

Comparative Analysis of Fragmentation Process Differences between Plantation and Natural Forests: A Case Study of Washington and Mississippi States, USA (Postprint)

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Abstract

Forest loss and fragmentation have long been major environmental issues of widespread international concern. According to Forman's theory that landscape change comprises five spatial processes—perforation, dissection, fragmentation, shrinkage, and attrition—a forest fragmentation process model was developed using ArcGIS Modeler to explicitly characterize the spatial processes and ecological dynamics of forest landscape fragmentation. Based on three-period NLCD data from 2001, 2006, and 2011, with Washington State and Mississippi State in the United States as study areas, the forest fragmentation process model was employed to classify forest loss patches into four fragmentation processes (the dissection type was incorporated into the fragmentation type due to its linear characteristics), thereby conducting a comparative analysis of spatiotemporal differences in fragmentation processes between natural forests and plantation forests. The study reveals that fragmentation patches in natural forests are predominantly distributed at the boundaries between urban/forest, cropland/forest, and shrubland/forest, whereas the distribution pattern of fragmentation patches in plantation forests is relatively scattered. In natural forests, fragmentation and shrinkage patches mostly occur at the edges of shrinkage, fragmentation, and perforation patches from the preceding stage, while the succession relationships among the four spatial processes in plantation forests are less pronounced than in natural forests. Nevertheless, both forest types exhibit a similar overall pattern of “shrinkage-attrition-perforation/fragmentation” change, primarily characterized by the dominance of the shrinkage type that gradually recedes, with perforation and fragmentation progressively increasing to assume new dominance.

Full Text

Preamble

Differences in Fragmentation Processes Between Western Natural Forests and Southeastern Forest Plantations in the United States: A Case Study Comparing Washington and Mississippi States

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Abstract

Forest loss and fragmentation have long been among the most vital concerns of the international community. Landscape fragmentation includes five different spatially explicit processes: perforation, dissection, subdivision, shrinkage, and attrition. Following this theory, a forest fragmentation process model that can detect these spatially explicit processes, as well as the ecological consequences of forest landscape fragmentation, was developed using ArcGIS Modeler. Using the National Land Cover Database (NLCD 2001, 2006, and 2011), the forest fragmentation process model was applied to Washington and Mississippi in the USA. Deforested patches were quantified and categorized into one of four fragmentation processes, by merging the dissection spatial process into the subdivision spatial process (because of its principal linear feature). Furthermore, the spatio-temporal differences in fragmentation patterns between natural forests and plantations were compared. For natural forests, forest fragmentation mainly occurred in the urban/forest, cultivated/forest, and shrubland/forest interfaces, whereas the pattern of deforested plantation patches dispersed sparsely and irregularly throughout the region. The subdivision and shrinkage patches in natural forests usually followed the perforation, subdivision, and shrinkage patches of the previous period. In contrast, for the plantations, the spatial transition relationships of the four fragmentation processes were not as apparent as for the natural forests. Nonetheless, for both natural forests and plantations, the overall temporal fragmentation pattern tended to have a similar “shrinkage-attrition-perforation/subdivision” tendency. This tendency was characterized by an early shrinkage dominance, followed by its gradual disappearance. Furthermore, perforation and subdivision components increased gradually, and a new dominance was established accordingly.

Keywords: forest fragmentation process; natural forests; plantation forests; difference analysis

Introduction

Forest landscape fragmentation has become a global phenomenon, particularly pronounced in some developing countries and regions. Forest fragmentation refers to the process whereby large, continuous forest blocks are divided into smaller, independent patches. This process alters regional vegetation structure and the biogeographic environment required for species survival, severely impacting species diversity while disrupting energy balance and material flow within ecosystems. It also triggers a series of biological consequences such as edge effects and crowding effects. Consequently, research on forest landscape patterns and their fragmentation has remained a central focus in landscape ecology.

Forman proposed a theory of five spatial processes in landscape change: perforation, dissection, subdivision, shrinkage, and attrition. Perforation is the process where large landscape element units form small patches under external forces. Dissection involves dividing regions with belts of equal width, further fragmenting the original landscape. Subdivision divides original patches into smaller ones, with increasing distances between the newly formed small patches. During the shrinkage stage, original patch sizes progressively diminish until they disappear entirely. Forest fragmentation processes follow this pattern, manifested as increasing forest patch numbers, decreasing average patch area, increasingly irregular patch shapes, interrupted corridors, and ultimately isolated forest islands. Each fragmentation process possesses distinct spatial attributes that profoundly influence landscape spatial patterns and ecological processes.

According to forest origin, forests formed through natural regeneration or sprouting can be classified as natural forests, whereas plantations are defined as forest areas that lack certain characteristics and key elements of native ecosystems due to human activities such as sowing or intensive afforestation. Natural forests exhibit higher species richness and typically surpass plantations in both production and ecological functions. Based on differences in species composition, structure, and stability between natural forests and plantations, we can anticipate that they will also demonstrate distinct characteristics in landscape fragmentation patterns and spatial processes.

