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Variability after 15 Years of Vegetation Recovery in Natural Secondary Forest with Timber Harvesting at Different Intensities in Southeastern China: Community Diversity and Stability

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Received: 21 November 2017; Accepted: 16 January 2018; Published: 18 January 2018

Abstract: The mixed *Cunninghamia lanceolata* (Lamb.) Hook., *Pinus massoniana* Lamb., and hardwood forest in southeastern China is a major assemblage in natural secondary forests, and of national and international importance in terms of both timber and ecosystem services. However, over-harvesting has threatened its long-term sustainability, and there is a knowledge gap relating to the effect of harvesting on the ecosystem. After conifer species were selected for harvesting, the mixed Chinese fir, pine, and hardwood forest was changed into mixed evergreen broadleaf forest. In this context, we observed the restoration dynamics of plant communities over a period of 15 years (1996 to 2011) with different levels of harvesting intensity, including selective harvesting at low (13.0% removal of growing stock volume), medium (29.1%), high (45.8%), and extra-high (67.1%) intensities, as well as clear-cut harvesting (100.0%), with non-harvesting as the control, based on permanent sample plots established in a randomized block design in these forests in southeastern China. The impact on the richness, diversity, and evenness of plant species derived from descriptive statistical analyses was shown to initially increase, and then decrease, with an increase in harvesting intensity. The most critical impacts were on the richness, diversity, and evenness of shrub and herb species. Richness, diversity, and evenness of plant species recovered and increased under selective harvesting at low and medium intensities, while these parameters had not recovered and significantly decreased under selective harvesting at high and extra-high intensities, as well as with clear-cut harvesting. The impact on the plant community stability was derived from the stability test method of the improved Godron M. The plant community stability was closest to the point of stability (20/80) under selective harvesting at medium intensity, followed by selective harvesting at low intensity. The plant community stability was far from the point of stability (20/80) under selective harvesting at high and extra-high intensities, as well as with clear-cut harvesting. Of these treatments, clear-cut harvesting had the greatest effect with regard to reducing stability. Therefore, these results indicate that the selective harvesting at low and medium intensities is conducive to preserve or increase the species diversity and community stability. In order to prioritize promoting plant species diversity, clear-cut harvesting and selective harvesting at high and extra-high intensities should be avoided with regard to this type of forest in this region. This study sheds light on the practice of forest operation in the study region and subtropical forests with the same environment.

Keywords: plant diversity; plant community stability; selective harvesting; harvesting intensity; mixed forest

1. Introduction

Forests are increasingly recognized as a critical element of the global ecosystem, given their importance in providing multiple environmental services, such as carbon sequestration and storage, biodiversity conservation, climate change mitigation, poverty alleviation, and watershed protection [1]. Conservation of species diversity in managed forests is an important objective in sustainable forest management [2,3]. Plant diversity in forests, a measure of community structural and functional complexity, maintains the operation of an ecosystem on a complex spatial–temporal scale [4,5]. High species diversity is the basis of ecosystem stability, and this factor likely facilitates the optimization of ecosystem functions [6]. As a comprehensive feature of plant community structure and function, stability is not only closely related to community structure and function, but is also correlated with the nature and intensity of external interference [7–9]. Most tropical forests, even those in protected areas, are influenced by human activity [10]. To meet livelihoods, forest harvesting needs can impact forest regeneration, structure, and diversity [11], but there is scope for considerable variation with location, human activities, and histories [12]. Different types and intensities of local resource extraction can lead to varying outcomes even within one forest [13]. So, the diversity in human activities and their impacts call for different interventions.

Southeast China is located in the subtropical zone. The mixed Chinese fir (*Cunninghamia lanceolata* (Lamb.) Hook.), pine (*Pinus massoniana* Lamb.), and hardwood forest in southeastern China is a major assemblage in natural secondary forests. After conifer species were selected for harvesting, the mixed Chinese fir, pine, and hardwood forest was changed into the mixed evergreen broadleaf forest. Evergreen broadleaf forest is the common zonal vegetation found in the northern Fujian Province of China and is one of the typical types of vegetation in subtropical areas. Evergreen broadleaf forest is characterized by a rich floristic composition and biodiversity, as well as significant ecological functions. However, many primary forests have been or are currently being converted into secondary forests because of historical reasons and human interference [14]. Except for several natural conservation areas, only a few primitive, evergreen, broadleaf forests are left because of human interference, which is unsustainable at the landscape and timber stand level. Sustainable forest management is being advanced by the forestry sector with the expectation, amongst others, that it will reduce the environmental impacts caused by deforestation [15]. Conservation and utilization are both integral parts of sustainable forest management. Forest selective harvesting and clear-cut harvesting are the management practices most frequently used for silvicultural rotation and timber harvesting worldwide [16,17]. In terms of the ecological perspective of forest harvesting, selective harvesting is common and most reasonable as applied to natural secondary forests based on forest characteristics and geographic locations [18,19]. Evergreen broadleaf forest is widely recognized as providing ecological, economic, and social benefits and supporting governmental efforts related to biodiversity conservation and forest protection [20]. A major challenge of forest management is to maintain the biodiversity and integrity of the forests, while at the same time satisfying human needs through productive activities. While the selective extraction of natural resources has less severe consequences on biodiversity and ecosystem function than the complete removal of vegetation, such consequences need to be evaluated in detail [21–23]. Therefore, investigating the long-term impact of harvesting intensity on community species diversity and stability is significant to forest management theory and practice.

