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Dominant Species Abundance, Vertical Structure and Plant Diversity Response to Nature Forest Protection in Northeastern China: Conservation Effects and Implications

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Abstract: The conservation of species diversity and improvement of forest structure are essential roles of the Natural Reserve Policy and the Natural Forest Protection Program (NFPP) in China. However, the long-term effects of NFPP are still not well-defined, and a natural reserve (Liangshui) and surrounding region were surveyed as a proxy of NFPP for approaching the protection effects. Our results showed that long-term conservation significantly altered the dominant species in the herb layer (80% of species), followed by shrub (58%) and tree layers (50%); there was a 1.6-8.0-fold increase in abundance in *Corylus* shrubs, *Acer* trees and *Carex* grass, but a 1.3–10.0-fold abundance decrease in larch trees, *Athyrium* herbs and *Lonicera* shrubs. In contrast, tree species diversity and distribution evenness increased by 31% and 23.4% in the reserve, respectively. Forest protection in the reserve also led to the forest structural alteration with the observation of larger-sized trees and shorter herbs, but relatively sparse forests (smaller tree density). Structural equation modeling manifested that the reserve directly altered forest structure, at a coefficient of 0.854, nearly two-fold higher than its impact on diversity (0.459) and dominant species (−0.445). The most affected parameters were plant size (trees and herbs) and tree density related to forest structure, tree diversity, herb richness and evenness for diversity traits, and Oxalidaceae and Rosaceae for dominant species. This study provides basic data that can be used to evaluate the impact of the nature reserve in NE China, and these findings can be used to guide the implementation of NFPP in the long-term in the future.

Keywords: dominant species abundance; community structure; diversity; coupling relationship; structural equation modeling

1. Introduction

The Natural Forest Protection Program (NFPP) was launched in 1998 with the initial aim of protecting natural forests, covering an area of 45 million ha in China [1]. Since then, evaluations have been assessed in land use and land cover change [2], and carbon stocks and overall forest quality [3,4], indicating sharp declines in timber harvest with increasing forest area and slow increases in biomass stocks in northeast (NE) China [5]. However, there is a lack of detailed information about species composition and diversity alternations as well as forest structure of plant size and forest density at different vertical layers, owing to experimental design difficulty. Broadly speaking, Nature Reserve Policy is a natural conservation method (even stricter than NFPP), with much longer implementation times, and comparison inside and outside a reserve possibly gives implications for NFPP.

For a specific region, more detailed investigations will most likely yield more reliable results at the expense of more funds and more labor forces. Parameters used by most scholars to quantitatively represent characteristics of forest structure and species diversity includes species abundance, Simpson index and Shannon–Wiener index, the richness index, the Pielou evenness index and community traits such as tree diameter, height and stem density [6–9]. Data recorded at different vertical layers of trees, shrubs and herbs could benefit a holistic view of the forest characteristics. Good knowledge of tree sizes, stand density and the compositional features could contribute to the evaluation of forest carbon sequestration and productivity [10] and promote mechanical understanding of species coexistence in a complex community [11,12]. A statistical definition of the parameters most likely to be affected by forest protection will assist future investigation via less surveyed parameter design for the precise evaluation, while decoupling their association possibly supports the suitable management to reach standardized and accepted conclusions [13–15].

The Xiaoxing'an mountains are an important national forest base for China and have been recognized as a priority region for the NFPP [16]. Liangshui National Nature Reserve is one of the longest conserved reserves, located in the central part of this region. Similar to all other reserves in China, the border of the reserve was strictly defined, and the core region (human disturbance strictly prohibited), buffer region (only allow scientific survey) and experimental region (only allow scientific experiments, teaching and training, visiting and travel) were classified for protection. In the implementation of NFPP, any timber could not be harvested in natural forests. Areas inside and outside the nature reserves have different levels of protection and provide a proxy of the NFPP under different conservation intensities.

In this paper, a detailed investigation of the structural characteristics and species diversity was conducted using a field survey with the aim of determining the effects of natural forest protection, and association decoupling was used to find the complex relations behind the protection on species composition and forest structure. We were particularly interested to explore the following:

(1) How natural forest protection has affected dominant species, community structure and species diversity in the tree, shrub and herb layers;

(2) What the associations are between species diversity, forest structure and dominant species abundance and how they are realized under the conservation effects;

(3) What kind of implications could be derived for future natural forest conservation and precise evaluations of natural forest protection in China?

2. Materials and Methods

2.1. Study Areas Description

The study area was inside and outside of the Liangshui National Nature Reserve, administratively belonging to the Northeast Forestry University (Figure 1a) (128°47′25″~128°58′58″ E, 47°07′07″~47°15′58″ N) in the central region of the Xiaoxing'an mountains. Typical hilly terrain is surrounded by complex mountainous topography, with most mountains in the north–south direction. The average slope is 10–15 degrees. The altitude is from 280 to 707 m, with an average altitude of 400 m (the relative altitude is 80 to 300 m). The mean annual air temperature is −0.3 °C, accompanying a short frost-free period of 100 to 120 days and mean annual precipitation 676.0 mm. The outcrop rocks are Hercynian granite and granite phenocrysts, with a few of Archean granitic gneiss. The main soil types are dark brown forest soils [17].

Natural forest protection in this region was as follows. Before 1950, the forest in this region was dominated by natural climax vegetation of Korean pine-broadleaf mixed natural forests. Thereafter, a logging base was established in 1952 for the first timber logging in 1953. In 1958, the establishment of

Liangshui Experimental Forest Farm was aligned with the stop of massive timber logging. In 1980, a department-level reserve was established by the Forestry Administration of China and was upgraded to a national nature reserve in 1997 (https://ls.nefu.edu.cn/info/1109/1245.htm). The total area of Liangshui National Nature Reserve is 12133 ha. Since 2000, NFPP has been initiated by the central government for prevention of natural flood disasters of Songhuajiang River, and this region was recognized as top priority with implementation of strict prohibition of timber harvest from natural forests thereafter [1].

