Density Management Is More Cost Effective than Fertilization for *Chimonobambusa pachystachys* Bamboo-Shoot Yield and Economic Benefits

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Abstract: Stand-density management and fertilization practices are the main two factors affecting bamboo-shoot yield. However, the appropriate density and fertilization rates are still unclear for improving the bamboo-shoot yield and its economic benefits, especially for a high economic value bamboo-shoot forest. To fill this gap, we conducted a two-year split-plot design experiment in a *Chimonobambusa pachystachys* shoot forest. The main plots were assigned to five density rates, 40,000, 50,000, 60,000, 70,000, and 100,000 culms ha⁻¹, and the subplots were assigned to four fertilization rates (nitrogen:phosphorus:potassium = 23:3:15): 0, 820, 1640, and 2460 kg ha⁻¹ a⁻¹. Results showed that the bamboo-shoot yield increased first and then decreased with stand density, while it increased with fertilization rates. Density management and fertilization regulate bamboo-shoot yield by changing the soil’s Olsen P, available nitrogen, organic matter, and available potassium contents. The maximum bamboo-shoot yield was 9315.92 kg ha⁻¹, which appeared in the density of 60,000 culms ha⁻¹ and the fertilization of 2460 kg ha⁻¹ a⁻¹. However, the maximum bamboo-shoot net profit was 135,242.63 CNY ha⁻¹, which appeared at the density of 60,000 culms ha⁻¹ and the fertilization of 1640 kg ha⁻¹ a⁻¹. The economic-benefit analysis shows that density management achieves a net-profit growth comparable to fertilizer application at a much lower cost. The study results provide a basis for the scientific management of *C. pachystachys* shoot forests and bamboo farmers to improve their income.

Keywords: density management; fertilization; bamboo-shoot yield; economic benefit; *Chimonobambusa pachystachys*

1. Introduction

Non-timber forest product (NTFP) is defined as the biological products, other than high-value timber, harvested by humans from wild biodiversity in natural or human-modified environments [1]. NTFP transactions have been an essential livelihood strategy for forest residents, especially mountain farmers in less-developed areas [2]. In the global context, especially for low-income households, NTFPs can represent 10%–60% of household income [3]. Bamboo is one of the most important NTFPs [4,5]. About 2.5 billion people depend economically on bamboo, international trade in bamboo amounts to over USD
2.5 billion per year, and bamboo shoots occupy a vital share [5]. China is the country with the largest bamboo-forest area globally, and its bamboo-forest resources and bamboo-shoot export-volume rank among the top in the world [6–8]. In many areas of southern China, bamboo-forest planting has replaced grain planting, and bamboo-shoot trading has become the primary source of income for local farmers [9]. However, large amounts of nutrients are removed from bamboo forests every year due to the frequent shoot harvests [10]. The conventional bamboo farmer’s practice, only harvesting bamboo shoots without forest management, would cause the loss of soil nutrients, reduce forest productivity, and lead to the unsustainable management of bamboo forests [11,12].

Abundant evidence indicates that an appropriate stand density is crucial for increasing shoot yield and maintaining productivity in the bamboo forest [10,13,14]. Density management regulates the stand’s spatial structure (both above and below ground) and mother culm number, directly affecting the competition between culms for nutrients, sunlight, and growth space, altering the bamboo-shoot yield [10]. Moreover, a higher or lower stand density would destroy the suitable temperature and humidity for bamboo-shoot growth, delay the rhythm of bamboo-shoot germination, and reduce production [14]. Some studies have shown that the productivity of bamboo-forest stands increases with increasing stand density within a certain density range, and bamboo-shoot yield shows a pattern of increasing and then decreasing [14,15]. However, the stand density for the highest shoot yield in different bamboo species is inconsistent. Most of the existing bamboo-forest studies have focused on the effects of density management on stand growth [16] and ecological processes [17], so we know little about the “optimal density” for yield in bamboo-shoot forests.

Fertilization is an important source of nutrients for plant growth and stand productivity, which has been confirmed in both crop and forest ecosystems [18,19]. In most study, the application of nitrogen (N), phosphorus (P), and potassium (K) fertilizers can effectively increase crop yield by improving soil-nutrient availability [20,21]. On the other hand, fertilization increases the crop yield by improving the growth status, photosynthetic characteristics, and nutrient content of the mother culms [21–24]. However, it has also been shown that excessive fertilizer can lead to lower soil pH, causing soil acidification and compaction [25]. So, it is crucial to determine a reasonable amount of fertilizer application. Currently, few bamboo farmers fertilize bamboo forests, which leads to lower and lower yields of bamboo shoots in extensive bamboo-shoot forests. For bamboo-shoot forests, fertilization can effectively replenish the soil nutrients taken away by harvesting bamboo shoots [10,26]. Therefore, fertilizing and determining the amount of fertilizer application is indispensable for maintaining the high yield of a bamboo-shoot forest.

In addition, it must be pointed out that the management of bamboo-shoot forests must conform to the economic benefit of bamboo farmers. Density management and fertilization require more labor and fertilizer costs than traditional extensive-management models. Therefore, we need to consider and evaluate whether density management and fertilizer are economically feasible for bamboo farmers [18]. This information can provide a reference for bamboo farmers and local forestry technical departments for bamboo-shoot production. However, for a bamboo-shoot forest, how density management and fertilization affect the bamboo-shoot yield, and whether it can improve the economic benefits for the bamboo farmers, are still unknown.