Vast expanses of tropical forests worldwide are being impacted by selective harvesting [24]. To select the appropriate level of harvesting intensity for a certain stand is a basic challenge in forest management planning. The decision depends on economic as well as biological factors [25]. Forest management employing clear-cut harvesting and artificial reforestation has been the dominant silviculture regime in natural forests in China for 50–60 years. After 1998, the implementation of natural forest protection projects saw increased attention drawn to uneven-aged forests, selective harvesting, and natural reforestation. This increased interest is partly due to expected enhancements for landscape aesthetics and biodiversity, and to expected benefits for reforestation costs, timber quality, and profits.

Selective harvesting has certain characteristics: (i) only a part of the standing volume is harvested; (ii) conditions for recruitment are favoured in order to maintain or develop an uneven-aged forest structure; (iii) the decision unit is the individual tree, or small groups of trees; and (iv) the choice of trees to be harvested is based on certain specified attributes (e.g., tree size, timber quality, volume increment, or financial maturity) [25]. Long-term field experiments with selective harvesting in uneven-aged coniferous forests have shown that inappropriate forest structures and poor conditions for natural reforestation can cause low volume production, and hence, low profitability [26]. Previous research on plant diversity in forests mainly focused on biodiversity features and differences among various undisturbed forest types and communities [27]. In terms of human interference, the effect of selective harvesting intensity on species diversity and stability should be described in detail. For instance, the monitoring of changes in species diversity and stability during vegetation restoration after different harvesting intensities is one of the main research goals of sustainable forest management [28,29]. Many studies have referred to the impact of harvesting intensity on biodiversity [30–32].

For the purpose of timber production, the traditional clear-cut harvesting was a productive forest operation. It only considered economic benefits and seriously damaged the ecological environment. A large number of studies have shown that selective harvesting is the most suitable management of natural secondary forests [19,25,33]. But, for specific natural secondary forest, in order to protect species diversity and maintain community stability, the suitable selective harvesting intensity is not yet clear. To date, only a few studies have reported on the effect of selective harvesting intensity on plant species diversity and community stability of natural, secondary forests in subtropical areas. Most of the studies used space instead of time (temporary plots) to analyze the short-term effects of harvesting on species diversity, but few established long-term, fixed plots for the study [19,33]. In order to manage the forest scientifically, our study examined the long-term effects of harvesting intensity on the species diversity and community stability of natural secondary forests in subtropical areas 15 years after harvesting. We addressed the following two questions. Was the plant species diversity different in natural secondary forests with different harvesting intensities? Was plant community stability different in natural secondary forests with different harvesting intensities?

2. Methods

2.1. Study Area

The selected study area was in the Dayuan Forest Farm, Jianou County, Fujian Province, southeastern China (117°58′45″–118°57′11″ E, 26°38′54″–27°20′26″ N). The study area was located between two mountains, with the Wuyi Mountains to the northwest and the Jiufeng Mountains to the southeast. The experimental site is characterized as low mountain hilly terrain. The elevation of the site ranges from 600 to 800 m, with a slope of 25–34°. This area has a subtropical maritime monsoon climate. The mean annual temperature is 15–17 °C, and annual precipitation is 1890 mm. According to the United States Department of Agriculture (USDA) soil taxonomy, the soil at the study site is oxisol [33].

Main tree species in the natural secondary forest are *Castanopsis eyrei* (Champ.) Tutch., *Castanopsis carlesii* (Hemsl.) Hayata, *Daphniphyllum oldhamii* (Hemsl.) Rosenth, *Schima superba* Gardner and Champ., *Pinus massoniana* Lamb. and *Adinandra millettii* Hook. Main shrub species on the site include *Adinandra millettii* Hook. and Arn., *Lithocarpus glaber* (Thumb.) Nakai, *Engelhardtia fenzelii* Merr., *Symplocos congesta* Benth., *Eurya nitida* Korth., and *Rhaphiolepis indica* (L.) Lindl. Ex Ker Gawl. Underground herbaceous and liana species are dominated by *Dicranopteris dichotoma* (Thunb.) Bernh., *Smilax china* L., *Woodwardia japonica* (L.f.) Sm., *Hicriopteris chinensis* (Rosenst.) Ching, and *Gahnia tristis* Nees. More details about the characteristics of this forest can be found in a previous study [33].

2.2. Sampling Design and Survey

The experiment plots (20 m × 20 m) were established using a randomized block design. Blocking factors included topography, soil, and initial forest stand conditions. There were five treatments, including four selective harvesting intensities, clear-cut harvesting, and non-harvesting as the control. Three replicates plots were set up for each treatment. The four selective harvesting intensities were low intensity (13.0% removal of growing stock volume), medium intensity (29.1%), high intensity (45.8%), and extra-high intensity (67.1%). The plots were established in March, 1996. The characteristics of the forest stands in the treatment plots before and immediately after the harvesting were shown in our previous study [33].

Selective harvesting was executed in accordance with the technical requirements established by the single-tree selection method [34]. Defective and inferior trees were cut out first, followed by over-mature and some mature trees, to create healthy and vigorous forest stands that had a similar species composition to the original forest and the target density under each harvesting intensity. The low intensity mainly harvested *Pinus massoniana* Lamb. and *Schima superba* Gardn. et Champ. The medium intensity mainly harvested *Pinus massoniana* Lamb. The high and extra-high intensity mainly harvested *Pinus massoniana* Lamb. and *Castanopis carlesii* (Hemsl.) Hay. After conifer species were selected for harvesting, the mixed Chinese fir, pine, and hardwood forest was changed into mixed evergreen broadleaf forest. The harvesting operations were as follows: harvesting used a chainsaw, branching and bucking also used a chainsaw on site, and skidding used manual power. Branches of >5 cm in diameter were collected and utilized. This harvesting method is common in this region. The plots were investigated again in August 2011 (15 years after harvesting).

