Effects of Different Anthropogenic Disturbance Measures on Soil Fertility and Water Storage Capacity of Natural Secondary Shrublands (Postprint)

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Abstract

Natural secondary shrub forests formed by the degradation of subtropical evergreen broad-leaved forests after repeated disturbances are difficult to restore to arbor forests under unmanaged conditions. Typical natural secondary shrub forests were selected in Lin' an City, Zhejiang Province, with intensive human disturbance as the control, and protective disturbance and moderate human disturbance were applied respectively to explore the response of soil water storage capacity and fertility quality in the shrub forests. Four-year experimental results showed that: compared with intensive human disturbance, soil total water storage, retained water storage, and detained water storage increased by 12.41%, 5.33%, and 17.37% under protective disturbance, and by 29.13%, 33.23%, and 26.24% under moderate human disturbance, respectively; maximum water holding capacity, capillary water holding capacity, and minimum water holding capacity increased by 23.35%, 9.51%, and 17.55% under protective disturbance, and by 48.63%, 56.08, and 71.05% under moderate human disturbance, respectively; compared with intensive human disturbance, comprehensive fertility increased by 1.9% and 38.5% under protective disturbance and moderate human disturbance, respectively, with hydrolyzable nitrogen, organic carbon, and organic matter content increasing by 12.11%, 38.91%, and 38.94% under protective disturbance, and hydrolyzable nitrogen, available phosphorus, organic carbon, and organic matter content increasing by 61.97%, 90.57%, 130%, and 130.04% under moderate human disturbance, respectively; the comprehensive soil evaluation index increased by 15.43% and 58.94% under protective disturbance and moderate human disturbance, respectively. The study demonstrates that compared with protective disturbance, moderate human disturbance can better achieve the desired objectives in terms of soil water storage and retention,

fertility, and carbon sequestration and sink enhancement. Under conditions where management is feasible, moderate human disturbance measures can be selected to manage natural secondary shrub forests, thereby accelerating soil restoration.

Full Text

Effects of Different Human Disturbance Measures on Soil Fertility and Water Storage Capacity of Natural Secondary Shrublands

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Abstract

Natural secondary shrublands formed from degraded subtropical evergreen broadleaf forests under repeated disturbance struggle to recover to arboreal forest without protective management. To explore how shrubland soil water storage capacity and fertility quality respond to different disturbance regimes, we conducted a four-year experiment (2012–2015) in typical natural secondary shrublands in Lin' an, Zhejiang Province, using high human disturbance as a control. Compared with high disturbance, protective human disturbance (PHD) and moderate human disturbance (MHD) increased soil total storage, retention storage, and short-term storage by 12.41%, 5.33%, 17.37% and 29.13%, 33.23%, 26.24%, respectively. Soil maximum water-holding capacity, capillary water-holding capacity, and minimum water-holding capacity increased by 23.35%, 9.51%, 17.55% under PHD and by 48.63%, 56.08%, 71.05% under MHD. Comprehensive soil fertility increased by 15.43% under PHD and 58.94% under MHD. Available nitrogen, organic carbon, and organic matter content increased by 12.11%, 38.91%, and 38.94% under PHD, respectively, while under MHD, available nitrogen, available phosphorus, organic carbon, and organic matter content increased by 61.97%, 90.57%, 130%, and 130.04%, respectively. The integrated soil quality index increased by 15.43% under PHD and 58.94% under MHD. Bivariate correlation analysis revealed strong positive correlations between comprehensive soil fertility, water storage, and organic carbon. Protective disturbance decreased soil bulk density while increasing total porosity, water storage, available nitrogen, and organic matter, attributable to accelerated tree growth and increased litterfall from prohibiting fuelwood collection. Moderate disturbance not only banned fuelwood collection but also selected and tended target trees, reducing competition, accelerating shrub closure and biomass accumulation, enhancing precipitation interception, and reducing soil erosion. Tended biomass retained on-site increased litter quantity. Compared with high and protective disturbance, moderate disturbance most effectively decreased soil density while increasing capillary, non-capillary, and total porosity, total water storage, available nitrogen, and organic matter. Both protective and moderate disturbance reversed retrogressive succession, accelerated tree growth, improved stand structure, enhanced nutrient cycling, increased organic matter and integrated fertility, creating a mutually reinforcing relationship between tree growth and soil recovery. In conclusion, moderate human disturbance is superior to protective disturbance for achieving desired goals of soil water conservation, fertility improvement, and carbon sequestration in secondary shrub communities. Under favorable operating conditions, moderate disturbance should be selected to accelerate soil restoration in natural secondary shrublands.

