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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*

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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	Stand Density (culms ha^{-1})	Mean Ground Diameter (cm)	Mean Height (m)	Age Structure (1 a:2–3 a:>3 a)
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_2O_5), and potassium chloride (62% K_2O) 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 (pHS-3C$^+$ 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 anticolorimetry, 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_p)

The economic benefit (E_b) was calculated as follows:

$$E_b = Y \times U_p \tag{1}$$

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:

$$N_p = E_b - F_l - F_w \tag{2}$$

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:

$$E_g = \frac{E_{bi} - E_{bc}}{E_{bc}} \tag{3}$$

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:

$$N_g = \frac{N_{pi} - N_{pc}}{N_{pc}} \tag{4}$$

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 $p < 0.5$ level. Stepwise 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.

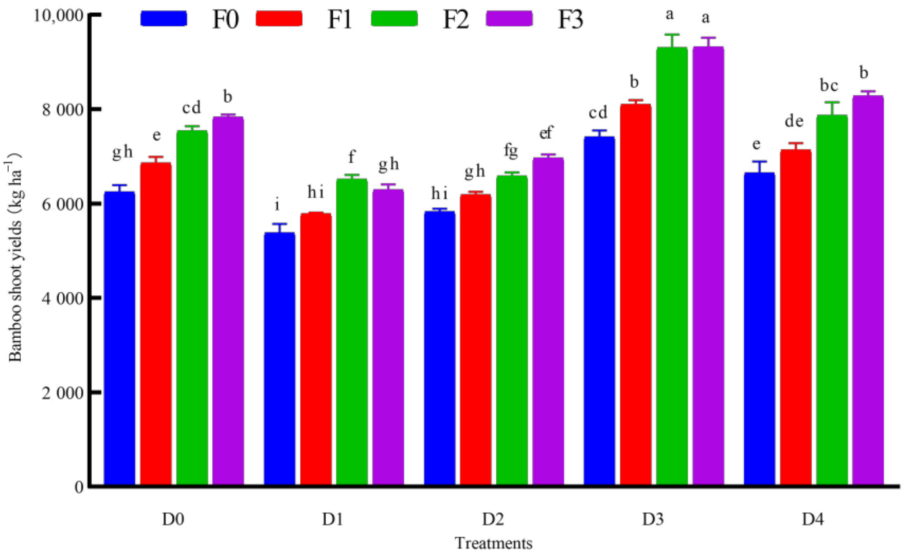

Figure 1. The bamboo-shoot yields of *C. pachystachys* forests by treatments. Error bars indicate standard error (n = 3). Different lowercase letters show significance at the 0.05 level according to Bonferroni's test.

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.

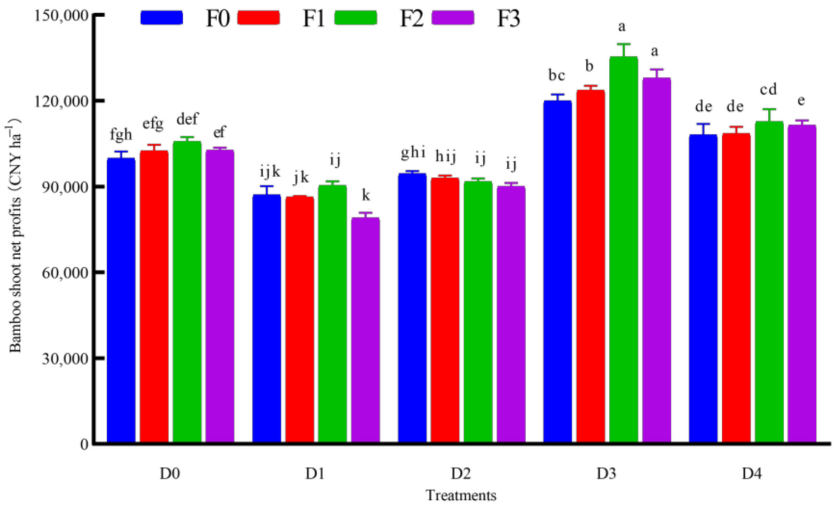

Figure 2. The bamboo-shoot net profit of *C. pachystachys* forests by treatments. Error bars indicate standard error (n = 3). Different lowercase letters show significance at the 0.05 level according to Bonferroni's test.