Here, we investigated the effects of density management and fertilizer application on the soil-nutrient content, bamboo-shoot yield, and economic efficiency in a Chimonobambusa pachystachys shoot forest. We will answer: (1) How does shoot yield in a C. pachystachys bamboo forest change after density management and fertilization? (2) Which C. pachystachys shoot forest-management strategy can maximize the economic benefit for bamboo farmers? This study will provide scientific support for the density regulation and fertilization management of a C. pachystachys shoot forest and guarantee the increased income for bamboo farmers.
2. Materials and Methods

2.1. Site Description

The study area is located in Gulin County (GLC) State Forest Farm (1300–1842 m in elevation, 105°34′–106°20′ E, 27°41′–28°20′ N) in Luzhou, Sichuan province, southwest China (Figure A1). GLC has a humid mid-subtropical monsoon climate, with a mean annual temperature of 18.3 °C, ranging from a minimum temperature of −4.9 °C to a maximum temperature of 40.3 °C. There are about 260 frost-free days with mean annual precipitation of 748.4 mm–1112.7 mm. The monthly average relative humidity is above 80%. The C. pachystachys shoot forests in this study were pure stands and have not any management measures carried out before the experiment. Bamboo shoots were harvested in autumn every year. The characteristics of the bamboo-forest stands before the experiment are in Table 1. The soil type is Udalfs (according to the World Reference Base for Soil Resources 2015) with pH of 3.58, and the 0–20 cm soil layer contained 48.68 g kg\(^{-1}\) organic matter (SOC), 2.96 g kg\(^{-1}\) total N (TN), 0.47 g kg\(^{-1}\) total P (TP), 13.55 g kg\(^{-1}\) total K (TK), 133.44 mg kg\(^{-1}\) available N (AN), 5.50 mg kg\(^{-1}\) Olsen P, and 88.54 mg kg\(^{-1}\) available K (AK).

Table 1. The characteristics of the bamboo-forest stands before the experiment.

| Canopy Density (culms ha\(^{-1}\)) | Stand Density | Mean Ground Diameter (cm) | Mean Height (m) | Age Structure (1a:2–3a:>3a) |
|---------------------------------|---------------|--------------------------|----------------|----------------------------|
| 0.9–1                          | 100,000       | 1.20                     | 2.70           | 3:5:2                      |

2.2. Experimental Design

In June 2017, representative C. pachystachys pure forests were selected as experiment plots at 1700-1800 m in the study area. The experiments were conducted using a split-plot design. The main plots were assigned to five density rates: 100,000 culms ha\(^{-1}\) (D0), 40,000 culms ha\(^{-1}\) (D1), 50,000 culms ha\(^{-1}\) (D2), 60,000 culms ha\(^{-1}\) (D3), and 70,000 culms ha\(^{-1}\) (D4), applied by thinning in June every year from 2017 to 2019. According to local fertilization practice, subplots were assigned to four fertilizer rates (N:P:K = 23:3:15): no fertilization (F0), low fertilization (F1): 820 kg ha\(^{-1}\) a\(^{-1}\), medium fertilization (F2): 1640 kg ha\(^{-1}\) a\(^{-1}\), and high fertilization (F3): 2460 kg ha\(^{-1}\) a\(^{-1}\). The size of each subplot was 25 m\(^2\) (5 m × 5 m). Three replicates were set up for each treatment, giving a total of 60 subplots. A boundary buffer zone with a width of at least 3 m was set between subplots to avoid mutual interference. Urea (46% N), superphosphate (12% P\(_2\)O\(_5\)), and potassium chloride (62% K\(_2\)O) were mixed according to the design and then correspondingly applied for each plot in March, June, and November every year from June 2017 to November 2019, the amount of fertilizer applied each time is 40%, 30%, and 30% of the whole year, respectively. There were no observed pest or disease outbreaks.

2.3. Soil Sampling and Measurement

Soil samples were collected from five points in a “W” pattern from 0 to 20 cm depth [27] in each plot in June of 2017, 2018, and 2019 and bulked together. The samples were air-dried and divided into two. One part of the ground soil samples was sieved through a 2 mm mesh sieve for pH and available nutrients’ content measures, and the other part was sieved through a 0.25 mm mesh sieve for soil organic matter and total nutrients’ content measures. The pH was measured in a 2.5:1 soil suspension in water (pH5-5C+ acidimeter, Chengdu Century Fangzhou Technology Co., Ltd., Chengdu, China). The pH of KCl solution is 5.5–6. Soil organic matter was obtained by the combustion method (Vario TOC, Elementar Analysensysteme GmbH, Frankfurt, Germany). Total N was determined by colorimetry (Smart-Chem 200, Alliance Instruments, Frépillon, France), and the available N was determined by the alkali hydrolysis diffusion method. Total P was determined by sulfuric acid perchloric acid digestion molybdenum antimony anticotolometry, and the Olsen P was determined sodium bicarbonate and determined using the molybdenum blue method. Total K was determined by flame photometry after fusion of NaOH, and
the available K was extracted by NH4OAc (SK6880, Qingdao Sankai Medical Technology Co., Ltd., Qingdao, China). All soil sample analyses were done at the SICAU laboratory, Chengdu, China.

2.4. Yield Assessment

Bamboo shoots of *C. pachystachys* were observed every three days in each plot from 1 September to 31 October each year. We collected the bamboo shoots 30–60 cm above the ground in each plot and weighed them with an electronic platform scale (0.01 kg, ACS-JE/C81W, Guangdong Senssun Weighing Apparatus Group Ltd., Zhongshan, China.) in situ. We ignored the bamboo shoots below 30 cm, and those above 60 cm were considered future bamboo.

2.5. Data Calculation

2.5.1. Economic Benefit (*E_b*)

The economic benefit (*E_b*) was calculated as follows:

\[ E_b = Y \times U_p \]  

where \( Y \) is the bamboo-shoot yield (kg ha\(^{-1}\)), \( U_p \) is the unit price (CNY kg\(^{-1}\)).

2.5.2. Net Profit (*N_p*)

The net profit (*N_p*) was calculated as follows:

\[ N_p = E_b - F_l - F_w \]  

where \( F_l \) is the labor fee (CNY ha\(^{-1}\)), and \( F_w \) is the fertilizer input (CNY ha\(^{-1}\)).

