Impacts of close-to-nature management on the stand states of Masson pine forests

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ABSTRACT

Introduction: Research on the effect of close-to-nature management (CTNM) on stand states and dynamics of forests is crucial for the evaluation of CTNM implemented and sustainable development of forestry.

Outcomes: We analyzed and compared the stand states and dynamics of Masson pine (*Pinus massoniana*) plantations in the young, middle-aged, and near-mature stages under CTNM eight years after selective cutting and unmanaged control. Both paired-sample T-tests and RDA ordination results demonstrated that the overall stand states with CTNM were superior to the control treatment in all three stages. The interaction of the CTNM and stand age significantly affected the Shannon-Wiener index of diameter class and regeneration density.

Discussion and Conclusion: CTNM and stand age jointly affected the stand state of forests and CTNM accelerated the forest development, which promoted an increase in the heterogeneity of stand parameters and shortened the formation time of a target stand. Greater tree size differentiation and adequate regeneration are particularly important aspects for improving the quality of Masson pine forests during the management processes.

Introduction

The state of forest stands reflects the history of forest disturbance and can provide important information for management practices (Zhang et al. 2014). A better understanding of stand states and the dynamics of forests is crucial for close-to-nature management (CTNM) planning (Rehush and Waser 2017; Schutz et al. 2016). CTNM is one of the most promising options for plantation silviculture and has received widespread attention in recent years (Brang et al. 2014; O’Hara 2016). Close-to-nature forestry is characterized by accepting the species composition present at the site, avoiding clear-felled areas from timber harvest, enhancing forest stability, utilizing natural processes, and focusing on the development of individual trees, so that mixed, unevenly aged, richly structured stands are formed (Sackov et al. 2017). Thus, CTNM has a significant impact on the structure, species composition, ground vegetation, and regeneration of forest stand (Ming et al. 2018).

Masson pine (*Pinus massoniana*) is a major afforestation and pioneer coniferous tree species which is widely distributed in central and southern China (Guan and Wen 2011; Maleki, Mohammadi, and Ji 2018). It is economically important for timber, wood pulp, and rosin and ecologically important for water conservation and environmental enhancement in forest ecosystems (Chen et al. 2015; Du, Ding, and Cai 2018). There has been a huge increase in the area of forest planted with Masson pine in southern China, especially in Guizhou Province, over the past several decades because of an increasing demand for turpentine and because of the species’ fast growth and environmental adaptability (Zhang et al. 2019). However, the creation of Masson pine monocultures over large areas, as well as destructive harvest methods, have generated a series of ecological problems such as low productivity, soil degradation, pests and diseases, and a reduction in biodiversity. Therefore, these forests require more effective management practices to ensure their sustainability (Wang et al. 2018; Zhang et al. 2019).

Thinning is an essential forestry practice (Shen et al. 2017). Numerous studies and observations have shown that thinning induces a change in the succession and recovery of forests, including stand structure, species composition, and vegetation cover (de Groot et al. 2016; Nagel et al. 2017; Wan et al. 2019). The dynamics of stand states after thinning can be used to understand the mechanisms of CTNM for sustainable forestry. We hypothesized that CTNM could significantly improve the stand states of Masson pine forests compared with unmanaged forests. Therefore, we investigated a range of stand parameters for trees, shrubs, herbs, and regenerating plants at different developmental stages, analyzed and compared the stand states of Masson pine plantation (young, middle-
aged, and near-mature stages) under CTNM and unmanaged control, eight years after selective cutting. The goals of this study are (1) to compare the stand states of managed and unmanaged Masson pine plantation; (2) to analyze the effect of CTNM and stand age on the overall stand states; (3) to identify the key indices for assessing the forest stand state. The present study provides a theoretical basis for the sustainable management of Masson pine forests.

Materials and methods

Study area

The study area is located in Kaiyang and Xifeng county of Guizhou Province in China, with geographical coordinates of 26°48′–27°22′N, 106°45′–107°17′E, and 26°57′–27°19′N, 106°27′–106°53′E, respectively. These counties have similar climatic conditions, experiencing a subtropical humid and mild climate with a mean annual temperature of 15.3°C. The mean annual rainfall is 1200 mm concentrating from July to September. The original vegetation has been destroyed, leaving Pinus massoniana, Cunninghamia lanceolata, and evergreen broad-leaved forest as the main forest types.