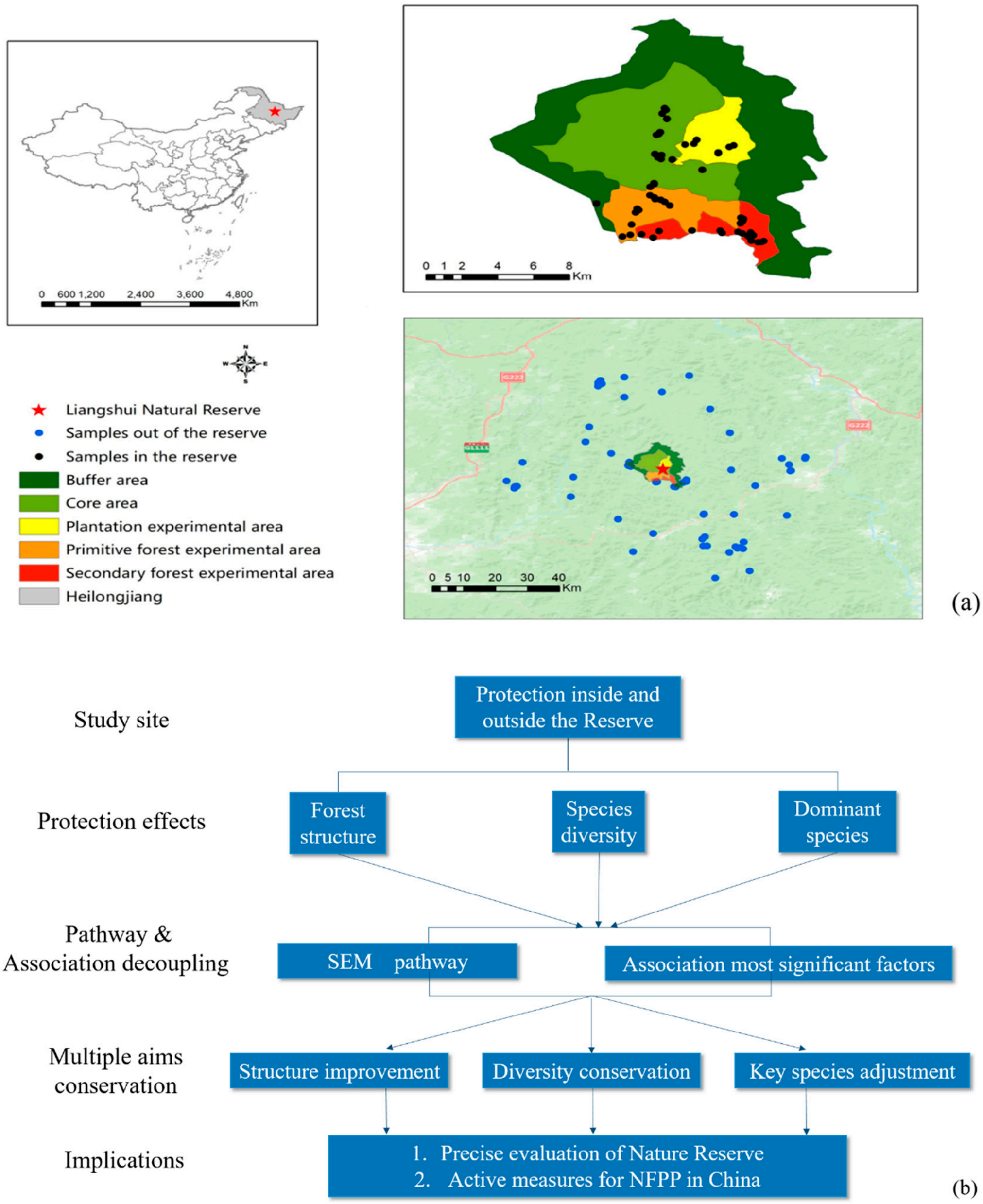


Figure 1. Study plot in and out of the Liangshui National Nature Reserve (**a**) and the technical route of this study (**b**). Note: (**a**) The relative location of the study site in China (left); sampling sites in the reserve (upper right); sampling sites outside the reserve (lower right). Most of the forest types are secondary forests, accompanied by planted forests.

2.2. Experimental Design, Field Investigation and Data Dollection

In this study, the sampling plots were located inside and outside the national nature reserve. Plot sizes for the tree layer survey were 30 × 30 m, and in each tree plot, two 5 × 5 m shrub subplots and five 1 × 1 m herb subplots were surveyed, respectively, to sample the shrub and herb layers. In the experimental design, a total of 120 sampling plots were surveyed, included 60 plots in the reserve and 60 plots outside the reserve. There were 20 plots in the core zone, buffer zone and experimental zone in the reserve, respectively (total of 60 plots in the reserve). The plot locations outside the reserve were within about 30 km from the edge of the reserve in our study (Figure 1a). This sampling distance in studying the conservation effects ranged from 2 to 70 km in previous references [18–20].

In the survey, plant species names of all trees, shrubs and herb layer species in the plots and tree sizes, and community traits of the forests were recorded in detail. For trees, the diameters at breast height (DBH), tree height (Th), and tree density (Td) were measured. Shrub surveyed items included shrub density (Sd), shrub height (Sh) and shrub coverage (Sc). In the case of the herb layers, relative coverage of each species (Hc) and herb height (Hh) were recorded. The coverage of herbs was measured as the proportion of the area of the surveyed species to the total surveyed area in percentage. Tree, shrub and herb density were calculated as the number of total individuals in the plots divided by the plot area. We also recorded the altitude, slope aspect (sunny, shade and half-sunny-shade slope), slope position (upper, middle, bottom of the slope or flat), slope gradient in degrees, and latitude and longitude of each sampling plot in the survey.

2.3. Species Diversity Calculation

Species diversity was calculated with the field survey data, as richness index (1), diversity indices (2) and (3) and evenness indices (4) [21].

$$\text{Richness index: R=S} \tag{1}$$

$$\text{Diversity indices : Shannon–Wiener index } \mathrm{H}' = -\sum P_i ln P_i \tag{2}$$

$$\text{Simpson index : } \mathrm{D} = 1 - \sum P_i^2 \tag{3}$$

$$\text{Pielou evenness indices : Jsw} = \left(-\sum P_i ln P_i\right)/\ln \mathrm{S} \tag{4}$$

P_i is the proportion of the number of species i to the total number of the species, and S is the total of species i in the sampling plot.

2.4. Structural traits calculation

All the structural characteristics of the species were averaged in the plot. A number of community structural parameters were used: tree diameter at breast height (DBH), tree height (Th), tree density (Td), shrub density (Sd), shrub height (Sh), shrub coverage (Sc), relative coverage of each herb species (Hc), and herb height (Hh). Tree DBH and the height of trees, shrubs and herbs were calculated using the formulas outlined below (5 and 6). Tree and shrub density are referred to in Formula (7), and shrub and herb coverage are referred to in Formula (8).

$$\mathrm{DBH} = \left(\sum_{i=1}^{m} \sum_{j=1}^{n} D_{ij}\right) / \sum_{i=1}^{m} n \tag{5}$$

$$\mathrm{Height} = \left(\sum_{i=1}^{m} \sum_{j=1}^{n} H_{ij}\right) / \sum_{i=1}^{m} n \tag{6}$$

$$\mathrm{Density} = \sum_{i=1}^{m} n / A \tag{7}$$

$$\mathrm{Coverage} = \left(\sum_{i=1}^{m} c_1 + c_2 + \ldots + c_i\right) / m \tag{8}$$

where D_{ij} and H_{ij} are the DBH and height of the jth tree in the ith species, respectively; m is total species number; n is the measured tree for each species, C_i is the coverage of ith species, and A is the area of the plot.