Keywords: natural secondary shrubland; human disturbance; soil water storage; soil fertility; soil organic carbon; closed forest management

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1. Introduction

Evergreen broadleaf forest is the zonal vegetation type in China’ s subtropical region and constitutes an important component of subtropical terrestrial ecosystems. However, intense human disturbance has led to degradation, replacing these forests with large areas of secondary forests, shrublands, and herbaceous communities at various stages of degradation. Shrublands cover approximately one-third of China’s subtropical region and represent a common vegetation type in eastern China. These degraded ecosystems exhibit poor resistance to disturbance, weakened water conservation capacity, reduced soil fertility quality, and soil degradation. Implementing appropriate human disturbance measures to reverse this retrogressive succession and restore positive vegetation development is crucial for ecological balance and sustainable forest development in the region.

The relationship between vegetation succession and soil property evolution is not only a key focus of ecological research but also a critical consideration for forest managers confronting widespread forest site degradation. However, few studies have examined human disturbance methods for secondary shrubland restoration and associated changes in soil physicochemical properties. Appropriate management interventions can improve community structure, biodiversity, and productivity while promoting succession and influencing soil ecosystems, ultimately affecting the comprehensive restoration of degraded ecosystem functions. Plants and soil are mutual environmental factors, and plant community succession represents an interactive process among vegetation, climate, and soil.

Soil serves as the foundation for water balance, litter decomposition, and nutrient cycling in ecosystems, making its restoration an indispensable component of degraded forest ecosystem recovery. As vegetation type transitions during long-term successional processes, human disturbance patterns and frequencies must adapt accordingly. For secondary shrubland restoration, changes in plant composition, coverage, and litter properties and quantity affect numerous ecological processes that influence the soil ecosystem. Both forest closure and near-natural management represent effective restoration models for fragile and degraded forest ecosystems. Due to low cost and minimal technical requirements, closure management is often adopted as a protective disturbance measure for secondary shrubland communities, minimizing non-natural and anthropogenic interference. Near-natural management, which fully utilizes natural productivity and forest self-recovery capacity, represents a moderate disturbance approach.

This study applied the tree classification method from near-natural management to select target trees for tending in natural secondary shrublands, implementing moderate disturbance to promote target tree growth and formation of an arbor layer while monitoring soil changes. Soil water storage capacity and fertility are fundamental soil attributes that reflect the degree of secondary shrubland recovery. With shrubland area in Zhejiang Province reaching approximately 2,153,400 hectares, this research used typical secondary shrublands in Lin' an City as study sites to investigate soil water storage capacity and fertility responses to different disturbance measures, providing scientific guidance for regional shrubland restoration and soil recovery.

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2. Study Area Overview

The study site is located in Lin' an City, northern Zhejiang mountainous region (29°56 -30°23 N, 118°51 -119°52 E), characterized by a mid-subtropical monsoon climate with low hills terrain. The area has a mean annual temperature of 15.9°C, annual precipitation of 1,614 mm, annual sunshine hours of 1,774 h, and a frost-free period of 237 days. Soils are predominantly slightly acidic red soils. Zonal vegetation is subtropical evergreen broadleaf forest, with dominant species including *Schima superba*, *Cyclobalanopsis glauca*, and *Castanopsis sclerophylla*. Due to human disturbance and destruction, evergreen broadleaf forests have degraded into secondary shrubland vegetation, with extremely slow recovery of zonal vegetation. Some shrubland communities have become relatively stable human-induced climax communities, with severe soil degradation and long-term stagnation at the secondary shrub stage, threatening sustainable forest ecosystem development.

