

Response of young *Dendrocalamus asper* bamboo to variable rate phosphorus fertilization

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Research Article

Keywords: Dendrocalamus asper, dry matter accumulation, phosphorus use efficiency

Posted Date: October 16th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-11377477/v1>

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Additional Declarations: The authors declare no competing interests.

Abstract

Bamboo production is expanding in the United States, particularly in Florida, where bamboo is cultivated for edible shoots, construction materials, manufactured products, ornamental landscaping, and other commercial uses. Bamboo production in Florida occupies approximately 700 ha. Nitrogen (N), phosphorus (P), and potassium (K) fertilizers are commonly applied to improve bamboo growth, yield, and quality. However, P fertilization guidelines for bamboo production are lacking, despite the essential role of P in plant growth and biomass production. This study evaluated the effects of varying P fertilization rates on *Dendrocalamus asper* under greenhouse conditions. Two trials were conducted on one-year-old bamboo plants for five months in 2023 and 2024. Treatments were different P rates (0, 22.4, 44.8, and 89.6 kg P ha⁻¹ yr⁻¹) distributed in a completely randomized design with five replicates. Growth, physiological parameters, and biomass accumulation were assessed. Data were analyzed using one-way analysis of variance with a linear mixed model for repeated measures. The P rate significantly affected bamboo growth, culm biomass accumulation, culm production, and chlorophyll content across both years. The highest biomass in culms, total biomass, number of culms, and clump height occurred at 22.4 and 44.8 kg P ha⁻¹ yr⁻¹ in 2023 and 2024, respectively. Higher P rates (44.8 and 89.6 kg P ha⁻¹ yr⁻¹) increased below-ground biomass. Although no clear optimal P rate was established, moderate P application (22.4 and 44.8 kg P ha⁻¹ yr⁻¹) improved the growth of bamboo plants. These findings provide a foundation for developing P fertilization guidelines in Florida and 31 kg P ha⁻¹ yr⁻¹ seems to be the optimal P fertilization rate for bamboo production in southern Florida.

Highlights

1. Phosphorus fertilization significantly improved bamboo growth
2. Culm production increased at 22.4 kg P ha yr
3. Phosphorus fertilization influenced dry matter partitioning in above- and below-ground bamboo components
4. Phosphorus use efficiency decreased with higher application rates
5. 31 kg P ha yr was the estimated optimal P rate.

Introduction

Bamboo production has gained worldwide recognition due to its sustainability and adaptability to modern applications (Emamverdian et al., 2020). Applications include construction materials, furniture, textiles, bioenergy, food (edible young shoots), and soil conservation (Lobovikov et al., 2007; Vivas et al., 2024; Van Der Lugt et al., 2003). Bamboo is a carbon-sequestering and regenerative plant that significantly benefits mitigating climate change (Nath et al., 2015), particularly biomass accumulation and long-term carbon storage in durable products (Van der Lugt et al., 2012). In subtropical regions, the

giant bamboo species *Dendrocalamus asper* is particularly of interest due to large culms, quick growth, and edible shoots (Mustafa et al., 2021). As such, it is a promising alternative crop for industrial and agricultural use (Coyle et al., 2019).

Although bamboo is a valuable crop worldwide, the United States (U.S.) has historically relied on Asian imports to meet domestic demand for bamboo products. The U.S. imports bamboo as flooring, furniture, textiles, and processed shoots, contributing to a trade imbalance and missing out on potential local economic benefits (International Bamboo and Rattan Organisation [INBAR], 2018). The favorable environment and growing demand for sustainable crops in the southeastern U.S., including Florida, have fueled interest in domestic bamboo cultivation in recent years (Vivas et al., 2024). However, the scale of commercial bamboo cultivation remains limited, with most production systems still in early developmental stages (Kadyampakeni et al., 2023).

To cultivate bamboo clumping species such as *D. asper*, it is important to optimize planting density, control underground rhizomes, and manage fertilizer and water supplies effectively to meet the requirements for rapid development and high biomass (Banik, 2015). The fertilization techniques in bamboo have not been well studied in the U.S., among other farming practices, including vegetative propagation, regular shoot thinning, and mulching. Currently, there are no fertilizer recommendations for Florida sandy soil, and most bamboo nutrient management in Florida is based on extrapolations from other regions (Kadyampakeni et al., 2023; Januarie and Kadyampakeni, 2025).

Bamboo growth and development depend heavily on P availability, especially in the early establishment stage when root expansion and shoot initiation are at their peak. Phosphorus is a crucial macronutrient that supports vital physiological processes like energy transfer (ATP), nucleic acid synthesis, and root system development (Kirkby, 2001). These processes provide the basis for biomass formation and clump development. However, P management is particularly important in sandy soils, where excessive P application can increase leaching losses and contribute to eutrophication of surface waters (Yang et al., 2007), while insufficient P availability can restrict bamboo growth and biomass accumulation (Hang et al., 2024). An appropriate P supply is crucial for maximizing productivity in nutrient-deficient soils, since studies on bamboo species have demonstrated that it improves shoot production, chlorophyll content, and nutrient uptake efficiency (Lin et al., 2023; Hang et al., 2024). Various studies in other regions have demonstrated a wide range of optimal P rates for efficient bamboo growth and productivity. Applying P at $93.75 \text{ kg P ha}^{-1}$ proved optimal for bamboo yield components such as culm diameter and number of culms (Maoyi et al., 1991). Piouceau et al. (2014a) found that in a bamboo with a standing density of $1,600 \text{ clumps ha}^{-1}$, 57 kg P ha^{-1} accumulated in different organs. Other studies have indicated that the optimal rate of P fertilization for bamboo growth is between 50 and 300 kg ha^{-1} (Bo et al., 2021; Zhang et al., 2019). Sustaining availability within this goal range ensures efficiency while meeting the nutritional requirements of plants. The need for species- and region-specific research is emphasized by the fact that P fertilization recommendations for bamboo in Florida are still either generic or extrapolated from other regions.

The bamboo sector in Florida lacks guidelines on best management practices (BMPs), which presents a significant risk of environmental pollution from excessive fertilizer use resulting from try-and-error methods by commercial growers. Therefore, it is necessary to assess the impact of P fertilization on bamboo production in Florida. This study aimed to (1) assess the impact of different P rates on the growth of young *D. asper* plants, (2) determine the optimal P rate for efficient early-stage development, and (3) evaluate P use efficiency (PUE) under various fertilization rates. It was hypothesized that varying P fertilization would lead to differences in growth, dry matter accumulation, and phosphorus use efficiency.

Materials and methods

Site description

The study was conducted at the University of Florida Institute of Food and Agricultural Sciences (UF/IFAS), Citrus Research and Education Center in Lake Alfred, Florida (28°06'28.6" N, 81°41'07.8" W) in 2023 and 2024. The first trial was conducted from 22 June to 1 November, 2023, and the second study was conducted from 1 February to 2 July, 2024. One-year-old *D. asper* bamboo clumps were transplanted into 38-L plastic pots and trimmed to 40 cm for a homogeneous height (Fig. 1). Twenty pots were filled with a potting mix composed of peat moss and perlite at a ratio of 4:1 (v/v). Peat moss has a low nutrient content and generally has fewer weed seeds and plant pathogens. Florida sandy soils are known to have high background P, which could interfere with the study; thus, this mix was used instead of regular sand. Additionally, perlite provides excellent drainage properties to the mix (hereafter referred to as soil) compared to sandy soil.

Phosphorus application

After filling the pots, a growth-medium sample was collected from each pot for nutrient analysis using Mehlich-3 extraction method (Mehlich, 1984). Following a two-week acclimation period, plant tissue samples were collected before treatment application for macro- and micronutrient analyses. Each pot planted with one clump of *D. asper* bamboo served as an experimental unit, and the pots were arranged in a completely randomized design (CRD) with four replicates per treatment. The treatments consisted of four P application rates: 0 (control), 22.4, 44.8, and 89.6 kg P ha⁻¹ yr⁻¹.

Following the two-week acclimation period, the P treatments and basal fertilizer were applied to the pots. Since there are no recommended rates of N-P-K, 0.11 kg pot⁻¹ was applied using the 18-0-6 fertilizer blend, thereby providing the plants with N and K requirements. The P source used was triple superphosphate (0-46-0). This water-soluble, granulated P source was soil-applied and hand-mixed into the top 5 cm of the soil of each experimental unit. The amounts per pot were calculated and scaled down to the area of the pot at a field-plant density of 476 clumps ha⁻¹. During the 2023 trial, plants were irrigated daily for 5 min using an automated drip irrigation system equipped with a pressure-

compensating emitter (Maxi-Jet, Dundee, FL) operating at a flow rate of 8 L h^{-1} . During the 2024 trial, the system was modified to use a multi-stream dripper operating at 41 L h^{-1} for 2 min daily. This modification increased water distribution across the pot surface because localized drying had been observed in portions of the pots during the 2023 trial.

