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Transplanting date shifts the model-derived P optimum in lowland rice on P-deficient acid soil

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Abstract

Blanket phosphorus (P) recommendations for lowland rice do not account for the effect of transplanting date on attainable yield. A two-year split-plot experiment was conducted on a P-deficient acidic soil in Meghalaya, India, with four transplanting dates (3 July, 13 July, 23 July and 2 August) combined with four P rates (0, 13.1, 26.2 and 39.3 kg P ha^{-1}). Seedling age was maintained at 23 d by staggered nursery sowing. Delaying transplanting from 3 July to 2 August reduced grain yield by 24.8%, biomass by 23.0% and aboveground P uptake by 38.7%. Effective tillers, panicle weight and grain number were also reduced, while harvest index changed little. Grain yield and P uptake increased with P application up to 26.2 kg P ha^{-1} and declined at 39.3 kg P ha^{-1}, while post-harvest available soil P remained high. The transplanting date × P interaction was significant for grain yield, tissue P concentration and P uptake. Fitted quadratic response functions placed the model-derived agronomic optimum at 25.5 kg P ha^{-1} (95% bootstrap confidence interval, CI: 24.7–26.2) for 3 July and 21.8 kg P ha^{-1} (20.5–23.7) for 2 August, a difference of 3.7 kg P ha^{-1} (95% CI: 2.2–4.5). Delayed transplanting therefore lowered attainable yield and aboveground P acquisition and was associated with a modest downward shift in the model-derived P optimum. These site-specific model estimates indicate that establishment timing can modify the yield–P response, but finer P-rate intervals and multi-environment validation are required before date-specific P adjustments can be recommended.

1. Introduction

Phosphorus plays an essential role in root growth, energy transfer, tiller production and reproductive development of rice. In acidic soil, availability of phosphorus is limited, as iron and aluminium oxides sorb phosphate strongly and it gets precipitated into moderate soluble forms (Hinsinger 2001; Vance et al. 2003). In lowland rice, crop response to P-deficiency depends on both inherent soil P supply and ability of root to acquire applied P (Fageria and Baligar 1997; Rakotoson et al. 2022). Northeastern hill region (NEHR) is characterised by humid climate with heavy rainfall, strongly acidic soil and high P-fixation making it difficult for effective P management (Prusty et al. 2022; Kalita et al. 2025). However, application of P fertiliser in NEH region rely largely on blanket recommendation assuming similar crop demand regardless of planting time and establishment conditions (Panwar 2014).

Transplanting time is a major factor determining achievable rice yield, since it regulates temperature, solar radiation and time needed by crop for canopy development, survival of tillers, panicle formation, anthesis and grain filling. Delayed transplanting leads to accumulation of lesser amount of heat unit resulting in lower biomass accumulation, reduced productive tillers and grain yield (Biswas and Salokhe 2001; Baloch et al. 2006; Cao et al. 2022; Ji et al. 2024). Two major abiotic factors, temperature and solar radiation prevailing during panicle initiation to physiological maturity governs dry matter accumulation and grain formation (Deng et al. 2015).As a result, shifting transplanting dates can therefore alter potential yield as well as response of crop to additional fertiliser. Keeping seedling age uniform across dates separates the establishment-date effect from differences caused by nursery duration.

Attainable yield and nutrient responsiveness follows production- ecology theory. According to Production ecology theory, environmental constraints which limits biomass or potential sink size reduce the capacity of crop to convert added nutrients into harvestable yield, lowering the marginal returns to fertiliser ((van Ittersum and Rabbinge 1997). In rice, yield attributing characters such as number of effective tillers, panicle size, no. of grains panicle^{-1} and test weight of grain jointly determine the sink capacity and, in turn, attainable yield ceiling (Yoshida 1981). Deficiency of phosphorus (P) results in restricted root proliferation, early tillering, panicle differentiation and biomass production, while adequate P supply improves formation of sink and overall crop growth (Vance et al. 2003; Rakotoson et al. 2022). As a result, yield benefit from application of phosphorus, therefore, depend on whether the establishment environment allows the crop to realise the additional yield potential that P creates.

Evidence from previous studies involving nitrogen (N) shows that planting date can modify fertilizer responsiveness, resource-use efficiency and the estimated optimum nutrient rate in rice (Hussain et al. 2022, 2023). Comparable evidence for P is more limited. In the central highlands of Madagascar, P response varied among transplanting dates because P-induced changes in phenological development altered crop exposure to late-season cold stress (Andrianary et al. 2021). That study demonstrated the climatic context dependence of P response, but it did not estimate date-specific yield–P functions or agronomic optima. It therefore remains unclear whether delayed transplanting changes the height, curvature and fitted optimum of the yield–P response when seedling age is held constant. Such an interaction may arise not only from variation in soil P availability, but also from reductions in sink formation and biomass production that limit the conversion of added P into grain yield.

We hypothesized that delayed transplanting would reduce effective tillering, panicle development, grain number, biomass production and aboveground P acquisition, thereby lowering attainable grain yield and producing a downward shift in the fitted P optimum. The objectives were to: (i) quantify the effects of transplanting date and P rate on yield components, biomass production and harvest index; (ii) determine whether the grain-yield response to P differed among establishment dates; (iii) quantify grain and stover N, P and K concentration and uptake, post-harvest soil fertility and acid phosphatase activity; (iv) fit date-specific quadratic response functions and estimate site-calibrated agronomic optima; and (v) evaluate the implications of any response-curve modification for blanket and site-specific P recommendations in P-deficient acidic lowland rice systems.