As shown in Figure 1, the adjacent gridding method was used to measure the trees. Each plot was divided into sixteen 5 m × 5 m quadrats by nylon rope. Trees with a diameter at breast height (DBH) >5 cm within the plots were identified individually, with their species name, DBH, height, and crown breadth recorded. Eight quadrates of 5 m × 5 m (200 m^2) were selected along the diagonal of the plot to measure shrubs, with their species name, number, and height recorded. One quadrate of 1 m × 1 m in every shrub quadrate (8 m^2) was selected to measure herbs, with their species name, number, and coverage recorded.

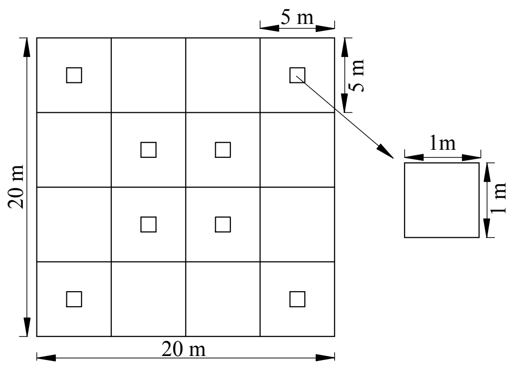

Figure 1. Quadrat layout for one sample plot.

2.3. Data Analysis

In a 20 m × 20 m plot for each harvesting treatment, all survey samples of the tree, shrub, and herb layer were merged together, respectively. To determine the plant species diversity of different harvesting intensities, plant diversity was evaluated by computing three classical indices: the Margalef species richness index [35], the Shannon–Wiener diversity index [36], and the Pielou evenness index [37,38], as follows:

$$\text{Margalef richness index}: R = (S - 1)/\ln N \quad (1)$$

$$\text{Shannon-Wiener diversity index}: H = -\sum_{i=1}^{s} P_i \ln P_i \quad (2)$$

$$\text{Pielou evenness index}: J = H/\ln S \quad (3)$$

where N is the total number of individuals in a plot; P_i is the relative frequency of ith species within a plot ($P_i = N_i/N$, N_i is the number of individuals of ith species in a plot); and S is the total number of species in a plot. According to various layers (tree, shrub, and herb), their diversity indices were calculated separately. R_1, H_1, and J_1 are the richness, diversity, and evenness of the tree layer, respectively. R_2, H_2, and J_2 are the richness, diversity, and evenness of the shrub layer, respectively. R_3, H_3, and J_3 are the richness, diversity, and evenness of the herb layer, respectively.

One-way ANOVA and Scheffe multiple tests were performed to compare the impacts on species diversity indices of various layers and overall plants. Scheffe is one of multiple comparisons based on t statistics. It can make a comparison between any two treatments. Means for groups in homogeneous subsets are displayed. These methods have been confirmed to be effective in previous studies [39,40].

Community diversity indices:

$$R_4 = \alpha R_1 + \beta R_2 + \gamma R_3 \quad (4)$$

$$H_4 = \alpha H_1 + \beta H_2 + \gamma H_3 \quad (5)$$

$$J_4 = \alpha J_1 + \beta J_2 + \gamma J_3 \quad (6)$$

where R_4, H_4, and J_4 are the richness, diversity, and evenness of overall plants (community), respectively; α, β, and γ are the given weighting coefficients of tree, shrub, and herb, which are determined to be 0.50, 0.25, and 0.25, respectively [41,42].

With the date derived from field measurements and the mean value of three species diversity indices, we calculated the percentage change in species diversity indices under different harvesting intensities relative to non-harvesting. That is, we computed the ρ value [33,43] as follows:

$$\rho = \frac{X_{ij} - X_{i0}}{X_{i0}} \times 100\% \quad (7)$$

where X_{ij} is the mean value of the species diversity index i at the sites with harvesting intensity j and X_{i0} is the mean value of the species diversity index i in the non-harvesting plots. The percentage change (ρ) reflects the change in species diversity indices at a specific harvesting intensity when compared to non-harvesting 15 years after the harvesting.

The stability test method of Godron M. was discovered by the French ecologists from industrial production and introduced into plant ecology [44]. After this method was introduced into China, it was improved by Zheng (2000) and has been confirmed to be reliable in previous studies of community stability [45]. This method considers the relative frequency of a community in a variety of plants and the stability of the relationship between the plants species as a decision basis [45]. The species number and individuals reflected to a certain extent the characteristics of a community, and reflected the stage of development and the degree of community stability. The frequency of different species is conversed into relative frequency, is accumulated according to the cumulative from big to small order together, and then, a smooth curve and fuzzy model is set. At last, the coordinate of the crossing point is determined by the curve and linear aspect ($y = 100 - x$). According to the stability test method of improved Godron M., the stability point of a community is 20/80 [44,45]. That is to say when the accumulative inverse of the species number reached 20% and the accumulative relative frequency of these species reached exactly 80%, the plant community was considered a stable community. The gap between the point of the intersection and the point of stability was measured by the Euclidean distance (d), so as to judge the degree of proximity of the actual community and the stable community. The farther the Euclidean distance, the less stable the community.