Data collection

Soil and tissue P were measured at the beginning and the end of the experiment. Clump height, culm diameter, and number of shoots were determined biweekly. Using a measuring ruler, clump height was measured from the upper end of the pot since measuring from the soil (base of the clump) can cause variability, leading to inaccurate measurements. One culm was identified in each pot and marked at a height of 5 cm from the soil surface, from where the culm diameter was measured using a digital caliper. Since culm emergence is important for bamboo productivity, as it signifies farm sustainability, the culms were counted to determine culm production. Other measured variables included leaf chlorophyll content and leaf P concentration, which were measured monthly. This would also enable a clear understanding of the relationship between nutrient uptake and its use in chlorophyll production. The leaf chlorophyll content was measured using a portable Soil Plant Analysis Development (SPAD) chlorophyll meter (SPAD-501, Konica Minolta Inc., Tokyo, Japan).

Bamboo plants were destructively sampled at the end of the experiment (i.e., ~five months), during which total dry matter for all clumps was determined. Furthermore, leaves, culms, rhizomes, and roots were partitioned as highlighted by Shanmughavel and Francis (1996). The dry mass and P concentration in each organ were determined by oven-drying the tissue samples at 65°C until a constant weight and then measuring elemental analysis using the inductively coupled plasma method (Huang and Schulte, 1985). The data were used to quantify P accumulation in specific parts (Kleinhenz and Midmore, 2001) and overall nutrient use efficiency (Baligar et al., 2001). All soil and tissue nutrient analyses were done at Waters Agricultural Laboratories, Inc. (Camilla, Georgia). Phosphorus use efficiency metrics and root-to-shoot ratio were calculated using the following formulae (Eqs. 1 to 5) adapted from Baligar et al., (2001) and Lopez et al., (2023). The metrics calculated included Nutrient use efficiency (NER), Physiological Efficiency (PE), Agronomic efficiency (AE) and Apparent Nutrient Recovery as described by different authors (De Gissi et al., 2025; Pande et al., 2022; Toprak and Seferoğlu, 2024),

$$NER (g/g) = \frac{Y}{U_{et}} \text{ (Eq. 1)}$$

$$PE (g/g) = \frac{Y_1 - Y_0}{N_{u1} - N_{u0}} \text{ (Eq. 2)}$$

$$AE (g/g) = \frac{Y_1 - Y_0}{Q_{na}} \text{ (Eq. 3)}$$

$$ANR (\%) = \frac{N_{u1} - N_{u0}}{Q_{na}} \times 100 \text{ (Eq. 4)}$$

$$R : S \text{ ratio} = \frac{BGB}{AGB} \text{ (Eq. 5)}$$

Where:

Y= yield as dry matter in g

Ue_t= unit of elements in tissue in g

Y₁= yield as dry matter in fertilized plants in g

Y₀= yield as dry matter in the control plants in g

Nu₁= nutrient uptake in fertilized plants in g

Nu₀= nutrient uptake in the control plants in g

Q_{na}= quantity of nutrient applied in g

BGB = Below-ground dry matter in g

AGB = Above-ground dry matter in g

R = root

S = shoot

Data Analysis

Data were analyzed separately by trial in R version 4.1.2 using linear mixed-effects models in the nlme package because irrigation regime, season, and plant cohorts differed between trials. Phosphorus rate and time were treated as fixed effects, subject as a random effect, and residual variances were allowed to differ among treatments. Treatment estimated marginal means were obtained using the emmeans package, and three a priori orthogonal contrast inquiries were conducted: the control versus all P-fertilized treatments (ψ^1), the combined low and intermediate P rates versus the highest P rate (ψ^2), and 22.4 versus 44.8 kg P ha⁻¹ yr⁻¹ (ψ^3), with significance determined at $\alpha = 0.05$. A linear plateau model was used to estimate optimal P rate using the dry matter data from the two trials.

Results

Trial 1- 2023 Study

Phosphorus fertilization rate and time significantly influenced the morphological development of the one-year-old bamboo, whereas their interaction did not (Table 1). Phosphorus fertilization rates affected

clump height and the total number of culms, unlike on culm diameter. Similarly, time had a significant main effect on all three morphological parameters .

Table 1

Summary Analysis of variance of some *D. asper* bamboo traits under variable P rate supply (Trial 1-2023).

Factors	Clump Height	Culm diameter	Number of Culms	Tissue P Concentration	SPAD
Intercept	***	***	***	***	***
Phosphorus rate (P)	*	ns	*	ns	***
Time (T)	***	***	***	***	***
P x T	ns	ns	ns	ns	ns

*, ***, and ns indicate statistically significant correlations at $p < 0.05, 0.001$ and nonsignificant respectively.

The physiological responses of *D. asper* varied between the tested parameters under the different treatment factors. For relative chlorophyll content (SPAD), both P fertilization rate and time demonstrated significant main effects. In contrast, tissue P concentration was not significantly affected by the varying P application rates, though it was affected by time. There was no significant interaction effect (P x T) detected for either tissue P concentration or SPAD values.

Structural traits as influenced by variable P fertilization

The response of cumulative clump height to P fertilization was primarily driven by differences among the fertilizer application rates rather than a simple contrast against the control group (Fig. 2A). There was no difference between unfertilized control and all P treatments (ψ^1) on cumulative clump height. However, the low and medium rates differed from the highest application rate (ψ^2). Clump height peaked at the medium application rate ($44.8 \text{ kg P}_2\text{O}_5 \text{ ha}^{-1} \text{ yr}^{-1}$) at approximately (0.35m) before declining at the highest rate ($89.6 \text{ kg P}_2\text{O}_5 \text{ ha}^{-1} \text{ yr}^{-1}$). There was no significant difference (ψ^3) between the 22.4 and 44.8 $\text{kg P}_2\text{O}_5 \text{ ha}^{-1} \text{ yr}^{-1}$ rates.

For cumulative culm diameter, the only differences occurred between the moderate application rates (Fig. 2B). The broad comparison between the control group and all fertilized groups (ψ^1) was not significant, nor was there a significant difference when comparing the combined lower rates against the highest rate (ψ^2). Conversely, the direct contrast between the low and medium fertilization rates (ψ^3) was significant. Culm diameter reached its maximum growth of approximately 0.36 mm at the lowest

fertilizer rate, 22.4 kg P₂O₅ ha⁻¹ yr⁻¹, and sharply decreased to its lowest levels at the 44.8 kg P₂O₅ ha⁻¹ yr⁻¹ rate.

The cumulative number of culms produced was influenced by the presence of fertilizer rather than the rate applied (Fig. 2C). The contrast comparing the unfertilized control against all P-fertilized treatments (ψ^1) was significant, with the control producing the fewest culms (~ 1.1 culms clump⁻¹). Once fertilizer was applied, increasing the rate did not yield additional culms produced; no significant differences were detected when comparing the combined lower rates against the highest rate (ψ^2), or when evaluating the low rate directly against the medium rate (ψ^3).

Table 2
Tissue P concentration and Soil Plant Analysis Development (SPAD) as influenced by variable P rate (Trial 1-2023). Values represent treatment means $\pm$ SE.

Rates	Tissue P concentration	SPAD
(kg P ₂ O ₅ ha ⁻¹ yr ⁻¹)	(%)	
0	0.30 $\pm$ 0.06	28.43 $\pm$ 3.12
22.4	0.31 $\pm$ 0.05	30.68 $\pm$ 3.05
44.8	0.36 $\pm$ 0.07	27.34 $\pm$ 2.86
89.6	0.40 $\pm$ 0.08	28.83 $\pm$ 3.08
Contrasts		
Control vs fertilized P	ψ^1 ns	ψ^1 ns
Low + medium P vs high P	ψ^2 ns	ψ^2 ns
22.4 vs 44.8 kg P ₂ O ₅ ha ⁻¹	ψ^3 ns	ψ^{3***}

***, and ns indicate statistically significant correlations at $p < 0.001$ and nonsignificant respectively.

The internal allocation of P within the plant tissue remained statistically similar across all P rates. The broad comparison between contrasts showed no significant differences in tissue P accumulation. Tissue P concentration ranged from 0.3% in the control group to 0.4% at the highest application rate of 89.6 kg P₂O₅ ha⁻¹ yr⁻¹. In contrast to tissue P concentration, SPAD had a response to specific mid-range P rate differences. The initial presence of P did not broadly influence SPAD levels, with the control group performing statistically similarly to all combined P additions (ψ^1). Furthermore, lower application rates did not differ from the maximum rate (ψ^2). However, significant contrast was detected between the low and medium P fertilization rates (ψ^3). The SPAD peaked at the 22.4 kg P₂O₅ ha⁻¹ yr⁻¹ rate (30.68) before declining to its lowest observed levels at the 44.8 kg P₂O₅ ha⁻¹ yr⁻¹ rate (27.34).