2.5.3. Economic Benefit Growth

The economic-benefit growth (*E_g*) was calculated as follows:

\[ E_g = \frac{E_{bi} - E_{bc}}{E_{bc}} \]  

where \( E_{bi} \) is the economic benefit of treatments (CNY ha\(^{-1}\)), and \( E_{bc} \) is the economic benefit of control check (CNY ha\(^{-1}\), D0F0).

2.5.4. Net-profit growth (*N_g*)

The net-profit growth (*N_g*) was calculated as follows:

\[ N_g = \frac{N_{pi} - N_{pc}}{N_{pc}} \]  

where \( N_{pi} \) is the net profit of the treatments (CNY ha\(^{-1}\)), and \( N_{pc} \) is the net profit of the control check (CNY ha\(^{-1}\), D0F0).

Fertilizer and labor fees are calculated based on the actual cost of various expenditures during the two years of the experiment. The unit price of bamboo shoots refers to the actual local purchase price.

2.6. Data Analyses

Analysis of variance was performed with SPSS 25.0 software (SPSS Institute Inc., Chicago, IL, USA), means were tested by the Bonferroni adjustment method at the \( p < 0.05 \) level. Step-wise multiple linear regression was performed by Sigma-Plot 10.0 (Aspire Software Intl., Ashburn, VA, USA) to identify the relationship between bamboo-shoot yield and soil-nutrient characteristics. Furthermore, multicollinearity, which refers to a situation in which two or more explanatory variables in a multiple-regression model are highly linearly related, can be
detected using the variance-inflation factor (VIF). A rule of thumb is that if VIF is more than 10 then multicollinearity is too high. If this occurred, we deleted the explanatory variable with the highest VIF and refitted the model. We repeated this procedure until the condition that all VIFs are below 10 was satisfied. Next, we used the ‘confint’ function in the ‘stats’ package (v3.6.2) to check the statistical significance of the remaining explanatory variables.

3. Results

3.1. Bamboo-Shoot Yield

The density management and fertilizer had significant effects on the bamboo-shoot yield (sum of two years, Figure 1). The bamboo-shoot yield increased from 7116.11 to 8529.50 and 7481.56 kg ha$^{-1}$ (mean of four fertilizer rates), as the density decreased from D0 to D3 and D4, respectively, while as the density decreased from D0 to D1 and D2, the bamboo-shoot yield decreased from 7116.11 to 5989.12 and 6388.60 kg ha$^{-1}$ (mean of four fertilizer rates), respectively. The bamboo-shoot yield increased from 6300.98 to 6809.80, 7559.88, and 7733.26 kg ha$^{-1}$ (mean of five density rates) as the fertilizer rates increased from F0 to F1, F2, and F3, respectively. The maximum yield was 9315.92 kg ha$^{-1}$, which appeared in D3F3.

![Figure 1. The bamboo-shoot yields of C. pachystachys forests by treatments. Error bars indicate standard error ($n = 3$). Different lowercase letters show significance at the 0.05 level according to Bonferroni’s test.](image)

3.2. Economic-Benefit Indexes

The density management and fertilizer had significant effects on the bamboo-shoot net profit (sum of two years, Figure 2, Table A3). The net profit increased from 102,661.01 to 126,675.15 and 110,108.10 CNY ha$^{-1}$ (mean of four fertilizer rates) as the density decreased from D0 to D3 and D4, respectively, while as the density decreased from D0 to D1 and D2, the net profit decreased from 102,661.01 to 85,629.16 and 92,220.81 CNY ha$^{-1}$ (mean of four fertilizer rates), respectively. The net profit increased from 101,855.63 to 102,732.21, 107,068.97, and 102,178.56 CNY ha$^{-1}$ (mean of five density rates) as the fertilizer rates increased from F0 to F1, F2, and F3, respectively. The maximum net profit was 135,242.63 CNY ha$^{-1}$, which appeared in D3F2.
3.3. Soil Nutrients’ Properties

The density management and fertilizer had significant effects on the soil-nutrient content (Tables A1 and A2). With the increase in bamboo-forest density, the soil pH and the contents of soil SOM, AN, and Olsen P increased first then decreased; the contents of soil TN, TP, and AK increased; and the content of soil TK decreased. With the increase in fertilizer rates, the contents of soil SOM, TN, AN, TP, Olsen P, TK, and AK increased, while the soil pH decreased. Overall, the soil-nutrient content increased with the increase in fertilization rates, and it first increased then decreased with the increase in bamboo-forest density.
3.4. Relationship between Bamboo-Shoot Yield and Soil Nutrients’ Properties

Significant positive correlations were found between the bamboo-shoot yield and SOM, TN, AN, TP, Olsen P, TK, and AK (Figure 4b–h), while the bamboo-shoot yield and pH had no significant correlation (Figure 4a).

Figure 4. Relationships of bamboo-shoot yield to the soil pH (a), SOM (b), TN (c), AN (d), TP (e), Olsen P (f), TK (g), and AK (h) in *C. pachystachys* shoot forest. SOM: soil organic matter; TN: total nitrogen; AN: available nitrogen; TP: total phosphorus; Olsen P: Olsen phosphorus; TK: total potassium; AK: available potassium.

The stepwise multiple linear regression analysis showed that the relative importance of Olsen P, AN, SOM, and AK in the bamboo-shoot yield was 44.0%, 12.3%, 3.9%, and 1.4%,
respectively (Table 2). The total explanatory degree of the soil of Olsen P, AN, SOM, and AK on the yield of bamboo shoots was 61.6%. The soil contents of Olsen P, AN, SOM, and AK were the crucial factors for a higher bamboo-shoot yield.