Previous comparisons of natural and plantation forests have concentrated on community structure, species diversity, biomass, and carbon storage, with few reports analyzing and contrasting their landscape fragmentation processes. Traditional forest fragmentation studies primarily use landscape pattern indices to describe landscape type composition and structure, failing to comprehensively elucidate changes in fragmented patch area and quantity and their influencing factors during long-term forest evolution. Clarifying forest fragmentation spatial processes to reveal evolution mechanisms of different forest resource types under varying ecological conditions, and quantitatively describing landscape fragmen-

tation patterns in natural versus plantation forests, would provide important guidance for developing rational, differentiated forest management strategies from a landscape ecology perspective.

This study establishes a forest fragmentation process model (SCS) based on Forman's theory to compare differences in fragmentation spatial processes between natural and plantation forests. As the world's fourth most forest-rich country, the United States has long been the world's largest timber exporter and a major pulp and paper product exporter. Large natural forests distributed along the Pacific Northwest coast and Rocky Mountains constitute important timber sources. Due to over-harvesting of natural forests and deteriorating ecological conditions, extensive plantations in the southeastern United States have compensated for natural forest shortages but have also introduced problems such as poor forest stability and soil degradation. The northwestern natural forests and southeastern plantations represent relatively typical modern forestry production and management models. The US also shares geographic and climatic similarities with China, making it a valuable case study for providing beneficial references for improving China's forestry management system.

This paper selects Washington State, with its dense natural forests, and Mississippi State, with its vast plantation area, as study regions. Using the landscape fragmentation process evaluation method, we established a forest fragmentation process model to classify forest fragmentation patches during 2001-2011 into four explicit spatial processes: perforation, shrinkage, attrition, and fragmentation (with subdivision merged into fragmentation). This allows comparison of fragmentation patterns between natural and plantation forests in both spatial processes and temporal sequences, providing decision support for consolidating natural forest resources, improving forest stability, and reforming plantation management practices. The findings also offer reference value for achieving sustainable forest resource development in China.

1. Study Area Overview

Washington State (45°33 N-49°N, 116°55 W-124°46 W) covers 184,800 km². The Cascade Mountains divide the state longitudinally. The western portion features temperate rainforests, while the eastern region is primarily the Columbia Plateau basalt. Forestland accounts for approximately 40% of the state's area, dominated by coniferous forests. Broadleaf forests are mostly distributed in areas with frequent flooding or severe disturbances such as avalanches or logging. The state's forestry zone concentrates in the Cascade Mountains and eastern regions, ranking second nationally in timber production. Douglas fir and western hemlock are the primary commercial species, with over 40% of raw materials processed into lumber and panels, and the remainder used as pulp and plywood raw materials. The state leads the nation in forest product exports, representing a typical natural forest growth region.

Mississippi State (30°12 N–35°N, 88°06 W–91°39 W) covers 125,400 km². The state features low elevation and dense river networks, adjacent to the Mississippi River' s east bank. The region between the Yazoo and Mississippi rivers has formed a crescent-shaped fertile alluvial valley through sediment deposition. Forests cover 65% of the state' s area, with pine forests dominating the south, cypress primarily distributed along the lower Mississippi River, and mixed broadleaf forests in the northeast. The plantation area is extensive, with private forests accounting for 88.6% of the state' s forest area. Mills and other manufacturing industries export over \$1 billion in forest products annually, with pulp and resin generating substantial economic benefits for the state.

2. Data Sources

[Figure 1: see original paper] The state diagram of USA

The study utilized National Land Cover Database (NLCD) data for 2001, 2006, and 2011, with a spatial resolution of 30 m. The NLCD is produced by the Multi-Resolution Land Characteristics Consortium (MRLC) to provide national land cover data and change information. The 2011 version represents the latest release, covering the entire United States and achieving wall-to-wall spatially explicit connectivity from Landsat imagery decision tree classification, enabling direct comparison and detection of land cover dynamics across the three periods.

Product accuracy varies by geographic location and classification type. Wickham et al. used sampling and response design to evaluate Anderson Level II and Level I classifications, achieving overall accuracies of 78.7% and 85.3%, respectively, with forest class user accuracy of 87.0% for NLCD 2001. For NLCD 2006, multi-temporal high-resolution remote sensing imagery was used with stratified random sampling, yielding Anderson Level II classification accuracy of 78.0% and forest user accuracy of 87.0%. Accuracy assessment for NLCD 2011 based on sample point extraction was completed in 2015.