Dry matter accumulation in young *D. asper* bamboo

The overall plant dry matter accumulation and its distribution to leaves and roots were unaffected by varying P rates. For total dry matter (Fig. 3A), leaf dry matter (Fig. 3B), and root dry matter (Fig. 3E), no statistically significant differences were observed across any of the evaluated orthogonal contrasts. Total dry matter peaked at the $22.4 \text{ kg P}_2\text{O}_5 \text{ ha}^{-1} \text{ yr}^{-1}$ application rate (240 g clump^{-1}). In contrast to total allocation, dry matter partitioned specifically to the culms showed localized sensitivity to lower fertilization rates (ψ^3) as demonstrated in Fig. 3C. While the contrasts comparing the control to all P applications (ψ^1) and the lower rates to the highest rate (ψ^2) were non-significant. Culm dry matter reached a maximum of 112 g clump^{-1} at the $22.4 \text{ kg P}_2\text{O}_5 \text{ ha}^{-1} \text{ yr}^{-1}$ rate before declining significantly to 85 g clump^{-1} at the $44.8 \text{ kg P}_2\text{O}_5 \text{ ha}^{-1} \text{ yr}^{-1}$ rate.

Belowground partitioning had an inverse response compared to the aboveground vegetative traits (Fig. 3D). Comparing the unfertilized control against all combined P applications (ψ^1), there was greater dry matter in the control, driven by the reduction in rhizome dry matter at middle rates (22.4 and $44.8 \text{ kg P}_2\text{O}_5 \text{ ha}^{-1} \text{ yr}^{-1}$ rate). Furthermore, the low and medium rates had less rhizome mass than the highest rate (ψ^2). The direct comparison between the two moderate rates (ψ^3) was not significant.

Phosphorus use efficiency in bamboo

The efficiency of P utilization generally declined with increasing fertilization rates for the metrics evaluated; snutrient efficiency ratio (NER), physiological efficiency (PE), or agronomic efficiency (AE) where no statistically significant differences were detected across any of the evaluated orthogonal contrasts ($p > 0.05$) (Table 3). Nevertheless, these metrics showed sharp reductions as P fertilizer application intensified; as AE decreased from 23.36 to 3.64 g g^{-1} , PE from 339.76 to 217 g g^{-1} , across 22.4 – $89.6 \text{ kg P}_2\text{O}_5 \text{ ha}^{-1} \text{ yr}^{-1}$ rates, while NER ranged from 710.78 – 530.30 g g^{-1} across 0 – $89.6 \text{ kg P}_2\text{O}_5 \text{ ha}^{-1} \text{ yr}^{-1}$ rates. On the other hand, the Apparent Nutrient Recovery (ANR) demonstrated a significant response at moderate rate thresholds (ψ^3). The ANR ranged from 1.27 – 18.96% with a trend of declining recovery across P rates (22.4 – $89.6 \text{ kg P}_2\text{O}_5 \text{ ha}^{-1} \text{ yr}^{-1}$).

Table 3

Phosphorus use efficiency metrics of one-year-old *Dendrocalamus asper* subjected to varying phosphorus application rates. Values represent treatment means $\pm$ SE.

Rate	Efficiency metrics			
(kg P ₂ O ₅ ha ⁻¹ yr ⁻¹)	NER (g g ⁻¹)	PE (g g ⁻¹)	AE (g g ⁻¹)	ANR (%)
0	710.78 $\pm$ 122.55	-	-	-
22.4	439.87 $\pm$ 116.06	339.76 $\pm$ 130.70	23.36 $\pm$ 6.05	18.96 $\pm$ 10.03
44.8	550.69 $\pm$ 22.32	323.95 $\pm$ 41.71	7.43 $\pm$ 0.79	2.35 $\pm$ 0.28
89.6	530.30 $\pm$ 25.25	217.11 $\pm$ 108.62	3.64 $\pm$ 1.91	1.27 $\pm$ 0.30
Contrasts				
Control vs fertilized P	ψ^1 ns	-	-	-
Low + medium P vs high P	ψ^2 ns	ψ^2 ns	ψ^2 ns	ψ^2 ns
22.4 vs 44.8 kg P ₂ O ₅ ha ⁻¹	ψ^3 ns	ψ^3 ns	ψ^3 ns	ψ^3 *

* and ns indicate statistically significant correlations at $p < 0.05$ and nonsignificant respectively.

- = NA

Trial 2- 2024 Study

Similar to trial one, a two-way ANOVA was conducted, analyzing the main effects and interactions of P fertilization rates and time, to evaluate the reproducibility of the P fertilization rates under trial 2 conditions (Table 4). The morphological traits of the bamboo exhibited distinct responses to the experimental factors, with time serving as the most consistent driver of growth.

Table 4

Summary analysis of variance table of some *D. asper* bamboo traits under variable P rate supply (Trial 2- 2024).

Factors	Clump Height	Culm diameter	Number of Culms	Tissue P Concentration	SPAD
Intercept	***	***	***	***	***
Phosphorus rates (P)	ns	***	***	***	ns
Time (T)	***	***	***	***	***
P x T	ns	ns	ns	ns	ns

*** and ns indicate statistically significant correlations at $p < 0.001$ and nonsignificant respectively.

Varying P fertilization rates did not significantly influence clump height or culm diameter in trial 2. However, the main effect of P application remained highly significant for the cumulative number of culms produced. No significant interaction effect ($P \times T$) was detected for any of the three morphological parameters. On the other hand, physiological parameters demonstrated contrasting responses to P nutrient supply in trial 2. Both tissue P concentration and SPAD were significantly affected by the main effect of time. There was no difference in SPAD among P rates. Bamboo tissue P concentration significantly responded to varying P application rates. The interaction between phosphorus rates and time remained non-significant for both physiological parameters.

Bamboo structural traits as influenced by variable phosphorus (P) fertilization

Phosphorus fertilization did not significantly affect cumulative clump height after 5 months under greenhouse conditions (Fig. 4A). Clump height increased slightly with increasing P rate, from the control to $89.6 \text{ kg P}_2\text{O}_5 \text{ ha}^{-1} \text{ yr}^{-1}$, but none of the planned comparisons were significant, including control versus fertilized treatments (ψ^1), low plus medium versus high P (ψ^2), and 22.4 versus $44.8 \text{ kg P}_2\text{O}_5 \text{ ha}^{-1} \text{ yr}^{-1}$ (ψ^3). Cumulative clump height averaged 0.28 m in the control group and peaked at the $89.6 \text{ kg P}_2\text{O}_5 \text{ ha}^{-1} \text{ yr}^{-1}$ rate with an average of 0.37 m (Fig. 4A).

In contrast, cumulative clump diameter differed among P rates (Fig. 4B). The $44.8 \text{ kg P}_2\text{O}_5 \text{ ha}^{-1} \text{ yr}^{-1}$ rate had the greatest cumulative diameter ($\sim 0.62 \text{ mm}$), followed by $89.6 \text{ kg P}_2\text{O}_5 \text{ ha}^{-1} \text{ yr}^{-1}$ ($\sim 0.4 \text{ mm}$), whereas the control and $22.4 \text{ kg P}_2\text{O}_5 \text{ ha}^{-1} \text{ yr}^{-1}$ rates had lower clump diameters (less than 0.2 mm). The orthogonal contrast between control and fertilized plants was significant (ψ^1), and the contrast between 22.4 and $44.8 \text{ kg P}_2\text{O}_5 \text{ ha}^{-1} \text{ yr}^{-1}$ was also significant (ψ^3), while the comparison between the lower/medium rates and the high rate was not significant (ψ^2 , ns).