2. Materials and Methods

2.1. Experimental site and soil

The field experiment was conducted during two consecutive rice-growing seasons, 2020–2021 and 2021–2022, hereafter referred to as the 2021 and 2022 harvest years, respectively. The experimental site was the Agronomy Farm of the College of Post Graduate Studies in Agricultural Sciences, Umiam, Meghalaya, India (25°41'54" N, 91°54'43" E; 950 m above sea level), within the humid mid-hill zone of Ri-Bhoi district. Annual rainfall totalled 3255.85 mm in 2021 and 2976.03 mm in 2022. Mean weekly

maximum temperature during the crop period was 23.58 and 23.60°C, and the corresponding minimum temperature was 16.20 and 16.21°C, respectively.

Before crop establishment, composite soil samples were collected from the 0–15 cm layer, air-dried, finely ground and used for initial soil characterization. Soil pH was measured in a 1:2.5 soil:water suspension using a standard pH meter (Piper 1966), and soil organic carbon was determined by the rapid dichromate wet-oxidation method (Walkley and Black 1934). Available N was estimated by alkaline permanganate distillation (Subbiah and Asija 1956): 5 g soil was treated with 25 mL of 0.32% $KMnO_4$ and 25 mL of 2.5% NaOH, and the released NH_3 was collected in 2% boric acid containing mixed indicator and titrated with 0.02 N H_2SO_4. Available P was determined by Bray-1 extraction (Bray and Kurtz 1945) using 5 g soil and 50 mL of 0.03 N NH_4F in 0.025 N HCl; after shaking for 5 min and filtration through Whatman No. 42 paper, colour was developed with Dickman and Bray reagent and $SnCl_2$ and measured at 660 nm. Available K was extracted from 5 g soil with 25 mL neutral 1 N ammonium acetate for 5 min, filtered through Whatman No. 1 paper and measured by flame photometry (Hanway and Heidel 1952). The soil was a sandy clay loam with moderately acidic reaction, high organic carbon, medium available N and K, and low available P (Table 1).

Table 1
Initial soil properties (0–15 cm) at the experimental site.

Property	Unit	Value
Texture	-	Sandy clay loam
pH	-	5.0
Organic carbon	%	2.3
Available nitrogen	kg ha^{-1}	310
Available phosphorus	kg ha^{-1}	16.4
Available potassium	kg ha^{-1}	198.56

2.2. Experimental design and crop management

The experiment was arranged in a split-plot design with three replications. Transplanting date was assigned to main plots and P rate to subplots. Four nurseries were established at 10-d intervals on 10 June, 20 June, 30 June and 10 July. Seedlings were transplanted 23 d after sowing on 3 July (D_1), 13 July (D_2), 23 July (D_3) and 2 August (D_4), respectively. This staggered nursery schedule maintained a constant seedling age across dates and thereby separated the effect of transplanting time from that of nursery age (Fig. 1).

The subplot treatments were 0, 13.1, 26.2 and 39.3 kg P ha^{-1} (P_0–P_3). The 26.2 kg P ha^{-1} treatment represented the prevailing blanket recommendation for transplanted rice in the mid-hill zone of Meghalaya (Panwar 2014). The treatment structure produced 16 transplanting date × P combinations

and 48 experimental units in each year. Twenty-three-day-old seedlings of rice cultivar CAU-R-107 were transplanted at 20 cm × 15 cm spacing. P was applied basally as single superphosphate. Nitrogen was supplied at 80 kg N ha^{-1} as urea in three splits (50% basal, 25% at active tillering and 25% at panicle initiation), while 40 kg K_2O ha^{-1} was applied basally as muriate of potash. All remaining crop-management practices were uniform across treatments.

2.3. Crop measurements and weather data

Grain yield was measured from a 10 m^2 net plot and adjusted to 14% grain moisture. Effective tillers were counted per hill, and panicle weight, panicle length, grains per panicle and 1000-grain weight were recorded from representative harvest samples. Stover yield was converted to a hectare basis. Biological yield was calculated as the sum of grain and stover yield, and harvest index as grain yield divided by biological yield × 100. Daily maximum temperature, minimum temperature and rainfall for the experimental coordinates were obtained from the NASA POWER database (Sparks 2018). Daily growing degree days (GDD) were calculated as [(Tmax + Tmin)/2] − 10, using a base temperature of 10°C (Ambardekar et al. 2015), and cumulative GDD was calculated separately for each sowing date and year.

Phenological development was assessed at active tillering, panicle initiation, flowering, milking and dough stage. The calendar date of each stage was recorded for every experimental unit and converted to days after transplanting (DAT) using the corresponding transplanting date. In parallel, the stage-specific cumulative GDD records were aligned with the daily cumulative GDD series for each sowing date and season to reconstruct and cross-check stage timing. The calendar dates and the thermal-time records were compared and the calculated DAT values averaged over years and replications for treatment comparisons.

The number of cooling-degree days (CDD) was determined around the directly recorded flowering dates from 15 days before to 7 days after flowering as $(22 - T_{mean})$ for days where $T_{mean} < 22°C$ and zero otherwise, as per Andrianary et al. (2021). This association between reproductive stage CDD and 1000-grain weight has been studied at all combinations of the three factors: transplanting date, phosphorus fertilization rate, and year.

Figure 2. Seasonal temperature pattern during the 2021 and 2022 crop seasons. (A) Daily mean temperature; the gray band indicates the envelope between years. (B) Daily maximum and minimum temperature. Vertical dashed lines indicate the four transplanting dates.