2.5. Dominant Species Abundance Calculation

Dominant species in the tree, shrub and herb layers were first recognized by ranking all the species of the pooled data for all plots in and outside the reserve. All species names as well as their quantity were listed (Table S1), and the top three kinds of species in and outside the reserve were defined as dominant species in the tree, shrub and herb layers.

Thereafter, the relative abundance of dominant species, genera and families (as recognized above) in each plot, in and outside the reserve, were calculated as the mean value of the ratio of the individual number of the species and the total individual number of all recorded species in each sampling plot.

2.6. Data Processing and Association Decoupling

For finding the differences inside and outside the reserve of different tested parameters, analysis of variance (ANOVA) was used to find the statistical significance of the differences in dominant species abundance, species diversity and forest structure factors in and outside the reserve. All these analyses were performed using SPSS 22.0 (SPSS, Chicago, IL, USA).

For further exploring the possible reasons for the conservation effects observed, we also tested the edge-effect reason (mainly from natural origin) and forest-type reason (mainly from human-impact origin). In the case of edge-effect, plots in central region of the reserve (border line −8 km; 46 plots), at the edge region around the reserve border (border line ± 1 km; 27 plots) and far region outside the reserve (border line + 30 km; 47 plots) were classified (Table S3). Given the significant contribution of the edge effect, significantly higher or lower values in different parameters should be observed in the edge region; otherwise, linear changes from far outside the reserve (the least protection) to inside the reserve (the strongest protection) should be observed. In the case of forest-type region, all plots were divided into original natural forests (with the least human disturbance), secondary forests (forests naturally regenerated after original natural forest harvest) and plantation forests (pure human-aided planted forests). Their percentage changes inside and outside the reserve, together with averages of all above-mentioned parameters were analyzed (Table S2). Human impact could be identified by the concurrent observation of forest type changes and significantly different tree sizes, species abundance and species diversity. All analyses were performed using SPSS 22.0 (SPSS, Chicago, IL, USA).

Selecting an appropriate statistical analysis method was crucial to decouple the associations between species diversity and forest structure and find the most likely pathway of forest structural improvement, species diversity and dominant species protection [9,22,23]. We chose structural equation modeling (SEM) to identify the structural relationship among the complex associations. In the SEM analysis, three latent variables were selected as diversity (species diversity, richness and evenness), structural traits (height, diameter, density and coverage) and dominant species abundance (top three frequently observed species, genus and family). Direct effects from conservation and indirect effects from other latent variables towards dominant species, diversity and structure factors were selected as three independent models. The criterion for identifying the fitness of the model was as follows: the more significant coefficients the model has, the more probable the model-related pathway is that the case occurred from natural conservation practice. The SEM was implemented using the lavaan package in R software [24], and details of the SEM description were found in a previous publication [25].

3. Results

3.1. Species Abundance Differences

When the data from each plot were assessed using ANOVA, significant differences between inside and outside the reserve were found (Table 1). In the tree layer, the relative abundance of Aceraceae, the *Acer* genus, and *Acer mono* increased 2.5–2.8 times ($p < 0.01$), while 1.3–4-fold decreases were found in Pinaceae, the *Larix* genus and *Larix gmelinii* ($p < 0.05$). In the shrub layer, the Betulaceae family, *Corylus* genus, *Corylus mandshurica* species, and the Saxifragaceae family inside the reserve increased by 1.6–2-fold ($p < 0.05$). While some other groups, i.e., the Rosaceae family and *Lonicera* genus, showed a nearly 10 times decrease in relative abundance in the reserve ($p < 0.01$). In the case of dominant herb species, some were significantly richer in the reserve, such as an 8-fold increase in *Carex pilosa* ($p < 0.01$), the Oxalidaceae family, *Oxalis* genus and *Oxalis corniculata* increased by 6-fold; the Umbelliferae family, *Aegopodium* genus and *Aegopodium alpestre* showed a 1.8–2.6-fold increase; while some other groups showed sharp decreases in the reserve, such as *Athyrium brevifrons*, *Athyrium* genus and Athyriaceae family that decreased 2.3–3 times; and the Rosaceae family and *Filipendula palmata* that decreased nearly 1.7-fold ($p < 0.01$) (Table 1).

Table 1. Abundance changes due to natural conservation of dominant species, genus and family in tree, shrub and herb layers.

Layers	No	Species, Genus and Family	Relative Abundance Inside	Outside	Sig.
Increased group ($p < 0.05$)					
Tree layer	1	*Acer mono*	11%	4%	<0.01
	2	*Acer*	15%	6%	<0.01
	3	Aceraceae	15%	6%	<0.01
Shrub layer	1	*Corylus mandshurica*	24%	12%	<0.01
	2	*Corylus*	26%	16%	0.04
	3	Betulaceae	26%	16%	0.04
	4	Saxifragaceae	18%	9%	<0.01
Herb layer	1	*Carex pilosa*	8%	1%	<0.01
	2	*Oxalis corniculata*	6%	1%	<0.01
	3	*Oxalis*	6%	1%	<0.01
	4	Oxalidaceae	6%	1%	<0.01
	5	*Aegopodium alpestre*	13%	6%	<0.01
	6	*Aegopodium*	13%	5%	<0.01
	7	Umbelliferae	14%	8%	<0.01
Decreased group ($p < 0.05$)					
Tree layer	1	*Larix gmelinii*	6%	24%	< 0.01
	2	*Larix*	6%	24%	< 0.01
	3	Pinaceae	38%	48%	0.04
Shrub layer	1	*Lonicera*	1%	10%	< 0.01
	2	Rosaceae(shrub)	3%	29%	< 0.01
	3	*Syringa*	5%	13%	0.01
Herb layer	1	*Athyrium brevifrons*	3%	7%	0.01
	2	*Athyrium*	3%	7%	0.01
	3	Athyriaceae	3%	9%	< 0.01
	4	*Filipendula palmata*	7%	11%	0.01
	5	Rosaceae(herb)	7%	12%	0.01
Non-significant changes ($p > 0.05$)					
Tree layer	1	*Betula platyphylla*	13%	17%	0.27
	2	*Betula*	16%	19%	0.34
	3	Betulaceae	17%	21%	0.21
	4	*Picea koraiensis*	13%	11%	0.43
	5	*Picea*	14%	11%	0.43
	6	*Pinus*	10%	9%	0.77
Shrub layer	1	*Acanthopanax senticosus*	10%	7%	0.22
	2	*Acanthopanax*	11%	7%	0.19
	3	*Philadelphus schrenkii*	8%	6%	0.3
	4	*Spiraea salicifolia*	16%	22%	0.22
	5	*Spiraea*	17%	26%	0.09
Herb layer	1	*Filipend*	7%	11%	0.05
	2	*Carex*	19%	16%	0.34
	3	Cyperaceae	19%	17%	0.64
Percentage of significant changes					
Tree layer	6 out of 12 parameters significant changes				50%
Shrub layer	7 out of 12 parameters significant changes				58%
Herb layer	12 out of 15 parameters significant changes				80%

Notes: Sig. indicates the p-value for differences between inside and outside the reserve.