The absolute generation of new culms was primarily driven by high-intensity P fertilizer applications, as shown in Fig. 4C. The highest number of culms was observed at $89.6 \text{ kg P}_2\text{O}_5 \text{ ha}^{-1} \text{ yr}^{-1}$, while the other treatments were similar to each other. There was a significant difference between the control and fertilized treatments, and between the lower/medium and high P rates, but no significant difference between 22.4 and $44.8 \text{ kg P}_2\text{O}_5 \text{ ha}^{-1} \text{ yr}^{-1}$. There was a stable new culm emergence between 0 , 22.4 , and $44.8 \text{ kg P}_2\text{O}_5 \text{ ha}^{-1} \text{ yr}^{-1}$ (ranging between 2.3 – 2.6 culms) followed by a significant increase to 4.7 culms produced at the highest application rate ($89.6 \text{ kg P}_2\text{O}_5 \text{ ha}^{-1} \text{ yr}^{-1}$).

Tissue P and SPAD

At the end of the 5-month greenhouse period, tissue P concentration increased with P fertilization rate. The control plants had the lowest tissue P concentration (0.10%), and the highest value was recorded at

89.6 kg P₂O₅ ha⁻¹ yr⁻¹ (0.16%) (Table 5). There was a significant difference between control and fertilized plants (ψ^1) and between the low plus medium rates and the high rate (ψ^2), whereas the comparison between 22.4 and 44.8 kg P₂O₅ ha⁻¹ yr⁻¹ was not significant (ψ^3 , ns). The chlorophyll index measured as SPAD, was similar across treatments, ranging from 33.38 in the control to 34.99 at 22.4 kg P₂O₅ ha⁻¹ yr⁻¹. None of the orthogonal contrasts for SPAD were significant, indicating that P rate did not affect this trait under the conditions evaluated.

Table 5		
Leaf tissue phosphorus concentration and SPAD chlorophyll index of one-year-old <i>Dendrocalamus asper</i> under varying phosphorus application rates in trial 2.		
Rates	Tissue P concentration	SPAD
(kg P ₂ O ₅ ha ⁻¹ yr ⁻¹)	(%)	
0	0.10 ± 0.02	33.38 ± 1.04
22.4	0.13 ± 0.02	34.99 ± 1.45
44.8	0.13 ± 0.02	34.41 ± 1.22
89.6	0.16 ± 0.02	34.65 ± 1.33
Contrasts		
Control vs fertilized P	ψ^{1***}	ψ^1 ns
Low + medium P vs high P	ψ^{2**}	ψ^2 ns
22.4 vs 44.8 kg P ₂ O ₅ ha ⁻¹	ψ^3 ns	ψ^3 ns

******,*******, and ns indicate statistically significant correlations at *p* < 0.01,0.001 and nonsignificant respectively. Values represent treatment means ± SE.

Dry matter accumulation in young *D asper* bamboo

Phosphorus fertilization increased dry-matter accumulation, although responses differed among plant components (Fig. 5). Total dry matter increased from approximately 107 g clump⁻¹ in the control to 190–210 g clump⁻¹ at 44.8 and 89.6 kg P₂O₅ ha⁻¹ yr⁻¹; the pooled fertilized treatments were significantly higher than the control (ψ^1), and dry matter at 44.8 kg P₂O₅ ha⁻¹ yr⁻¹ exceeded that at 22.4 kg P₂O₅ ha⁻¹ yr⁻¹ (ψ^3), while the low-plus-medium versus high-P contrast was not significant (Fig. 5A). Leaf dry matter also increased with P application, with fertilized plants producing more leaf dry matter than the control (ψ^1), although neither the low-plus-medium versus high-P contrast nor the 22.4 versus 44.8 kg P₂O₅ ha⁻¹ yr⁻¹ contrast was significant (Fig. 5B). Culm dry matter showed a significant increase between 22.4 and 44.8 kg P₂O₅ ha⁻¹ yr⁻¹ (ψ^3), but the control-versus-fertilized and low-plus-medium

versus high-P contrasts were not significant (Fig. 5C). Rhizome dry matter was numerically greater at the two highest P rates but did not differ significantly among contrasts (Fig. 5D). Root dry matter increased with P fertilization overall (ψ^1) and was greater at 44.8 kg P₂O₅ ha⁻¹ yr⁻¹ than at 22.4 kg P₂O₅ ha⁻¹ yr⁻¹ (ψ^3), whereas the low-plus-medium versus high-P contrast was not significant (Fig. 5E).

Phosphorus use efficiency in young bamboo

The P-use efficiency did not differ significantly among P-fertilized treatments. Nevertheless, a typical trend of reducing efficiency with increasing P rates was observed among all the metrics analyzed (Table 6). ForNER, the range was from 404.76 to 465.81 g g⁻¹ among fertilized plants, compared with 577.78 g g⁻¹ of the control. The highest PE estimate occurred at 44.8 kg P₂O₅ ha⁻¹ yr⁻¹ (435.05 g g⁻¹), followed by 89.6 kg P₂O₅ ha⁻¹ yr⁻¹ (413.31 g g⁻¹) and 22.4 kg P₂O₅ ha⁻¹ yr⁻¹ (274.24 g g⁻¹). Similarly, highest AE occurred at 44.8 kg P₂O₅ ha⁻¹ yr⁻¹ (18.16 g g⁻¹), while ANR was numerically highest at 22.4 kg P₂O₅ ha⁻¹ yr⁻¹ (5.5 %). Nevertheless, neither the low-plus-medium versus high-P contrast nor the comparison between 22.4 and 44.8 kg P₂O₅ ha⁻¹ yr⁻¹ was significant for NER, PE, AE, or ANR.

Table 6
Phosphorus use efficiency of one-year-old *Dendrocalamus asper* subjected to varying phosphorus application rates. Values represent treatment means ± SE.

Rate	Efficiency metrics			
(kg P ₂ O ₅ ha ⁻¹ yr ⁻¹)	NER (g g ⁻¹)	PE (g g ⁻¹)	AE (g g ⁻¹)	ANR (%)
0	577.78 ± 88.89	-	-	-
22.4	404.76 ± 41.24	274.24 ± 51.69	14.50 ± 3.89	5.56 ± 1.39
44.8	465.81 ± 37.10	435.05 ± 51.32	18.16 ± 3.28	4.64 ± 1.11
89.6	448.28 ± 51.72	413.31 ± 60.15	11.61 ± 1.15	3.02 ± 0.76
Contrasts				
Control vs fertilized P	ψ^1 ns	-	-	-
Low + medium P vs high P	ψ^2 ns	ψ^2 ns	ψ^2 ns	ψ^2 ns
22.4 vs 44.8 kg P ₂ O ₅ ha ⁻¹	ψ^3 ns	ψ^3 ns	ψ^3 ns	ψ^3 ns

ns indicates nonsignificant.

-=NA

Estimation of optimal phosphorus fertilization rate using dry matter data from both trials

Total dry matter increased with P rate up to an estimated rate of $31.5 \text{ kg P}_2\text{O}_5 \text{ ha}^{-1} \text{ yr}^{-1}$, after which dry matter reached a plateau (Fig. 6). The linear-plateau model indicated that total dry matter increased by approximately $2.81 \text{ g clump}^{-1}$ for each additional $\text{kg P}_2\text{O}_5 \text{ ha}^{-1} \text{ yr}^{-1}$ below the breakpoint ($31.5 \text{ kg P}_2\text{O}_5 \text{ ha}^{-1} \text{ yr}^{-1}$). At rates above this threshold, predicted total dry matter stabilized at approximately 208 g clump^{-1} . Observed dry matter increased from about 119 g clump^{-1} in the control to 183 g clump^{-1} at $22.4 \text{ kg P}_2\text{O}_5 \text{ ha}^{-1} \text{ yr}^{-1}$, with only small additional increases at 44.8 and $89.6 \text{ kg P}_2\text{O}_5 \text{ ha}^{-1} \text{ yr}^{-1}$.

Discussion

Phosphorus fertilization influenced early bamboo establishment, but responses to increasing P rates were inconsistent and differed between trials. The most consistent structural response was culm production: P addition increased culm number between 22.4 and $44.8 \text{ kg P}_2\text{O}_5 \text{ ha}^{-1} \text{ yr}^{-1}$ relative to the control in trial 1 (ψ^3), while in trial 2 the P fertilization promoted substantially greater culm emergence than the control (ψ^1). This indicates that an adequate P supply supports new culm initiation and clump development during early establishment. Phosphorus is essential for energy transfer, cell division, and meristematic growth, which are particularly important during rapid bamboo shoot and culm development (Shou et al., 2020). Similar responses have been reported in Moso bamboo, where adequate P availability increased tiller bud number and development (Lin et al., 2023), while increased nutrient availability has also been associated with greater shoot or culm production in other bamboo studies (Li et al., 2000; Piouceau et al., 2014a).