Study site and data collection

In the spring of 2009, the CTNM began with the implementation of the Sino-German cooperation project. Different CTNM measures were adopted for different development stages of Masson pine plantations, which contained tending, thinning, selective logging, and natural restoration (Table 1). No forestry operations were conducted during the different development stages, which were referred to as the control.

Nineteen sample blocks were set in the major distribution areas of Pinus massoniana CTNM by considering different development stages. Since most Masson pine plantations were at middle to mature development stages, 3, 7, and 9 blocks were selected for the young, middle-aged, and near-mature forest, respectively. Each block contained an unmanaged sample plot (control treatment) and a CTNM sample plot (managed treatment), they showed similar site conditions at different ages of Masson pine plantation and were randomly established and surveyed at the research area (Figure 1). Data from a total of 38 sample plots (20 × 20 m) were collected. Five 2 × 2 m quadrats were chosen along the diagonals of each plot to investigate shrubs and the regenerating saplings. Five internal 1 × 1 m quadrats were also chosen in each plot for detailed inventories of the herbaceous vegetation. Canopy closure, stem height (height of the first major branch), tree height, DBH (breast height was 1.3 m), crown width, and health status were measured for all trees in each plot with a DBH ≥ 5.0 cm. Shrubs were identified and measured for numbers, layer coverage, and total height. The numbers of regenerating saplings with height ≥ 1.3 m and DBH < 5 cm were measured. Herbs were identified and their numbers, layer coverages and heights were measured. In each shrub and herb quadrat, individual plants of average growth condition and size for each species were selected and dug out with roots. Each plant was divided into the above- and below-ground parts. The fresh weight of each part of the shrub and herb plants was determined in the field. Then, multiple sub-samples were weighed into plastic bags and sealed for transportation to the laboratory. There, the shrub and herb samples were oven-dried at 80°C to constant weight and then weighed to calculate the biomass.

Index system for forest stand state

We constructed an index system for the forest stand state from trees, shrubs, herbs, and regenerating plants, which consisted of 12 stand parameters that closely affected stand state. The specific measurements and details of the stand parameters are presented in Table 2, and descriptive statistics are summarized in Table 3.

Statistical analyses

The effects of the CTNM (managed vs. control) were examined using paired-sample T-tests, RDA (redundancy ordination analysis), and ANCOVA (analysis of covariance). R version 3.2.3 (R Core Team 2017) was used for all statistical analyses. The RDA was conducted using the vegan package (Oksanen et al. 2008), and ANCOVA was conducted using the car package. The figures were drawn using the ggplot2 package (Hadley 2007).

Results

Stand parameters under close-to-nature management

Paired-sample T-tests showed that CTNM led to significantly higher values for stand parameters T.SW, T.CC, and S.CC than in the control treatment. However, T.
H.SW, T.VLM, and H.BS showed no significant difference between the managed and control treatments in all three stand development stages. The parameters T.SW, T.DSW, T.CC, and S.CC in the managed treatment were significantly higher than in the control in the young stands. In both middle-age stands and near-mature stands, T.SW, T.CC, S.CC, R.DEN, H.SW, and H.CC in the managed treatment were significantly higher than in the control. S.BS was also higher than the control in middle-age stands, while S.SW was higher in near-mature stands with the managed treatment (Table 4).

**Overall stand states under close-to-nature management**

The RDA ordination plots from the CTNM and control treatment at the three stand development stages were clearly separated and clustered in ordination space with no overlaps, which verified that the CTNM produced very different results to the control treatment. The overall states of the managed stands were superior to control treatment stands in all three development stages (Figure 2).