2.4. Plant nutrient and post-harvest soil analyses

At harvest, five representative plants were selected from each net plot, oven-dried, separated into grain and stover, finely ground and used for chemical analysis. Total N concentration was determined from 0.5 g of powdered sample after digestion with concentrated H_2SO_4 and a $CuSO_4$–Se–K_2SO_4 catalyst mixture. The digest was subjected to micro-Kjeldahl distillation, the liberated NH_3 was collected in 2% boric acid containing mixed indicator and titrated against standard acid (Piper 1966).

For P and K determination, 1 g of powdered plant material was pre-digested overnight with concentrated HNO_3 and then heated with 5 mL of an HNO_3–$HClO_4$ diacid mixture in a sand bath until a white residue was obtained. After addition of 6 N HCl and complete digestion, the solution was filtered through Whatman No. 42 paper, transferred to a 100-mL volumetric flask and made to volume with double-distilled water; a reagent blank was prepared in parallel. Phosphorus in the digest was determined by the vanadomolybdophosphoric-yellow colour method at 430 nm, and K was measured by flame photometry (Piper 1966). Grain and stover nutrient uptake (kg ha^{-1}) was calculated as nutrient concentration (%) × corresponding oven-dry yield (kg ha^{-1})/100, and total aboveground uptake was the sum of grain and stover uptake.

After harvest, composite soil samples were collected from the 0–15 cm layer of each experimental unit, air-dried and analysed for pH, organic carbon and available N, P and K using the same procedures described for the initial soil. Acid phosphatase (acid phosphomonoesterase) activity was assayed in fresh soil following Tabatabai and Bremner (1969). Fresh soil (1 g) was incubated with 4 mL modified universal buffer at pH 6.5, 0.25 mL toluene and 1 mL p-nitrophenyl phosphate substrate at 37°C for 1 h. The reaction was terminated with 1 mL of 0.5 M $CaCl_2$ and 4 mL of 0.5 M NaOH, and the suspension was filtered. Released p-nitrophenol was quantified at 400 nm using a UV–visible spectrophotometer (Spectrascan 2600, Thermo Scientific, USA) against a p-nitrophenol standard curve and expressed as µg p-nitrophenol g^{-1} dry soil h^{-1}. Plant P concentration and uptake and post-harvest available soil P are presented in the main text; the complete N, P and K concentration and uptake data and post-harvest soil properties are reported in Supplementary Tables S2–S4.

2.5. Statistical and response-function analysis

Each variable was analysed as a split-plot experiment repeated over two years. The model included year, replication nested within year, transplanting date, P rate and their interactions. Transplanting date and its interaction with year were tested against the main-plot error, whereas P, date × P and their interactions with year were tested against the subplot error. Treatment means were compared using the critical difference at $P \leq 0.05$ following a significant F-test. Interactions involving year were non-significant for grain yield and most yield components. Panicle weight showed significant date × year and P × year interactions; pooled means are therefore presented to describe the common treatment ranking while recognising that the magnitude of the response differed between seasons.

For each transplanting date, a quadratic grain-yield response function, $Y = aP^2 + bP + c$, was fitted to the four pooled P-treatment means. The model-derived agronomic optimum was calculated as $Popt = -b/(2a)$, and the predicted yield at the vertex was obtained from the fitted equation. Uncertainty in Popt was quantified using a stratified cluster bootstrap with 100,000 resamples. Within each year, the three replication blocks were resampled with replacement, while all transplanting date × P observations belonging to a selected block were retained together. For every bootstrap sample, treatment means were recalculated, the four date-specific quadratic functions were refitted and Popt was re-estimated. The 95% confidence intervals were defined by the 2.5th and 97.5th percentiles of the bootstrap distributions. A fixed random seed (20260718) was used for reproducibility. Quadratic fertilizer-response models are

appropriate for describing a curvilinear treatment pattern, but estimated optima may vary depending on model form, rate spacing and experimental variability (Cerrato and Blackmer 1990; Hernandez and Mulla 2008). Due to the limited number of means fitted to each function in the present study (3 parameters per function), the vertices were treated as site-specific model-derived estimates rather than independently validated fertilizer recommendations. R^2 was also reported for the four pooled means and for all plot-level observations to distinguish between the visual fit and the variability among observations at each plot level.

3. Results

3.1. Seasonal temperature environment

The two crop seasons showed broadly similar temperature patterns during the main vegetative period, followed by marked cooling from late October onward (Fig. 2). Daily mean temperature generally remained near 20-24 °C from June through September. Thereafter, minimum temperature declined rapidly to approximately 10-14 °C during much of November, while maximum temperature also decreased. Consequently, later-transplanted crops completed a greater proportion of reproductive and grain development under cooler late-season conditions.

Across all treatment combinations, reproductive-stage cooling was negatively associated with 1000-grain weight (Fig. 3). Cooling-degree days accumulated around the directly recorded flowering dates increased sharply from the early to the late transplanting windows, while 1000-grain weight declined ($R^2 = 0.62$, $P < 0.001$). D_4 treatments clustered at the highest cooling loads and lowest grain weights, whereas D_1 treatments occupied the lowest cooling range and highest grain weights. This association indicates that delayed transplanting shifted flowering and early grain filling into a cooler thermal environment, which was consistent with the reduction in grain weight under late establishment.

Direct calendar observations, cross-checked with the corresponding GDD-based reconstruction, were used to describe stage progression (Table 2). Early-stage timing varied little among transplanting dates: active tillering ranged from 36.7 to 37.2 DAT and panicle initiation from 49.3 to 50.3 DAT. Greater divergence appeared at later stages. From D_1 to D_4, flowering shifted from 83.6 to 88.7 DAT, milking from 91.6 to 103.2 DAT and dough stage from 104.5 to 133.3 DAT. Across P rates, stage timing changed only slightly; relative to P_0, P_3 was associated with advances of approximately 0.3 d at panicle initiation, 0.5 d at flowering, 0.5 d at milking and 1.6 d at dough stage. The close agreement between the calendar and thermal-time records supported the use of pooled DAT values for descriptive treatment comparison.

