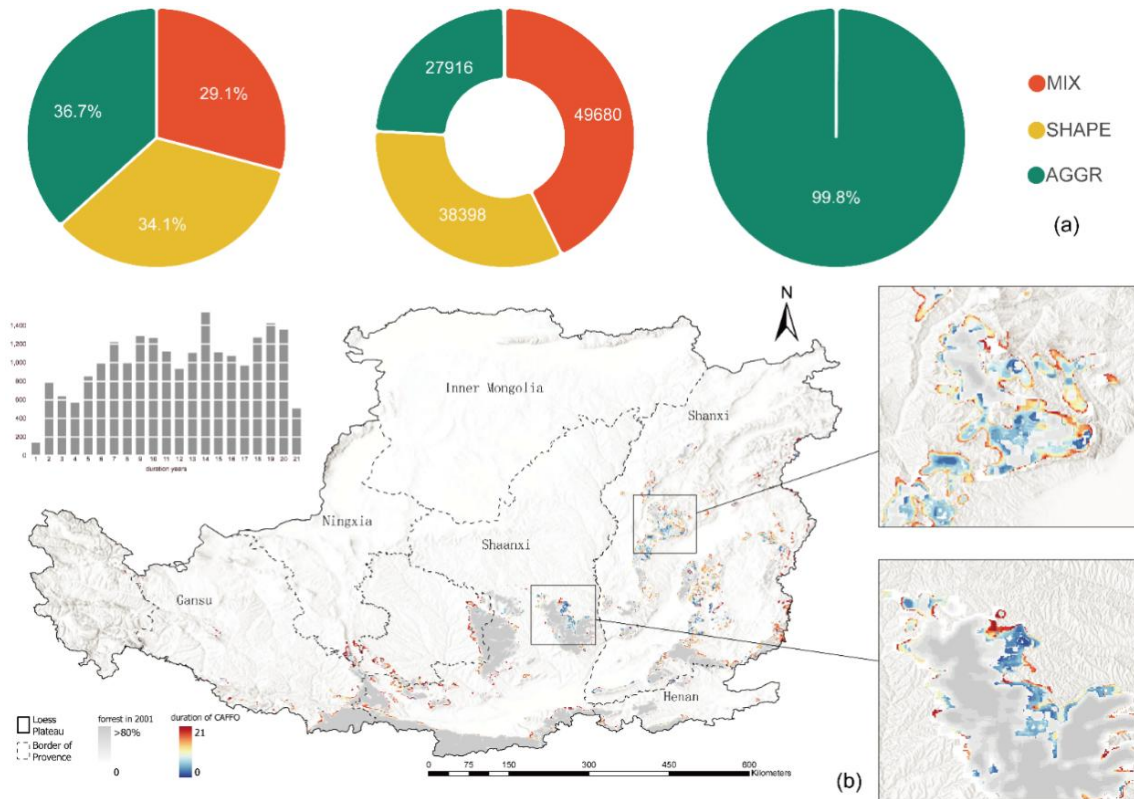


Figure 2: Changes in DSP proportions during CAFFO and spatial distribution of CAFFO durations across the Loess Plateau. (a): Changes in the proportion of DSP throughout the CAFFO process. The left side represents DSP proportions at the onset of CAFFO, the right side shows proportions at its conclusion, and the middle illustrates the number of Trans-in occurrences for each DSP type during CAFFO. (b): Spatial distribution of CAFFO duration (in years) across the Loess Plateau.

The histogram of CAFFO durations reveals three prominent peaks at 9, 14, and 19 years (Figure 2b). Spatially, longer-duration CAFFOs are concentrated in the western Loess Plateau, particularly in Gansu, Ningxia, and Qinghai provinces, where afforestation processes extended up to 16 years in some areas. In contrast, shorter-duration CAFFOs—typically lasting around 10–11 years—are more common in the eastern regions, including Shaanxi and Shanxi provinces. This suggests that afforestation efforts in the east were largely completed by around 2010, while those in the west continued and were finalized closer to 2020 (Figure 2b).