On the basis of the stability test method of improved Godron M., we implemented curve fitting by using the quadratic equation, compound curve, geometric progression curve, logarithmic equation, exponential equation, and power function. Finally, the quadratic equation and the logarithmic equation with the maximum relevant coefficient (R^2) were selected as the optimal fitting model. In this study, we filtered the following smooth curve models.

The selected curve model:

$$y = ax^2 + bx + c \tag{8}$$

$$y = d\ln(x) + e \tag{9}$$

where x is the accumulative inverse of species number (%); y is the accumulative relative frequency of these species (%); and a, b, c, d, and e are the undetermined coefficients.

3. Results

3.1. General Situation of Stand in Studied Area

Harvesting intensity had a significant impact on the stand characteristics of natural secondary forest 15 years after harvesting (Table 1).

Table 1. ANOVA results on the impacts of harvesting intensity on the stands.

	Sum of Squares	df	Mean Square	F	p-Value
Stand Density					
Between Groups	5,840,552.500	5	1,168,110.500	346.226	0.000 *
Within Groups	40,486.000	12	3373.833		
Total	5,881,038.500	17			
Mean Diameter at Breast Height (DBH)					
Between Groups	239.823	5	47.965	273.216	0.000 *
Within Groups	2.107	12	0.176		
Total	241.929	17			
Mean Height					
Between Groups	61.964	5	12.393	98.704	0.000 *
Within Groups	1.507	12	0.126		
Total	63.471	17			
Volume of Growing Stock					
Between Groups	193,707.658	5	38,741.532	131.992	0.000 *
Within Groups	3522.171	12	293.514		
Total	197,229.828	17			

* The significance level was $p < 0.05$.

Compared with non-harvesting (Table 2), the stand density of selective harvesting at different intensities increased significantly, but that of clear-cut harvesting decreased significantly. After different harvesting intensities, the mean DBH and height values were significantly lower than non-harvesting. The volume of growing stock exhibited no significant differences among non-harvesting and selective harvesting at low, medium, and high intensities, but it was significantly lower than non-harvesting after selective harvesting at extra-high intensity and clear-cut harvesting.

Table 2. General situation of stand in studied area 15 years after different harvesting intensities.

Harvesting Intensity	Harvesting Intensity (% of Growing Stock Volume)	Stand Density (No. of Tree/ha)	Mean DBH (cm)	Mean Height (m)	Volume of Growing Stock (m^3/ha)
Non-harvesting	0	1350 ± 25 d	18.6 ± 0.1 a	12.9 ± 0.3 a	317.83 ± 8.4 a
Low	13.0	1809 ± 29 c	16.2 ± 0.5 b	10.4 ± 0.4 b	302.73 ± 8.7 a
Medium	29.1	2825 ± 43 a	13.1 ± 0.6 c	10.6 ± 0.2 b	283.42 ± 15.5 a
High	45.8	2000 ± 66 b	15.1 ± 0.3 b	10.9 ± 0.2 b	276.32 ± 25.0 a
Extra-high	67.1	1925 ± 90 bc	10.6 ± 0.2 d	10.0 ± 0.4 b	166.36 ± 27.1 b
Clear-cut harvesting	100	1000 ± 66 e	7.5 ± 0.6 e	6.6 ± 0.6 c	23.77 ± 3.9 c

Scheffe multiple test; the significance level was $p < 0.05$; Mean ± S.D; 95% confidence interval for mean. Letters of the same column indicated differences between different harvesting intensities. The same letter indicated that the difference was not significant, for example, a and a, or a and ab, et al. Only the different letters indicated that the difference was significant, for example, a and b, b and c, et al.

3.2. Impacts on Species Diversity Indices of Various Layers

According to the ANOVA results (Table 3), 15 years after harvesting, the harvesting intensity had a significant impact on the species richness and evenness of tree, shrub, and herb layers ($p < 0.05$). Harvesting intensity had a significant impact on the species diversity of shrub and herb layers ($p < 0.05$), but it had no significant impact on the species diversity of the tree layer ($p > 0.05$).

Table 3. ANOVA results on the impacts of harvesting intensity on diversity indices of various layers.

	Sum of Squares	df	Mean Square	F	*p*-Value
Species Richness of Tree Layer					
Between Groups	5.983	5	1.197	49.803	0.000 *
Within Groups	0.288	12	0.024		
Total	6.271	17			
Species Richness of Shrub Layer					
Between Groups	16.384	5	3.277	573.200	0.000 *
Within Groups	0.069	12	0.006		
Total	16.453	17			
Species Richness of Herb Layer					
Between Groups	3.306	5	0.661	2032.217	0.000 *
Within Groups	0.004	12	0.000		
Total	3.310	17			
Species Diversity of Tree Layer					
Between Groups	0.161	5	0.032	0.772	0.588
Within Groups	0.499	12	0.042		
Total	0.660	17			
Species Diversity of Shrub Layer					
Between Groups	4.838	5	0.968	520.159	0.000 *
Within Groups	0.022	12	0.002		
Total	4.860	17			
Species Diversity of Herb Layer					
Between Groups	4.669	5	0.934	2358.294	0.000 *
Within Groups	0.005	12	0.000		
Total	4.674	17			
Species Evenness of Tree Layer					
Between Groups	0.084	5	0.017	115.385	0.000 *
Within Groups	0.002	12	0.000		
Total	0.086	17			
Species Evenness of Shrub Layer					
Between Groups	0.009	5	0.002	11.709	0.000 *
Within Groups	0.002	12	0.000		
Total	0.011	17			

Table 3. *Cont.*

	Sum of Squares	df	Mean Square	F	p-Value
		Species Evenness of Herb Layer			
Between Groups	1.317	5	0.263	793.629	0.000 *
Within Groups	0.004	12	0.000		
Total	1.321	17			

* The significance level was $p < 0.05$.