Compared to D0, the net profit decreased by 17.06% and 10.46% for D1 and D2, respectively, and increased by 24.05% and 7.46% for D3 and D4 (mean of four fertilizer rates), respectively. Compared to F0, the net profit increased by 4.39%, 26.10%, and 1.62% (mean of five density rates). The maximum net profit growth was 35.44%, which appeared in D3F2 (Figure 3).

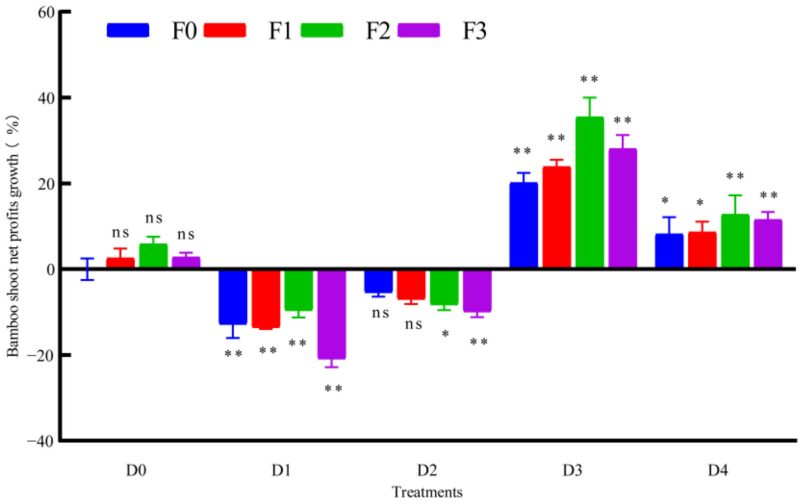

Figure 3. The bamboo-shoot net-profits-growth indexes of *C. pachystachys* forests by treatments. Error bars indicate standard error (n = 3). * and ** show significance at the 0.05 and 0.01 levels according to Bonferroni's test, respectively.

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).