Table 2. The stepwise multiple linear regression analysis of bamboo-shoot yield and soil nutrients’ properties of bamboo forest. Significant effects are given in bold.

| Model | \( R^2 \) | \( F \) | \( p \) |
|-------|----------|-------|-------|
| Yield = 1066.09 + 0.67 Olsen P | 0.440 | 94.43 | <0.001 |
| Yield = −1701.94 + 0.46 Olsen P + 0.41 AN | 0.563 | 77.58 | <0.001 |
| Yield = −1963.85 + 0.43 Olsen P + 0.32 AN + 0.23 SOM | 0.610 | 60.98 | <0.001 |
| Yield = −2003.24 + 0.36 Olsen P + 0.32 AN + 0.21 SOM + 0.16 AK | 0.616 | 48.67 | <0.001 |

Olsen P: Olsen phosphorus; AN: available nitrogen; SOM: soil organic matter; AK: available potassium.

4. Discussion

4.1. The Bamboo-Shoot Yield

Density management can modulate the number of mother culms, soil-nutrient content, and the stand spatial structure in the shoot forest, altering the bamboo-shoot yield. In general, forest-product yield increases with stand density until it reaches the upper optimum-density limit for the species, after which increasing stand density can only maintain maximum yield (constant final yield) or even cause yield reduction due to excessive competition [28,29]. In consistent with this theory, in our study, the bamboo-shoot yields increased to their maximum at the density of 60,000 culms ha\(^{-1}\), while subsequently decreasing at 70,000 and 100,000 culms ha\(^{-1}\) (Figure 1). There are two reasons accounting for this result. Firstly, density management can change stand structure and mother-culm numbers, affecting crop yields [29,30]. A reduction in the number of mother culms in a low-density stand will directly lead to a reduction in yield. Meanwhile, the direct sunlight on the ground caused by the low-density changes the external temperature and humidity conditions suitable for the new shoots, inhibiting the growth of the bamboo shoots and causing yield reduction [14]. However, superabundant mother culms in high-density stands caused increased competition for nutrients, water, sunlight, and stand space [31–33] and were not conducive to increased bamboo-shoot yield. Secondly, density management can change soil physical and chemical properties, affecting crop yield [15,34,35]. In our study, soil-nutrient content increased and then decreased with increasing stand density (Tables A1 and A2), which was almost consistent with the changes in shoot yield and density. This was confirmed by the results of our correlation analysis (Table 2, Figure 4b–h).

Numerous studies have shown that crop yields increase with increased fertilization [19,36,37]. Our results likewise showed that bamboo-shoot yield increased with increasing fertilizer application (Figure 1), which was due to the increases in soil nutrients (Olsen P, AN, SOM, and AK) contents via applying NPK inorganic compound fertilizers (Tables A1 and A2). The correlation-analysis results also showed a significant positive correlation between bamboo-shoot yield and the soil’s Olsen P, AN, SOM, and AK contents (Figure 4b,d,f,h, Table 2). Thus, fertilization increased the nutrient sources of mother culms, ensured nutrient supply for new shoots, and, hence, improved bamboo-shoot yield. Alternatively, fertilization can improve the photosynthetic capacity of crops [21,23,38] and increase the bamboo-shoot yield. In summary, the bamboo-shoot yield of the C. pachystachys forest increased with increasing fertilizer rates, and the highest shoot yield was achieved when the fertilizer application was 2460 kg ha\(^{-1}\) a\(^{-1}\).

It should be noted that, in our study, fertilization decreased the soil pH in bamboo forests, which to some extent resulted in soil acidification (Tables A1 and A2), in line with most studies [18,39]. The loss of base cations (Ca\(^{2+}\), Mg\(^{2+}\), etc.) caused by fertilization, especially by nitrogen fertilizers, and the enrichment of Al\(^{3+}\) and H\(^{+}\), caused by the enhancement of nitrification and denitrification controlled by ammonia oxidizing bacteria, are the main reasons for the decrease in soil pH [40,41]. The enrichment of Al\(^{3+}\) in low-pH soils, its toxic effects, and reduced nutrient effectiveness can inhibit crop growth and re-
duce productivity [42]. Therefore, the proper ratio of NPK-nutrient content in compound fertilizer and control of the total amount of fertilization should be carefully considered.

The regression analysis results showed that the regression coefficients of all the soil available nutrients were higher than the total nutrients (Figure 4). This is because the plants are more likely to obtain the available nutrients compared to the total nutrients [43]. Stepwise linear regression analysis indicated that the soil’s Olsen P content was the most important nutrient factor affecting bamboo-shoot yield in the current study (Table 2). Two reasons may account for this phenomenon. On the one hand, our previous report in the same region indicated that the *C. pachystachys* growth is usually limited by phosphorus [44]. On the other hand, the soil’s Olsen P effective in our study is low, due to the soil type is Udalfs. The Udalfs usually has a high Al$^{3+}$ content, resulting in the combination of phosphate ions and Al$^{3+}$ to form aluminophosphate that cannot be absorbed by plants [45]. Therefore, Olsen P input from fertilization is critical for *C. pachystachys* shoot yield.

### 4.2. Bamboo-Shoot Economic Benefit

In this study, D1 (−17.06%) and D2 (−10.46%) density management decreased the bamboo-shoot net profit, while D3 (24.05%) and D4 (7.46%) density management increased the bamboo-shoot net profit (Figure 3, Table A3). This result can be explained by the effect of density management on bamboo-shoot yield. Since density management requires only tiny labor costs, its net profit comes mainly from the bamboo-shoot yield. Therefore, controlling the standing bamboo density of a *C. pachystachys* shoot forest at D3 can reap greater net profit.

Our study also found that the F2 (26.10%) fertilization rate improved the bamboo-shoot net profit (Figure 3). In contrast, the F1 (4.39%) and F3 (1.62%) fertilization measures did not significantly improve the bamboo-shoot net profit in the *C. pachystachys* forest (Figure 3). This is because when the fertilizer application was small, the increase in economic benefits was also small. The increase in economic benefit was not significantly higher than the cost of fertilizer and labor, so there was no significant change in the increase in the bamboo-shoot net profit. In contrast, when the amount of fertilization is large, fertilizer and labor costs are also high. According to the “law of diminishing returns” [46], the input of a large amount of fertilizer and labor costs cannot be converted into more economic benefits, which will also lead to a decline in the bamboo-shoot net profit. Therefore, for a *C. pachystachys* shoot forest, the maximum net-profitable fertilizer application for bamboo farmers is F2.