Overall, conservation resulted in the largest change of the dominant species in the herb layer (80% of all tested ones), followed by shrub (58% of all tested ones) and tree layers (50% of all tested ones), such as increased in abundance in *Corylus* shrubs, *Acer* trees, and *Carex* grass, but significantly decreased in larch trees, *Athyrium* herbs and *Lonicera* shrubs.

3.2. Differences of Forest Structure, Species Diversity and Forest Type

Nature conservation resulted in significant changes in tree structural factors, such as nearly half decreases of tree density, followed by 45.2% and 24.1% increase in DBH and tree height ($p < 0.05$) in the reserve. In the case of the shrub layer, no significant changes were found in shrub height and shrub coverage, while a 33.3% decrease was discovered in shrub density ($p < 0.05$) in the reserve. Herb height outside the reserve was one quarter higher than that in the reserve ($p < 0.05$), while no evident changes were found in herb coverage ($p > 0.05$). In general, natural forest protection resulted in the appearance of larger-sized trees, shorter herbs, and relative sparse forest both for trees and shrubs (Table 2).

Table 2. Differences of the structure features, species diversity and forest type in and outside the reserve.

Parameters and Abbreviations	Unit	In the Reserve	Outside the Reserve	Improvement (%)
Structural traits				
Tree height, Th	m	14.14(0.28) a	11.39(0.51) b	24.1
Diameter at breast height, DBH	cm	18.94(0.58) a	13.04(0.55) b	45.2
Tree density, Td	Tree m^{-2}	0.08(0.01) a	0.15(0.02) b	−46.7
Shrub height, Sh	m	1.36(0.04) a	1.23(0.05) a	10.6
Shrub coverage, Sc	%	6.84(0.4) a	7.37(0.8) a	−7.2
Shrub density, Sd	Shrub m^{-2}	0.4(0.03) a	0.6(0.07) b	−33.3
Herb height, Hh	m	0.27(0.01) a	0.36(0.02) b	−25.0
Herb coverage, Hc	%	5.49(0.18) a	5.17(0.4) a	6.2
Species diversity traits				
Tree richness, TR		9.52(0.36) a	7.62(0.51) b	24.9
Tree Simpson, TD		0.76(0.02) a	0.58(0.03) b	31.0
Tree Shannon–Wiener, TH′		1.75(0.06) a	1.27(0.08) b	37.8
Tree evenness, TJsw		0.79(0.02) a	0.64(0.03) b	23.4
Shrub richness, SR		4.85(0.23) a	4.52(0.27) a	7.3
Shrub Simpson, SD		0.63(0.02) a	0.57(0.03) a	10.5
Shrub Shannon–Wiener, SH′		1.25(0.05) a	1.12(0.07) a	11.6
Shrub evenness, SJsw		0.83(0.02) a	0.8(0.02) a	3.7
Herb richness, HR		13.35(0.4) a	13.43(0.54) a	−0.6
Herb Simpson, HD		0.82(0.01) a	0.82(0.01) a	0.0
Herb Shannon–Wiener, HH′		2.08(0.04) a	2.09(0.05) a	−0.5
Herb evenness, HJsw		0.81(0.01) a	0.82(0.01) a	−1.2
Percentage of forest types				
Natural forests		50%	3%	+47%
Secondary forests		32%	57%	−25%
Plantation		18%	40%	−22%

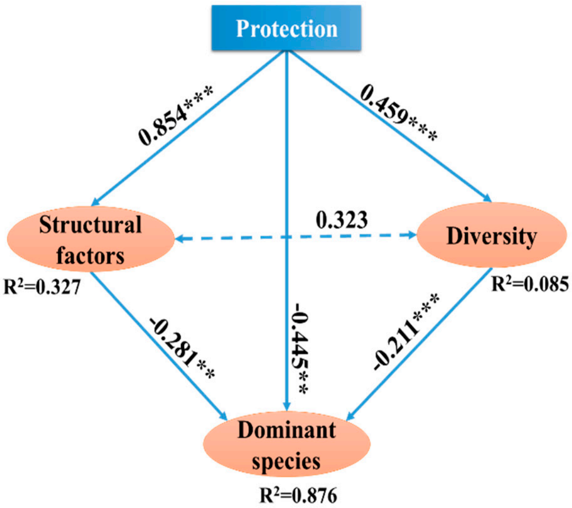
Notes: For structural and diversity traits, standard error in the brackets, and the improvement was calculated from the formula (in the reserve—outside the reserve)/outside the reserve in percentage. For forest types, the improvement was calculated as a difference between in the reserve and outside the reserve directly.

The tree diversity and evenness were significantly higher in the reserve compared with outside the reserve, which improved 23.4%–37.8%. While no significant changes were found in the shrub and herb layers, but diversity and evenness of shrub in the reserve was higher than outside, and herb layer was opposite (Table 2). Furthermore, both inside and outside the reserve, herb diversity index (Richness, Simpson, and Shannon–Wiener) was the highest, followed by tree, and shrub diversity was the lowest. The evenness of shrubs and herbs was higher than that of the trees. Most of the distribution of structure and diversity showed a concentrated region on average and had a single peak in the frequency distribution (Figure S1 and Figure S2).

Half of the forests in the reserve were original natural forests, but a few were found outside the reserve (3%). Contrary to this, the secondary forests and plantations outside were 1.8–2-fold higher than those in the reserve (Table 2).

3.3. Association Decoupling by SEM

We found that the most statistically significant SEM model was the dominant species-aimed SEM with five significant direct and two indirect pathways (Figure 2), compared with the other two models (Figure S3). This SEM showed that the direct influence of nature conservation on forest structure (0.854 coefficient, $p < 0.001$) was two-fold higher than species diversity improvement (0.459, $p < 0.001$) and dominant species abundance (−0.445, $p < 0.01$). Significant direct impacts from diversity and structure traits on the dominant species changes were also observed, and their impacting power manifested by the path coefficient was quite similar in size (−0.211 to −0.281). The indirect influence of protection on regulating dominant species abundance via diversity ($-0.211 \times 0.459 = -0.097$, $p < 0.01$) was weaker than structure ($-0.281 \times 0.854 = -0.24$, $p < 0.01$). Overall, taking full advantage of the most important contribution of protection, the second force of structure was available for the species composition change (Figure 2).