**Influence of close-to-nature management and stand age on stand parameters**

The CTNM significantly increased the T.SW, T.CC, R.DEN, S. CC, S.BS, H.SW, and H.CC (P < 0.05 or P < 0.01 or P < 0.001). Stand age significantly increased T.DSW, T.VLM, R.DEN, S. SW, S.CC, S.BS, and H.CC (P < 0.05 or P < 0.01 or P < 0.001). The interaction of the management treatment and stand age significantly affected T.DSW and R.DEN (P < 0.05 or P < 0.001) (Table 5 and Figure 3).

**Discussion**

The RDA ordination results demonstrated that the overall stand states with CTNM were superior to the control treatment in all three development stages (Figure 2). The performance of stand parameters under CTNM (Tables 4–5, Figure 3) indirectly supported this viewpoint because more heterogeneous stand parameters were found where CTNM practices had rapidly modified the stand state. Multiple studies have verified that the greater the heterogeneity, the better the stand quality (de Groot et al. 2016; Leso et al. 2016; Rehush and Waser 2017; Wan et al. 2019) and CTNM is an effective method for improving the quality of plantation forests (He et al. 2018). The main reason for our finding was that in Masson pine forest after CTNM, the stand density decreased and, therefore, competition was reduced among the remaining trees for water, nutrients, and living space. Improved light conditions enhanced the vitality and photosynthesis of tree crowns, thus promoting the growth of remaining trees and increasing the heterogeneity of stand parameters.
Table 2. Definition and measurement of stand parameters.

| Dimension | Stand parameter | Abb. | Definition and measurement | References |
|-----------|-----------------|------|-----------------------------|------------|
| Tree      | Tree Shannon-Wiener index | T.SW | Calculated according to the formula: 
\[ H = - \sum_{i} p_i \ln(p_i); \]  
where \( S \) = number of tree species, \( p_i = n_i/N; \) \( n_i = \) number of tree species \( i \) in the tree community, and \( N = \) all individual trees | (Shannon and Weaver 1949) |
|          | Shannon-Wiener index of DBH class | T.DSW | Calculated according to the formula: 
\[ H = - \sum_{i} p_i \ln(p_i); \]  
where \( S \) = number of DBH class (2 cm); \( p_i = n_i/N; \) \( n_i = \) number of trees in DBH class \( i \) and \( N = \) all individual trees | (Burkhardt and Tome 2012) |
|          | Shannon-Wiener index of height class | T.HSW | Calculated according to the formula: 
\[ H = - \sum_{i} p_i \ln(p_i); \]  
where \( S \) = number of height class (1 m); \( p_i = n_i/N; \) \( n_i = \) number of trees in height class \( i \) and \( N = \) all individual trees | |
| Canopy closure (%) | T.CC | Expressed as the proportion (0–100) of the plot covered by tree canopy (DBH ≥ 5 cm) | (Chai and Wang 2016) |
| Tree volume (t hm⁻²) | T.VLM | Calculated according to the reported formulas | (Guiyang forestry afforestation investigation planning and design institute and Guizhou forestry investigation planning and design institute 2016) |
| Regeneration density (trees hm⁻²) | R.DEN | Number of saplings (tree height ≥1.3 m and DBH < 5 cm) per hectare | (Chai and Wang 2016) |
| Shrub     | Shrub Shannon-Wiener index | S.SW | Calculated according to the formula: 
\[ H = - \sum_{i} p_i \ln(p_i); \]  
where \( S \) = number of shrub species, \( p_i = n_i/N; \) \( n_i = \) number of shrub species \( i \) in the shrub community, and \( N = \) all individual shrub plants | (Shannon and Weaver 1949) |
| Shrub     | Shrub Shannon-Wiener index | S.CC | Expressed as the proportion (0–100) of the plot covered by shrub canopy | (Duncan et al. 1993) |
| Shrub     | Shrub biomass (t hm⁻²) | S.BS | See the field sampling in the Materials and Methods | (Zhang et al. 2014) |
| Herb      | Herb Shannon-Wiener index | H.SW | Calculated according to the formula: 
\[ H = - \sum_{i} p_i \ln(p_i); \]  
where \( S \) = number of herb species; \( p_i = n_i/N; \) \( n_i = \) number of herb species \( i \) in the herb community, and \( N = \) all individual herb plants | (Shannon and Weaver 1949) |
| Herb      | Herb Shannon-wiener index | H.CC | Expressed as the proportion (0–100) of the plot covered by herb canopy | (Duncan et al. 1993) |
| Herb      | Herb biomass (t hm⁻²) | H.BS | See the field sampling in the Materials and Methods | (Zhang et al. 2014) |