Table 2. Pooled days after transplanting to selected phenological stages based on calendar observations and GDD-supported reconstruction.

Factor	Level	Active tillering	Panicle initiation	Flowering	Milking	Dough
Transplanting date	D_1	36.7	49.3	83.6	91.6	104.5
Transplanting date	D_2	36.7	50.0	84.7	92.3	108.7
Transplanting date	D_3	37.2	50.2	85.2	95.5	118.8
Transplanting date	D_4	37.2	50.3	88.7	103.2	133.3
P rate	P_0	36.9	50.1	85.8	95.9	117.0
P rate	P_1	36.9	50.1	85.7	95.8	116.8
P rate	P_2	36.9	50.0	85.5	95.6	116.2
P rate	P_3	36.9	49.8	85.3	95.4	115.4

Values are pooled means across two years and three replications. Phenological stages were recorded as calendar dates and converted to DAT; the corresponding cumulative GDD records were used to reconstruct and cross-check stage timing.

3.2. Yield components, biomass production and harvest index

Transplanting date significantly affected all measured yield components and biomass traits. Delaying transplanting from 3 July to 2 August reduced effective tillers by 22.3%, panicle weight by 44.5%, panicle length by 15.1%, grains per panicle by 23.8%, 1000-grain weight by 21.3%, stover yield by 21.5% and biological yield by 23.0% (Tables 3 and 4). Harvest index varied only slightly, indicating that delayed transplanting mainly reduced total crop growth and sink formation rather than causing a large shift in dry-matter partitioning to grain.

Phosphorus improved most yield attributes up to 26.2 kg P ha^{-1}. Relative to P_0, P_2 increased effective tillers from 8.97 to 14.16 $hill^{-1}$, panicle weight from 31.66 to 114.33 g $hill^{-1}$, panicle length from 26.55 to 34.45 cm, grains per panicle from 104.7 to 164.4, biological yield from 6.84 to 9.73 t ha^{-1} and harvest index from 39.61 to 45.93%. At 39.3 kg P ha^{-1}, effective tillers, panicle weight, grain number, stover yield, biological yield and harvest index declined relative to P_2, although 1000-grain weight increased slightly.

The transplanting date × P interaction was significant for effective tillers, panicle weight, grains per panicle, stover yield and biological yield, but not for panicle length, 1000-grain weight or harvest index. The interaction response showed that D_1 produced the largest response to P, particularly between 13.1 and 26.2 kg P ha^{-1}, whereas the response became progressively smaller with delayed transplanting (Fig. 4).

Table 3. Main effects of transplanting date and phosphorus rate on yield components, pooled over two years.

Factor	Level	Effective tillers (no. hill^{-1})	Panicle weight (g hill^{-1})	Panicle length (cm)	Grains panicle^{-1}	1000-grain weight (g)
Transplanting date	D_1 (3 July)	14.07	111.60	34.35	164.2	26.08
Transplanting date	D_2 (13 July)	11.80	79.55	31.48	140.0	23.23
Transplanting date	D_3 (23 July)	10.95	62.72	29.52	122.6	21.68
Transplanting date	D_4 (2 August)	10.93	61.89	29.17	125.1	20.53
Phosphorus rate	P_0 (0)	8.97	31.66	26.55	104.7	22.03
Phosphorus rate	P_1 (13.1)	12.24	86.03	31.91	143.5	22.78
Phosphorus rate	P_2 (26.2)	14.16	114.33	34.45	164.4	23.18
Phosphorus rate	P_3 (39.3)	12.39	83.73	31.60	139.4	23.53

For transplanting date, SE(m) = 0.231, 1.241, 0.453, 1.611 and 0.277, respectively; CD (P = 0.05) = 0.712, 3.824, 1.395, 4.962 and 0.855. For P rate, SE(m) = 0.130, 0.784, 0.436, 1.656 and 0.332; CD (P = 0.05) = 0.370, 2.228, 1.240, 4.709 and 0.944. Panicle weight showed significant interactions of date and P with year; other year interactions for these traits were non-significant.

Table 4. Main effects of transplanting date and phosphorus rate on grain yield, stover yield, biological yield and harvest index, pooled over two years.

Factor	Level	Grain yield (t ha⁻¹)	Stover yield (t ha⁻¹)	Biological yield (t ha⁻¹)	Harvest index (%)
Transplanting date	D_1 (3 July)	4.23	5.45	9.68	43.03
Transplanting date	D_2 (13 July)	3.41	4.88	8.28	41.07
Transplanting date	D_3 (23 July)	3.23	4.49	7.72	41.59
Transplanting date	D_4 (2 August)	3.18	4.28	7.46	42.35
Phosphorus rate	P_0 (0)	2.71	4.12	6.84	39.61
Phosphorus rate	P_1 (13.1)	3.46	4.88	8.34	41.53
Phosphorus rate	P_2 (26.2)	4.49	5.25	9.73	45.93
Phosphorus rate	P_3 (39.3)	3.39	4.85	8.24	40.96

For transplanting date, SE(m) = 0.080, 0.079, 0.143 and 0.456, respectively; CD (P = 0.05) = 0.248, 0.243, 0.440 and 1.403. For P rate, SE(m) = 0.054, 0.059, 0.075 and 0.536; CD (P = 0.05) = 0.154, 0.169, 0.213 and 1.524.