Figure 2 gives zoomed-in plots of 2 areas whereby a ring-like structure is observed about the spatial distribution of CAFFO duration and year of completion. It is notable that regions with longer CAFFO periods (warm colors) are surrounding regions with shorter periods (cooler colors) which indicates a spatial progressive trend of forest growth. These trends follow a spatiotemporal afforestation sequence consisting of outward expansion of already forested regions- these data show that afforestation in the Loess Plateau was accomplished to a large extent by progressive transformation of earlier smallest forested zones.

3.2 Spatiotemporal Characteristics of Forest Spatial Patterns on the Loess Plateau

In summary, from 2001 to 2022 on the Loess Plateau, the AGGR pattern was the most widely distributed and exhibited the greatest growth. And the distribution and transition frequency of

SHAPE and MIX patterns were strongly constrained by the CA levels.

The CA analysis result gives detailed information on the development of forest patches during the period of study (Figure 3a). In particular, the area covered by forest, obtained in accordance with the MODIS data, grew in 2001 to 30,179.5 km² and in 2022 to 54,411.25 km², which is an increase of 80.29 percent. The percentage of forest cover within the total area of the study increased by 4.83 to 8.71 percent within the same area in terms of percentage. Although CA is determined with the help of a 9 × 9 pixel moving window, the analysis shows the obvious afforestation trend. The CA value grew by 65.34 percent showing an increase of 117 versus 70.76 ha in 2022 and 2001 respectively. Notably, areas within the CA ≤10% and CA >80% levels were significantly more than other CA levels. While all CA levels exhibited upward trends throughout the study period, the most pronounced growth occurred at the extremes as CA ≤10% and CA >80% (Figure 3a). The increase in CA >80% showed a near-perfect linear relationship with total forest growth ($R^2 = 0.99$), while CA ≤10% also demonstrated a strong linear correlation, with both exceeding $R^2 = 0.5$.

The DSP that represent the most significant configuration form 2001-2022 on the Loess Plateau were quantified and presented as bar charts Figure 3. Among them, the AGGR was the majority DSP, while SHEAP and MIX accounted for a relatively small proportion, and they tended to occur in areas with low levels of CA. Specifically, the AGGR accounted for 85.79% of all DSP in 2022, an average increase of 0.3% from 79.7% in 2001. While the SHEAP and MIX accounted for 1.26% and 2.84% respectively in 2022, and the FRAG was less than 0.1%, which would not be described further due to its small percentage (Figure 3b,d). The amount of the SHEAP and MIX did not show a significant trend over the study period, while the AGGR linear fit to time reached an R² of 0.95. About 90% of the CA that with the pattern of SHAPE or MIX were at the CA ≤10% level, and about 9% were distributed in the 10% < CA ≤20% level (Figure 3b,d). For AGGR, except the CA > 80% level which takes more than 30% proportions, the other CA levels was evenly distributed (Figure 3c). The AGGR increased mostly in the CA > 80%, about 20.94 thousand km², and 8 to 10 thousand km² in the other CA levels.