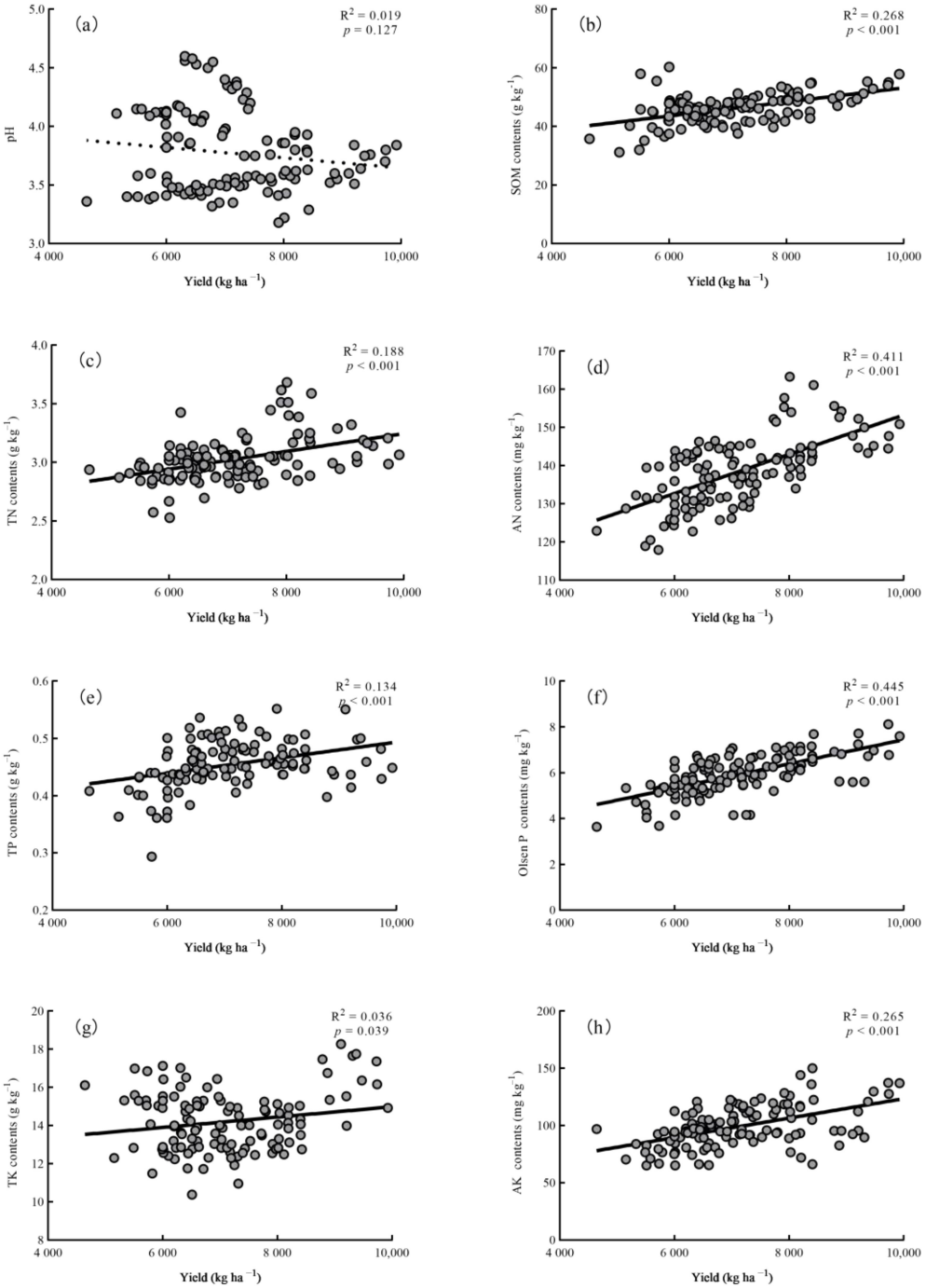

Figure 4. Relationships of bamboo-shoot yield to the soil pH (**a**), SOM (**b**), TN (**c**), AN (**d**), TP (**e**), Olsen P (**f**), TK (**g**), and AK (**h**) in *C. pachystachys* shoot forest. SOM: soil organic matter; TN: total nitrogen; AN: available nitrogen; TP: total phosphorus; Olsen P: Olsen 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 + 0.0.46 Olsen P + 0.41 AN	0.563	77.58	**<0.001**
Yield = −1963.85 + 0.43 Olsen P + 0.32 AN + 0.23 SOM	0.602	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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Informed Consent Statement: Not applicable.

Data Availability Statement: Data presented in this study are available from the authors upon request.

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

Appendix A

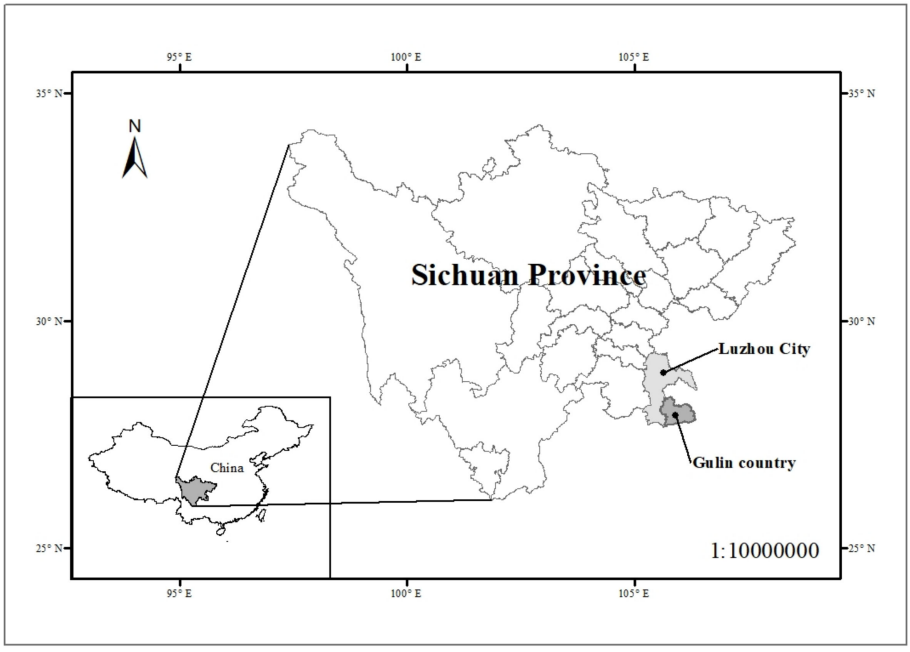

Figure A1. Location of the study area.

