Optimizing stand structure for trade-offs between overstory timber production and understory plant diversity: A case-study of a larch plantation in northwest China

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Abstract
Trade-offs are often required for an optimal and sustainable supply of competing services from forests. A study was conducted in northwest China to explore a practical trade-off approach, for promoting the rehabilitation of service-degraded plantation, focusing on the two main competing services of timber production and understory plant diversity conservation (expressed by understory vegetation species number [UVSN]). To describe the stand structure parameter variation with age and tree density, the logistic growth model and power function were coupled and fit with field data from 82 plots of larch (Larix principis-rupprechetti Mayr) plantation within the estimated age range of 12–33 years. The UVSN variation with canopy density and tree density were also quantified. These models and relations developed can serve as a tool for estimating trade-offs. The results showed that with rising tree density, the single tree timber volume decreased but the stand timber volume increased. The UVSN increased until its maximum, at the canopy density range of 0.6–0.7, and then decreased quickly. A proper tree density corresponding to the optimal canopy density of around 0.7 should be kept for maintaining higher UVSN and adequate timber production. In case of the larch plantation studied, optimal tree densities were found around 2,600, 2,000, 1,600, 1,250, and 1,000 trees/ha for the ages of 15, 20, 25, 30, and 35 years, respectively. Although only two main services were considered, the trade-off approach developed here can be a reference for future studies to guide the rehabilitation and multifunctional management of service-degraded plantation.

KEYWORDS
larch plantation, services trade-offs, stand structure, timber production, understory plant diversity conservation

1 | INTRODUCTION

Afforestation has gained significant attention as an effective measure to combat the global shrinkage of natural forests cover (Mason & Zhu, 2014; Zerbe, 2002) and to restore the degraded environment (Chazdon, 2008; Ren, Lü, Fu, & Zhang, 2017) mainly caused by climate change (Singh, Shi, Foresman, & Fosnight, 2001) and improper land use (Daramola, 2012). However, traditional plantation management, with the sole aim of maximizing timber production, does not consider the balance supply of forest ecosystem services (FESs) for meeting the
increasing and diverse service demand by society. Therefore, traditional forest management has been amended to a FES-oriented approach (Wang et al., 2015; Wang et al., 2017).

The understory vegetation (UV) is a crucial component of forest ecosystem and an important indicator for forest health and stability (Suchar & Crookston, 2010; Zhang, Young, Oliver, & Fiddler, 2015). It is closely related with many FES (e.g., erosion control, carbon sequestration, and hydrological regulation; Bauhus, Aubin, Messier, & Connell, 2001; Deng, Han, Zhang, & Shangguan, 2017; Naeem & Li, 1997), the natural regeneration of trees (Légaré, Bergeron, & Paré, 2002), and biodiversity conservation (Dauber et al., 2003).

However, sharp competition exists worldwide between overstory timber production and UV maintenance in traditional plantation (Zhang et al., 2015). Timber production oriented management has led to proliferation of overdense canopy and many related problems, such as very low understory plant diversity and coverage (Barbier, Gosselin, & Balandier, 2008; McKenzie, Halpem, & Nelson, 2000; Smith, Larson, Kelty, & Ashton, 1997), very poor natural regeneration, deteriorated site quality (Islam, Ahmed, Bhuiyan, & Badruddin, 2001), lowered FES (Chazdon, 2008; Bauhus, van der Meer, & Kanninen, 2010), and land degradation (Blakie & Brookfield, 2015; Lal, 2012; Reed et al., 2011). Therefore, a multistoried stand with enough UV and sapling should be established and maintained (Huo, Feng, & Su, 2014) for rehabilitating the degraded forest land (Bauhus et al., 2010; Chazdon, 2008) and achieving the multiple goals of quality timber production, biodiversity conservation, long-term ecosystem stability, and higher FES provision (Barbier et al., 2008; Keenan, Lamb, Woldring, Irvine, & Jensen, 1997). However, controversy still exists whether there are trade-offs and how to realize them between timber production and understory plant diversity conservation. Thus, it is vitally important to understand and quantify the response of UV species number (UVSN) to tree density and canopy density (Duguid, Frey, Ellum, Kelty, & Ashton, 2013), to direct plantation management.