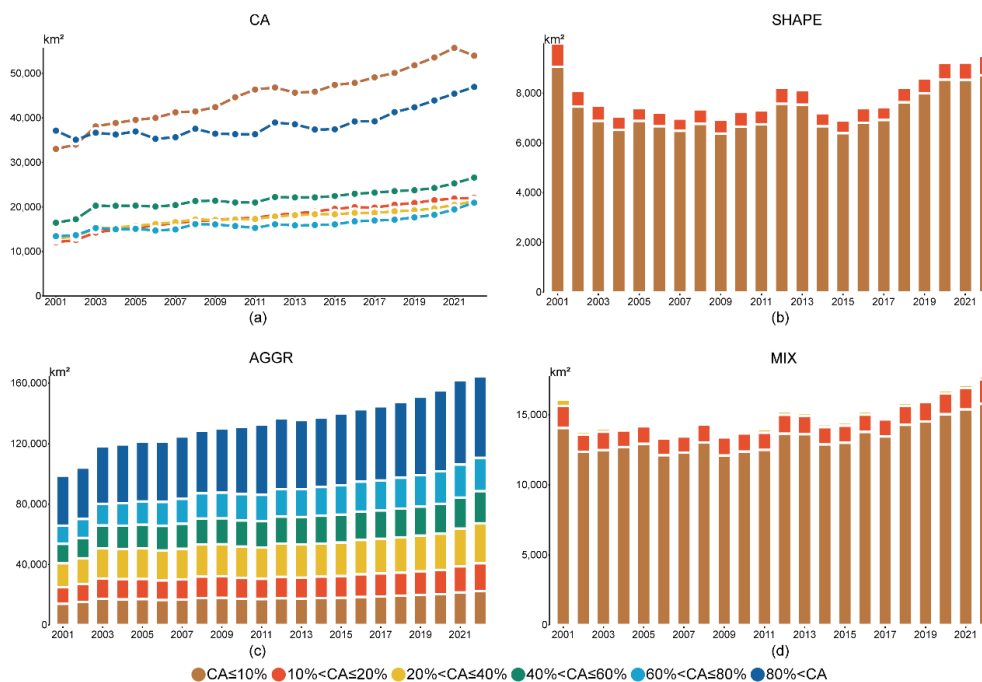


Figure 3: Statistics of area of DSPs on the Loess Plateau from 2001 to 2022. (a): CA, (b): SHAPE, (c): AGGR, (d): MIX

Forest DSPs tended to convert as forest area increased, and we quantified these changes by tracking whether DSPs shifted in the subsequent year (Figure 4c,d). From 2001 to 2022, over 90% of forest DSPs remained unchanged year-over-year, indicating high spatial consistency. Among the pixels that experienced DSP transitions, the total number of Trans-out events (in descending order) was MIX (439.3 thousand), SHAPE (293.7 thousand), and AGGR (251.7 thousand). Conversely, the total number of Trans-in events followed the order: AGGR (448.7 thousand), MIX (283.6 thousand), and SHAPE (252.5 thousand). For both MIX and SHAPE, Trans-out events exceeded Trans-in, suggesting a net decline in their prevalence. In contrast, AGGR exhibited more Trans-in than Trans-out, indicating its growing dominance. Moreover, SHAPE also had an equivalent likelihood to become AGGR or MIX, and MIX had more transitions in and out than SHAPE (Figure 4c). Further comparison of the analysis of DSP transitions between the various CA levels (Figure 4d) indicated that there were overall greater in- and out-transitions in regions with CA 10 or less. AGGR was always gaining more on the Trans-in than losing to the Trans-out and as the CA levels rose, AGGR transitions became less frequent. For MIX, Trans-out exceeded Trans-in, especially in CA $\leq 10\%$ regions, and transitions mostly shifted toward AGGR with increasing CA levels. SHAPE maintained a balance between Trans-in and Trans-out at CA $\leq 10\%$, but its Trans-in dropped sharply at the $10\% < CA \leq 20\%$ level—becoming lower than both its own Trans-out and the Trans-in values of other DSPs. In summary: (i) At CA $\leq 10\%$, DSP trans-in and trans-out occurred at roughly equal rates; (ii) at $10\% < CA \leq 20\%$, SHAPE exhibited the highest rate of Trans-out among all DSPs; and (iii) as forest area increased further, the AGGR rapidly became the DSP with absolutely majority of Trans-in.