In this study, we found that density management had almost only labor costs (Table A3), but the net-profit growth of D3 (24.05%) was comparable to the fertilizer rate of F2 (26.10%) (Figure 3). Although the F2 fertilization treatment also harvested higher bamboo-shoot yields, the additional fertilizer costs and labor requirements also needed to be a tradeoff for bamboo farmers. In addition, the application of compound fertilizer lowered the soil pH and caused soil acidification to some extent (Tables A1 and A2). Thus, we assume that density management is a more ‘economical’ and ‘environmental’ strategy than fertilization for *C. pachystachys* shoot-forest management.

Considering the combined benefits of density management and fertilization, D3F2 is the most efficient management strategy for a *C. pachystachys* shoot forest, owing to the maximum bamboo-shoot net profit in D3F2 (135,242.63 CNY ha$^{-1}$, Figure 3). Therefore, the recommended density of a *C. pachystachys* shoot forest with the maximum net profit is 60,000 culms ha$^{-1}$, and the recommended fertilization rate is 1640 kg ha$^{-1}$ a$^{-1}$.

### 5. Conclusions

This study demonstrated that the *C. pachystachys* bamboo-shoot yield increased first and then decreased with culm density, while it increased with the fertilization rates. The appropriate density for the maximum shoot yield and economic benefit in a *C. pachystachys* shoot forest is 60,000 culms ha$^{-1}$. When the fertilization rate was F3, the bamboo-shoot yield of a *C. pachystachys* shoot forest was the highest, but the greatest bamboo-shoot economic benefit appeared in F2. In terms of the combined benefits of density management and
fertilizer-application practices, D3F2 achieves the greatest net profit. Density management and fertilization regulate bamboo-shoot yield and economic benefit by changing stand structure and the soil's Olsen P, AN, SOM, and AK contents. For bamboo farmers, density management requires only a minimal labor cost to achieve a net profit nearly identical to fertilizer application. Therefore, density management is more cost effective than fertilizer application in the management of a *C. pachystachys* shoot forest. However, the effect of density management and fertilization on mother culms is unclear, as we did not observe the plants. Therefore, further research on the above-ground culms should be conducted in a *C. pachystachys* forest.

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**Appendix A**

![Figure A1. Location of the study area.](image-url)
### Table A1. Effects of fertilizer and density management on the soil nutrients' properties in bamboo forests (2018).

| Treatment | pH   | SOM (g kg⁻¹) | TN (g kg⁻¹) | AN (mg kg⁻¹) | TP (mg kg⁻¹) | Olsen P (mg kg⁻¹) | TK (g kg⁻¹) | AK (mg kg⁻¹) |
|-----------|------|--------------|-------------|--------------|-------------|----------------|-------------|-------------|
| D0F0      | 4.05 | 43.01 + 0.12 | 3.04 + 0.12 | 127.02 + 0.12 | 9.56 + 0.12 | 13.11 + 0.12   | 7.65 + 0.12  | 89.82 + 0.12 |
| D0F1      | 4.05 | 43.01 + 0.12 | 3.04 + 0.12 | 127.02 + 0.12 | 9.56 + 0.12 | 13.11 + 0.12   | 7.65 + 0.12  | 89.82 + 0.12 |
| D0F2      | 4.05 | 43.01 + 0.12 | 3.04 + 0.12 | 127.02 + 0.12 | 9.56 + 0.12 | 13.11 + 0.12   | 7.65 + 0.12  | 89.82 + 0.12 |
| D0F3      | 4.05 | 43.01 + 0.12 | 3.04 + 0.12 | 127.02 + 0.12 | 9.56 + 0.12 | 13.11 + 0.12   | 7.65 + 0.12  | 89.82 + 0.12 |
| D0F4      | 4.05 | 43.01 + 0.12 | 3.04 + 0.12 | 127.02 + 0.12 | 9.56 + 0.12 | 13.11 + 0.12   | 7.65 + 0.12  | 89.82 + 0.12 |

Different lowercase letters show significance at the 0.05 level according to Bonferroni's test (n = 3). SOM: soil organic matter; TN: total nitrogen; AN: available nitrogen; TP: total phosphorus; Olsen P: Olsen phosphorus; TK: total potassium; AK: available potassium.

### Table A2. Effects of fertilizer and density management on the soil nutrients' properties in bamboo forests (2019).

| Treatment | pH   | SOM (g kg⁻¹) | TN (g kg⁻¹) | AN (mg kg⁻¹) | TP (mg kg⁻¹) | Olsen P (mg kg⁻¹) | TK (g kg⁻¹) | AK (mg kg⁻¹) |
|-----------|------|--------------|-------------|--------------|-------------|----------------|-------------|-------------|
| D0F0      | 4.05 | 43.01 + 0.12 | 3.04 + 0.12 | 127.02 + 0.12 | 9.56 + 0.12 | 13.11 + 0.12   | 7.65 + 0.12  | 89.82 + 0.12 |
| D0F1      | 4.05 | 43.01 + 0.12 | 3.04 + 0.12 | 127.02 + 0.12 | 9.56 + 0.12 | 13.11 + 0.12   | 7.65 + 0.12  | 89.82 + 0.12 |
| D0F2      | 4.05 | 43.01 + 0.12 | 3.04 + 0.12 | 127.02 + 0.12 | 9.56 + 0.12 | 13.11 + 0.12   | 7.65 + 0.12  | 89.82 + 0.12 |
| D0F3      | 4.05 | 43.01 + 0.12 | 3.04 + 0.12 | 127.02 + 0.12 | 9.56 + 0.12 | 13.11 + 0.12   | 7.65 + 0.12  | 89.82 + 0.12 |
| D0F4      | 4.05 | 43.01 + 0.12 | 3.04 + 0.12 | 127.02 + 0.12 | 9.56 + 0.12 | 13.11 + 0.12   | 7.65 + 0.12  | 89.82 + 0.12 |

Different lowercase letters show significance at the 0.05 level according to Bonferroni's test (n = 3). SOM: soil organic matter; TN: total nitrogen; AN: available nitrogen; TP: total phosphorus; Olsen P: Olsen phosphorus; TK: total potassium; AK: available potassium.