Stand structure regulations based on quantitative modeling can further define the required trade-offs to balance the competing services of overstory timber production and understory plant diversity conservation. For the even-aged plantation at any given site and age, tree density is the key factor directly affecting timber growth and canopy density (Tappeiner, Huffman, Marshall, Spies, & Bailey, 1997) and indirectly affecting the UVSN (Garcia-Gonzalo, Peltola, Gerendiaín, & Kellomäki, 2007; Roberts & Zhu, 2002) mainly through the modified microclimate (Will, Narahari, Shiver, & Teskey, 2005). Thus, it is urgent and vitally important to understand and quantify the response of UVSN to stand structure, mainly of tree density and canopy density (Duguid et al., 2013). With such aim, this study on larch (Larix principis-rupprechtii Mayr) plantation (LP) was carried out.

The LP has been widely established in north and northwest China since 1950s, and in the Liupan Mountain (LPM) region since 1982, mainly for increasing forest coverage and timber production. Relatively more studies have been conducted for the individual services of LP, such as timber production, carbon sequestration, and water regulation. However, few studies exist on the UV response to overstory tree density and canopy density, and on the integrated management under the guidance of optimal tree density and canopy density to realize multiple FES (Alkemade, Burkhard, Crossman, Nedkov, & Petz, 2014; Mason & Zhu, 2014).

The purpose of this study was to find a practical quantitative trade-off approach between the competing main services of overstory timber production and understory plant diversity conservation, based on the evaluation of the influences of tree density at varying ages on tree growth, timber volume, canopy density, and UVSN, with help of the simulation of models fit with field inventory data. The trade-off approach developed in this study can help establish guidelines to create and maintain a stable and service-rich plantation.

2 | METHODS

2.1 | Study area

The study area is located in the small watershed of Xiangshuihe (XSH, 106°9′–106°30′E, 35°15′–35°41′N) of LPM (Figure 1) situated in the central and western parts of the Loess Plateau, northwest China. XSH has an area of 43.74 km² and an elevation range of 2,060–2,931 m. The climate is warm temperate continental monsoon, with a mean annual air temperature of 5.8°C and a mean annual precipitation of 771 mm. The forest coverage in XSH is 72.9%, mainly of natural secondary forests composed of Armand Pine (Pinus armandii Franch), white birch (Betula platyphylla Suk), red birch (Betula albosinensis Burk), and poplar (Populus davidiana Dode). The plantation coverage is 23.6%, mainly of LP (70% of plantation area). The main soil type is grey cinnamon, covering more than 90% of XSH, and being rich in gravels from weathered sandy mudstone, shale, and limestone.

2.2 | Sample plot setting

During 2012–2016, 82 LP plots were set up, with a size of 30 m × 30 m or 20 m × 20 m depending on local landform. They were stratified into tree layer, shrub layer, and herb layer. Based on the low yet evenly distributed UV coverage, three subplots (5 m × 5 m) for shrubs layer and five quadrates (1 m × 1 m) for the herb layer were distributed at representative places within 31 plots of the 82 LP plots.

2.3 | Data collection and calculation

The elevation of each plot center was measured with GPS. The slope gradient, position, and aspect were measured with a compass. The canopy density was visually estimated based on the ratio of crown projection area to the plot area. The height and diameter at breast height (DBH) of all trees with a DBH ≥ 5 cm were measured. The age of individual sample trees was determined by counting the number of annual rings of increment cores taken by Swedish increment borer. Because all investigated stands were even-aged, the stand age was the same of sampled trees. Furthermore, the mean age of some stands was their age average. The tree density (trees/ha) was calculated by dividing the total number of trees by plot area.

The species, number, and height of shrubs and herbs were measured at each subplot and quadrat within 31 LP plots. The coverage of shrub and herb layers were measured along the diagonals of each plot. The understory plant species diversity in shrub and herb
layers were expressed first by the species number in each plot, and then by three plant species diversity indices calculated using Equations 1–3 (Olawusi-Peters & Ajibare, 2014):

Margalef species richness index ($R$):

$$ R = \frac{S-1}{\ln(N_r)} \quad (1) $$

Simpson index ($D$):

$$ D = 1 - \sum_{i=1}^{S} (P_i)^2 \quad (2) $$

Shannon-wiener index ($H$):

$$ H = -\sum_{i=1}^{S} (P_i \times \ln(P_i)) \quad (3) $$

where $S$ is species number, $N_r$ is the total number of individuals of all species, and $P_i$ is the proportion of the number of individuals of the $i$th species to $N_r$.