Furthermore, the increase in culm production observed in this study agrees with previous bamboo research showing that adequate nutrient supply can enhance culm recruitment. In *D. asper*, Luchese et al., (2021) reported the greatest culm production at $40 \text{ kg P}_2\text{O}_5 \text{ ha}^{-1}$, which is within the effective range observed in this study ($22.4\text{--}44.8 \text{ kg P}_2\text{O}_5 \text{ ha}^{-1} \text{ yr}^{-1}$), although their differences were not significant. Their study was conducted in the field and evaluated mature clumps several years after fertilization, whereas the present study assessed one-year-old plants during short-term greenhouse trials. Similarly, Piouceau et al., (2014a) found that greater nutrient supply increased new culm production in container-grown bamboo, supporting the importance of adequate nutrient availability during clump development.

Unlike in trial 1, the increase in tissue P concentration in trial 2 confirms that the applied P fertilizer altered plant P status. Tissue P was greater in fertilized plants than in the control (ψ^1), and the highest P treatment differed significantly from the combined low and medium rates (ψ^2). Tissue P peaked between 22.4 and $44.8 \text{ kg P}_2\text{O}_5 \text{ ha}^{-1} \text{ yr}^{-1}$; thus, further P addition would not lead to a beneficial tissue P increase in trial 2. This response is because application of P-based fertilizer increases soil available P, which directly drives greater P accumulation in bamboo tissues. Furthermore, in bamboo, P is mobile within the plant and may be preferentially directed toward newly developing tissues, including emerging culms and leaves. This response agrees with previous bamboo research showing that fertilization can increase P concentration in leaves and other aboveground components, reflecting improved nutrient availability and

uptake. In *Dendrocalamus asper* cuttings grown with phosphate fertilization at 80 and 160 kg P₂O₅ ha⁻¹, P concentration in leaves significantly increased compared to the control (Dunaiki et al., 2019). In addition to that, Yang and Zhou (2025) found that P fertilization at 25, 50, and 100 mg kg⁻¹ significantly increased P content in aboveground culms and leaves compared to the control in Moso bamboo.

Phosphorus fertilization significantly affected cumulative culm diameter in both trials ($p < 0.001$), observed when comparing unfertilized and P-fertilized plants (ψ^1) and between 22.4 and 44.8 kg P₂O₅ ha⁻¹ yr⁻¹ (ψ^3), indicating that P supply influenced structural development even though clump height was unaffected (ψ^1) in trial 2, unlike in trial 1. In this study, culm diameter consistently increased with increasing P rate, peaking at 89.6 kg P₂O₅ ha⁻¹ yr⁻¹. However, it seems to be beneficial to apply between 22.4 and 44.8 kg P₂O₅ ha⁻¹ yr⁻¹ for better culm production at a young age than 89.6 kg P₂O₅ ha⁻¹ yr⁻¹, since there is no significant increase in culm diameter comparing these rates. Additionally, the size of the culms was significantly influenced by P supply. This pattern corresponds with the dry matter response, in which it leveled off beyond the estimated optimum P rate, indicating that additional P above an adequate level did not consistently improve bamboo growth.

Dry matter partitioning results highlighted how P availability shapes biomass allocation in young bamboo (Zuo et al., 2023). Phosphorus fertilization also affected dry matter accumulation and partitioning. In trial 1, P affected culm and rhizome dry matter, with more dry matter observed at 22.4 kg P₂O₅ ha⁻¹ yr⁻¹ compared to 44.8 kg P₂O₅ ha⁻¹ yr⁻¹, indicating that P supply influenced bamboo plant dry matter accumulation between aboveground growth and the belowground rhizome systems. In trial 2, P fertilization increased total, leaf, culm, and root dry matter, with the 44.8 kg P₂O₅ ha⁻¹ yr⁻¹ rate producing greater total dry matter than the 22.4 kg P₂O₅ ha⁻¹ yr⁻¹ treatment. These results suggest that P supply promoted both photosynthetic capacity through greater leaf dry matter and structural development through increased culm dry matter (Dunaiki et al., 2019; Piouceau et al., 2014a). These findings are consistent with results from Dunaiki et al., (2019), who found that P significantly affected biomass allocation, with leaf, culm, and total dry matter, and that the highest P rate (320 kg P₂O₅ ha⁻¹) declined dry matter, indicating that increasing P beyond an adequate level did not further enhance growth. Likewise, Oliveira et al., (2008) observed differential allocation of biomass among leaves, culms, and roots of *Bambusa vulgaris* in response to P supply, while Yang and Zhou (2025) reported increased root, stem, and leaf biomass of one-year-old Moso bamboo seedlings with increasing soil P availability.

Most P use efficiency metrics resulted in nonsignificant differences between the P rates except ANR when comparing 22.4 and 44.8 kg P₂O₅ ha⁻¹ yr⁻¹ in trial 1 (ψ^3). Th (NER) was consistently highest in the control group, followed by the other rates. However, AE, PE and ANR generally peaked between 22.4 kg and 44.8 P₂O₅ ha⁻¹ yr⁻¹, although non-significant. is particularly important from a nutrient-management perspective. No studies have reported the findings on indices such as AE, PE and ANR in bamboo studies; nevertheless, the range of NER (515–710 g g⁻¹) found in this study is comparable to ~ 720–1,120 g g⁻¹ discovered by He et al., (2023). It is important to mention that the yield (i.e., dry matter as

used in this study) might be affected by other factors such as nutrients like N, although only P was considered during PUE calculations as a nutrient of interest since basal fertilizer containing N and K was applied in this study. This was emphasized by Shi et al., (2025) in a study where they observed that P use efficiency was improved by ammonium and nitrate available in the soil in Moso bamboo. Additionally, trial variation might be attributed to changes in agronomic management practices deployed between the trials.

The linear-plateau model used in this study provided the overall estimate of the P requirement for dry matter production. Total dry matter increased until an estimated breakpoint of $31.5 \text{ kg P}_2\text{O}_5 \text{ ha}^{-1} \text{ yr}^{-1}$, after which biomass plateaued at approximately 208 g clump^{-1} . Therefore, the biological optimum under these greenhouse conditions appears to lie between the 22.4 and $44.8 \text{ kg P}_2\text{O}_5 \text{ ha}^{-1} \text{ yr}^{-1}$ treatments. Rates above approximately $31.5 \text{ kg P}_2\text{O}_5 \text{ ha}^{-1} \text{ yr}^{-1}$ produced little additional total dry matter, while the lower recovery efficiency at higher P rates suggests reduced fertilizer-use efficiency. However, because the model had a moderate fit ($R^2 = 0.346$), this optimal rate should be treated as a provisional estimate rather than a universal recommendation, and a follow-up trial including rates near $30\text{--}35 \text{ kg P}_2\text{O}_5 \text{ ha}^{-1} \text{ yr}^{-1}$ would help validate the estimated optimum. Oliveira et al., (2008) observed maximum total biomass of greenhouse-grown *Bambusa vulgaris* at 10 kg P ha^{-1} ($\sim 22.9 \text{ kg P}_2\text{O}_5 \text{ ha}^{-1} \text{ yr}^{-1}$). While Dunaïski et al., (2019) reported a maximum total dry matter of older *D. asper* at $80 \text{ kg P}_2\text{O}_5 \text{ ha}^{-1}$, this finding followed a pattern similar to that observed in this study. Using an optimal P rate for fertilizing Florida bamboo is beneficial in both economic and environmental terms, thereby saving fertilizer costs to growers and at the same time sustaining Florida natural resources such as groundwater sources, which would easily be polluted by fertilizer overapplication. These results show that excessive P supply can lower use efficiency by exceeding plant demand, resulting in residual P prone to leaching, as suggested by Li et al., (2022). Such inefficiencies have been highlighted as a key risk for Florida's sandy soils, which are particularly susceptible to P loss to groundwater by Yang et al., (2007) and Kadyampakeni et al., (2014).

Variation in irrigation, seasonal growing conditions, and plant cohorts may have influenced bamboo responses in this trial (Poorter et al., 2012; Petropoulos et al., 2008; Piouceau et al., 2014b). Because these factors varied simultaneously across trials, their individual effects could not be disentangled; therefore, differences between trials should not be attributed solely to year.