### Table A3. Effects of fertilizer and density management on the bamboo shoot economic benefit in bamboo forests (sum of two years).

| Treatment | Economic Benefit (CNY ha⁻¹) | Fertilizer Fee (CNY ha⁻¹) | Labor Fee (CNY ha⁻¹) | Net Profit (CNY ha⁻¹) | Benefit Growth (%) | Net-Profit Growth (%) |
|-----------|-----------------------------|--------------------------|----------------------|-----------------------|-------------------|-----------------------|
| D0F0      | 99,856.27                   | 0                        | 0                    | 0.00                  | 0.00              | 0.00                  |
| D0F1      | 109,715.09                  | 3832.26                  | 200                  | 102,450.09            | 9.87              | 2.60                  |
| D0F2      | 120,593.39                  | 7664.52                  | 200                  | 105,664.35            | 20.77             | 2.82                  |
| D0F3      | 123,256.40                  | 11,496.77                | 1000                 | 102,762.85            | 25.45             | 2.82                  |
| D1F0      | 88,153.71                   | 3832.26                  | 200                  | 86,271.59             | 13.86             | 12.86                 |
| D1F1      | 92,536.11                   | 3832.26                  | 1000                 | 92,671.59             | 18.71             | 13.60                 |
| D1F2      | 104,181.60                  | 7664.52                  | 1000                 | 90,252.47             | 4.30              | 9.63                  |
| D1F3      | 100,572.32                  | 11,496.77                | 1000                 | 97,987.78             | 7.02              | 20.91                 |
| D2F0      | 93,268.35                   | 0                        | 700                  | 94,468.35             | 6.60              | 5.40                  |
| D2F1      | 98,866.94                   | 3832.26                  | 900                  | 92,933.24             | 10.96             | 7.03                  |
| D2F2      | 105,335.57                  | 7664.52                  | 900                  | 101,364.57            | 5.49              | 5.26                  |
| D2F3      | 111,369.97                  | 11,496.77                | 900                  | 108,874.97            | 11.53             | 9.89                  |
| D3F0      | 118,542.88                  | 0                        | 600                  | 119,942.88            | 18.71             | 20.12                 |
| D3F1      | 129,518.47                  | 3832.26                  | 800                  | 123,635.92            | 29.70             | 23.83                 |
| D3F2      | 148,771.66                  | 7664.52                  | 800                  | 153,242.86            | 48.99             | 35.44                  |
Table A3. Cont.

| Treatment | Economic Benefit (CNY ha\(^{-1}\)) | Fertilizer Fee (CNY ha\(^{-1}\)) | Labor Fee (CNY ha\(^{-1}\)) | Net Profit (CNY ha\(^{-1}\)) | Benefit Growth (%) | Net-Profit Growth (%) |
|-----------|----------------------------------|-------------------------------|--------------------------|---------------------------|-------------------|---------------------|
| D3F3      | 149,054.67                       | 11,496.77                     | 800                      | 127,861.12                | 49.27             | 28.05               |
| D4F0      | 106,396.96                       | 0                             | 500                      | 107,996.96                | 6.55              | 8.15                |
| D4F1      | 114,117.55                       | 3832.26                       | 700                      | 108,453.03                | 14.28             | 8.61                |
| D4F2      | 125,907.80                       | 7664.52                       | 700                      | 112,578.77                | 26.09             | 12.74               |
| D4F3      | 132,397.17                       | 11,496.77                     | 700                      | 111,403.62                | 32.59             | 11.56               |

Fertilizer and labor fees are calculated based on the actual cost of various expenditures during the two years of the experiment. The unit price of bamboo shoots refers to the actual local purchase price.