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3. Sample Plot Establishment

We selected typical natural secondary shrublands with consistent natural environmental conditions as experimental forests, formed through repeated logging degradation of secondary evergreen broadleaf forests, with an average height of approximately 1.6 m. The stand was dominated by *Quercus glandulifera*, *Quercus acutissima*, *Quercus fabri*, *Loropetalum chinensis*, *Vaccinium bracteatum*, and *Ilex chinensis*. The area was divided into two distinct zones: one under high human disturbance (control) without any protective measures, where activities such as fuelwood collection and herb gathering occurred occasionally; and another under closure management with strict prohibition of human entry.

The closure zone was further divided: half received pure closure management as protective human disturbance (PHD), while the other half received near-natural management with target tree tending as moderate human disturbance (MHD). Within the shrubland, we surveyed and selected competitive arbor species as priority target trees, identifying *Pinus massoniana*, *Liquidambar formosana*, *Dalbergia hupeana*, and *Diospyros kaki* as primary target species, with *Quercus glandulifera* as an alternative. We selected well-growing, competitively superior individuals as target trees, conducted sprout removal and understory vegetation cutting around them, and retained the cut material near target trees.

In 2012, we established three 20 m × 20 m sample plots for each treatment (high disturbance, protective disturbance, and moderate disturbance), with 400 m spacing between plots. Characteristics during remeasurement in 2015 are shown in .

** Basic plot properties under different human disturbance measures**

<table>
<tr><th>Disturbance measure</th><th>Average DBH in 2015 (m)</th><th>Average height in 2015 (m)</th><th>Litter weight (g/m^2)</th></tr>
<tr><td>High human disturbance</td><td colspan="3">1.32$±0.41a|2.08±0.56a|130.01±13.33c||Protectivehumandisturbance|2.71±0.95b|2.90±0.8</td></tr>
</table>

Note: Different lowercase letters within the same column indicate significant differences (P<0.05).

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4. Soil Sample Collection and Measurement

Within each plot, we selected the center and four points 100 cm from the center as sampling locations. After removing surface litter, we collected soil samples using a 100 mL ring cutter at the central point to determine soil bulk density and field maximum water-holding capacity. At all five sampling points, we collected 300 g of soil at 20 cm depth, which were mixed into one composite sample, air-dried in the laboratory, and sieved to remove vegetation roots and organic residues >2 mm.

Soil porosity was determined using the Wilcox method. Maximum water-holding capacity, capillary water-holding capacity, and minimum water-holding capacity were measured following the *Soil Agrochemical Analysis Manual*. Soil chemical properties were measured using conventional methods: soil organic carbon by potassium dichromate oxidation, hydrolyzable nitrogen by alkali diffusion method, available phosphorus by Bray et al. (1945) method, available potassium by flame photometry, and pH using a PHS-3C precision pH meter.

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5. Soil Layer Water Storage Calculation

Soil porosity is a critical indicator of water-holding and storage capacity. Higher porosity indicates stronger water retention. Non-capillary porosity reflects short-term precipitation detention, while capillary porosity reflects long-term water storage and infiltration capacity. Soil layer maximum water-holding capacity and water storage refer to the soil' s maximum water retention, while non-capillary water storage refers to short-term water storage after rainfall—both are important indicators for calculating soil water conservation capacity. Formulas are as follows:

$$W_t = P_t \times h \times s$$
$$W_{nc} = P_{nc} \times h \times s$$
$$W_c = P_c \times h \times s$$

Where:
W_t, W_{nc}, and W_c represent total soil layer water storage, retention water storage, and short-term storage, respectively;
P_t, P_{nc}, and P_c represent total porosity, non-capillary porosity, and capillary porosity, respectively;
h is the average soil layer thickness (20 cm in this experiment);
s is the vegetation-covered area.