The growth of tree DBH (cm), height ($H$, m), and canopy density (CD) normally follow a logistic growth model (LGM) with tree age ($t$, year; Luo & Liao, 2008) and a power function of tree density ($N$, trees/ha). These single factor functions were confirmed using the upper boundary line of observed data (see section 3) and then coupled as shown in Equations 4–6:

$$ DBH = \frac{DBH_{\text{max}}}{1 + a \cdot e^{-kt}} \cdot N_c \quad (4) $$

$$ H = \frac{H_{\text{max}}}{1 + a \cdot e^{-kt}} \cdot N_c \quad (5) $$

$$ CD = \frac{CD_{\text{max}}}{1 + a \cdot e^{-kt}} \cdot N_c \quad (6) $$

where DBH, $H$, and CD are the stand means and $DBH_{\text{max}}$, $H_{\text{max}}$, and $CD_{\text{max}}$ are the maximum values of DBH, $H$, and CD in the study region, determined either according to literature or based on field inventory. The parameters of $a$, $k$, and $c$ are fit with field data. The $c$ and $k$ are related with the tree density and age effects, respectively, whereas the $a$ affects the location of the growth curve in time.

The single tree timber volume ($V$, m$^3$) was calculated using a general formula (Equation 7), the field data of DBH (cm), and $H$ (m), along with the average form factor ($f$) of each DBH segment for LP (Ma et al., 2011):

$$ V = f \times G \times H \quad (7) $$

where $G$ is the basal area of trees ($m^2$, $G = 3.14 \cdot [DBH/200]^2$). The sum of the timber volume of all single trees ($TV_i$, m$^3$) in each plot was
divided by the plot area \((S, m^2)\) to get the stand timber volume per hectare \((TV_s, m^3/ha)\), as Equation 8 below:

\[
TV_s = \sum TV_i \cdot 10,000 / S
\] (8)

2.4 | Statistical analysis and trade-off

The data were analyzed by several statistical software packages: SPSS-19 for fitting the parameters of LGM (Equations 4–6) through nonlinear regression, MS Excel-13 for calculation and SigmaPlot-12.5 for regression analysis.

The variation in stand structure parameters (DBH, \(H\), and CD) was influenced by many factors. This limited the determination of a specific function (proper function type) to describe the responses of stand structure parameters to a single driving factor (e.g., tree age and tree density). To exclude interference from other factors, the data at least one standard deviation higher than the mean value within each x-axis segment (Schmidt, Thöni, & Kaupenjohann, 2000), or those as the highest value in some segments with low data intensity, were selected to derive the upper boundary line which can express the function types of the response of stand structure parameters (or called growth indices) to a single driving factor.

The trade-off principle in this study was to achieve a possibly higher UVSN with adequate timber production through a proper tree density regulation. This was realized through following steps: (a) The variation in tree growth, timber production, and canopy density were analyzed and modeled with tree density and age; (b) based on the regression line describing the variation of UVSN with canopy density, an optimal canopy density range was determined for improving UVSN; and finally, (c) using the model calculated canopy density, stand timber volume, and UVSN at various tree densities and ages, the age-dependent proper tree density of LP was suggested for balancing the competing services of timber production and understory plant diversity conservation.

3 | RESULTS

3.1 | Variation of maximum tree density with age

The long-term logging ban policy since 1998 in the study area resulted in many overdense stands, creating an opportunity to quantify the variation of maximum tree density with stand age. Generally, the tree
density of any given stands decreases with rising age because of enhanced competition among older trees with enlarged crowns.

A regression line based on upper boundary data was derived to roughly estimate the maximum tree density at a given age (Figure 2). For example, the maximum tree densities are about 2,700, 2,400, 1,900, 1,500, and 1,300 trees/ha at the ages of 15, 20, 25, 30, and 35 years, respectively.

3.2 | Effects of tree density and age on tree growth

According to the upper boundary lines in Figure 3, the growth of tree DBH and height followed the LGM of age and the power function of tree density well, as expected (Equations 4 and 5). Tree DBH and height increased continuously with rising age until a certain age threshold and then leveled off, although it was a less obvious leveling in this study due to the relatively young ages (≤33 years) of LP.