3. Methods

The forest landscape fragmentation process model builds upon Forman' s landscape fragmentation theory. By overlaying land cover classification data from two time periods, patches where forest landscape elements transformed into other types can be identified. The landscape fragmentation process model then classifies these missing forest patches into four spatial processes: perforation, fragmentation (subdivision merged here), shrinkage, and attrition.

- **Perforation:** Missing forest patch completely surrounded by retained forest patch

- **Fragmentation:** Missing forest patch adjacent to two or more retained forest patches
- **Shrinkage:** Missing forest patch adjacent to only one retained forest patch
- **Attrition:** Missing forest patch isolated from any retained forest patch

[Figure 2: see original paper] Diagram of four spatial processes of landscape fragmentation. White indicates missing forest patches, green indicates retained forest patches, gray indicates non-forest patches.

3.1 Data Preprocessing

For subsequent analysis, the original NLCD 2001, 2006, and 2011 classification themes were aggregated into forest and non forest classes for both study areas. The specific aggregation rules are shown in Table 1.

Aggregation of NLCD classes

3.2 Forest Fragmentation Process Model

The model was applied to Washington and Mississippi for two time periods (2001-2006 and 2006-2011) to detect forest landscape changes and identify corresponding spatial processes. The implementation involved:

1. Overlaying forest/non-forest classification maps from two periods using ArcGIS Modeler to obtain missing forest pixels and retained forest pixels
2. Aggregating missing forest pixels using the eight-neighborhood Moore method to form missing forest patches
3. Similarly aggregating retained forest pixels
4. Creating a forest loss layer representing missing forest pixels, with different values representing different retained forest patches
5. Setting the background value of the forest loss layer to 0
6. Using focal analysis to calculate the number of different values within each missing forest pixel' s eight-neighborhood
7. Conducting zonal statistics for each missing forest patch to classify processes based on adjacency patterns

[Figure 3: see original paper] Forest fragmentation process model

The model does not include the dissection type because dissection typically begins with linear corridors, and the moderate spatial resolution of the land cover data cannot adequately capture linear features like roads. Since dissection and fragmentation both involve missing forest patches adjacent to two or more retained forest patches, and dissection develops into areal patterns only at the fragmentation stage, dissection was merged into fragmentation. No minimum patch area threshold was set, with the smallest fragmentation patch area being 30 m × 30 m (one pixel) to ensure more scientific and accurate statistical results.

4. Results

4.1 Overall Land Cover Change

Table 2 shows land cover changes in Washington and Mississippi from 2001 to 2011. Values represent the proportion of each land cover type' s area relative to total study area.

In Washington, shrubland and grassland cover increased substantially (5.82% to 5.97%), urban land increased slightly (6.17% to 6.43%), forest cover decreased continuously (43.39% to 40.06%), and cultivated land fluctuated. Barren land and wetlands remained relatively stable.

In Mississippi, forest cover also decreased continuously (39.60% to 37.73%), while cultivated land cover decreased consistently. Wetlands increased slightly, water decreased, and barren land remained stable initially then increased slightly.

Comparing both states, Washington had the largest forest cover proportion, followed by shrubland, with substantial agricultural land. Mississippi ranked forest cover first, cultivated land second, and wetlands third (proportionally larger). Mississippi' s forest and shrubland proportions were lower than Washington' s, while cultivated land and wetland proportions were significantly higher.

Summary of land-cover statistics for Washington and Mississippi after aggregation

4.2 Forest Loss

Table 3 presents forest loss in both states during the two periods. Forest area data at interval start and end points were derived from land cover data, with the difference representing net forest loss.

Mississippi' s forest loss far exceeded Washington' s in both periods. During 2001-2006, Mississippi' s annual forest loss rate was nearly double Washington' s. Mississippi also showed higher forest recovery area and rates. Washington' s annual forest recovery rate was only 0.01%, indicating that while plantations experience more disturbance, they also recover faster, resulting in smaller net losses.

Area of lost forest during 2001-2006 and 2006-2011 in Washington and Mississippi

4.3 Spatial Processes of Forest Fragmentation

Overlaying multi-temporal land cover data revealed distinct spatial patterns. Overall, Washington' s forest loss concentrated in western coastal areas and northeastern inland regions—natural forest distribution zones. Fragmentation patches clustered at urban-forest and soil transition zones, diffusing outward from urban centers. Perforation patches occurred mainly within large original

forest interiors, while shrinkage patches appeared at edges of previous shrinkage, fragmentation, and perforation patches. Fragmentation patches predominantly converted forest to shrubland and grassland, with larger average areas than other types. Shrinkage patches had the smallest average area and were the most common fragmentation form. Attrition patches were fewest, primarily distributed within medium-large shrub patches.

In Mississippi, fragmentation patches distributed more sparsely and irregularly throughout forest regions, not concentrated at urban-forest interfaces. Except for some northeastern areas following agricultural belts, patches showed no clear pattern. The temporal succession relationships among the four processes were less apparent than in Washington.