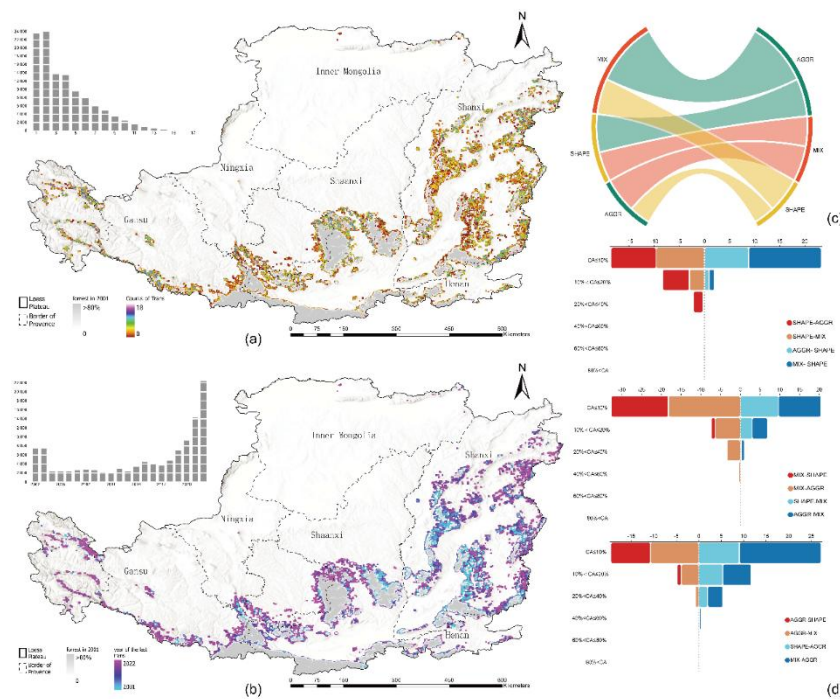


Figure 4: Statistics and spatial distribution of forest DSP conversions on the Loess Plateau. (a): Total number of DSP conversions during the study period. (b) Spatial distribution of the year in which the last DSP conversion occurred (2001–2022). (c) Schematic representation of DSP transitions from 2000 to 2022, with initial DSPs on the left and their conversion destinations on the right. (d): Frequency of DSP conversions (in 10,000s of occurrences) for SHAPE, AGGR, and MIX across different CA levels. Warm colors (left) represent Trans-out events, while cool colors (right) represent Trans-in events.

Conversion frequency and timing On a per-pixel basis, investigation of the past 2001-2022 of DSP conversions showed that DSP conversions exhibit specific patterns in spatiotemporal distribution (Figure 4a,b). It is important to note that less than four DSP conversions were carried out on 54.6% of pixels within the study period. The total conversions of forest DSP were counted as well as the final year of occurrence of each pixel was mapped. The frequency of conversions was also low and early in the eastern area of the research area (namely, in Shaanxi and Shanxi provinces). Conversely, other areas like Qinghai Province on the west had increased frequencies of conversion and cessation years were near the termination of the study period. These results indicate that in the eastern part of the Loess Plateau the afforestation was faster whereas in the West parts of the plateau the process of afforestation was slower and more continuing and featured by recurrent conversions of DSP.