Conclusions

The results of this study clearly demonstrated that P fertilization significantly influences the early growth and productivity of *D. asper* bamboo under controlled conditions. Across two trials, P fertilization influenced the early growth, culm production, and biomass accumulation of young *D. asper*, although responses varied among traits and between trials. Low to moderate P rates generally supported productive growth without consistent additional benefits at the highest application rate. Based on the combined total dry matter response, the linear-plateau model estimated $31.5 \text{ kg P}_2\text{O}_5 \text{ ha}^{-1} \text{ yr}^{-1}$ as the optimum P fertilization rate under the greenhouse conditions evaluated. Therefore, $31.5 \text{ kg P}_2\text{O}_5 \text{ ha}^{-1}$

yr⁻¹ represents a provisional rate for young *D. asper* production under these conditions. While this study provides an important first step toward evidence-based P management guidelines for bamboo in Florida sandy soils, further research should extend these findings through multi-year field trials, integration with N and irrigation management, and long-term monitoring of soil P dynamics and potential environmental impacts. This will be vital for establishing robust best management practices (BMPs) that optimize productivity while safeguarding the environment.

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Figures

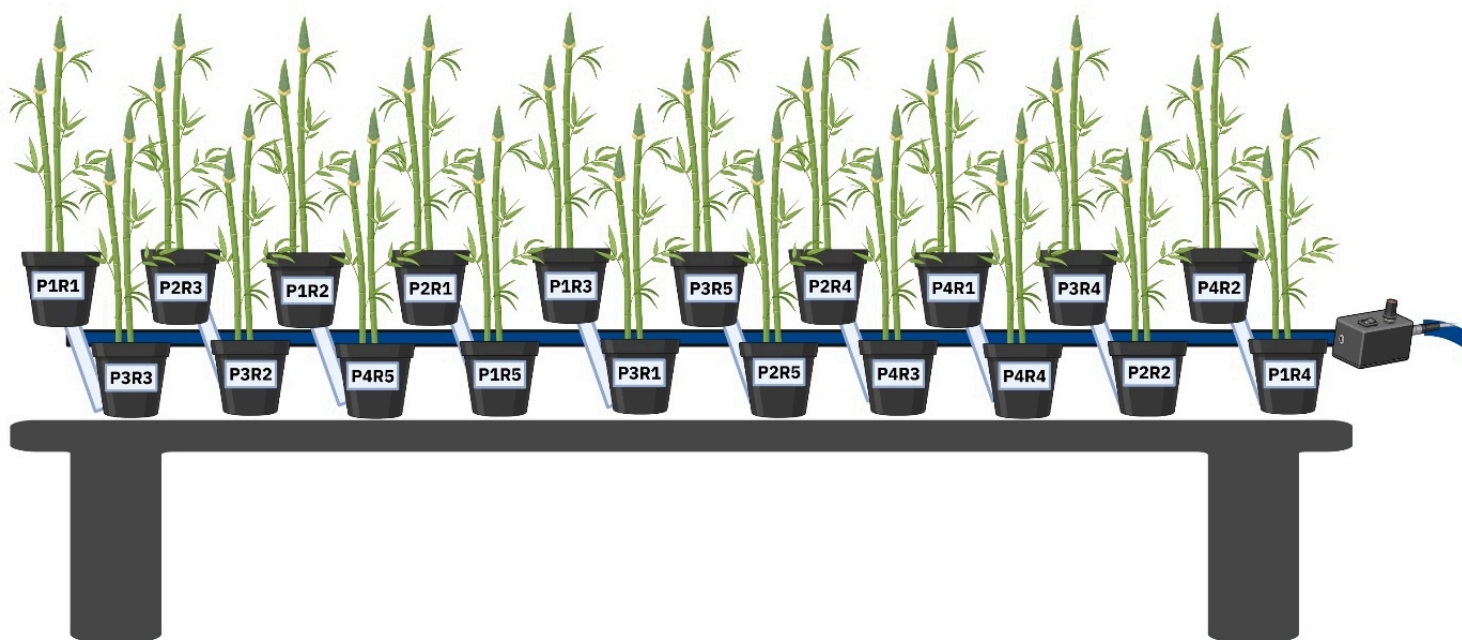


Figure 1

Layout of the experiment in the greenhouse.

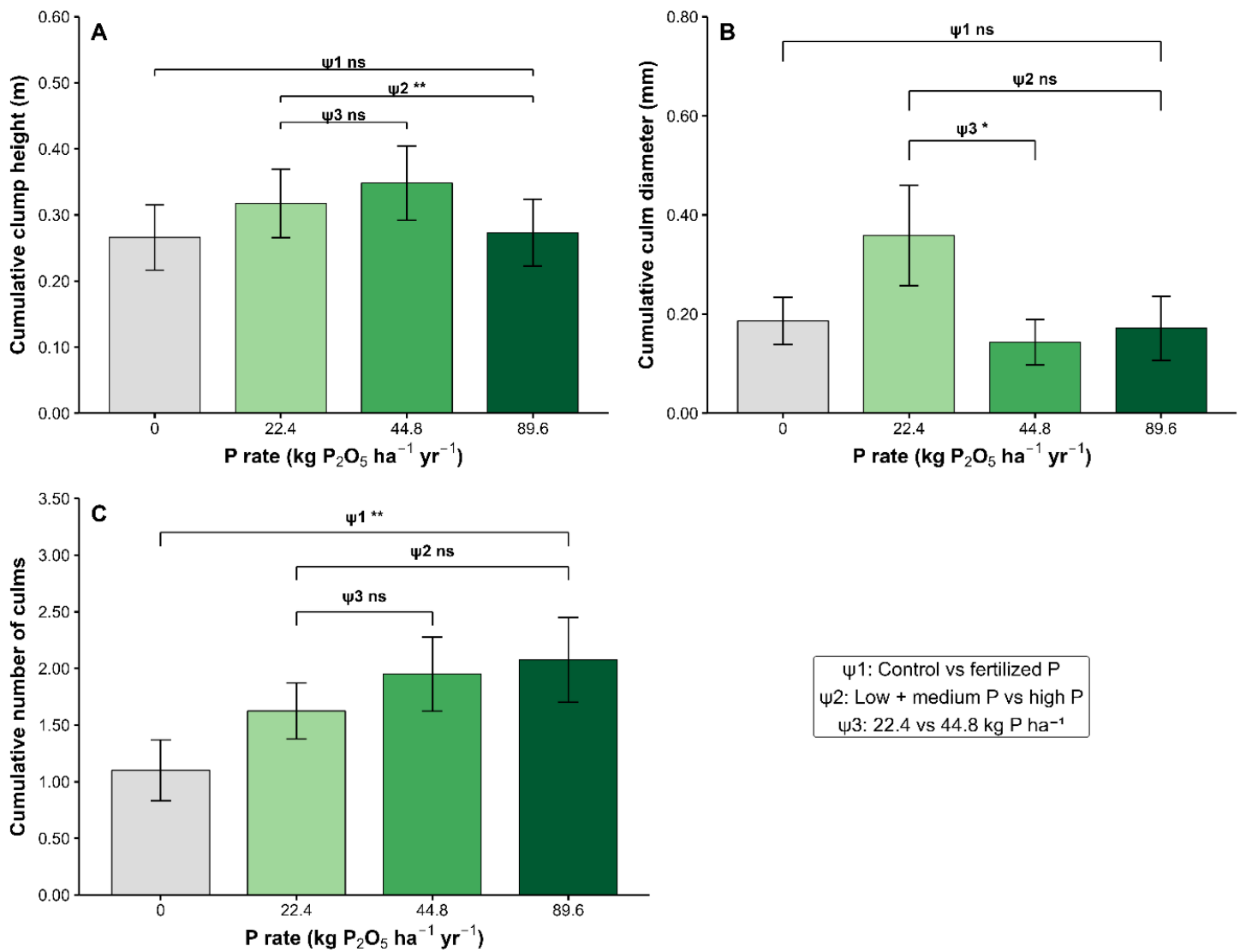


Figure 2

Cumulative growth responses of one-year-old *Dendrocalamus asper* bamboo under varying phosphorus application rates (0, 22.4, 44.8, and 89.6 kg P₂O₅ ha⁻¹ yr⁻¹): **(A)** cumulative clump height, **(B)** cumulative culm diameter, and **(C)** cumulative number of culms. Vertical bars represent mean values ($\pm$) standard error (SE). *, **, and ns indicate statistically significant correlations at $p < 0.05, 0.01$, and nonsignificant respectively.