Response variable	Mediate variable	Predictor variable	Pathway	Standard	P-value	Sig. / total
Direct effects						
Structure		Protection	Direct	**0.854**	**0.000**	
Abundance		Protection	Direct	**-0.445**	**0.001**	
Diversity		Protection	Direct	**0.459**	**0.000**	
Structure		Diversity	Inter	0.027	0.323	
Abundance		Diversity	Direct	**-0.211**	**0.000**	83%
Abundance		Structure	Direct	**-0.281**	**0.002**	(5/6)
Indirect effects						
Abundance	Structure	Protection	Indirect	**-0.24**	**0.004**	
Abundance	Diversity	Protection	Indirect	**-0.097**	**0.004**	
Abundance	Structure	Diversity	Indirect	-0.008	0.377	50%
Abundance	Diversity	Structure	Indirect	-0.006	0.336	(2/4)
Total effects						
Abundance		Protection	Total	**-0.783**	**0.000**	
Abundance		Diversity	Total	**-0.219**	**0.000**	100%
Abundance		Structure	Total	**-0.287**	**0.002**	(3/3)

Figure 2. The most significant SEM for the complex association among protection (protection was scored as 1 for outside the reserve and 2 for inside the reserve for the modelling), structure, diversity and dominant species variations. The direct, indirect and total effects' standardized coefficient (standard), statistical significance (*P*-value) and the proportion of significant pathway to total pathway number (Sig. /total) under different aims to identify the possibility are listed in the right table. Interaction: Inter. In the SEM on the left, solid arrows represent significant paths (*** indicated $p < 0.001$, ** indicated $p < 0.01$, * indicated $p < 0.05$), and dashed arrows represent non-significant paths ($p > 0.05$). For each path, the standardized regression coefficient is shown. R^2 indicates the total variation in a dependent variable that is explained by the combined independent variables. In the table on the right, significant path coefficients ($p < 0.05$) are indicated in bold. The factors contained in latent variables are seen in Figure 3. Compared with the two models in Figure S3, the SEM paths were more significant, and there was more probability available in the nature field condition.

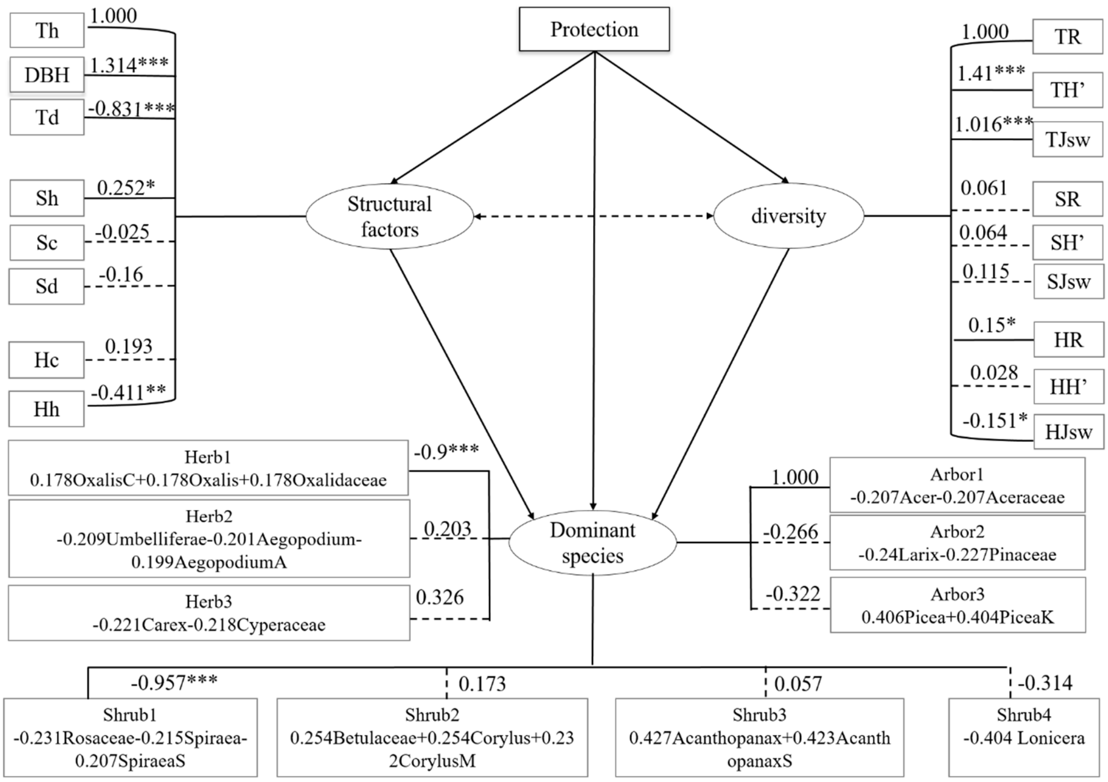


Figure 3. The most significant parameters related to 3 latent variables of dominant species, diversity and forest structure. Due to the strong correlation between Simpson and Shannon–Wiener index (see Table S5, $r > 0.85$), we removed the Simpson index (TD). For simplifying the SEM modelling, 3 or 4 principal components were extracted from arbor (arbor1, arbor2 and arbor3), shrub (shrub1, shrub2, shrub3 and shrub4) and herb (herb1, herb2 and herb3), respectively (see Table S6). Most of the structure attributes did not show strong correlation (Table S4, $r < 0.85$), so all structure factors were included.

The parameters with significant contributions to the three latent variables are also shown in Figure 3. Forest structure latent variable became larger with increasing tree size (DBH) and shrub height, but it became lower with herb height and relatively sparse tree density. Diversity latent variable positively related with tree diversity, evenness and herb richness, but negatively related with herb evenness. Together with data from Figure 2, protection had more effects on trees and their diversity, with more impacts on herb shrub dominant species. Moreover, structural and diversity regulation on dominant species (mainly understory) were also achieved via overstory tree layers compared with those in shrub and herb layers (Figure 3).

4. Discussion

The NFPP has been implemented for 20 years, while Natural Reserve Policy has been implemented for over 60 years in China. A comprehensive and quantitative evaluation of the effectiveness of protected area is needed. The data in this paper give a basis for this precise evaluation, and also for the assessment of future active measures to improve the efficacy for forest rehabilitation under the NFPP.

4.1. Conservation-Induced Dominant Species Changes with Increasing Tree Diversity, Larger Trees and Lower-Density Forests

Long-term historical recorded data manifested considerable species differences before and after the conservation, and the inside–outside comparison showed that human disturbance has enlarged this species alternation. The vegetation in this region was climaxed as broad-leaved Korean pine forest with high abundance of *Pinus koraiensis* [26]. Today, *Pinus koraiensis* abundance inside the reserve is less than one-tenth, much lower than birch and *Acer mono*. This species become even less outside the reserve, and has been ranked as a second-level protecting plant of China. Human-aided plantation has resulted in the most abundance of *Larix gmelinii* (22%), and harvest disturbance induced the dominance of pioneer species of birch (16%) (Table S1). These results strongly suggest that the dominant species of this region have converted from *Pinus koraiensis*, *Franxinus mandshurica* and *Phellodendron amurense* [27] to some pioneer species (birch and maple) and planted tree species (larch). Species alternation from human disturbance has also been observed in northern America [28], showing similar pioneer species dominance.