References

1. Shackleton, S. Non-Timber Forest Products in the Global Context; Springer: Berlin/Heidelberg, Germany; London, UK, 2011; pp. 255–280.
2. Singhal, P.; Bal, L.M.; Satya, S.; Sudhakar, P.; Naik, S.N. Bamboo shoots: A novel source of nutrition and medicine. *Crit. Rev. Food Sci. Nutr.* 2013, 53, 517–534. [CrossRef] [PubMed]
3. Lovrić, M.; Da Re, R.; Vidale, E.; Prokofieva, I.; Wong, J.; Pettenella, D.; Verkerk, P.J.; Mavsar, R. Non-wood forest products in Europe—A quantitative overview. *For. Policy Econ.* 2020, 116, 102175. [CrossRef]
4. Peng, Z.; Lu, Y.; Li, L.; Zhao, Q.; Feng, Q.; Gao, Z.; Lu, H.; Hu, T.; Yao, N.; Liu, K.; et al. The draft genome of the fast-growing non-temper forest species moso bamboo (Phyllostachys heterocycla). *Nat. Genet.* 2013, 45, 456–461. [CrossRef] [PubMed]
5. Maxim, L.; Shyam, P.; Marco, P.; Hong, R.; Junqi, W. World bamboo resources—A thematic study prepared in the framework of the Global Forest Resources Assessment 2005. *FAO Tech. Pap.* 2007, 1, 1–74. [CrossRef]
6. Li, X.; Mao, F.; Du, H.; Zhou, G.; Xing, L.; Liu, T.; Han, N.; Liu, Y.; Zhu, D.; Zheng, J.; et al. Spatiotemporal evolution and impacts of climate change on bamboo distribution in China. *J. Environ. Manag.* 2019, 248, 109265. [CrossRef]
7. Du, H.; Li, Y.; Zhu, D.; Li, Y.; Chen, L.; Fan, W.; Li, P.; Shi, Y.; Zhou, Y.; Mao, F.; et al. Mapping global bamboo forest distribution using multisource remote sensing data. *IEEE J-STARS* 2018, 11, 1458–1471. [CrossRef]
8. FAO. *Global Forest Resources Assessment 2010 Main Report; Forestry Paper; FAO: Rome, Italy, 2010; Volume 163.*
9. Lu, H.F.; Cai, C.J.; Zeng, X.S.; Campbell, D.E.; Fan, S.H.; Liu, G.L. Bamboo vs. crops: An integrated emergy and economic evaluation of using bamboo to replace crops in south Sichuan Province, China. *J. Clean Prod.* 2018, 177, 464–473. [CrossRef]
10. Liu, G. *Study on the Mechanism of Maintaining Long-Term Productivity of Bamboo Forest; Chinese Academy of Forestry: Beijing, China, 2009.*
11. Guan, F.; Xia, M.; Tang, X.; Fan, S. Spatial variability of soil nitrogen, phosphorus and potassium contents in Moso bamboo forests in Yong’an City, China. *Caten.* 2017, 150, 161–178. [CrossRef]
12. Chen, S.; Jiang, H.; Cai, Z.; Zhou, X.; Peng, C. The response of the net primary production of Moso bamboo forest to the On and Off-year management: A case study in Anji County, Zhejiang, China. *For. Ecol. Manag.* 2018, 409, 1–7. [CrossRef]
13. Zhao, J.; Fan, S.; Yu, L.; Su, W.; Yan, Y. Integrated evaluation on soil quality of Phyllostachys edulis plantations under different densities. *Sci. Silv. Sin* 2015, 51, 1–9. [CrossRef]
14. Liu, X.; Chen, L.; Tan, J.; Li, L.; Dai, X.; Huang, C. The effect of bamboo density on the yield of Chimonobambusa pachystachys shoots in Guanlin county. *J. Sichuan For. Sci. Technol.* 2018, 39, 40–43. [CrossRef]
15. Hu, W.; Pang, H.; Yang, J.; Hu, X.; Xu, L.; Huang, F.; Gong, M. Effects of bamboo forest density and fertilizer types on the yield and quality of Phyllostachys edulis bamboo shoots and soil physicochemical properties in Mufu Mountain area. *Sci. Silv. Sin* 2021, 57, 32–42. [CrossRef]
16. Inoue, A.; Sato, M.; Shima, H. Maximum size-density relationship in bamboo forests: Case study of Phyllostachys pubescens forests in Japan. *For. Ecol. Manag.* 2018, 425, 134–144. [CrossRef]
17. Lv, W.; Zhou, G.; Chen, G.; Zhou, Y.; Ge, Z.; Niu, Z.; Xu, L.; Shi, Y. Effects of Different Management Practices on the Increase in Phyllostachys-Occluded Carbon in Moso Bamboo Forests. *Front. Plant Sci.* 2020, 11, 591852. [CrossRef]
18. Matson, P.A.; Rosamond, N.; Ivan, O.-M. Integration of environmental, agronomic, and economic aspects of fertilizer management. *Science* 1998, 280, 112–115. [CrossRef]
19. Wang, S.; Yang, L.; Su, M.; Ma, X.; Sun, Y.; Yang, M.; Zhao, P.; Shen; J.; Zhang, F.; Goulding, K.; et al. Increasing the agricultural, environmental and economic benefits of farming based on suitable crop rotations and optimum fertilizer applications. *Field Crop Res.* 2019, 240, 78–85. [CrossRef]
20. Adiele, J.G.; Schut, A.G.T.; van den Beuken, R.P.M.; Ezui, K.S.; Pypers, P.; Ano, A.O.; Egiesi, C.N.; Giller, K.E. Towards closing cassava yield gap in West Africa: Agronomic efficiency and storage root yield responses to NPK fertilizers. *Field Crop Res.* 2020, 253, 107820. [CrossRef]
21. Fang, X.; Li, Y.; Nie, J.; Wang, C.; Huang, K.; Zhang, Y.; Zhang, Y.; She, H.; Liu, X.; Ruan, R.; et al. Effects of nitrogen fertilizer and planting density on the leaf photosynthetic characteristics, agronomic traits and grain yield in common buckwheat (Fagopyrum esculentum M.). *Field Crop Res.* 2018, 219, 160–168. [CrossRef]
22. Fan, L.; Zhao, T.; Tarin, M.W.K.; Han, Y.; Hu, W.; Rong, J.; He, T.; Zheng, Y. Effect of various mulch materials on chemical properties of soil, leaves and shoot characteristics in Dendrocalamus Latiflorus Munro forests. *Plants* 2021, 10, 2302. [CrossRef]
23. Guo, J.; Wu, Y.; Wang, B.; Lu, Y.; Cao, F.; Wang, G. The Effects of Fertilization on the Growth and Physiological Characteristics of Ginkgo biloba L. *Forests* 2016, 7, 293. [CrossRef]

24. Wu, J.; Lin, H.; Guo, L.; Dong, J.; Zhang, L.; Fu, W. Biomass and Nutrients Variation of Chinese Fir Rooted Cuttings under Conventional and Exponential Fertilization Regimes of Nitrogen. *Forests* 2019, 10, 615. [CrossRef]

25. Liu, E.K.; Yan, C.R.; Mei, X.R.; He, W.Q.; Bing, S.H.; Ding, L.P.; Liu, Q.; Liu, S.A.; Fan, T.L. Long-term effect of chemical fertilizer, straw, and manure on soil chemical and biological properties in northwest China. *Geoderma* 2010, 158, 173–180. [CrossRef]

26. Zou, N.; Huang, L.; Chen, H.J.; Hu, X.F.; Song, Q.N.; Yang, Q.P.; Wang, T.C. Nitrogen form plays an important role in the growth of moso bamboo (Phyllostachys edulis) seedlings. *PeerJ* 2020, 8, e9938. [CrossRef]