Table 3. Descriptive statistics of stand parameters.

| Dimension | Stand parameters | Abb. | Min. | Max. | Mean | SD |
|-----------|-----------------|------|------|------|------|----|
| Tree      | Tree Shannon-Wiener index | T.SW | 0.000 | 1.807 | 0.549 | 0.440 |
|           | Shannon-Wiener index of height class | T.DSW | 1.682 | 2.637 | 2.247 | 0.223 |
|           | Shannon-Wiener index of diameter class | T.HSW | 1.463 | 2.869 | 2.196 | 0.394 |
|           | Canopy closure (%) | T.CC | 70.000 | 95.000 | 80.263 | 6.571 |
|           | Tree volume (m³ hm⁻²) | T.VLM | 168.758 | 671.490 | 365.553 | 145.548 |
| Regeneration density (trees hm⁻²) | R.DEN | 0.000 | 7000.000 | 1947.368 | 1947.935 |
| Shrub     | Shrub Shannon-wiener index | S.SW | 0.000 | 2.212 | 1.561 | 0.441 |
| Shrub     | Shrub biomass (t hm⁻²) | S.CC | 10.000 | 60.000 | 28.816 | 12.326 |
|           | Shrub cover (%) | S.BS | 0.304 | 3.553 | 1.257 | 0.710 |
| Herb      | Herb Shannon-wiener index | H.SW | 0.000 | 1.959 | 1.422 | 0.383 |
| Herb      | Herb biomass (t hm⁻²) | H.CC | 10.000 | 80.000 | 37.105 | 17.920 |
|           | Herb cover (%) | H.BS | 0.046 | 1.436 | 0.432 | 0.421 |

CTNM significantly affected the indices from trees (T.SW, T.CC), shrubs (S.CC, S.BS), herbs (H.SW, H.CC), and regeneration (R.DEN). This was because most of the original Masson pine forests were single species, even-aged, and densely vegetated. The CTNM approach decreased tree density and canopy closure by thinning and also preserved associated tree species to increase species diversity. The forest gaps created by thinning provided a suitable forest microclimate and light conditions for undergrowth species (Meng, Lu, and Zeng 2014), so a greater heterogeneity of stand parameters was found in the managed treatment than the control (Table 3). Visnjic et al. (2013) reported that CTNM had a significant impact on the stand states, especially stand structure and regeneration in the comparison of virgin forest remnant and managed forest on Grmeč Mountain in Western Bosnia. Forests are dynamic biological systems that are continuously changing (Comas et al. 2009). Stand development or succession is the result of self-thinning, so that the forest gradually forms a diverse stable structure even in the absence of management disturbance. Our results showed that stand age significantly affected multiple indices from trees (T.DSW, T.CC), shrubs (S.
Table 4. Stand parameters for Masson pine forest under close-to-nature management and natural restoration (control).