According to the results of multiple comparisons (Table 4), under different intensities of selective harvesting and clear-cut harvesting, the diversity of the tree layer was not significantly different with non-harvesting; the richness of the shrub layer was significantly different with non-harvesting; and the richness, diversity, and evenness of the herb layer were significantly different with non-harvesting.

Compared with non-harvesting (Tables 4 and 5), under the low harvesting intensities, a few diversity indices of various layers significantly increased; under the medium harvesting intensities, most of the diversity indices of various layers significantly increased; under the high and extra-high harvesting intensities, most of the diversity indices of various layers significantly decreased; and under clear-cut harvesting, almost all of the diversity indices of various layers significantly decreased.

Table 4. Results of multiple comparisons of diversity indices of various layers 15 years after harvesting.

Layer	Harvesting Intensity					
	Non-Harvesting	Low	Medium	High	Extra-High	Clear-Cut Harvesting
			Species Richness			
Tree	2.956 ± 0.093 b	3.034 ± 0.162 ab	3.529 ± 0.173 a	2.746 ± 0.187 b	2.678 ± 0.079 b	1.627 ± 0.195 c
Shrub	4.062 ± 0.069 b	4.388 ± 0.102 a	4.498 ± 0.031 a	2.533 ± 0.055 c	2.569 ± 0.103 c	2.216 ± 0.068 d
Herb	0.554 ± 0.033 c	0.845 ± 0.022 b	1.407 ± 0.008 a	0.402 ± 0.014 d	0.269 ± 0.010 e	0.110 ± 0.004 f
			Species Diversity			
Tree	1.923 ± 0.212 a	1.948 ± 0.089 a	2.109 ± 0.188 a	1.978 ± 0.208 a	1.955 ± 0.283 a	1.786 ± 0.194 a
Shrub	2.431 ± 0.050 a	2.442 ± 0.025 a	2.543 ± 0.041 a	1.748 ± 0.064 b	1.735 ± 0.045 b	1.104 ± 0.017 c
Herb	0.590 ± 0.036 c	0.730 ± 0.004 b	1.552 ± 0.022 a	0.276 ± 0.022 d	0.115 ± 0.005 e	0.047 ± 0.011 f
			Species Evenness			
Tree	0.825 ± 0.015 a	0.742 ± 0.014 b	0.748 ± 0.006 b	0.820 ± 0.017 a	0.778 ± 0.009 b	0.620 ± 0.007 c
Shrub	0.978 ± 0.010 a	0.925 ± 0.009 b	0.926 ± 0.007 b	0.968 ± 0.010 a	0.976 ± 0.009 a	0.946 ± 0.022 ab
Herb	0.537 ± 0.023 c	0.635 ± 0.012 b	0.902 ± 0.010 a	0.285 ± 0.021 d	0.165 ± 0.027 e	0.158 ± 0.010 e

Scheffe multiple test; the significance level was $p < 0.05$; Mean ± S.D; 95% confidence interval for mean. Letters of same row indicated differences between different harvesting intensities. The same letter indicated that the difference was not significant, for example, a and a, or a and ab, et al. Only the different letters indicated that the difference was significant, for example, a and b, b and c, et al.

Table 5. Percentage changes in species diversity indices of various layers due to different harvesting intensities relative to non-harvesting.

Layer	Harvesting Intensity				
	Low	Medium	High	Extra-High	Clear-Cut Harvesting
			Species Richness		
Tree	2.6	19.4	−7.1	−9.4	−45.0
Shrub	8.0	10.7	−37.6	−36.8	−45.4
Herb	52.5	154.0	−27.4	−51.4	−80.1
			Species Diversity		
Tree	1.3	9.7	2.9	1.7	−7.1
Shrub	0.5	4.6	−28.1	−28.6	−54.6
Herb	23.7	163.1	−53.2	−80.5	−92.0
			Species Evenness		
Tree	−10.1	−9.3	−0.6	−5.7	−24.8
Shrub	−5.4	−5.3	−1.0	−0.2	−3.3
Herb	17.3	68.0	−46.9	−69.3	−70.6

3.3. Impacts on Community Diversity Indices of Overall Plants

Harvesting intensity had a significant impact on the species richness, diversity, and evenness of overall plants 15 years after different harvesting intensities (Table 6).

Table 6. ANOVA results on the impacts of harvesting intensity on community diversity indices.

	Sum of Squares	df	Mean Square	F	*p*-Value
Richness of Overall Plants (R_4)					
Between Groups	6.468	5	1.294	213.620	0.000 *
Within Groups	0.073	12	0.006		
Total	6.541	17			
Diversity of Overall Plants (H_4)					
Between Groups	1.444	5	0.289	26.413	0.000 *
Within Groups	0.131	12	0.011		
Total	1.575	17			
Evenness of Overall Plants (J_4)					
Between Groups	0.116	5	0.023	228.978	0.000 *
Within Groups	0.001	12	0.000		
Total	0.118	17			

* The significance level was $p < 0.05$.

According to the results of multiple comparisons (Figure 2), the species richness, diversity, and evenness of overall plants were not significantly different after selective harvesting at low intensity. These parameters significantly increased after selective harvesting at medium intensity. The species richness and evenness of overall plants significantly decreased after selective harvesting at high and extra-high intensities. The species richness, diversity, and evenness of overall plants significantly decreased after clear-cut harvesting.