3.3. Plant phosphorus concentration, uptake and post-harvest soil phosphorus

Delayed transplanting reduced both tissue P concentration and plant P acquisition (Table 5; Fig. 5). Grain P concentration declined from 0.67% under D_1 to 0.54% under D_4, while stover P concentration declined from 0.32 to 0.27%. The decline in P uptake was larger: grain P uptake decreased from 29.67 to 17.56 kg ha⁻¹ and total aboveground P uptake from 47.66 to 29.23 kg ha⁻¹, a reduction of 38.7%. These changes paralleled the reductions in grain and biological yield under delayed establishment.

Across P rates, grain P concentration increased from 0.44% at P_0 to 0.69% at P_2 and then declined to 0.61% at P_3. Grain P uptake increased from 11.96 kg ha⁻¹ at P_0 to 31.61 kg ha⁻¹ at P_2 but fell to 21.01 kg ha⁻¹ at P_3. Total aboveground P uptake followed the same pattern, increasing from 20.94 to 49.58 kg ha⁻¹ before declining to 35.90 kg ha⁻¹. Transplanting date × P interactions were significant for grain and stover P concentration and uptake, and the largest total P uptake was recorded under D_1P_2 (69.44 kg ha⁻¹).

Post-harvest available soil P increased from 18.75 kg ha⁻¹ at P_0 to 25.53 kg ha⁻¹ at P_2 and averaged 24.81 kg ha⁻¹ at P_3. It also increased from 20.09 kg ha⁻¹ under D_1 to 24.72 kg ha⁻¹ under D_4. The higher residual soil P under later transplanting occurred together with lower aboveground P uptake, indicating that delayed establishment constrained crop acquisition rather than simply exhausting the available soil

P pool. Available soil P showed significant interactions with year; pooled values are therefore used as descriptive treatment summaries.

Post-harvest acid phosphatase activity also varied with establishment date and P supply. It declined from 214.32 µg p-nitrophenol g^{-1} soil h^{-1} under D_1 to 177.93 µg p-nitrophenol g^{-1} soil h^{-1} under D_4. Across P rates, activity increased from 146.50 under P_0 to 224.66 under P_2 and then declined to 196.31 µg p-nitrophenol g^{-1} soil h^{-1} under P_3. Because the transplanting date × P × year interaction was significant, these pooled main effects are presented as descriptive summaries in Supplementary Table S4.

Table 5. Main effects of transplanting date and phosphorus rate on plant P concentration, P uptake and post-harvest available soil P, pooled over two years.

Factor	Level	Available soil P (kg ha^{-1})	Grain P (%)	Stover P (%)	Grain P uptake (kg ha^{-1})	Stover P uptake (kg ha^{-1})	Total aboveground P uptake (kg ha^{-1})
Transplanting date	D_1 (3 July)	20.09	0.67	0.32	29.67	17.99	47.66
Transplanting date	D_2 (13 July)	20.88	0.58	0.29	20.25	14.30	34.55
Transplanting date	D_3 (23 July)	22.86	0.54	0.27	18.01	12.46	30.47
Transplanting date	D_4 (2 August)	24.72	0.54	0.27	17.56	11.68	29.23
Phosphorus rate	P_0 (0)	18.75	0.44	0.22	11.96	8.98	20.94
Phosphorus rate	P_1 (13.1)	19.46	0.60	0.30	20.91	14.58	35.49
Phosphorus rate	P_2 (26.2)	25.53	0.69	0.34	31.61	17.96	49.58
Phosphorus rate	P_3 (39.3)	24.81	0.61	0.30	21.01	14.89	35.90

For transplanting date, SE(m) = 0.254, 0.011, 0.004, 0.711 and 0.304 for available soil P, grain P concentration, stover P concentration, grain P uptake and stover P uptake, respectively. For P rate, the corresponding SE(m) values were 0.239, 0.006, 0.004, 0.372 and 0.280. Total P uptake is the sum of grain and stover P uptake. Main effects and D × P interactions were significant ($P \leq 0.05$) for the plant P variables; available soil P also showed year-dependent interactions.

3.4. Grain-yield response and transplanting date × phosphorus interaction

Year, transplanting date and P rate significantly affected grain yield, and the transplanting date × P interaction was highly significant ($F_{9,48}$ = 12.47, P < 0.001; Table 6). All treatment interactions involving year were non-significant, indicating that the relative grain-yield response was stable across the two seasons.

Pooled grain yield declined from 4.23 t ha^{-1} under D_1 to 3.18 t ha^{-1} under D_4, representing a reduction of 24.8%. Across P rates, yield increased from 2.71 t ha^{-1} at P_0 to 4.49 t ha^{-1} at P_2, but declined to 3.39 t ha^{-1} at P_3. The interaction reflected a much larger P response under early establishment: increasing P from 0 to 26.2 kg P ha^{-1} increased yield by 3.09 t ha^{-1} under D_1, but by only 1.34-1.47 t ha^{-1} under D_2-D_4 (Table 6). The highest pooled yield was recorded under D_1P_2, at 5.91 t ha^{-1}.

Table 6. Split-plot analysis of variance for grain yield pooled over 2021 and 2022.

Source	df	SS	Mean square	F-value	Significance
Year	1	0.8023	0.8023	80.40	S
Year × replication	4	0.0399	0.0100	-	-
Transplanting date (D)	3	17.1525	5.7175	36.86	S
D × Year	3	0.0047	0.0016	0.01	NS
Error a	12	1.8613	0.1551	-	-
Phosphorus (P)	3	38.6164	12.8721	183.52	S
D × P	9	7.8741	0.8749	12.47	S
P × Year	3	0.0241	0.0080	0.11	NS
D × P × Year	9	0.1061	0.0118	0.17	NS
Error b	48	3.3667	0.0701	-	-
Total	95	69.8480	-	-	-

S = significant at P ≤ 0.05; NS = not significant. Year × replication was the error term for year; Error a and Error b were the main-plot and subplot error terms, respectively.