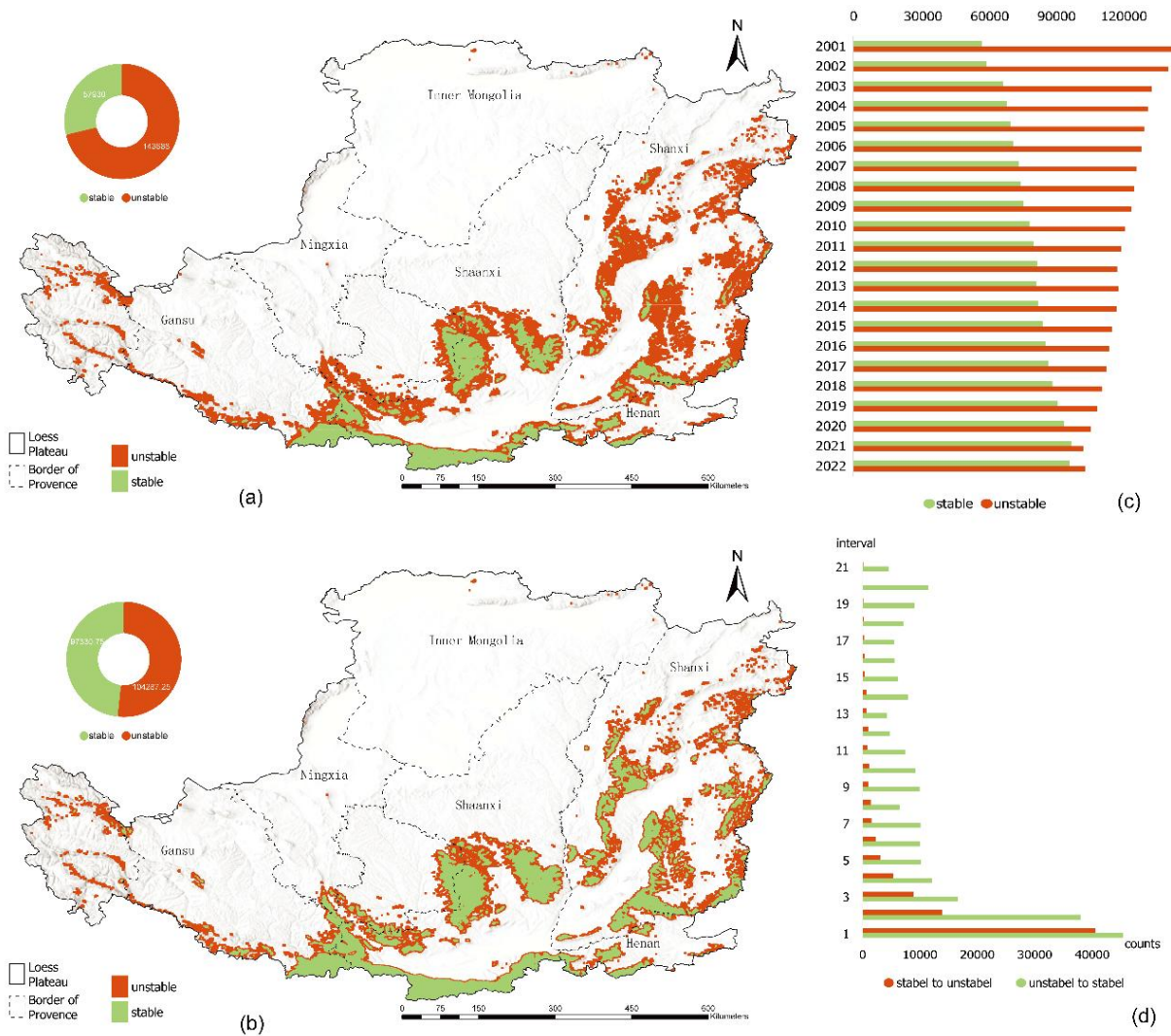


Figure 5: Statistics on the state of forest spatial patterns across the Loess Plateau. (a): Forest spatial pattern states in 2001. (b) Forest spatial pattern states in 2022. (c) Frequency of each forest spatial pattern state observed from 2001 to 2022. (d) Distribution of time intervals between successive state conversions across the study period.)

Applying the transition rules of DSP derived from the CAFFO process, we observed a clear trend of forest landscapes in the Loess Plateau evolving from unstable to stable states

(Figure 5a,b,c). Specifically, the area of unstable and stable DSPs in 2001 was 101,769.5 km² and 33,435.75 km², respectively, shifting to 74,887.25 km² and 60,318.0 km² by 2022. The proportion of stable states increased steadily over the study period, with an average annual growth of 1,280.11 km². A total of 18,303,050 transitions from unstable to stable states were recorded, which is approximately 7.39 times the number of transitions from stable to unstable. In most cases, transitions between states occurred within 1–2 years (Figure 5d). However, while the transition from unstable to stable states spanned a broad range from 1 to 21 years, transitions from stable to unstable typically occurred over much shorter durations. Both the frequency and duration of transitions further support the robustness of our definition of stable and unstable DSP states in forest landscapes. The stable DSP areas in 2022 were spatially located in Shaanxi and Shanxi provinces that had the highest numbers at that time Gansu (Table 3). As the share of forests in Shandxi and Gansu remained at 66 per cent and 54 per cent belonged to the category of the unstable ones, the more remarkable is that though comprising only 35 per cent of the total, Shaanxi had been experiencing a relatively advanced stage of afforestation, that is, there was a substantial number of activities and successes in the area of the forest re-establishing in the province.