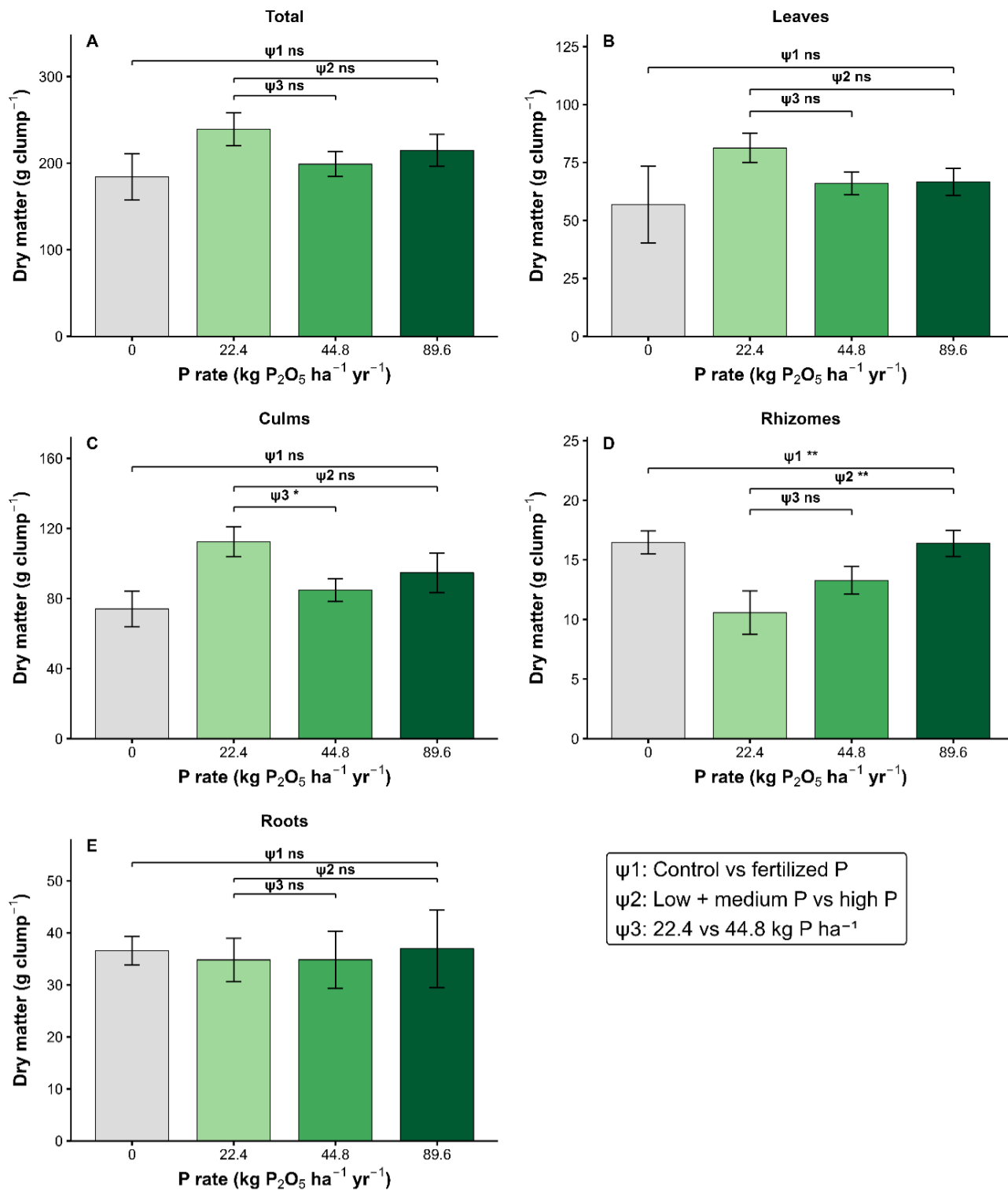


Figure 3

Dry matter accumulation and partitioning of one-year-old *Dendrocalamus asper* under varying phosphorus application rates: (A) total dry matter, (B) leaf dry matter, (C) culm dry matter, (D) rhizome dry matter, and (E) root dry matter. Vertical bars represent mean values ($\pm$) standard error (SE). *, **, and ns indicate statistically significant correlations at $p < 0.05, 0.01$, and nonsignificant respectively.

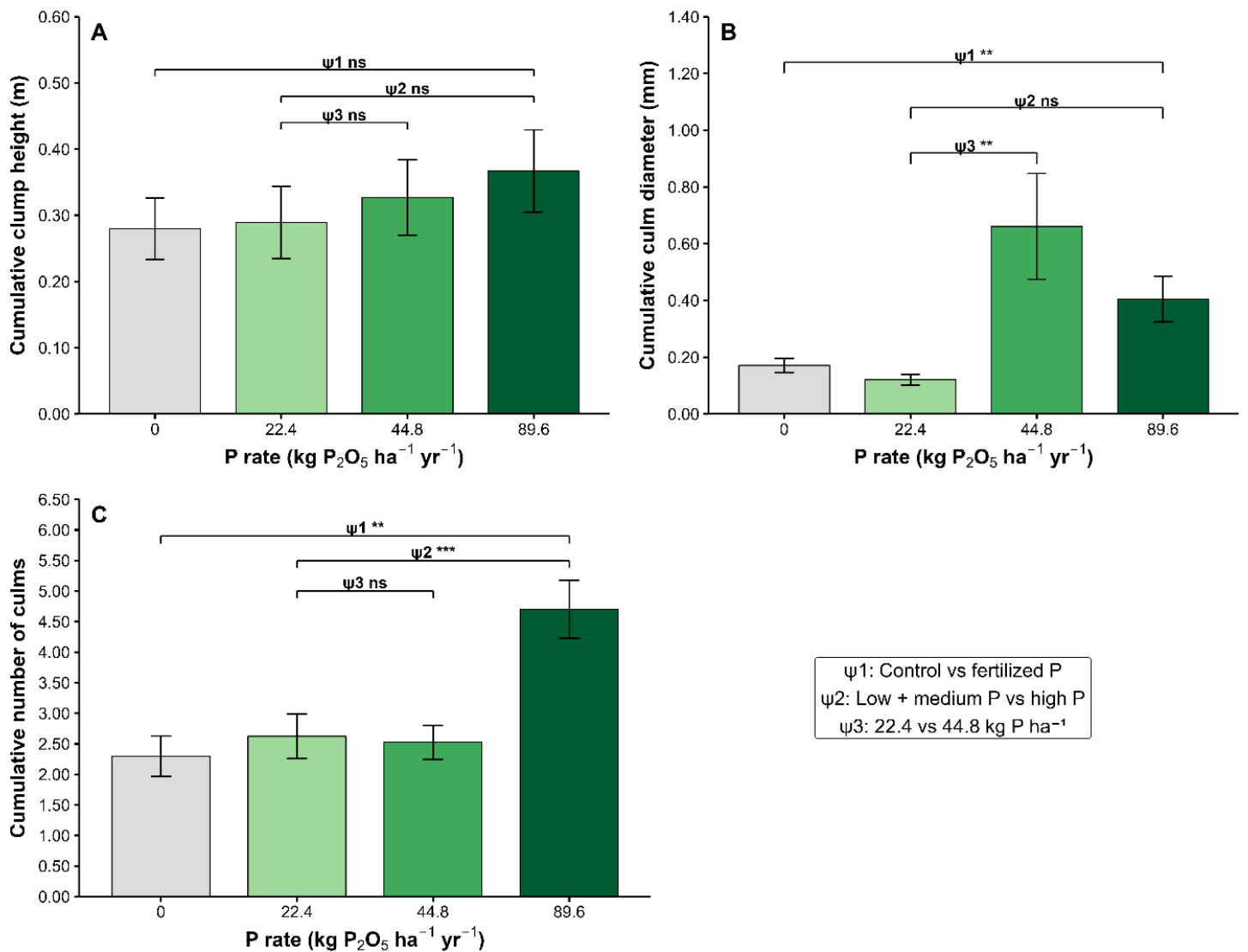


Figure 4

Cumulative structural growth performance of one-year-old *Dendrocalamus asper* under varying phosphorus application rates in trial 2: **(A)** cumulative clump height, **(B)** cumulative culm diameter, and **(C)** cumulative number of culms. Vertical bars represent treatment means $\pm$ SE. **,***, and ns indicate statistically significant correlations at $p < 0.01$, 0.001 and nonsignificant respectively.