27. Qian, Z.; Sun, X.; Gao, J.; Zhuang, S. Effects of Bamboo (Phyllostachys praecox) Cultivation on Soil Nitrogen Fractions and Mineralization. *Forests* 2021, 12, 1109. [CrossRef]

28. Weiner, J.; Freckleton, R.P. Constant final yield. *Annu Rev. Ecol. Evol. Syst.* 2010, 41, 173–192. [CrossRef]

29. Deng, J.; Ran, J.; Wang, Z.; Fan, Z.; Wang, G.; Ji, M.; Liu, J.; Wang, Y.; Liu, J.; Brown, J.H. Models and tests of optimal density and maximal yield for crop plants. *Proc. Natl. Acad. Sci. USA* 2012, 109, 15823–15828. [CrossRef]

30. Moussaoui, L.; Leduc, A.; Girona, M.M.; Belisle, A.C.; Lafleur, B.; Fenton, N.J.; Bergeron, Y. Success Factors for Experimental Partial Harvesting in Unmanaged Boreal Forest: 10-Year Stand Yield Results. *Forests* 2020, 11, 1199. [CrossRef]

31. Liu, G.; Hui, C.; Chen, M.; Pile, L.S.; Wang, G.G.; Wang, F.; Shi, P. Variation in individual biomass decreases faster than mean biomass with increasing density of bamboo stands. *J. For. Res.* 2018, 31, 981–987. [CrossRef]

32. Li, H.B.; Wang, X.; Brooker, R.W.; Rengel, Z.; Zhang, F.S.; Davies, W.J.; Shen, J.B. Root competition resulting from spatial variation in nutrient distribution elicits decreasing maize yield at high planting density. *Plant Soil* 2019, 439, 219–232. [CrossRef]

33. Huang, Z.; Liu, Q.; An, B.; Wu, X.; Sun, L.; Wu, P.; Liu, B.; Ma, X. Effects of Planting Density on Morphological and Photosynthetic Characteristics of Leaves in Different Positions on Cunninghamia lanceolata Saplings. *Forests* 2021, 12, 853. [CrossRef]

34. Wang, T.; Xu, Q.; Gao, D.Q.; Zhang, B.B.; Zuo, H.J.; Jiang, J. Effects of thinning and understory removal on the soil water-holding capacity in Pinus massoniana plantations. *Sci. Rep.* 2021, 11, 13029. [CrossRef] [PubMed]

35. Duan, A.; Lei, J.; Hu, X.; Zhang, J.; Du, H.; Zhang, X.; Guo, W.; Sun, J. Effects of Planting Density on Soil Bulk Density, pH and Nutrients of Unthinned Chinese Fir Mature Stands in South Subtropical Region of China. *Forests* 2019, 10, 351. [CrossRef]

36. Waqas, M.A.; Li, Y.; Smith, P.; Wang, X.; Ashraful, M.N.; Noor, M.A.; Amou, M.; Shi, S.; Zhu, Y.; Li, J.; et al. The influence of nutrient management on soil organic carbon storage, crop production, and yield stability varies under different climates. *J. Clean Prod.* 2020, 268, 121922. [CrossRef]

37. Amiri, M.B.; Jahan, M.; Mohgaddam, P.R. An exploratory method to determine the plant characteristics affecting the final yield of Echium amoenum Fisch. & C.A. Mey. under fertilizers application and plant densities. *Sci. Rep.* 2022, 12, 1881. [CrossRef]

38. Evans, J.R.; Clarke, V.C. The nitrogen cost of photosynthesis. *J. Exp. Bot.* 2019, 70, 7–15. [CrossRef]

39. Zhang, Q.C.; Shamsi, I.H.; Wang, J.W.; Song, Q.J.; Xue, Q.Y.; Yu, Y.; Lin, X.Y.; Hussain, S. Surface runoff and nitrogen (N) loss in a bamboo (Phyllostachys pubescens) forest under different fertilization regimes. *Environ. Sci. Pollut. R* 2013, 20, 4681–4688. [CrossRef]

40. Nkoh, J.N.; Yan, J.; Xu, R.K.; Shi, R.Y.; Hong, Z.N. The mechanism for inhibiting acidification of variable charge soils by adhered Pseudomonas fluorescens. *Environ. Pollut.* 2020, 260, 114049. [CrossRef]

41. Shi, R.Y.; Hong, Z.N.; Li, J.Y.; Jiang, J.; Kamran, M.A.; Xu, R.K.; Qian, W. Peanut straw biochar increases the resistance of two Ultisols derived from different parent materials to acidification: A mechanism study. *J. Environ. Manag.* 2018, 210, 171–179. [CrossRef]

42. Shi, R.-Y.; Liu, Z.-D.; Li, Y.; Jiang, T.; Xu, M.; Li, J.-Y.; Xu, R.-K. Mechanisms for increasing soil resistance to acidification by long-term manure application. *Soil Tillage Res.* 2019, 185, 77–84. [CrossRef]

43. Miatto, R.C.; Wright, I.J.; Batalha, M.A. Relationships between soil nutrient status and nutrient-related leaf traits in Brazilian cerrado and seasonal forest communities. *Plant Soil* 2016, 404, 13–33. [CrossRef]

44. Liu, X.; Xiang, L.; Zhao, D.; Huang, J.; Zhou, F.; Liao, J.; Lan, S.; Du, M.; Zhou, Y.; Huang, C. Stoichiometric characteristics of nitrogen and phosphorus in Chimonobambusa utilis leaves at different elevations. *Chin J. Appl. Environ. Biol.* 2022, 28, 1–10. [CrossRef]

45. Barrow, N.J. The effects of pH on phosphate uptake from the soil. *Plant Soil* 2016, 410, 401–410. [CrossRef]

46. Kubanek, J. Optimal decision making and matching are tied through diminishing returns. *Proc. Natl. Acad. Sci. USA* 2017, 114, 8499–8504. [CrossRef]