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 (g kg^{-1})	Olsen P (mg kg^{-1})	TK (g kg^{-1})	AK (mg kg^{-1})
D0F0	3.46 ± 0.01 efg	45.21 ± 2.54 cdefg	3.00 ± 0.38 cdef	131.37 ± 1.60 hij	0.47 ± 0.03 ab	5.63 ± 0.46 cde	12.97 ± 1.12 cd	90.34 ± 6.56 cd
D0F1	3.51 ± 0.03 cde	47.85 ± 1.28 bcde	3.14 ± 0.14 bcde	137.12 ± 1.79 defghi	0.48 ± 0.05 ab	4.16 ± 0.01 fg	12.06 ± 1.16 d	103.77 ± 10.40 bc
D0F2	3.43 ± 0.02 gh	50.87 ± 1.81 abc	3.45 ± 0.06 ab	153.86 ± 1.56 ab	0.50 ± 0.05 a	5.86 ± 0.66 bcde	13.57 ± 1.05 cd	111.78 ± 6.21 ab
D0F3	3.23 ± 0.06 j	53.78 ± 0.99 ab	3.63 ± 0.05 a	160.75 ± 2.82 a	0.45 ± 0.01 ab	7.27 ± 0.37 a	13.29 ± 0.68 cd	125.72 ± 2.99 a
D1F0	3.38 ± 0.02 hi	38.57 ± 2.41 g	2.89 ± 0.06 def	128.89 ± 5.18 j	0.42 ± 0.02 ab	4.53 ± 0.81 efg	15.58 ± 0.46 abc	91.16 ± 6.62 cd
D1F1	3.40 ± 0.01 ghi	57.95 ± 2.36 a	2.91 ± 0.07 def	133.88 ± 2.19 fghij	0.41 ± 0.04 ab	5.28 ± 0.97 defg	15.07 ± 0.86 abcd	78.40 ± 3.75 def
D1F2	3.42 ± 0.01 gh	45.31 ± 0.80 cdefg	3.06 ± 0.05 bcde	144.48 ± 2.12 cde	0.44 ± 0.02 ab	5.07 ± 0.14 defg	14.76 ± 1.12 abcd	68.71 ± 4.99 f
D1F3	3.44 ± 0.02 fgh	48.62 ± 2.27 bcd	3.08 ± 0.03 bcde	142.51 ± 1.14 cde	0.41 ± 0.03 ab	5.44 ± 0.41 cdef	15.77 ± 1.16 abc	103.51 ± 4.63 bc
D2F0	3.58 ± 0.02 ab	45.35 ± 0.51 cdefg	2.65 ± 0.17 f	141.07 ± 2.44 def	0.37 ± 0.07 b	3.96 ± 0.25 g	16.76 ± 0.29 ab	65.73 ± 0.91 f
D2F1	3.49 ± 0.02 def	47.01 ± 1.58 bcdef	2.97 ± 0.09 cdef	142.42 ± 0.67 cde	0.44 ± 0.01 ab	5.24 ± 0.33 defg	12.46 ± 0.25 d	89.76 ± 5.40 cd
D2F2	3.45 ± 0.01 efg	43.16 ± 2.03 defg	3.00 ± 0.05 cdef	141.75 ± 4.24 def	0.50 ± 0.05 a	6.35 ± 0.26 abcd	12.75 ± 1.00 cd	80.19 ± 1.42 def
D2F3	3.34 ± 0.02 i	40.49 ± 0.77 efg	3.11 ± 0.05 bcde	144.63 ± 0.50 cd	0.50 ± 0.02 a	6.04 ± 0.18 abcd	14.60 ± 1.49 abcd	86.17 ± 8.95 de
D3F0	3.56 ± 0.02 abc	46.46 ± 4.58 bcdef	2.84 ± 0.04 ef	138.64 ± 2.50 defgh	0.50 ± 0.01 a	5.96 ± 0.28 abcd	12.76 ± 0.39 cd	94.24 ± 3.70 cd
D3F1	3.55 ± 0.02 bcd	42.18 ± 2.22 defg	2.97 ± 0.11 cdef	142.05 ± 0.49 de	0.46 ± 0.01 ab	6.80 ± 0.30 abc	14.70 ± 0.15 abcd	93.63 ± 0.44 cd
D3F2	3.53 ± 0.02 bcd	49.78 ± 0.64 bcd	2.98 ± 0.03 cdef	154.07 ± 1.70 ab	0.42 ± 0.02 ab	7.15 ± 0.49 ab	15.60 ± 1.75 abc	95.54 ± 0.14 bcd
D3F3	3.61 ± 0.02 a	48.88 ± 2.12 bcd	3.27 ± 0.07 abcd	150.20 ± 2.43 bc	0.50 ± 0.05 a	5.61 ± 0.02 cde	17.56 ± 0.76 a	88.41 ± 5.09 cde
D4F0	3.50 ± 0.01 cdef	46.39 ± 1.38 bcdef	2.84 ± 0.03 ef	130.36 ± 1.46 ij	0.49 ± 0.02 a	5.63 ± 0.39 cde	12.83 ± 0.50 cd	93.11 ± 7.42 cd
D4F1	3.51 ± 0.01 cde	39.69 ± 2.10 fg	2.98 ± 0.10 cdef	132.69 ± 4.03 ghij	0.47 ± 0.03 ab	5.80 ± 0.22 bcde	14.50 ± 0.79 abcd	93.18 ± 1.61 cd
D4F2	3.58 ± 0.01 ab	47.23 ± 5.11 bcdef	3.01 ± 0.14 cdef	136.49 ± 2.26 efghij	0.48 ± 0.02 ab	6.79 ± 0.14 abc	13.90 ± 1.33 bcd	88.85 ± 3.12 cd
D4F3	3.62 ± 0.01 a	51.13 ± 3.09 abc	3.36 ± 0.17 abc	139.76 ± 2.56 defg	0.46 ± 0.02 ab	6.29 ± 0.22 abcd	13.30 ± 0.19 cd	71.67 ± 5.30 ef