According to the percentage changes in species diversity indices of overall plants due to different harvesting intensities compare to non-harvesting (Table 7), the species richness, diversity, and evenness of overall plants significantly increased by 23.1%, 21.0%, and 5.1% after selective harvesting at medium intensity, respectively, and these parameters were the highest. However, after selective harvesting at high and extra-high intensities, the species richness of overall plants significantly decreased by 19.9% and 22.2%, respectively; and the species evenness of overall plants significantly decreased by 8.6% and 14.8%, respectively. The species richness, diversity, and evenness of overall plants significantly decreased by 47.0%, 31.2%, and 25.9% after clear-cut harvesting, respectively, and these parameters were the lowest.

Table 7. Percentage changes in species diversity indices of overall plants due to different harvesting intensities relative to non-harvesting.

Index	Harvesting Intensity				
	Low	Medium	High	Extra-High	Clear-Cut Harvesting
Species Richness of Overall Plants	7.3	23.1	−19.9	−22.2	−47.0
Species Diversity of Overall Plants	2.9	21.0	−12.9	−16.1	−31.2
Species evenness of Overall Plants	−3.8	5.1	−8.6	−14.8	−25.9

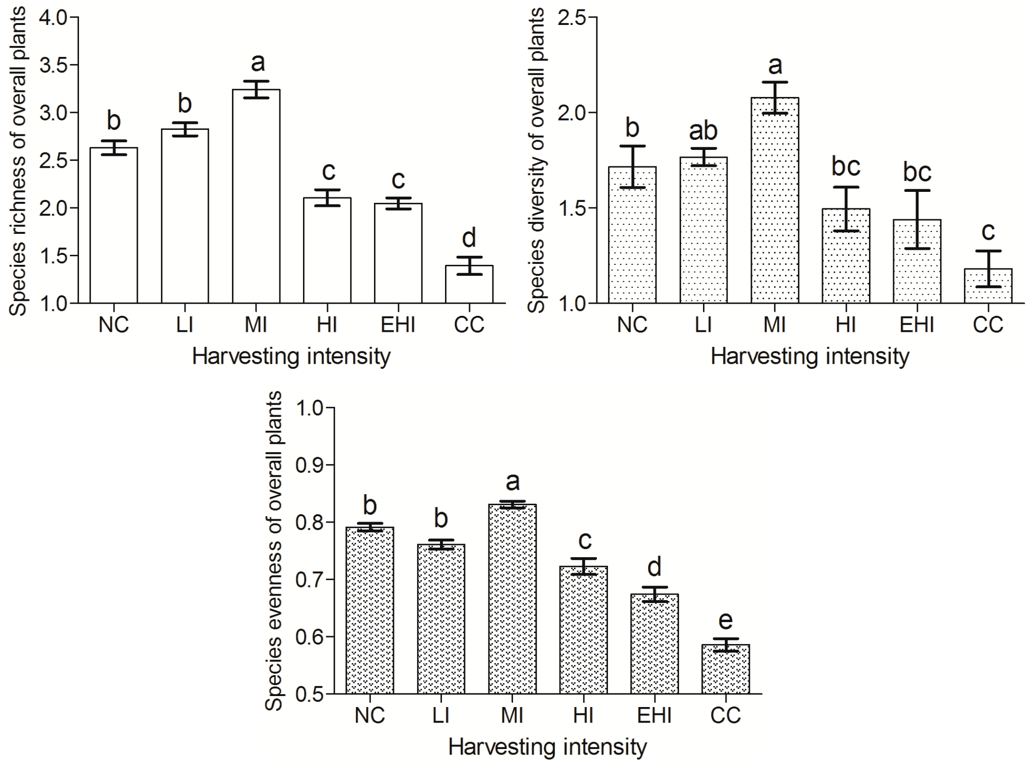

Figure 2. Results of multiple comparisons of diversity indices of overall plants 15 years after harvesting. Scheffe multiple test; the significance level was $p < 0.05$; Mean ± S.D; 95% confidence interval for mean. Letters indicate differences between different harvesting intensities. NC indicates non-harvesting; LI indicates selective harvesting at low intensity; MI indicates selective harvesting at medium intensity; HI indicates selective harvesting at high intensity; EHI indicates selective harvesting at extra-high intensity; CC indicates clear-cut harvesting.

3.4. Community Stability Analysis

Taking non-harvesting as an example, the coordinate of the intersection between the smooth curve and the straight line $y = 100 - x$ was 29.9/70.1. The coordinate of the stable point was 20/80. The Euclidean distance (d) between these two crossing points was 13.985 (Figure 3). In order to analyze the stability of the community with different treatments, the crossing point and the Euclidean distance were calculated by the same method for the other harvesting intensities (Figure 3).

According to the Euclidean distances (d) between the intersection and the stable point (20/80) (Table 8), there was a certain gap between the intersection and the stable point 20/80. The intersection at low intensity of selective harvesting was closest to the stable point, but intersections at high and extra-high intensities of selective harvesting and clear-cut harvesting were far from the stable point; especially, clear-cut harvesting was farthest from the stable point. The community stability comparisons of different harvesting intensities were as follows: medium intensity of selective harvesting > low intensity of selective harvesting > non-harvesting > high intensity of selective harvesting > extra-high intensity of selective harvesting > clear-cut harvesting. So, the medium intensity of selective harvesting was the most beneficial to promoting the development of the natural, secondary forest community in the direction of stability. Second, the low intensity of selective harvesting was to a certain degree also favorable.