| Item   | Young Control | Managed | Young Middle-aged | Managed | Young Near-mature | Managed |
|--------|---------------|---------|-------------------|---------|-------------------|---------|
| T.SW   | 0.227 ± 0.241 | 0.425 ± 0.251* | 0.410 ± 0.514 | 0.722 ± 0.505** | 0.362 ± 0.266 | 0.860 ± 0.408** |
| T.DSW  | 1.810 ± 0.199 | 1.968 ± 0.143* | 2.314 ± 0.082 | 2.252 ± 0.129 | 2.397 ± 0.160 | 2.281 ± 0.201 |
| T.HSW  | 2.205 ± 0.157 | 2.025 ± 0.452 | 2.557 ± 0.165 | 2.335 ± 0.471 | 1.988 ± 0.344 | 2.069 ± 0.382 |
| T.CC   | 88.333 ± 1.574 | 76.667 ± 7.638* | 86.429 ± 2.440 | 75.000 ± 4.082*** | 82.778 ± 4.410 | 75.556 ± 4.640*** |
| T.VLM  | 190.107 ± 27.846 | 198.315 ± 43.154 | 391.159 ± 128.576 | 314.751 ± 69.451 | 466.810 ± 132.058 | 398.122 ± 162.081 |
| R.DEN  | 0.601 ± 0.559 | 3.203 ± 0.167 | 1.345 ± 0.183 | 1.46 ± 0.11 | 1.864 ± 0.164 | 1.944 ± 0.206*** |
| S.BS   | 15 ± 5 | 28.333 ± 1.774* | 20.714 ± 7.319 | 34.286 ± 7.868*** | 23.889 ± 9.280 | 40.556 ± 13.333*** |
| S.CC   | 0.686 ± 0.332 | 0.972 ± 0.572 | 0.887 ± 0.331 | 1.457 ± 0.568* | 0.995 ± 0.455 | 1.936 ± 0.889 |
| S.M   | 1.067 ± 0.351 | 1.545 ± 0.13 | 1.294 ± 0.247 | 1.467 ± 0.263* | 1.228 ± 0.505 | 1.757 ± 0.233* |
| H.CCC  | 11.667 ± 2.887 | 0.20 ± 0.666 | 22.143 ± 5.669 | 35 ± 8.165*** | 41.667 ± 7.500 | 60.000 ± 12.990*** |
| H.BS   | 0.356 ± 0.502 | 0.368 ± 0.342 | 0.537 ± 0.581 | 0.511 ± 0.286 | 0.306 ± 0.396 | 0.462 ± 0.462 |

T.SW Tree Shannon-Wiener index; T.DSW Shannon-Wiener index of DBH class; T.CC Canopy closure; T.VLM Tree volume; R.DEN Regeneration density; S.SW Shrub Shannon-Wiener index; S.CC Shrub cover; S.BS Shrub biomass; H.SW Herb Shannon-Wiener index; H.CC Herb cover; H.BS Herb biomass

Figure 2. RDA plot of stand parameters for Masson pine forest under close-to-nature management and natural restoration (control).

Table 5. ANCOVA of Masson pine forest under close-to-nature management.

| Item   | Treatment | Sum of squares | F value | Treatment | Stand age | Sum of squares | F value | Treatment: Stand age | Sum of squares | F value |
|--------|-----------|----------------|---------|-----------|-----------|----------------|---------|-----------------------|----------------|---------|
| T.SW   | 1.389     | 8.395***       | 0.0112  | 0.677     | 0.157     | 5.104**        | 0.025  | 0.151                 | 1.128          | 5.719   |
| T.DSW  | 0.026     | 0.606          | 0.140   | 1.294     | 0.066     | 0.430          | 0.716  | 1.668                 | 0.716          | 1.210   |
| T.HSW  | 0.049     | 0.244          | 0.073   | 0.938     | 0.344     | 0.266          | 0.134  | 1.819                 | 0.134          | 1.819   |
| T.CC   | 852.630   | 43.707***      | 48.930  | 2.508     | 32.540    | 1.668          | 12.532 | 1.210                 | 12.532         | 1.210   |
| T.VLM  | 33.509.000| 3.235          | 385.597.000 | 37.226*** | 15.724.243 | 18.361***     | 21.627 | 1.210                 | 21.627         | 1.210   |
| R.DEN  | 42.105.263.000 | 49.165*** | 53.447.422.000 | 62.409*** | 15.724.243 | 18.361***     | 21.627 | 1.210                 | 21.627         | 1.210   |
| S.SW   | 0.297     | 3.983          | 4.297   | 58.809*** | 0.039     | 1.328          | 0.149  | 1.328                 | 0.149          | 1.328   |
| S.BS   | 4.670     | 14.256***      | 2.207   | 6.737*    | 0.659     | 2.012          | 0.470  | 1.328                 | 0.470          | 1.328   |
| H.SW   | 1.445     | 12.910***      | 0.391   | 0.352     | 0.149     | 1.328          | 0.149  | 1.328                 | 0.149          | 1.328   |
| H.CCC  | 1006.570  | 24.966***      | 675.900 | 81.763*** | 25.080    | 3.047          | 0.034  | 0.176                 | 0.034          | 0.176   |
| H.BS   | 0.041     | 0.217          | 0.003   | 0.017     | 0.034     | 0.176          | 0.034  | 0.176                 | 0.034          | 0.176   |