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 (g kg^{-1})	Olsen P (mg kg^{-1})	TK (g kg^{-1})	AK (mg kg^{-1})
D0F0	3.95 ± 0.06 f	43.00 ± 4.62 bcd	3.04 ± 0.12 abc	127.69 ± 3.31 de	0.46 ± 0.02 abc	5.06 ± 0.34 g	13.11 ± 0.78 bc	83.52 ± 8.60 fg
D0F1	4.53 ± 0.03 a	46.21 ± 2.48 bc	3.00 ± 0.04 bcd	134.02 ± 5.28 bcde	0.44 ± 0.01 abcd	5.76 ± 0.47 defg	13.11 ± 2.50 bc	94.56 ± 5.98 efg
D0F2	4.32 ± 0.03 b	46.25 ± 1.96 bc	3.07 ± 0.02 abc	137.76 ± 3.10 abcd	0.46 ± 0.02 abc	6.15 ± 0.36 abcdefg	13.57 ± 0.64 bc	109.96 ± 7.88 bcde
D0F3	3.75 ± 0.01 hi	49.04 ± 1.23 ab	3.06 ± 0.14 abc	146.46 ± 4.81 a	0.48 ± 0.01 ab	6.84 ± 0.24 abcd	14.60 ± 0.61 abc	116.54 ± 6.45 bcde
D1F0	4.13 ± 0.02 cde	33.23 ± 2.92 e	2.90 ± 0.06 cd	124.58 ± 5.06 e	0.40 ± 0.03 cd	5.04 ± 0.39 g	13.39 ± 1.45 bc	77.90 ± 8.16 g
D1F1	4.13 ± 0.02 cde	36.95 ± 1.55 de	2.97 ± 0.04 bcd	125.47 ± 5.77 e	0.40 ± 0.03 cd	5.39 ± 0.08 fg	13.23 ± 1.93 bc	85.53 ± 12.65 fg
D1F2	4.06 ± 0.02 e	41.04 ± 1.97 cd	3.02 ± 0.05 abc	134.55 ± 0.22 bcde	0.46 ± 0.02 abc	5.75 ± 0.42 defg	14.84 ± 0.54 abc	101.53 ± 3.20 defg
D1F3	3.84 ± 0.02 g	42.59 ± 1.30 bcd	3.05 ± 0.09 abc	141.00 ± 2.43 abc	0.51 ± 0.01 a	6.62 ± 0.11 abcde	16.24 ± 1.06 ab	116.16 ± 4.21 bcde
D2F0	4.10 ± 0.02 de	45.46 ± 2.24 bc	2.79 ± 0.10 d	124.50 ± 6.03 e	0.38 ± 0.02 d	5.45 ± 0.29 fg	15.10 ± 0.19 abc	83.07 ± 10.20 fg
D2F1	4.16 ± 0.03 cd	47.69 ± 0.73 abc	2.89 ± 0.05 cd	128.69 ± 2.17 de	0.43 ± 0.01 abcd	5.73 ± 0.44 defg	13.19 ± 0.36 bc	95.18 ± 2.13 efg
D2F2	4.06 ± 0.02 e	45.74 ± 0.15 bc	2.94 ± 0.05 cd	134.15 ± 2.51 bcde	0.46 ± 0.01 abc	6.46 ± 0.09 abcdef	14.28 ± 1.21 abc	101.57 ± 3.27 defg
D2F3	3.95 ± 0.03 f	46.26 ± 1.15 bc	3.05 ± 0.01 abc	142.81 ± 2.47 abc	0.48 ± 0.01 ab	6.93 ± 0.18 abc	15.75 ± 0.60 abc	119.60 ± 3.63 abcd
D3F0	4.19 ± 0.04 c	48.04 ± 1.54 abc	2.90 ± 0.05 cd	132.89 ± 2.29 cde	0.46 ± 0.05 abc	5.89 ± 0.38 cdefg	12.59 ± 0.21 c	114.12 ± 6.13 bcde