According to the geography of the vegetation in NE China [26,29], herb layers in this region were dominant by *Carex* spp., *Impatiens nolitangere* and *Deyeuxia angustifolia*. At the moment, the last two species sharply decreased (< 5%). Compared with references [26,29], shrub layers from history and today are dominated by similar species, and the top one is *Corylus mandshurica*. Importantly, medicinal plants in the understory seem to have been rehabilitated by conservation, such as *Acanthopanax senticosus,* which was two-fold more abundant under protection [30].

Conservation induced large tree appearance and higher tree species diversity and are the common cases from many studies [31,32], and 1.5-fold larger DBH with 1.2–1.4-fold higher tree diversity was found in this paper. Different vertical layer results also found that this was much more evident in tree layer than herb and shrub layers.

The first reason for these above-mentioned changes in species dominance, diversity and structural traits could be a result of two aspects of human disturbance and human aid. On the one hand, historical over-cutting of trees, overutilization of understory herb resources [33,34] in this region and, thereafter, human-aided afforestation and direct protection (reserve and NFPP, etc.) practices favor the appearance of larger trees and higher species diversity. This is also supported by the forest-type alteration data (Table 2 and Table S2). More natural forests are located in the reserve, while more secondary forests and plantations are found outside the reserve. Moreover, natural forests usually had larger trees and higher tree diversity and evenness than secondary and plantation forests (Table S2).

Secondly, the conservation effects were not achievable by the edge effect from sampling around the reserve border. Although the edge effect could diversify species composition and forest structure [35], our data did not support such a finding (Table S3), that is, in general, forest structure, species diversity and abundance in edge areas were not significantly higher or lower than surrounding areas (both in and outside the reserve). Instead, structural features like tree and shrub heights, and DBH in the edge area were similar to these in the reserve, obviously higher than outside the reserve (Table S3). Thus, the edge effect could not explain the observed differences between inside and outside the reserve.

The third reason for the large conservation effects may be related to sampling location. The farther away from the reserve, the larger the conservation effects on tree size, density and diversity were (Table S3). This indicates that sampling locations possibly biased the estimated conservation effects in forest structural traits and diversity traits, and our data also confirmed that dominant species abundance was not affected by the sampling distance from the reserve (Table S3). At the moment, different scientists sample at different distances when evaluating conservation effects, and this distance ranges from 2 to 70 km [18–20]. Our data strongly suggested that standardized sampling protocol including distance to the reserve should be developed in the future.

4.2. Complex Association Among Protection, Species and Forest Structure: The SEM Pathway Clarification

As implicated by the findings of this paper, conservation could alter dominant species, forest structure and species diversity in the tree, shrub and herb layers. However, these parameters also interact with each other, and these interactions make the associations between conservation and these parameters complex, and the driving force is difficult to identify. Recent studies have shown the ability of SEMs to identify soil depths and climates indirectly affected by glomalin-related soil protein using soil properties [36], functional trait composition and stand structural attribute-related driving factor identification [37], etc. This flexibility in SEM equational representation benefits the representation of complete hypotheses and the discovery of unanticipated relationships (e.g., effects of A on C not through B) [38].

Together with a statistically significant comparison, our findings in this paper found that SEMs could possibly identify the most probable pathway of the protection effects. Compared with other SEMs, over two-fold more path coefficients from the dominant species-aimed SEM were statistically significant ($p < 0.05$). According to basic probability theory and the statistical significance tests, this SEM pathway should be the most probable with the lowest risk of Type I and Type II errors [39]. The SEM with the most significant path coefficients in this paper was used to show the relative importance of conservation on dominant species, diversity and forest structure through the size of the direct effect coefficient and their indirect effect sizes. When comparing the conservation direct effects, SEM coefficient for the structural traits (0.854) was nearly two-fold higher than those of diversity and species abundance, indicating that conservation could much more easily increase tree sizes than dominant species abundance and species diversity. When comparing the influences on dominant species, direct effects from forest structure and species diversity traits were similar in power, about half of the direct influences from protection itself and the same to the indirect influences of protection via forest structure. Although it reported the complex associations in forests, and previous studies seldom statistically partition the relative importance, this paper gives an example on this.

However, this kind of mathematical deduction possibly has the risk of over analysis, with structural relationships as causal relations. Different methods, such as redundancy ordination, have been used to provide management hints to maximize ecological services and forest conservations during urbanization disturbance [7,22,40]. In the future, more specifically designed field experiments are needed to test this pathway and define the complex associations in the nature system, together with this kind statistical partitioning.

4.3. Implications

First, our paper defined the most informative parameters used in the evaluations of the nature reserve conservation effects. Some parameters such as the size and density of trees and understory, tree diversity and herb composition were statically derived from 20 parameters related to structure and diversity and abundance data for 39 species. The explicit evaluation of species composition and structure in nature reserves is an important means of predicting future species' distributions and biodiversity protection under climate change [41]. This parameter definition will benefit future policy development in NE China, where a total of 38 national natural reserves have been established.

Second, conservation management, rather than strict conservation without any management, should be deployed in the future in NFPP implementation. Though forests remained relatively intact in function, restoring through natural regeneration should be a priority [42], whereas active and effective restorations were required to overcome specific obstacles to recovery [43,44]. Our results further clarified nature conservation can rapidly regain their complex vertical structure, while species compositional improvement should need even longer protection. The results proved that forest structure, especially large-sized trees, had stronger resilience to conservation. Large old trees became extremely limited in this region, and their extreme height, like an umbrella, prolonged lifespans like mother trees provide their resistance to disturbance and key elements of biomass-related services [45,46]. Future active management in NFPP should pay more attention to these.

Third, the intricate association should be considered in future in NFPP. Natural forests with multiple functions are the product of long-term interactions among species and environment [4]. In NFPP practice, timber–harvest–prohibition has promoted the overutilization of understory plant species (*Acanthopanax senticosus*, *Aralia elata*, etc.) and environment as cultivation base for economic products (such as edible fungi, *Auricularia auricula*; wild boar breeding and different mushroom collections, etc.). Interactions observed in this study possibly provide suggestions on regulating forest cultivations via plant size selections, thinning and select-cutting of suiTable Species to achieve sustainable management of natural forests in this region. Moreover, the complex association also cautions to avoid the over-utilization of understory species and environment for future sustainable development.

The limitation of the study is that it has been conducted in one nature reserve, and this kind of one-point study possibly weakens its applicability to other places [18,47]. At the moment, the central government has launched at least three projects for field investigation of forests in NE China, including a project in all forest-related natural reserves in NE China (PI, Lihua Wang at Chinese Academy of Science). These data will soon be shared on the internet (http://www.geodata.cn/). By utilization of these shared field investigation works, multiple-reserve comparisons on the conservation effects will become available in the near future.