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6. Soil Organic Carbon Storage

Soil organic carbon storage per unit area was calculated using:

$$soc = SOC \times h \times SD$$

Where:
soc is soil organic carbon storage per unit area (g/m^2);
SOC is soil organic carbon content (g/kg);
h is soil layer depth (20 cm);
SD is soil bulk density (g/cm^3).

We then used the correlation coefficient method to comprehensively evaluate soil from three aspects: soil fertility, water storage, and carbon storage.

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7. Calculation of Soil Comprehensive Evaluation Index

7.1 Nemerow Index The Nemerow index, originally based on single-factor assessment for water quality evaluation, provides more precise results for long-term fertilized soil fertility assessment. Bao Yaoxian et al. found the Nemerow index method effective for soil fertility evaluation. Calculation involves first determining sub-fertility coefficients (IFI_i):

$$IFI_i = \frac{x - x_a}{x_b - x_a} \quad (x \leq x_b)$$
$$IFI_i = \frac{x - x_b}{x_c - x_b} \quad (x_b < x \leq x_c)$$
$$IFI_i = 1 \quad (x > x_c)$$

Where x is the measured value, and x_a, x_b, and x_c are the upper limits of grading standards from the Second National Soil Survey. These sub-fertility coefficients are then incorporated into a modified Nemerow formula to calculate comprehensive soil fertility:

$$F = \sqrt{\frac{IFI_{avg}^2 + IFI_{min}^2}{2}}$$

Where F is comprehensive soil fertility, IFI_{avg} is the mean of sub-fertility coefficients, and IFI_{min} is the minimum sub-fertility coefficient.

** Grading values of soil fertility indexes**

Grade	AN (mg/kg)	AP (mg/kg)	AK (mg/kg)	OM (g/kg)
...	...	...	...	...

7.2 Correlation Coefficient Method The correlation coefficient method, a type of fuzzy comprehensive evaluation, is commonly used for soil fertility assessment. Based on fuzzy mathematics principles, the integrated soil quality index (ISQI) is calculated as:

$$ISQI = \sum_{i=1}^{n} W_i \times N_i$$

Where $ISQI$ is the integrated soil quality index (0≤ISQI$ $1), with higher values indicating better quality; N_i is the membership degree of the ith evaluation index; W_i is the weight of the ith index; and n is the number of evaluation indexes. The weight is determined as the ratio of the mean correlation coefficient between one index and all other indexes to the sum of all such mean correlation coefficients.

We used variable correlation analysis to explore relationships among soil fertility, water storage, and organic carbon storage. SPSS 20.0 software performed one-way ANOVA to analyze significant differences in soil physicochemical properties among treatments, examining effects of different management approaches on soil fertility and water storage. The 2015 soil organic carbon content and comprehensive evaluation index were also analyzed.

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8. Results

8.1 Effects of Different Disturbance Measures on Soil Water Storage Capacity Soil bulk density and porosity are critical indicators of soil compactness and water storage capacity. Significant differences existed among treatments in bulk density, non-capillary porosity, total water storage, and retention storage. Moderate disturbance showed significant differences from other treatments in capillary porosity and water-holding storage. Protective disturbance differed significantly from high disturbance in capillary porosity and water-holding storage.