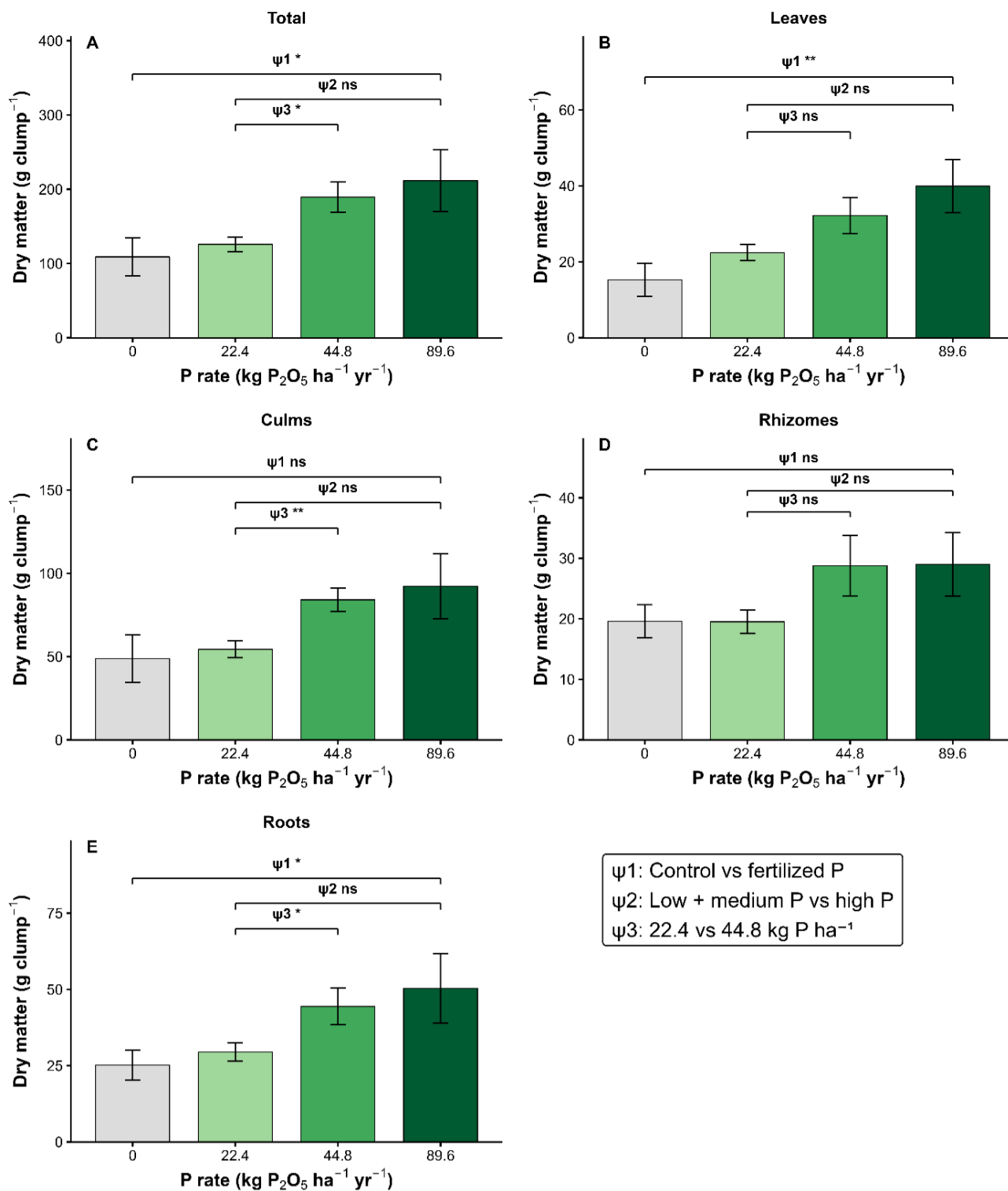


Figure 5

Dry matter accumulation and partitioning of one-year-old *Dendrocalamus asper* under varying phosphorus application rates in trial 2: (A) total dry matter, (B) leaf dry matter, (C) culm dry matter, (D) rhizome dry matter, and (E) root dry matter. Vertical bars represent means $\pm$ SE. *, **, and ns indicate statistically significant correlations at $p < 0.05, 0.01$ and nonsignificant respectively.

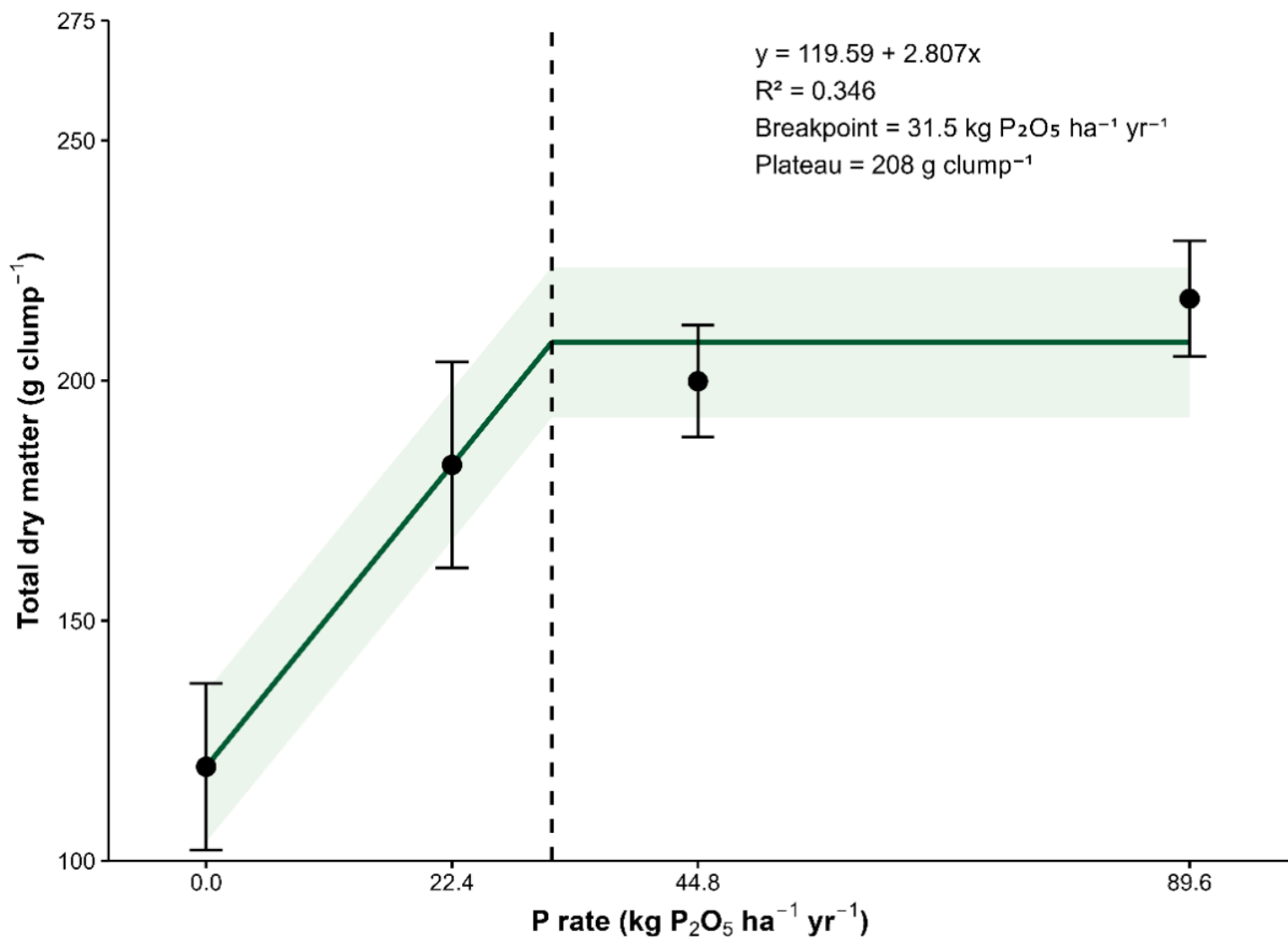


Figure 6

Optimization of P fertilizer rate for bamboo total dry matter using a linear-plateau model. Points show means $\pm$ SE; the dashed line indicates the estimated breakpoint.