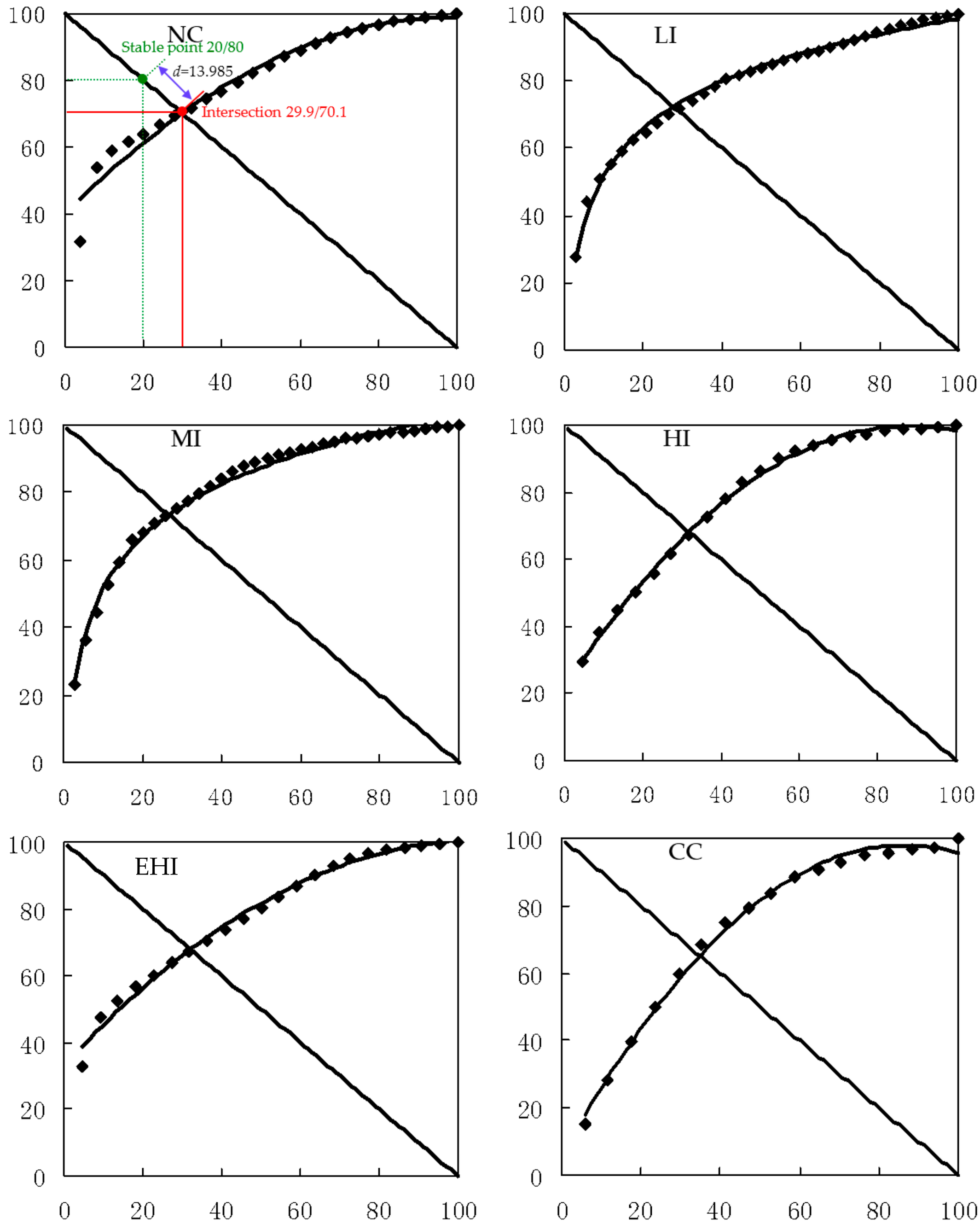

Figure 3. Plant community stability 15 years after different harvesting intensities. Horizontal axis (x): Accumulative inverse of species number. Vertical axis (y): Accumulative relative frequency. NC indicates non-harvesting; LI indicates selective harvesting at low intensity; MI indicates selective harvesting at medium intensity; HI indicates selective harvesting at high intensity; EHI indicates selective harvesting at extra-high intensity; CC indicates clear-cut harvesting.

Table 8. Changes of plant community stability 15 years after different harvesting intensities.

Harvesting Intensity	Curve Type	Relevant Coefficient (R^2)	Coordinate of Crossing Point (x/y)	Euclidean Distance (d)
Non-harvesting	$y = -0.0060x^2 + 1.1863x + 40.0140$	0.9651	29.9/70.1	13.985
Low	$y = 20.319\ln(x) + 4.9885$	0.9955	27.6/72.4	10.748
Medium	$y = 22.326\ln(x) + 0.1429$	0.9924	26.6/73.4	9.334
High	$y = -0.0101x^2 + 1.7684x + 21.9810$	0.9981	31.9/68.1	16.819
Extra-high	$y = -0.0060x^2 + 1.2694x + 33.2660$	0.9895	32.1/67.9	17.164
Clear-cut harvesting	$y = -0.0126x^2 + 2.1556x + 5.4024$	0.9956	34.8/65.2	20.956