After the confirmation of function type, the parameters in the growth models of stand mean DBH and height were fit with field data (Table 1). The variation of growth indices with rising age and tree density were then calculated using the fit models to assess the tree density and age effects on tree growth (Figure 4). Results showed that growth of tree DBH, height, and single tree volume were mostly controlled by tree age, rather than tree density. However, the stand timber volume per hectare was more affected by density than by age, as it increased nearly linearly with rising tree density at any age, but with an age‐depending rate which declined obviously if it was over 30 years.

3.3 | Canopy density variation with tree density and age

Canopy density can affect the UV more directly than other stand structure parameters. The canopy density variation with rising tree age and density was analyzed using upper boundary lines (Figure 5). Results showed that the LGM and power function were suitable to describe the canopy density variation with tree age and density, respectively. Thus, the model parameters in Equation 6 were fit using field data (Table 1).

Using the fit model, the responses of canopy density to tree density and age were calculated (Figure 6). Canopy density was primarily affected by tree density for all ages in the studied range. The age effect on canopy density was relatively small and even.

| Growth index | Parameters | Estimate | SE | 95% confidence interval | Lower bound | Upper bound | R² |
|--------------|------------|----------|----|------------------------|-------------|-------------|----|
| DBH          | a          | 13.950   | 6.254 | 1.452 26.447           | 0.74        |
|              | k          | 0.174    | 0.033 | 0.240 −0.108          |
|              | c          | −0.060   | 0.009 | −0.078 −0.042         |
|              | DBH MAX    | 26       |      |                       |             |
| Tree height  | a          | 17.782   | 7.327 | 3.140 32.424           | 0.79        |
|              | k          | 0.183    | 0.030 | 0.242 −0.124          |
|              | c          | −0.051   | 0.008 | −0.067 −0.035         |
|              | H MAX      | 22       |      |                       |             |
| Canopy density | a         | 29.52    | 10.584 | 8.382 50.658           | 0.53        |
|              | k          | 0.018    | 0.005 | 0.028 −0.008          |
|              | c          | 0.356    | 0.049 | 0.258 0.355           |
|              | CD MAX     | 1        |      |                       |             |

Note. DBH: diameter at breast height; CD, canopy density.

FIGURE 4 Variation of plot diameter at breast height (DBH) and tree height, single tree timber volume, and stand timber volume with tree density and age of larch plantation, based on model calculation.
Variation of understory plant diversity with tree density

All three biodiversity indices for both shrub and herb layers presented the same variation tendency with rising tree density (Figure 7), whereby it first increased and then decreased. However, the variation rate, the highest biodiversity index, and corresponding tree density differed greatly among the three indices. For shrub and herb layers, the highest index and corresponding tree density were 2.18 at 1,800 trees/ha and 2.17 at 1,300 trees/ha for Margalef species richness index, 0.89 at 1,800 trees/ha and 0.95 at 1,300 trees/ha for Simpson index, and 2.2 at 1,300 trees/ha and 1.98 at 1,100 trees/ha for Shannon-wiener index, respectively. This indicates that there is no identical proper tree density corresponding to the highest biodiversity index among the three indexes and between the shrub and herb layers. Therefore, only the UVSN index was used in further analysis for the effects of tree density and canopy density on understory plant diversity.

3.5 | UVSN variation with canopy density

According to the UVSN survey, there were 52 native species of UV, including 16 shrub species and 36 herb species, belonging to 20 families and 45 genera. The most frequently occurring species were Agropyron cristatum Linn Gaertn., Artemisia annua Linn, Artemisia argyi Lev. et Van., Berberis thunbergii DC, Carex lanceolata Boott, Carex rigescens Franch, Fragaria ananassa Duchesne, Prunus padus Linn, Prunus salicina Lindl, Radix acanthopanacis Semticosi, Rosa omeiensis Rolfe, Rubus corchorifolius L.f., Saussurea japonica Thumb DC., and Viburnum florida Hance.