Table 3: Statistics on the state of DSP by province

	Unstable in 2022		Stable in 2022		Average increasing of stable
	area	%	area	%	area
Gansu	11728.25	54.63	9740.25	45.37	166.85
Henan	3449.25	51.77	3213.5	48.23	56.81
Inner Mongolia	301.5	100.00	0	0.00	0.00
Ningxia	833	63.01	489	36.99	22.93
Qinghai	5103	98.34	86.25	1.66	3.48
Shanxi	38485.75	66.33	19531.75	33.67	693.71
Shaanxi	14986.5	35.48	27257.25	64.52	336.33

4 Discussion

4.1 The definition of forest dominant spatial pattern

It has been proposed that among the quantity of landscape elements, spatial arrangement frequently has comparatively small ecological consequences (Fahrig 2013; Gustafson 2019). Nonetheless, forest landscape organization has proved to have many significant ecological perks, and therefore should be considered in ecological restoration planning, management, and planting designs (César et al. 2020; Korosuo et al. 2014). Since there are hundreds of landscape measures, most of which are redundant, interpretation may be cumbersome and less informative. In this paper, the conceptualizations of forest patch growth are the idea that area aggregation, edge expansion, and patch addition take place. The most outstanding structural realization is regarded as the DSP at the local landscape level among them. We discovered that the SI, AI, and NP give a strong and meaningful measure of these dynamics. Although no explicit analysis was done of the metric redundancy, these indices were chosen due to their theoretical independence, as well as their ability to capture different features of spatial configuration.

In many cases, forest patches at a certain phase have the presence of a variety of spatial arrangements. There have been attempts to define such configurations holistically and analyze their spatiotemporal processes and produce many landscape indices (Frazier and Kedron 2017; Uuemaa et al. 2009). There are studies that considered particular aspects of configuration and

expanded on their ecological consequences, including forest fragmentation (Fahrig 2003; Ma *et al.* 2023) or edge effects (Banks-Leite *et al.* 2010; Pfeifer *et al.* 2017). In the current work, we pay attention to the DSP and discuss its transitions concerning growth of forest areas. In the frame of afforestation on the Loess Plateau, we suppose that the DSP needs to be not only measured but also highlighted because it will summarize the most beneficial spatial qualities of forest environments at a specific stage of development. The DSP notion has unique and, intuitively, more explanatory power than the use of multiple indices at once. Notably, this methodology does not ignore other spatial features; more to the point, it is a simplified reflex of a complex result, which implicitly takes into account a variety of configuration dimensions.

It should be mentioned that alongside SI, AI, and NP, there are other indices like LSI, DIVISION and PLADJ which can describe the aspects of the spatial configurations that are covered in this study. Nonetheless, these indices are not only dependent on spatial configuration, but also on the area of forests, and this may create ambiguity in the interpretation of configuration dynamics. To prevent such possible confusion, we instead should include the index of CA to examine the data on the change of landscape patterns. We realize that the indices that are sensitive to patch area, as well as both patch and configuration, are especially useful in analyses of time series, and are likely to be useful in future research to provide a more detailed description of forested landscape of the Loess Plateau.

4.2 Choice of Moving Window

A widespread method of quantifying features of regional landscape involves the utilization of regular grids in computing landscape measures. Nevertheless, the reason as to why grid size is picked in most studies is unclear (Fu *et al.* 2021). Although regular grids provide a simple and easy to understand platform of spatial analysis, they also provide strict lineaments to landscape features that in many instances are not in accord with ecological facts. In addition, the lack of effective ecological rationale of grid size may cause the confusion of operations. This paper is concerned with discrete pixels on remote sensing data, assuming that the ecological environment directly affects the values of the pixels. Thus, moving window method was implemented rather than constant grids in landscape pattern index calculations.