Table 7. Interaction of transplanting date and phosphorus rate on pooled grain yield (t ha^{-1}).

Date	P_0	P_1	P_2	P_3	Mean
D_1 (3 July)	2.82	3.94	5.91	4.24	4.23
D_2 (13 July)	2.81	3.41	4.06	3.36	3.41
D_3 (23 July)	2.60	3.22	4.03	3.08	3.23
D_4 (2 August)	2.62	3.27	3.95	2.87	3.18
Mean	2.71	3.46	4.49	3.39	-

SE(m): date within P = 0.126; P within date = 0.094. Critical difference (P = 0.05): date within P = 0.363; P within date = 0.266.

3.5. Date-specific response functions and model-derived optima

All four date-specific grain-yield response functions were concave, but both the vertical position and response magnitude declined sharply with delayed transplanting (Table 8; Fig. 6). The fitted yield ceiling decreased from 5.24 t ha^{-1} under D_1 to approximately 3.73–3.85 t ha^{-1} under D_2–D_4. The model-derived agronomic optima were 25.5 kg P ha^{-1} for D_1, 24.3 for D_2, 23.4 for D_3 and 21.8 for D_4. Their corresponding 95% bootstrap confidence intervals were 24.7–26.2, 22.8–26.4, 22.4–24.7 and 20.5–23.7 kg P ha^{-1}, respectively. All 100,000 bootstrap fits remained concave and produced vertices within the tested range of 0–39.3 kg P ha^{-1}. The D_1–D_4 difference in Popt was 3.7 kg P ha^{-1}, with a 95% bootstrap CI of 2.2–4.5 kg P ha^{-1}. Although this endpoint contrast excluded zero, the intervals for adjacent transplanting dates overlapped, indicating that the exact stepwise separation among neighbouring dates was less certain.

R^2 values calculated from the four pooled means were consistently higher than those obtained from all plot-level observations, particularly under D_4. This difference indicates that the fitted curves captured the average treatment pattern but did not fully represent plot-level variability. Relative to the blanket recommendation of 26.2 kg P ha^{-1}, the date-specific optima implied reductions of 1.9-4.4 kg P ha^{-1} under D_2-D_4, with predicted yield differences of no more than 0.05 t ha^{-1} (Table 8). These values are model outputs rather than independently validated recommendations.

Table 8. Date-specific quadratic grain-yield response functions, model-derived agronomic optima and bootstrap confidence intervals.

Date	Quadratic function	R^2 (4 means)	R^2 (all observations)	P_{opt} (95% bootstrap CI) (kg P ha^{-1})	Yield at P_{opt} (t ha^{-1})
D_1 (3 July)	$Y = -0.004071P^2 + 0.2076P + 2.593$	0.797	0.724	25.5 (24.7–26.2)	5.24
D_2 (13 July)	$Y = -0.001884P^2 + 0.0914P + 2.742$	0.873	0.763	24.3 (22.8–26.4)	3.85
D_3 (23 July)	$Y = -0.002289P^2 + 0.1070P + 2.501$	0.818	0.720	23.4 (22.4–24.7)	3.75
D_4 (2 August)	$Y = -0.002524P^2 + 0.1102P + 2.527$	0.840	0.657	21.8 (20.5–23.7)	3.73

Bootstrap confidence intervals were obtained by resampling replication blocks within year (100,000 resamples). Values in parentheses are percentile 95% confidence intervals. Popt values are model-derived estimates rather than independently validated fertilizer recommendations.

Figure 6. Date-specific quadratic grain-yield response to phosphorus rate, pooled over 2021 and 2022. Open circles are treatment means, error bars are SE for comparing P levels within a date, dashed lines indicate the point estimate of Popt and filled diamonds indicate the fitted yield at Popt. Bootstrap 95% confidence intervals for Popt are reported in Table 8.

Table 9. Model comparison of the date-specific optimum with the blanket rate of 26.2 kg P ha^{-1}.

Date	Popt (kg P ha^{-1})	Yield at Popt (t ha^{-1})	Yield at 26.2 kg P ha^{-1} (t ha^{-1})	Predicted difference (t ha^{-1})	P below 26.2 kg P ha^{-1} (kg P ha^{-1})
D_1	25.5	5.24	5.24	+0.00	0.7
D_2	24.3	3.85	3.84	+0.01	1.9
D_3	23.4	3.75	3.73	+0.02	2.8
D_4	21.8	3.73	3.68	+0.05	4.4

P rates are expressed as kg P ha^{-1} and yields as t ha^{-1}. Values are calculated from the functions in Table 8 relative to the 26.2 kg P ha^{-1} blanket rate and should not be interpreted as independently validated recommendations.

4. Discussion

4.1. Delayed transplanting reduced sink formation and attainable yield

Delayed transplanting consistently reduced grain yield, and this yield penalty was accompanied by coordinated declines in productive tillers, panicle weight, grains per panicle, 1000-grain weight, stover yield and biological yield. The 44.5% decline in panicle weight was particularly large, while effective

tillers, grains per panicle and 1000-grain weight each declined by approximately 21-24%. These changes show that delayed establishment constrained sink formation and lowered the attainable yield ceiling.

Harvest index remained within a relatively narrow range compared with the large reductions in biological and grain yield. This indicates that delayed transplanting primarily constrained the amount of biomass and sink capacity generated by the crop rather than causing an equivalent failure of biomass partitioning. The result is consistent with production-ecology theory, which predicts that a compressed or less favourable establishment window lowers attainable yield and consequently reduces the crop's capacity to respond to additional inputs (van Ittersum and Rabbinge 1997).