4. Discussion

Numerous studies have shown that disturbances such as harvesting and other human activities in some cases cause an immediate decline in plant diversity followed by a recovery [46,47]. But, some studies have shown an increase in species richness after harvesting or other disturbance. Sassen (2013) et al. found that human impacts, as well as natural gradients, had major impacts on species richness patterns, and several areas in intermediate states of disturbance showed higher tree species richness than either old-growth forest or more severely degraded areas [12]. The results of some perious studies were different because these influences had a close relationship with location, histories, harvesting intensity, and recovery time, and so on [48,49]. In our study, we found the plant species richness, diversity, and evenness in natural secondary forest increased after selective harvesting at low and medium intensities, and these parameters were the highest with selective harvesting at a medium intensity. This conclusion was similar to some related studies, and the course of succession in subtropical forests seems to support the intermediate disturbance hypothesis [21,50,51]. After selective harvesting at low and medium intensities, a certain amount of forest space was released, sunlight in the forest was enhanced, and the soil environment was improved [34]. Changes of these factors were conducive to creating good conditions for plant growth, promoting natural reforestation, and increasing species richness, diversity, and evenness [52,53].

Non-harvesting might require a long time to facilitate biological features of vegetation communities and restored species diversity [29]. Some studies have shown that the percent of species lost was significantly higher in reference (non-harvesting) than harvested plots [35]. In our study, species diversity indices of selective harvesting at a medium intensity were significantly greater than non-harvesting, but these parameters were not significantly different between non-harvesting and selective harvesting of low intensity. This was because the forest was inhibited by a high canopy density (>0.9) due to non-harvesting, which resulted in reduced sunlight exposure and thus, a limited growth of understory shrubs and herbs. Although a natural forests protection project was proposed by the Chinese government after 1998, the natural forests require scientific management.

Some studies assessing the effects of different types of disturbances, such as firewood harvesting [46,54], slash-and-burn [55], or cattle grazing [56,57], have found that species diversity was reduced as the intensity and frequency of disturbance increased [46,58]. In our study, plant species richness, diversity, and evenness significantly decreased with selective harvesting at high and extra-high intensities, as well as with clear-cut harvesting. This might be due to overly large canopy gaps under over-harvesting [33], resulting in major changes to the ecological environment, such as the stand structure, soil moisture, porosity, and nutrients [19,50,51]. For instance, the worst-case scenario was from clear-cut harvesting, which resulted in the disappearance of the tree layer and a significant change in stand structure. Moreover, the *Dicranopteris pedata* (Houtt.) Nakaike coverage rate was very high (>90%), so plant species of shrub and herb layers were few. The reduction in species diversity, changes in patterns of dominance, and the proliferation of species associated with disturbed sites suggested that current practices of selective harvesting at an exorbitant intensity require adjustments to make this forest management application more consistent with the local conservation of woody plant species diversity and community structure [23].

The relationship between community stability and species diversity has always been a complex theoretical issue of ecology. Most scholars have hypothesized that the higher species diversity resulted in higher forest community stability [59,60]. We obtained the same results in our study area. In our study, we found that the plant community was closer to stability after selective harvesting at low and medium intensities. But it was far from stable after clear-cut harvesting and selective harvesting at high and extra-high intensities. We tested the forest community stability based on the stability test method of improved Godron M., which made full use of the overall characteristics of the plant community and was a more comprehensive method including tree, shrub, and herb species. However, the forest community stability test could only determine whether the community was stable, but could not reveal community succession direction and trend [44,45]. Natural restoration of natural secondary forest after harvesting still exhibited dynamic change. The long-term tracking of permanent sample plots was very necessary to understand the long-term response mechanism of species diversity and stability to harvesting intensity. This measure was also needed to determine the relationship between species diversity and stability, as well as their mutual influencing mechanisms. Our study focuses on the impact of harvesting intensity on species diversity and community stability. Future studies should be conducted to obtain additional time series data. Coordinated multiple-regional studies can help explore the impact of other forcing such as environmental conditions together with timber harvesting intensity.

5. Conclusions

Results of this study showed that the plant species diversity indices of tree, shrub, and herb layers in this forest slightly increased with selective harvesting at low intensity. These parameters significantly increased with selective harvesting at medium intensity, but significantly decreased with selective harvesting at high and extra-high intensities, as well as with clear-cut harvesting. With increasing harvesting intensity, the richness, diversity, and evenness of the overall plants first increased, and then decreased, and these parameters achieved maxima with selective harvesting at medium intensity, but clear-cut harvesting reduced these parameters to their minima. The results of this study also showed that the plant community of this forest was closest to a stable community with selective harvesting at medium intensity. It was far from the stability with selective harvesting at high and extra-high intensities with clear-cut harvesting, and it was farthest from the stability with clear-cut harvesting.

With all the above impacts in mind, if diversity and community stability are prioritized, selective harvesting at low and medium intensities should be chosen in natural secondary forest management. Selective harvesting at medium intensity is the most favorable. However, clear-cut harvesting and selective harvesting at high and extra-high intensities should be avoided in this type of forest in this region.

Acknowledgments: This study was supported in part by grants from the National Natural Science Foundation of China (30972359 and 31070567) and the University Development Foundation of Fujian Agriculture and Forestry University (113-612014018). We also would like to thank the two anonymous reviewers for their valuable comments and suggestions which helped improve this paper.

Author Contributions: Zhilong Wu contributed to the field experiment, data collection, and analysis, and wrote the initial version of the manuscript. Chengjun Zhou contributed to the field experiment, data collection, and analysis. Xinnian Zhou was the project director and designed the study. Xisheng Hu participated in data collection and analysis. Jianbang Gan contributed to data analysis.

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

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