Just like the conventional grids, landscape ecology has a zoning issue wherein determining the size of the moving window is rather a challenge that has been discussed in the literature (Gustafson 1998; Turner 2001; Wiens 1989; Wu 2004). Since the MODIS data was used at a spatial resolution of 500m, too big windows would blur there around ecological information whereas too small windows would inflate local variation and skew index values (McGarigal 1995). We therefore chose a window of 9 x 9 in this study. We acknowledge optimal size of window depends on the particular ecological context and on a decision of the landscape indices, and it is necessary to realize that their influences on forest spatial configuration estimates are one of the areas of prospective studies.

4.3 Tendency of DSP Conversion in Afforestation on the Loess Plateau

The CA outcomes of this study indicate the variation in forest area in a sliding window and the referential result is easily readable, which depicts the trend of afforestation over the Loess Plateau in agreement with the outcomes of prior research (Kong *et al.* 2024; Song *et al.* 2022; Zhou *et al.* 2019). Interestingly, the pixels with CA of 10 percent and above which had a CA of more than 80 percent recorded the best changes between 2001 and 2022. Such trend shows that there is continued formation of new forest cover as well as the thickening of the existing forested areas. New forests kept being formed and their density increased with time during the forest restoration process. Subsequently due to the densification the increase of $CA \leq 10\%$ was restricted and this eventually caused a more dominant development of $CA > 80$ areas.

The forest landscape pattern which was the FRAG category took up a very low percentage in our analysis- so low to the extent that it was not regarded in the future presentation of results. This is not only because the spatial properties of the Loess Plateau are conducive to do so, but also because the moving window size had a bearing on the final outcome. Having a window of 9×9 higher chances of non-detection of highly fragmented pieces of wood are observed. In the event the analysis was done with an increased window say 90×90 , then perhaps it would cover more isolated patches thus increasing the apparent level of fragmentation. The observed prevalence of aggregation patterns could, therefore, have been non-statistically inflated by the selected window size.

The statistical findings show both spatial and transformation of DSP during the restoration of the forest is closely associated with CA. SHAPE and MIX configurations were also found most at low CA concentrations with AGGR although found in all CA concentrations, only portraying the most significant growth at high CA concentrations during the study period. Together with the CAFFO process, in which DSPs in the evolution process between different forms tend to become AGGR, we can propose a general trend in the Loess Plateau, at the beginning of the forest development where the CA is low, the existence of SHAPE, AGGR, and MIX patterns can be judged randomly or equally likely. Nonetheless, when the forest cover becomes more or less 40-60, almost all of the configurations will shift to AGGR. SHAPE generally appears at the lowest levels of CA and decreases easily as one moves to bigger forest areas, it moves to AGGR. MIX, although also being present at low CA levels, is later in time when compared to SHAPE. As a follow-up of SHAPE initially less common, MIX initially subsists briefly following the loss of SHAPE but eventually disappear too. In addition, MIX has the greatest total Trans-out which means it is a transient DSP in the growth of the forest and therefore it is unsteady. All these results together show that the spatial arrangements of forests are dynamic and undergo change throughout the afforestation period of the Loess Plateau. The formations or structure of the landscape at low forest cover takes many forms including shape complexity, aggregation or MIX. But as the area of forests increases, the patches assume a smaller and smaller size. Although there are certain short-term variations of DSP when the patch develops, finally, the landscape becomes aggregated and fixated to a more stable forest structure (Figure 6).