The negative association between reproductive-stage CDD and 1000-grain weight provides further support for this interpretation (Fig. 3). Treatments under D_4 experienced the greatest cold accumulation around flowering and early grain development and consistently showed the lowest grain weights, whereas D_1 treatments combined the lowest CDD values with the highest grain weights. This pattern suggests that delayed transplanting not only reduced sink formation but also exposed flowering and grain filling to a cooler thermal regime that further constrained grain filling.

The calendar observations, supported by the GDD-based reconstruction, showed little separation among transplanting dates at active tillering and panicle initiation but progressively greater divergence at flowering, milking and dough stage (Table 2). This pattern confirms that delayed transplanting altered the calendar duration of later developmental phases and increased crop exposure to cooler late-season conditions.

4.2. Phosphorus response was expressed through tillering, panicle development and biomass production

Phosphorus application improved yield formation mainly through increases in effective tillering, panicle size, grain number and total biomass, with the strongest response observed up to 26.2 kg P ha^{-1}. These responses are physiologically plausible because P supports root growth, early vigour, energy transfer and reproductive development, particularly in acidic soils where P availability is restricted (Prusty et al. 2022; Oo et al. 2023). The higher harvest index at 26.2 kg P ha^{-1} indicates more favourable partitioning of accumulated biomass to grain at that rate.

The decline at P_3 can be interpreted from observed crop traits rather than an unmeasured micronutrient mechanism. Compared with P_2, P_3 produced fewer effective tillers, lighter panicles, fewer grains per panicle, lower stover and biological yield and a lower harvest index. The slight increase in 1000-grain weight at P_3 did not compensate for the loss of sink number and size. Thus, the descending limb of the grain-yield response was associated with reduced sink formation and biomass production under the highest tested rate. The physiological cause of that reduction was not measured and should not be described as P toxicity or micronutrient antagonism without additional evidence.

4.3. Plant P acquisition and residual soil P clarify the response pattern

The nutrient data provide direct evidence that delayed transplanting was associated with lower P accumulation in aboveground biomass. Total aboveground P uptake declined by 38.7% from D_1 to D_4, a larger proportional reduction than the decline in grain yield. This pattern shows that the weaker yield response under delayed transplanting was accompanied by reduced crop P acquisition, rather than only by altered biomass partitioning. The decline in grain P uptake reflected the combined effects of lower grain yield and lower grain P concentration under later establishment. Acid phosphatase activity also declined with delayed transplanting and was greatest at P_2, indicating treatment-dependent variation in potential biological P mineralisation; however, the significant transplanting date × P × year interaction means that this response was not uniform across seasons.

The P-rate response further strengthens the interpretation of the yield decline at P_3. Both P concentration and total P uptake increased up to P_2 but declined at P_3, in parallel with reductions in effective tillers, panicle weight, grain number, biological yield and harvest index. Thus, the lower yield at 39.3 kg P ha^{-1} was associated with a broad reduction in crop growth and P acquisition rather than with concentration dilution alone. The experiment still does not identify the physiological cause of this decline, but the observed uptake pattern makes an exclusively soil-supply explanation unlikely.

Residual available soil P was greater under delayed transplanting and at the two highest P rates. The coexistence of higher residual P with lower aboveground P uptake under D_4 indicates that later establishment reduced crop demand or acquisition capacity despite the persistence of extractable soil P. This supports the production-ecology interpretation of the response-curve shift: the later crop had less capacity to convert available P into biomass and grain. Because residual soil P showed year-dependent interactions, the pooled means should be interpreted as evidence of a general treatment pattern rather than as a complete soil P balance.

4.4. Why the fitted optimum declined with transplanting delay

The fitted optimum declined modestly as transplanting was delayed because the response curve changed in both height and amplitude. Under D_1, the crop produced more tillers, larger panicles, more grains and greater biomass, and therefore converted additional P into a much larger yield gain. Under D_2–D_4, the lower attainable yield and smaller sink restricted the return to added P, causing the fitted vertex to shift leftward. The bootstrap analysis supported a difference between the two endpoint dates: the estimated D_1–D_4 decline was 3.7 kg P ha^{-1} and its 95% confidence interval did not include zero. However, the overlapping intervals for adjacent transplanting dates show that the smooth monotonic sequence of point estimates should not be interpreted as four precisely separated optimum rates.

This interpretation is more defensible than treating the optimum as a fixed soil property. The soil and cultivar were common to all treatments; what changed was the establishment window and the crop's capacity to use the applied nutrient. Similar context dependence may occur where transplanting delay or other stresses reduce attainable yield. Nevertheless, the estimated reduction from 26.2 kg P ha^{-1} was small relative to the 13.1-kg P ha^{-1} spacing between the tested rates. Intermediate treatments around 19.6-28.4 kg P ha^{-1} are therefore required before a date-specific adjustment can be recommended.

4.5. Implications for phosphorus recommendations

These results indicate that a fixed P recommendation may not fully capture changes in crop responsiveness across transplanting windows. Although the soil and cultivar remained unchanged, the model-derived agronomic optimum declined from 25.5 to 21.8 kg P ha^{-1} as transplanting was delayed, reflecting differences in attainable yield and crop responsiveness. The practical adjustment was modest, however, and requires validation using finer P-rate intervals. Establishment timing may therefore merit consideration when developing locally calibrated nutrient-management strategies, rather than being treated as evidence for four distinct operational P recommendations.