As shown by the regression line with a relative high fit ($R^2 = 0.64$, $p < 0.0001$) in Figure 8a, the UVSN increases rapidly with rising canopy density until the range of 0.6–0.7 and thereafter decreased.
quickly to nearly zero when the canopy was fully closed. The regression equation in Figure 8a, combined with Equation 6, was used in later analysis for trade-offs. Based on the results, it can be suggested to keep the canopy density within the optimal range of 0.6–0.7 from the viewpoint of regulating possibly higher UVSN.

3.6 | Trade-off between timber production and UVSN

Two attempts were made to determine the proper tree density which may balance the competing services of overstory timber production and understory plant diversity. The first attempt was based on the raw data from 31 plots. The variation curves of UVSN and stand timber volume against tree density were plotted together in Figure 8b and fit well ($R^2 = 0.84, p < 0.0001$ and $R^2 = 0.64, p < 0.0001$). They were used to make trade-offs without considering age effect. If selecting the density of 1,455 trees/ha at the intersecting point of two curves, it corresponds to a canopy density of 0.68, a UVSN of 27, and a stand timber volume of 169 m$^3$/ha. If using the optimal canopy density range of 0.6–0.7, it corresponds to a density range of 1,032–1,476 trees/ha, an UVSN range of 27–28, and a stand timber volume range of 135–170 m$^3$/ha. It looks that the selection of a canopy density of 0.6 or below will lead to too much and disproportionate timber production loss. Thus, the proper tree density associating the canopy density around 0.7 should be kept, for both higher UVSN and adequate timber production. It is around 1,500 trees/ha for the LP with the mean age of 26 years.

Because the proper tree density must vary with stand age, the second attempt was made based on the model simulation. The stand timber volume curve was based on the calculation using the fit LGM models (Equations 4, 5, 7, and 8), and the UVSN curve was derived based on the calculated canopy density using Equation 6 and the regression equation from Figure 8a. The results can be seen in Figure 9. When selecting the proper tree density corresponding to the optimal canopy density of around 0.7, it will be around 2,600, 2,000, 1,600, 1,250, and 1,000 trees/ha for the ages of 15, 20, 25, 30, and 35 years, with the corresponding UVSN of 25, 25, 25, 25, and 25, respectively. Under those tree densities, the USVN is 1.49%, 8.82%, 7.92%, 9.10%, and 16.13% higher but the stand timber volume is 3.18%, 14.03%, 13.28%, 14.03%, and 19.55% lower than that under the maximum densities of 2,700, 2,400, 1,900, 1,500, and 1,300 trees/ha for those ages, respectively. Meanwhile, the timber quality will be improved since the stand mean DBH has been increased by 0.23%, 1.10%, 1.04%, 1.10%, and 1.59%, and single tree timber volume increased by 0.65%, 3.17%, 2.98%, 3.17%, and 4.59%, respectively (Figure 4).

4 | DISCUSSION

4.1 | Variation of understory plant diversity with stand structure

A chain of relationships were found between overstory stand structure and UV (Ffolliott & Clary, 1972) and also between tree layer productivity and species diversity (Bohn & Huth, 2017). Even so, there is a scarcity of quantitative methods for optimizing the relationships for understory plant diversity (Bohn & Huth, 2017; McKenzie et al., 2000), especially under progressing tree age (MacLean & Wein, 1977).

Tree density exhibits a strong effect on understory plant diversity, and the majority of UV species do not exist in overdense plantation (Barbier et al., 2008), as shown by the variation of UVSN and all three biodiversity indices in this study. However, the estimated proper tree densities for higher UVSN and timber production were not identical among the three biodiversity indices, probably due to their different calculations. Comparatively, using the UVSN response to determine the proper tree density was easier and more intuitive.

In this study, both UVSN and stand timber volume increased with rising tree density until a certain threshold; thereafter, the stand timber volume increased continuously but the USVN decreased (Figure 8). This is similar to other studies (Barbier et al., 2008; Bohn & Huth, 2017; VanderSchAAF, 2008).

Canopy density is one of the important stand structure parameters directly affecting UVSN (Huo et al., 2014). Some studies have reported a decrease of UVSN with rising canopy density (Barbier et al., 2008; Berger & Puettmann, 2000). However, this study showed an increase and then a quick decrease of UVSN with rising canopy density, similar to the tree density effect and that reported by Zhang et al. (2015). Especially, the UVSN decreased very quickly when the
canopy density was above 0.8; therefore, keeping the canopy density within the range of 0.6–0.7 to maintain a higher UVSN is considered optimal. However, such a solution may not be realizable in some cases when the timber production losses incurred would be too high or other limitations/requirements exist; thus, further studies on precise trade-offs are required.