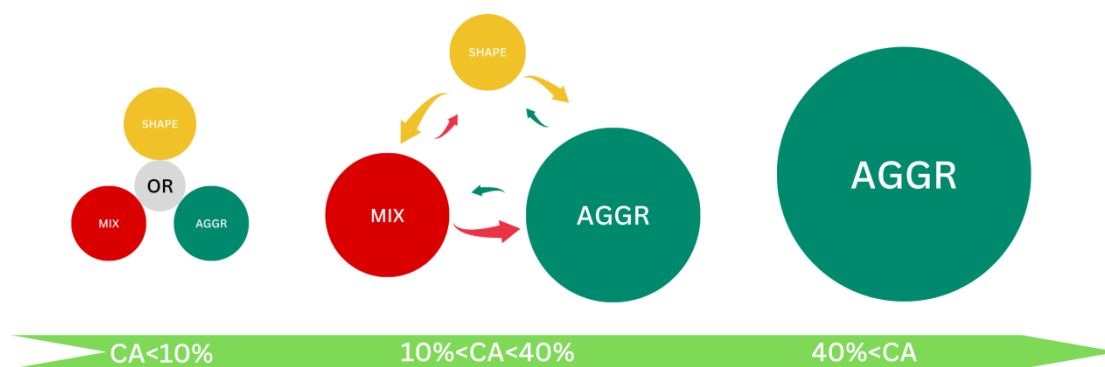


Figure 6: The evolution of DSP in afforestation on the Loess Plateau

5 Conclusions

To characterize forest landscape configurations in terms of shape complexity, patch aggregation, and fragmentation on the Loess Plateau, we calculated and graded three key landscape metrics: SI, AI, and NP. The metric with the highest grade at each pixel was identified as the DSP and categorized as SHAPE, AGGR or FRAG, corresponding to shape

complexity, aggregation, and fragmentation, respectively. In cases where no single metric clearly dominated, the configuration was considered to be in a mixed state and labeled as MIX. Subsequently, the spatial distribution and temporal evolution of these DSPs across the study area were examined with particular attention to areas where forest cover expanded from low to high levels.

Low- and high-density forested areas show a clear trend of increasing, which indicates the continuous expansion of newly established forest patches and increasing density within existing forested areas. The evolution of DSP on areas where forest cover expanded from low to high levels indicate that newly established forest patches initially exhibit a random dominant configuration between shape complexity, aggregation, and fragmentation. As forest patches expand, the spatial pattern rapidly transitions toward aggregation. Accordingly, from 2001 to 2022, aggregation consistently dominated the forest spatial pattern, and in contrast, shape complexity and fragmentation only occurs when the forest is very small. We consider this behavior is partly due to the size of the moving window used in our analysis. Despite this, we believe that the results of the study still reflect the fact that anthropogenic efforts have been directed primarily at expanding forest cover over pre-existing patches. This imply that the high density of the forest could not be the highest priority at the time of initial afforestation.

The spatial distribution of forest DSP characteristics—including CAFFO stages, frequency of occurrence, year of last conversion, and stability—was closely examined. The findings found a clear-cut spatial distribution of afforestation within the Loess Plateau. In the eastern parts of the country, especially the provinces of Shanxi and Shaanxi, the forest was being afforested at a faster rate, and the forest DSPs were stabilized earlier. On the contrary, afforestation in the west has been less rapid, and continued and even repeated conversions of DSP suggests that the setting up of forests continues to this day.

Author Contributions

Yazhou Zhang and Tiantian Ji conceived and designed the study, and edited the manuscript. Yazhou Zhang and Qi Diao administered the project and acquired funding, and provided resources. Chaoheng Guo performed code work. Qiuping Wang curated the data and created visualizations. All authors contributed substantially to manuscript drafts and approved of the final version.

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Data Availability: The data in the paper is stored on cloud storage Google Drive, see link for details: https://drive.google.com/drive/folders/1enGhOzcrMaWyYbwmGLKk-TQmz4RMtF2n?usp=drive_link

Declarations

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

CA Total Class Area

AI	aggregation index
SI	shape index
NP	number of patches
DSP	forest dominant spatial pattern
AGGR	a DSP that the AI is graded higher than SI and NP
FRAG	a DSP that the NP is graded higher than AI and SI
SHAPE	a DSP that the SI is graded higher than AI and NP
MIX	no single index among AI, SI, and NP graded higher than others
CAFFO	complete afforestation process

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