5. Conclusions

Nature conservation in NE China could strongly alter the vegetation-dominant composition in the herb layer and tree layer. Compared with the outside region, the inside of the reserve usually has much better forest structure with larger trees (tree height and DBH), but lower tree and shrub density. Inside the reserve, tree diversity and evenness increased 31% and 23.4%, while no significant impacts were observed in the shrub and herb layers. The most probable decoupling association showed that conservation could much more easily increase tree sizes, with about a two-fold effect, than species diversity and dominant species abundance. Our findings provide basic data for the evaluation of the effect of nature reserves on species diversity and forest structure, and also provide knowledge about the implications of further implementations of the NFPP.

Supplementary Materials: The following are available online at http://www.mdpi.com/1999-4907/11/3/295/s1, Table S1: Selection of dominant species in and outside nature reserve for dominant species abundance analysis. Table S2. Differences in dominant species abundance, forest structure and species diversity in plantation forests, secondary forests and natural forests of pooled plots used in this paper. Table S3. The edge effect on the forest parameters. Table S4. The Pearson correlation analysis on structure attributes. Table S5. The Pearson correlation analysis on species diversity. Table S6. PCA analysis of dominant tree, shrub and herb. Figure S1: The distribution of tree, shrub, herb structural characteristics inside the reserve and outside the reserve, Figure S2: The distribution of tree, shrub and herb diversity inside the reserve and outside the reserve. Figure S3. The probable pathway clarifications for conservation on (a) species diversity and (b) forest structure.

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References

1. Zhang, P.; Shao, G.; Zhao, G.; Le Master, D.C.; Parker, G.R.; Dunning, J.B., Jr.; Li, Q. China's forest policy for the 21st century. *Science* **2000**, *288*, 2135–2136. [CrossRef] [PubMed]
2. Shi, M.; Qi, J.; Yin, R. Has China's Natural Forest Protection Program Protected Forests?—Heilongjiang's Experience. *Forests* **2016**, *7*, 218. [CrossRef]
3. Hua, Y. China's Natural Forest Protection Program: Progress and impacts. *For. Chron.* **2017**, *93*, 113–117.
4. Dai, L.; Li, S.; Zhou, W.; Qi, L.; Zhou, L.; Wei, Y.; Li, J.; Shao, G.; Yu, D. Opportunities and challenges for the protection and ecological functions promotion of natural forests in China. *For. Ecol. Manag.* **2017**, *410*, 187–192. [CrossRef]
5. Hongbo, W. Discussion on forest resources management countermeasures in classified forest management. *For. Resour. Manag.* **2004**, *5*, 29–32. [CrossRef]

6. Xiao, L.; Wang, W.; He, X.; Hailiang, L.; Wei, C.; Zhou, W.; Zhang, B. Urban-rural and temporal differences of woody plants and bird species in Harbin city, northeastern China. *Urban For. Urban Green* **2016**, *20*, 20–31. [CrossRef]
7. Zhang, D.; Wang, W.; Zheng, H.; Ren, Z.; Zhai, C.; Tang, Z.; Shen, G.; He, X. Effects of urbanization intensity on forest structural-taxonomic attributes, landscape patterns and their associations in Changchun, Northeast China: Implications for urban green infrastructure planning. *Ecol. Indic.* **2017**, *80*, 286–296. [CrossRef]
8. Liang, J.; Buongiorno, J.; Monserud, R.A.; Kruger, E.L.; Zhou, M. Effects of diversity of tree species and size on forest basal area growth, recruitment, and mortality. *For. Ecol. Manag.* **2007**, *243*, 116–127. [CrossRef]
9. Zhang, J.; Wang, W.; Du, H.; Zhong, Z.; Xiao, L.; Zhou, W.; Zhang, B.; Wang, H. Differences in community characteristics, species diversity, and their coupling associations among three forest types in the Huzhong area, Daxinganling mountains. *Acta Ecol. Sin.* **2018**, *13*, 4684–4693.
10. Valbuena, R.; Packalén, P.; Martı´n-Fernández, S.; Maltamo, M. Diversity and equitability ordering profiles applied to study forest structure. *For. Ecol. Manag.* **2012**, *276*, 185–195. [CrossRef]
11. Swamy, V.; Terborgh, J.; Dexter, K.G.; Best, B.D.; Alvarez, P.; Cornejo, F. Are all seeds equal? Spatially explicit comparisons of seed fall and sapling recruitment in a tropical forest. *Ecol. Lett.* **2011**, *14*, 195–201. [CrossRef] [PubMed]
12. Kuang, X.; Zhu, K.; Yuan, Z.; Lin, F.; Ye, J.; Wang, X.; Wang, Y.; Hao, Z. Conspecific density dependence and community structure: Insights from 11 years of monitoring in an old-growth temperate forest in Northeast China. *Ecol. Evol.* **2017**, *7*, 5191–5200. [CrossRef] [PubMed]
13. Laurance, W.F.; Useche, D.C.; Rendeiro, J.; Kalka, M.; Bradshaw, C.J.; Sloan, S.P.; Laurance, S.G.; Campbell, M.; Abernethy, K.; Alvarez, P.; et al. Averting biodiversity collapse in tropical forest protected areas. *Nature* **2012**, *489*, 290–294. [CrossRef] [PubMed]
14. Craigie, I.D.; Baillie, J.E.M.; Balmford, A.; Carbone, C.; Collen, B.; Green, R.E.; Hutton, J.M. Large mammal population declines in Africa's protected areas. *Biol. Conserv.* **2010**, *143*, 2221–2228. [CrossRef]
15. Geldmann, J.; Barnes, M.; Coad, L.; Craigie, I.D.; Hockings, M.; Burgess, N.D. Effectiveness of terrestrial protected areas in reducing habitat loss and population declines. *Biol. Conserv.* **2013**, *161*, 230–238. [CrossRef]
16. Zhou, Y. *Vegetation Geography of Northeastern China*; Science Presss: Beijing, China, 1997.
17. Wang, W.; Du, H.; Xiao, L.; Zhang, J.; Zhong, Z.; Zhou, W.; Zhang, B.; Wang, H. Differences in Plant Composition and Forest Structure among of 3 Forest Types in Liangshui National Nature Reserve. *Sci. Silvae Sin.* **2019**, *55*, 166–176.
18. Yang, F.; Wu, R.; Jin, T.; Long, Y.; Zhao, P.; Yu, Q.; Wang, L.; Wang, J.; Zhao, H.; Guo, Y. Efficiency of unlocking or locking existing protected areas for identifying complementary areas for biodiversity conservation. *Sci. Total Environ.* **2019**, *694*, 133771. [CrossRef]
19. Xu, W.; Pimm, S.L.; Du, A.; Su, Y.; Fan, X.; An, L.; Liu, J.; Ouyang, Z. Transforming Protected Area Management in China. *Trends Ecol. Evol.* **2019**, *34*, 762–766. [CrossRef]
20. Khan, K.R.; Iqbal, Z.; Alam, J.; Farooq, M.; Shah, A.H.; Hussain, M.; Shah, G.M.; Ali, D. Comparative study on floristic diversity of protected and unprotected Forests of Sathan Gali, District Mansehra, KP, Pakistan. *Acta Ecol. Sin.* **2019**, *39*, 273–279. [CrossRef]
21. Ma, K.; Liu, C.; Yu, S.; Wang, W. Plant community diversity in Dongling mountain, Beijing, China III. Species-abundance relations of several types of forest communities. *Acta Ecol. Sin.* **1997**, *17*, 573–583.
22. Wang, W.; Zhang, B.; Xiao, L.; Zhou, W.; Wang, H.; He, X. Decoupling forest characteristics and background conditions to explain urban-rural variations of multiple microclimate regulation from urban trees. *PeerJ* **2018**, *6*, e5450. [CrossRef] [PubMed]
23. Wang, Q.; Wang, W.; Zhong, Z.; Wang, H.; Fu, Y. Variation in glomalin in soil profiles and its association with climatic conditions, shelterbelt characteristics, and soil properties in poplar shelterbelts of Northeast China. *J. For. Res.* **2020**, *31*, 279–290. [CrossRef]
24. Rosseel, Y. Lavaan: An R package for structural equation modeling and more. Version 0.5–12 (BETA). *J. Stat. Softw.* **2012**, *48*, 1–36. [CrossRef]
25. Wang, W.; Wang, Q.; Zhou, W.; Xiao, L.; Wang, H.; He, X. Glomalin changes in urban-rural gradients and their possible associations with forest characteristics and soil properties in Harbin City, Northeastern China. *J. Environ. Manag.* **2018**, *224*, 225–234. [CrossRef] [PubMed]
26. Zhou, Y.; Ni, H.; Zhou, R. Forest plant diversity characteristics in the DaXing'an mountains. *Territ. Nat. Resour. Stud.* **1998**, *3*, 66–68.