4.2 Effect of tree age and density on tree growth

Tree density and age jointly affect tree growth and timber production (Copenhaver & Tinker, 2014). This has been well described and predicted by the models fit in this study, through coupling the age effect and density effect. The tree growth followed the LGM well, that is, initially slow, then faster, and thereafter slow again with rising age, as observed by Luo and Liao (2008). The LGM was thought highly suitable under different tree densities (Zhao & Chang, 1991). However, in this study, only including the relatively young plantation with ages below 33 years limited a full observation of the age effect on tree growth.

An increase in tree density reduces the single tree volume, especially in higher density ranges, due to stronger competition of light, water, and nutrition (Bauhus et al., 2001); furthermore, it increases the total timber volume per unit area (Litton, Ryan, & Knight, 2004) with a varying rate due to the interaction of increasing tree numbers and decreasing tree size (Miller & Bender, 2016; Vanninen, 2004). Such a tree density effect has been well modeled by a power function, as shown by Smith et al. (1997).

4.3 Trade-off approach for timber production and understory plant diversity

The modern forestry oriented management for maximizing the total value of all FES to communities (Wang et al., 2017) requires a FES-oriented management based on the basic information of stand structure parameters (Chazdon, 2008) and their relationships to individual services. However, traditional forest inventories focus on overstory timber production, resulting in a shortage of UV data (Timilsina, Cropper, Escobedo, & Lima, 2013). Poor quantification of FES response to stand structure, especially the relationships between overstory and UV (Smith, 2011), still limits the multifunctional management decisions for incorporating trade-offs between overstory timber production and understory plant diversity in plantation.

Among the overstory stand structure parameters (tree density, tree age, and canopy density) which can directly or indirectly affect timber production and UV (MacLean & Wein, 1977; McKenzie et al., 2000), tree density is the most operational and decisive factor for
forest management practice. Excessively dense forest will lead to higher quantity but lower quality of timber, overdense canopy, and corresponding nonlinear decrease of UVSN (Koukoura & Kyriazopoulos, 2007; Liu, 2005). In this study, a general trade-off approach was developed, for maintaining a proper tree density corresponding to the optimal canopy density around 0.7. Such proper tree density of the studied LP was suggested to be around 2,600, 2,000, 1,600, 1,250, and 1,000 trees/ha at the ages of 15, 20, 25, 30, and 35 years, under the optimal canopy density of 0.7, respectively. As a more precise decision tool, the models and relationships developed and fit in this study can be used to determine the proper tree densities at any stand age, for balancing the competing services of overstory timber production and understory plant diversity conservation.

4.4 Limitation of current study and suggestions for future

The preliminary progress of this study can be viewed as a reference to further studies toward multifunctional forest management with various tree species and in different regions. However, the direct application of the models fit here was limited due to low age range (12–33 years), which does not fully cover the fast-growing period, no data from the mature stand in slow-growing period and limited number of plots. Therefore, future studies can include a broader variation of stand structure.

Soil drought is vitally important to limit the plant growth in dryland areas. The site factors of elevation, slope gradient, slope aspect, and soil thickness can modify soil moisture significantly. All these site factors and their effects should be considered in future studies.

Forests can supply numerous FES, such as hydrological regulation, water supply, erosion control, carbon sequestration, timber quantity, and quality-related economic income. These FESs were not considered in this study but should be included in future studies about multifunctional management or rehabilitation of service-degraded plantations.

5 CONCLUSION

Traditional plantation management for maximizing timber production is generally understood as high tree density, and unfortunate loss of numerous FES, including the understory plant diversity reduction. For a full use of FES, both adequate overstory timber production and higher UVSN should be considered for the rehabilitation and management of service-degraded plantations.

The timber production and UVSN of LP were contrarily affected by tree density, age, and canopy density. These competitions can be balanced through the trade-off approach of keeping a proper tree density corresponding to the optimal canopy density around 0.7. More precise trade-off decision at any age can be realized using the models and relations describing the tree age and density effects on timber production and UVSN.

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