T.SW Tree Shannon-Wiener index; T.DSW Shannon-Wiener index of DBH class; T.CC Canopy closure; T.VLM Tree volume; R.DEN Regeneration density; S.SW Shrub Shannon-Wiener index; S.CC Shrub cover; S.BS Shrub biomass; H.SW Herb Shannon-Wiener index; H.CC Herb cover; H.BS Herb biomass

CC, S.BS), herbs (H.SW, H.CC), and regenerating plants (R.DEN). Therefore, stand age has a relatively large impact on the heterogeneity of stand parameters, and increases forest quality. However, the process takes a long time to accomplish naturally. We conclude that stand age and management treatment jointly affected the stand state of Masson pine forests. Management practices can hasten forest development, which can increase the heterogeneity of stand parameters and shorten the formation time of a target stand (Li et al. 2014).

The interaction of the CTNM and stand age significantly affected T.DSW and R.DEN (Table 5 and Figure 3), which confirmed these two stand parameters were key indices for determining the state of forest stands. T.DSW can effectively represent the degree of size differentiation. On the one hand, management practices, e.g., selective
logging improved size differentiation by adjusting the DBH structure, on the other hand, tree size differentiation needs a long self-thinning process and leads to inter- and intra-specific competition among individual trees. Meissner et al. (2012) supported and assumed that CTNM fostered mixed stands of heterogenous diameters and further enhanced complementarity in soil water uptake among canopy trees in a temperate mixed forest of Germany. The Masson pine is an endemic species in south-western China. However, its failure to regenerate naturally is a widespread problem. The CTNM practices can provide a suitable forest microclimate and light conditions for species regeneration by creating forest gaps (Meng, Lu, and Zeng 2014), although the survival and establishment of regenerating plants may still take a long time. Madsen (2008) has noted that CTNM is an important and flexible toolbox to secure the sustainable development of forest by gap regeneration. Adequate natural regeneration plays an important role in the tree population, and can improve forest resources, maintain biological diversity, and reflect forest quality (Yu et al. 2013). The development of tree size differentiation and forest regeneration is complex ecological processes that are controlled by both management practices and stand age. Higher tree size differentiation and adequate regeneration mean a better stand quality, and they are also particularly important aspects for improving the quality of Masson pine forests during forest management.

Figure 3. The relationship of stand parameters with stand age for Masson pine forests under close-to-nature management and natural restoration (control) Note: T.SW Tree Shannon-Wiener index; T.DSW Shannon-Wiener index of DBH class; T.HSW Shannon-Wiener index of height class; T.CC Canopy closure; T.VLM Tree volume; R.DEN Regeneration density; S.SW Shrub Shannon-Wiener index; S.CC Shrub cover; S.BS Shrub biomass; H.SW Herb Shannon-Wiener index; H.CC Herb cover; H.BS Herb biomass.
Conclusions

CTNM clearly improves the forest stand state of Masson pine forests over the eight years. CTNM and stand age jointly affect the stand state of Masson pine forests, and CTNM accelerated forest development. The Shannon–Wiener index of diameter class and regeneration density are the key indices for determining the forest stand states, greater tree size differentiation, and adequate regeneration are two particularly important aspects during management to improve the forest quality of Masson pine forests.

Authors’ contributions

Zongzheng Chai performed the sample collection, analyzed the data, and wrote the manuscript. Wei Tan reviewed the manuscript. All authors approved the final manuscript.

Ethics approval and consent to participate

Not applicable

Consent for publication

Not applicable

Availability of data and materials

All data generated or analyzed during this study are included in this published article.

Disclosure statement

The authors declare that they have no competing interests.

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