D3F1	3.94 ± 0.01 f	48.44 ± 3.37 abc	2.90 ± 0.07 cd	141.39 ± 2.18 abc	0.45 ± 0.01 abcd	6.34 ± 0.34 abcdef	14.11 ± 0.24 abc	112.94 ± 6.72 bcde
D3F2	3.83 ± 0.02 gh	54.09 ± 4.32 a	3.03 ± 0.04 abc	147.80 ± 3.06 a	0.44 ± 0.01 abcd	7.21 ± 0.41 ab	15.54 ± 0.61 abc	125.66 ± 12.45 adc
D3F3	3.74 ± 0.03 i	54.08 ± 1.23 a	3.17 ± 0.03 ab	144.35 ± 0.98 ab	0.48 ± 0.02 ab	7.27 ± 0.75 a	17.16 ± 0.72 a	129.35 ± 8.30 ab
D4F0	4.58 ± 0.03 a	44.73 ± 1.06 bc	2.90 ± 0.08 cd	125.82 ± 3.10 e	0.45 ± 0.01 abcd	5.08 ± 0.29 g	12.60 ± 0.24 c	103.45 ± 7.29 cdef
D4F1	4.38 ± 0.03 b	48.13 ± 0.06 abc	2.88 ± 0.10 cd	129.18 ± 2.83 de	0.43 ± 0.02 bcd	5.61 ± 0.25 efg	13.12 ± 0.87 bc	112.15 ± 7.44 bcde
D4F2	3.87 ± 0.01 fg	43.58 ± 1.57 bcd	3.05 ± 0.01 abc	140.84 ± 2.60 abc	0.46 ± 0.01 abc	6.10 ± 0.26 bcdefg	13.06 ± 0.45 bc	116.87 ± 4.16 bcde
D4F3	3.79 ± 0.01 ghi	47.45 ± 4.02 abc	3.23 ± 0.03 a	143.71 ± 2.18 abc	0.48 ± 0.03 ab	6.91 ± 0.28 abc	14.68 ± 0.53 abc	143.42 ± 7.05 a

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	102,450.58	9.87	2.60
D0F2	120,593.39	7664.52	200	105,664.35	20.77	5.82
D0F3	125,266.40	11,496.77	200	102,672.85	25.45	2.82
D1F0	86,013.71	0	800	87,013.71	−13.86	−12.86
D1F1	92,536.11	3832.26	1000	86,271.59	−7.33	−13.60
D1F2	104,181.60	7664.52	1000	90,252.57	4.33	−9.62
D1F3	100,572.32	11,496.77	1000	78,978.77	0.72	−20.91
D2F0	93,268.35	0	700	94,468.35	−6.60	−5.40
D2F1	98,896.44	3832.26	900	92,831.92	−0.96	−7.03
D2F2	105,335.57	7664.52	900	91,606.54	5.49	−8.26
D2F3	111,369.97	11,496.77	900	89,976.42	11.53	−9.89
D3F0	118,542.88	0	600	119,942.88	18.71	20.12
D3F1	129,518.47	3832.26	800	123,653.95	29.70	23.83
D3F2	148,771.66	7664.52	800	135,242.63	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.

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