27. Zhou, Y.; Li, J. Characteristics and distribution of main vegetation types in mountainous areas of eastern China. *Acta Phytoecol. Geobot. Sin.* **1964**, *2*, 190–206.
28. Nowacki, G.J.; Abrams, M.D. Is climate an important driver of post-European vegetation change in the Eastern United States? *Glob. Chang. Biol.* **2015**, *21*, 314–334. [CrossRef]
29. Zhou, R.; Zhou, Y. Plant resources of Heilongjiang province. *Territ. Nat. Resour. Stud.* **1985**, *4*, 19–28.
30. Liu, C.; Zhang, P.; Ren, S.; Liu, J. Discussion on the protection and management of forest resources in Liangshui Nature Reserve. *Territ. Nat. Resour. Stud.* **1991**, *1*, 58–62.
31. Ma, Y. *Liangshui National Natural Reserve Spatial Structure and Species Diversity*; Northeast Forestry University: Harbin, China, 2013.
32. Gray, C.L.; Hill, S.L.; Newbold, T.; Hudson, L.N.; Borger, L.; Contu, S.; Hoskins, A.J.; Ferrier, S.; Purvis, A.; Scharlemann, J.P. Local biodiversity is higher inside than outside terrestrial protected areas worldwide. *Nat. Commun.* **2016**, *7*, 1–7. [CrossRef]
33. Phillips, O. The changing ecology of tropical forests. *Biodivers. Conserv.* **1997**, *6*, 291–311. [CrossRef]
34. Zheng, W.; Zhu, J.; Pan, C. Multi-scale response of plant diversity in grassland ecosystem to anthropogenic disturbances. *Pratacult. Sci.* **2009**, *26*, 72–80.
35. Guyot, V.; Jactel, H.; Imbaud, B.; Burnel, L.; Castagneyrol, B.; Heinz, W.; Deconchat, M.; Vialatte, A. Tree diversity drives associational resistance to herbivory at both forest edge and interior. *Ecol. Evol.* **2019**, *9*, 9040–9051. [CrossRef] [PubMed]
36. Wang, W.; Zhong, Z.; Wang, Q.; Wang, H.; Fu, Y.; He, X. Glomalin contributed more to carbon, nutrients in deeper soils, and differently associated with climates and soil properties in vertical profiles. *Sci. Rep.* **2017**, *7*, e13003. [CrossRef]
37. Ali, A.; Lohbeck, M.; Yan, E.-R. Forest strata-dependent functional evenness explains whole-community aboveground biomass through opposing mechanisms. *For. Ecol. Manag.* **2018**, *424*, 439–447. [CrossRef]
38. Schweiger, A.K.; Schütz, M.; Risch, A.C.; Kneubühler, M.; Haller, R.; Schaepman, M.E. How to predict plant functional types using imaging spectroscopy: Linking vegetation community traits, plant functional types and spectral response. *Methods Ecol. Evol.* **2017**, *8*, 86–95. [CrossRef]
39. Rice, J.A. *Mathematical Statistics and Data Analysis*, 3rd ed.; Duxbury Press: Belmont, CA, USA, 2006.
40. Zhang, B.; Wang, W.; He, X.; Zhou, W.; Xiao, L.; Lv, H.; Wei, C. Shading, cooling and humidifying effects of urban forests in Harbin city and possible association with various factors. *Chin. J. Ecol.* **2017**, *36*, 951–961.
41. Jian, F.; Yangjing, P.; Shaohua, X.; Guofa, C. Evaluation of the species protected value of nature reserves in northeast China. *Acta Ecol. Sin.* **2018**, *38*, 6473–6483.
42. Liu, S.; Dai, L.; Wen, Y.; Wang, H. A review on forest ecosystem management towards ecosystem services: Status, challenges, and future perspectives. *Acta Ecol. Sin.* **2015**, *35*, 1–9.
43. Suding, K.; Higgs, E.; Palmer, M.; Callicott, J.B.; Anderson, C.B.; Baker, M.; Gutrich, J.J.; Hondula, K.L.; LaFevor, M.C.; Larson, B.M.; et al. Conservation. Committing to ecological restoration. *Science* **2015**, *348*, 638–640. [CrossRef]
44. Liu, J.; Viña, A.; Yang, W.; Li, S.; Xu, W.; Zheng, H. China's Environment on a Metacoupled Planet. *Ann. Rev. Environ. Resour.* **2018**, *43*, 1–34. [CrossRef]
45. Lindenmayer, D.B.; Laurance, W.F.; Franklin, J.F. Global Decline in Large Old Trees. *Science* **2012**, *338*, 1305–1306. [CrossRef] [PubMed]
46. Sist, P.; Mazzei, L.; Blanc, L.; Rutishauser, E. Large trees as key elements of carbon storage and dynamics after selective logging in the Eastern Amazon. *For. Ecol. Manag.* **2014**, *318*, 103–109. [CrossRef]
47. Xu, W.; Xiao, Y.; Zhang, J.; Yang, W.; Zhang, L.; Hull, V.; Wang, Z.; Zheng, H.; Liu, J.; Polasky, S.; et al. Strengthening protected areas for biodiversity and ecosystem services in China. *Proc. Natl. Acad. Sci. USA* **2017**, *114*, 1601–1606. [CrossRef]