Compared with high disturbance, protective disturbance significantly increased total porosity (12.39%), non-capillary porosity (17.38%), total water storage (12.41%), and retention storage (17.37%), while decreasing soil bulk density by 5.33%. Moderate disturbance significantly increased capillary porosity, water-holding storage, and retention storage compared with high disturbance, with increases of 29.11%, 33.24%, and 26.26%, respectively, and total porosity, non-capillary porosity, and total water storage increased by 29.13%, 33.23%, and 26.24%, respectively, while soil bulk density decreased by 7.56%. Compared with protective disturbance, moderate disturbance showed significant improvements, with soil bulk density decreasing by 14.87% and capillary porosity, water-holding storage, and retention storage increasing by 26.48%, 29.77%, and 26.24%, respectively. These results indicate that moderate disturbance created the loosest soil with the strongest water storage capacity.

Soil moisture is a crucial factor promoting soil fertility and directly affects vegetation growth. Compared with high disturbance, protective disturbance significantly increased maximum water-holding capacity, capillary water-holding capacity, and minimum water-holding capacity by 23.35%, 9.51%, and 17.55%, respectively, while moderate disturbance increased them by 48.63%, 56.08%, and 71.05%, respectively. Compared with protective disturbance, moderate disturbance significantly increased these parameters by 20.49%, 42.53%, and 45.51%, respectively. Both protective and moderate disturbance improved soil water-holding capacity, with moderate disturbance showing superior effects.

** Soil water storage capacity under different disturbance measures**

Disturbance measure	Soil density (g/cm^3)	Total porosity (%)	Capillary (%)	Non-capillary (%)	Total storage (t/hm^2)	Retention storage (t/hm^2)	Short-term storage (t/hm^2)
High disturbance	1.31$±0.05c	50.43±2.05c	20.79±2.70b	29.63±2.61c	1008.5±41.02c	415.83±53.99b	592.67±52.19c||Pr

Note: Different lowercase letters within the same column indicate significant differences (P<0.05).

[Figure 1: see original paper] Soil water-holding capacity under different disturbance treatments

8.2 Effects of Different Disturbance on Soil Fertility and Carbon Storage Compared with high disturbance plots, protective disturbance plots showed significant increases in soil available nitrogen (12.11%), organic carbon (38.91%), and organic matter content (38.94%). Moderate disturbance plots exhibited even more substantial increases in available nitrogen (61.97%), available phosphorus (90.57%), organic carbon (130%), and organic matter (130.04%) compared with the control. However, available potassium and phosphorus contents decreased significantly under protective disturbance (by 12.06%). Variance analysis revealed significant differences between protective and moderate disturbance in available nitrogen, organic carbon, and organic matter (P<0.05), with moderate disturbance showing particularly pronounced effects on organic matter and organic carbon—its organic matter increase was 3.34 times that of protective disturbance, followed by available nitrogen (increase of 20.08%). Changes in available potassium were relatively small.

** Soil fertility and organic carbon under different disturbance measures**

Disturbance measure	Available nitrogen (mg/kg)	Available phosphorus (mg/kg)	Available potassium (mg/kg)	Organic carbon (g/kg)	Soil organic matter (g/kg)
High disturbance	85.45$±1.72b	4.88±0.37b	79.27±4.06a	10.1±0.55c	17.41±0.28c||Protectivedisturbance|95.8±2.36b|

Note: Different lowercase letters within the same column indicate significant differences (P<0.05).

8.3 Comprehensive Soil Quality Evaluation Soil comprehensive fertility, water storage, and organic carbon storage showed extremely strong positive correlations. The average correlation index was highest for soil comprehensive fertility (0.776), followed by soil organic carbon content (0.724), with soil layer water storage showing the lowest average correlation index (0.621). However, soil water storage showed higher correlation with comprehensive fertility than with organic carbon content, indicating that comprehensive fertility is more important than organic carbon, which is more important than water storage in the integrated quality evaluation.

The proportions of soil comprehensive fertility, water conservation capacity, and carbon sequestration capacity in the integrated soil quality evaluation index were 35.85%, 30.77%, and 33.38%, respectively. The integrated soil quality index under protective disturbance was 15.43% higher than under high disturbance, while under moderate disturbance it was 58.94% higher than high disturbance and 37.69% higher than protective disturbance. Moderate disturbance performed best across all evaluation indicators, demonstrating the highest comprehensive soil quality.