[Figure 4: see original paper] Forest fragmentation spatial processes in Washington during 2001-2011

[Figure 5: see original paper] Forest fragmentation spatial processes in Mississippi during 2001-2011

4.4 Temporal Dynamics of Forest Fragmentation

Table 4 shows temporal changes in the four spatial processes. In Washington during 2001-2006, fragmentation caused the largest forest loss area (50.27%), followed by shrinkage (41.46%). Perforation accounted for 16.81%, while attrition was smallest at 11.55%. In the subsequent period (2006-2011), all four process types decreased in area proportion, though fragmentation remained dominant at 40.52%.

In Mississippi during 2001-2006, fragmentation dominated forest loss at 52.35%, with shrinkage second at 40.52%. Perforation and attrition were minimal at 3.02% and 1.66%, respectively. By 2006-2011, fragmentation grew to 69.07% while shrinkage declined to 27.59%.

From a patch quantity perspective, Washington showed shrinkage patches most numerous (67.64%), followed by fragmentation (28.63%) in the first period. In the second period, shrinkage decreased to 61.11% while fragmentation increased to 34.71%. Mississippi exhibited similar patterns, with shrinkage dominant initially then declining as fragmentation increased.

Both natural and plantation forests showed similar temporal patterns: shrinkage dominance gradually receding while perforation and fragmentation increased to establish new dominance. Notably, while perforation area proportions decreased from first to second period in both states, their quantity proportions increased, indicating smaller average patch sizes for perforation.

Area and number percentages of forest patches experiencing different spatial processes in Washington and Mississippi during two time intervals

5. Conclusion

Comparing overall land cover between Washington and Mississippi, forest cover decreased continuously from 2001–2011 in both states. Shrubland and grassland increased consistently. Mississippi's dense river network means wetlands constitute a large land cover proportion. Plantation forest loss area far exceeded natural forest loss, with Mississippi's annual loss rate nearly double Washington's. However, plantations also demonstrated higher recovery area and rates, resulting in smaller net losses.

Spatial process comparison reveals that western natural forest fragmentation patches mostly distribute at interfaces between forests and urban areas, cultivated land, or shrubland, diffusing outward from large urban centers. Plantation fragmentation patches show more scattered, irregular distribution patterns distinct from natural forest ecosystems. Common characteristics include: perforation occurring mainly within large original forest interiors; shrinkage patches having the smallest average area and being most common; attrition patches being fewest; and fragmentation patches having the largest average area.

Examining temporal dynamics, Forman suggested perforation and fragmentation primarily occur in early fragmentation stages, followed by shrinkage and attrition. This study's comparison of Washington and Mississippi found that natural forest fragmentation and shrinkage patches mostly occurred at edges of previous shrinkage, fragmentation, and perforation patches, showing clear temporal succession. Plantation temporal succession was less apparent, though overall patterns were similar, following Forman's theory: initial shrinkage dominance gradually receding while perforation and fragmentation increased to new dominance.

6. Discussion

US natural forests concentrate in the Pacific Northwest and Rocky Mountains. Post-WWII timber demand surges led to extensive natural forest logging and legal disputes over endangered wildlife protection. In 1993, the US government launched the Northwest Forest Plan, a large-scale forestry initiative targeting natural forest conservation. Under this plan and various protection policies, the northwestern region developed strict forest management rules and high management standards, reducing timber supply from public lands, increasing natural forest area, and stabilizing ecosystems.

However, human impacts remain significant. Washington's average annual forest conversion rate was 0.37% during 2001–2006, increasing to 0.55% during 2006–2011, indicating persistent forest erosion. The southeastern US has very high forest cover and private forest ownership rates. By 2010, plantations (including Mississippi) reached 16.43 million hectares through artificial planting or regeneration. These monoculture plantations have low biodiversity, poor stress

resistance, and experience intense natural and anthropogenic disturbances, with average annual loss rates exceeding natural forests nearly twofold. However, plantations recover faster under management interventions, resulting in modest net losses.

Most southeastern states lack forest management laws, allowing private forest owners discretionary treatment without legal harvest limits, often employing clear-cutting. This creates scattered, irregular fragmentation patterns reflecting plantation ecological structure and management approaches.

This study's forest fragmentation process model clarifies spatial and temporal dynamics of northwestern natural forests and southeastern plantations, addressing the limitation of previous static pattern studies by quantifying fragmentation patch distribution and change processes using two time points. This provides scientific guidance for natural forest protection and plantation management, with important implications for interpreting policy, developing future ecological protection systems, and promoting sustainable forestry.

The study directly compares land cover data, so classification errors affect process classification accuracy. NLCD data accuracy averages 78–87%, and future use of more precise land cover data could improve results. Some errors and misclassifications remain unavoidable.

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