** Correlations among soil fertility, water storage, and carbon content**

Index	Integrated fertility	Soil layer water storage	Soil organic carbon
Integrated fertility	1	0.671**	0.776**
Soil layer water storage	0.671**	1	0.571**
Soil organic carbon	0.776**	0.571**	1

** Integrated soil quality index under different disturbance measures**

Disturbance measure	Integrated fertility index	Soil layer water storage (t/hm^2)	Soil organic carbon storage (g/m^2)	Integrated soil quality index
High disturbance	1.04$±0.00b	1008.50±41.02c	3.97±0.06c	0.28±0.01c
Protective disturbance	1.06±0.00b	1133.63±3		

9. Discussion and Conclusion

Soil quality is influenced by both natural factors and human activities. Human disturbance not only removes substantial nutrients from forests, significantly reducing light humus content and directly causing fertility decline, but also compacts soil through trampling and mechanical pressure, indirectly reducing porosity and infiltration capacity. In our high disturbance area, occasional fuelwood collection removed timber from the forest, resulting in slow increases in shrub height, porosity, water storage, and water-holding capacity. Non-capillary porosity and retention water-holding capacity were particularly affected, with significant declines in hydrolyzable nitrogen, organic matter, and organic carbon.

Our results demonstrate that both protective and moderate disturbance reversed retrogressive succession, accelerated community growth, improved stand structure, enhanced soil nutrient cycling, increased organic matter, improved integrated fertility, and created a mutually reinforcing relationship between aboveground tree growth and soil improvement. Intense human disturbance is the primary reason secondary shrubland soils fail to recover. Protective and moderate disturbance can enhance soil water conservation, carbon sequestration, and fertility.

Protective disturbance prohibited fuelwood collection, accelerating tree growth and increasing litterfall. Compared with high disturbance, protective disturbance significantly reduced soil bulk density, increased water storage capacity, and increased available nitrogen, organic carbon, and organic matter. Forest closure can significantly increase litter storage, reduce surface runoff velocity and erosion, enhance precipitation infiltration, and increase retention water storage, thereby improving overall soil water conservation capacity. Increased litter also promotes decomposition, significantly increasing available nitrogen, organic carbon, and organic matter.

Moderate disturbance, based on closure management, purposefully transformed the shrubland by selecting and tending target trees while stopping destructive activities. This reduced competition pressure on target trees, promoted their growth, accelerated shrub-to-forest transition, enhanced precipitation interception, reduced soil erosion, and increased vegetation cover and biomass. Combined with root system recovery, this significantly increased soil porosity and water conservation capacity. The increased water-holding capacity accelerated litter decomposition, further enhancing soil fertility. Unlike the slow litter increase under protective disturbance, moderate disturbance initially generated significantly more litter through tending activities around target trees, leading to higher total litter quantity and faster decomposition rates, resulting in significantly higher soil comprehensive fertility than protective disturbance.

Correlation analysis revealed strong positive relationships between soil fertility and water storage capacity, as organic matter promotes aggregate formation. Increased aggregates enhance total porosity. Soil fertility and organic carbon showed strong positive correlation because nitrogen addition promotes decomposition of lighter carbon compounds while stabilizing heavier carbon compounds. The high correlation among fertility, organic matter, and organic carbon occurs because these properties primarily derive from organic matter decomposition, which is the most important component of ecosystem productivity and renewal and a key factor in vegetation and soil recovery.

In conclusion, under favorable operating conditions, moderate human disturbance should be selected for managing natural secondary shrublands to accelerate soil restoration. Moderate disturbance more effectively achieves goals of water conservation, fertility improvement, and carbon sequestration compared with protective disturbance alone.

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Note: Figure translations are in progress. See original paper for figures.