The predicted yield differences between the fitted optima and the blanket rate were very small, so the present results do not justify an immediate change in fertilizer recommendation. Instead, they provide evidence that crop establishment modifies the shape and amplitude of the yield-P response and should be considered when developing locally calibrated nutrient-management strategies.

4.6. Limitations and future validation

The experiment was conducted at one location with one cultivar over two seasons. Each response curve was fitted to only four pooled P means, and the 13.1-kg P ha^{-1} spacing between tested rates was wider than the approximately 1.9–4.4 kg P ha^{-1} reduction in the fitted optimum relative to the 26.2 kg P ha^{-1} blanket rate under D_2–D_4. The bootstrap confidence intervals quantify sampling uncertainty arising from the experimental blocks, but they do not account for uncertainty caused by the choice of quadratic model or the coarse spacing of P rates. The lower R^2 values based on all plot observations, particularly under D_4, confirm that the smooth quadratic functions should not be overinterpreted as exact recommendations. Panicle weight also showed significant interactions with year, indicating that some response magnitudes varied between seasons. Future validation should include intermediate P rates around 19.6–28.4 kg P ha^{-1}, additional locations and cultivars, direct root measurements and more detailed soil P fractionation.

The study quantified grain and stover nutrient concentration and uptake, post-harvest available soil nutrients and acid phosphatase activity, but it did not measure root traits, soil P fractions, seasonal redox dynamics, whole-season P recovery or tissue micronutrients. Consequently, the data demonstrate that delayed transplanting reduced aboveground P acquisition and left more residual available P, but they do not fully resolve the physiological or soil-chemical mechanisms responsible for the decline at 39.3 kg P ha^{-1}. Future experiments should combine finer P-rate intervals with root measurements, sequential soil P fractionation, in-season P uptake, micronutrient analysis and multi-location validation. Economic optima should also be calculated using documented local grain and fertilizer prices for the relevant season.

5. Conclusion

Maintaining a uniform seedling age demonstrated that transplanting date strongly modified the P response of lowland rice. Delaying transplanting from 3 July to 2 August reduced grain yield by 24.8%

through coordinated reductions in effective tillers, panicle size, grain number, individual grain weight and total biomass. Total aboveground P uptake declined by 38.7%, while post-harvest available soil P increased, showing that later establishment was associated with lower crop P acquisition despite greater residual extractable P. P application improved sink formation, biomass production and P uptake up to 26.2 kg P ha^{-1}, whereas the decline at 39.3 kg P ha^{-1} was accompanied by lower P uptake, fewer tillers, lighter panicles, fewer grains, lower biological yield and a lower harvest index. The lower attainable yield and reduced P acquisition under delayed establishment weakened the response to P and produced a downward trend in the model-derived agronomic optimum, from 25.5 kg P ha^{-1} (95% bootstrap CI: 24.7–26.2) to 21.8 kg P ha^{-1} (20.5–23.7), with an endpoint difference of 3.7 kg P ha^{-1} (95% CI: 2.2–4.5). These model-derived vertices provide site-specific evidence that establishment timing can modify the yield–P response, but they should not be interpreted as operational fertilizer recommendations. Validation with finer P-rate increments, additional cultivars and multiple environments is required before date-specific P adjustments can be recommended.

Abbreviations

GDD, growing degree days; DAT, days after transplanting; CDD, cooling-degree days; ANOVA, analysis of variance; CD, critical difference; SEm, standard error of a mean; N, nitrogen; P, phosphorus; K, potassium; NEHR, Northeastern hill region

Declarations

Data Availability

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

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Competing interests

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Author contributions

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Figures

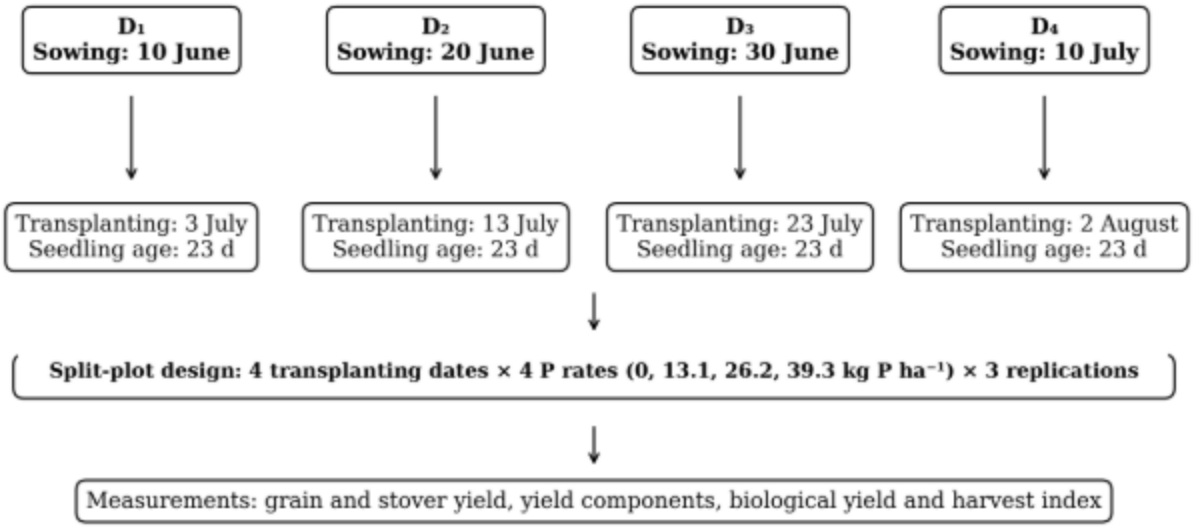


Figure 1

Staggered nursery establishment and treatment structure used to maintain a uniform seedling age across transplanting dates.

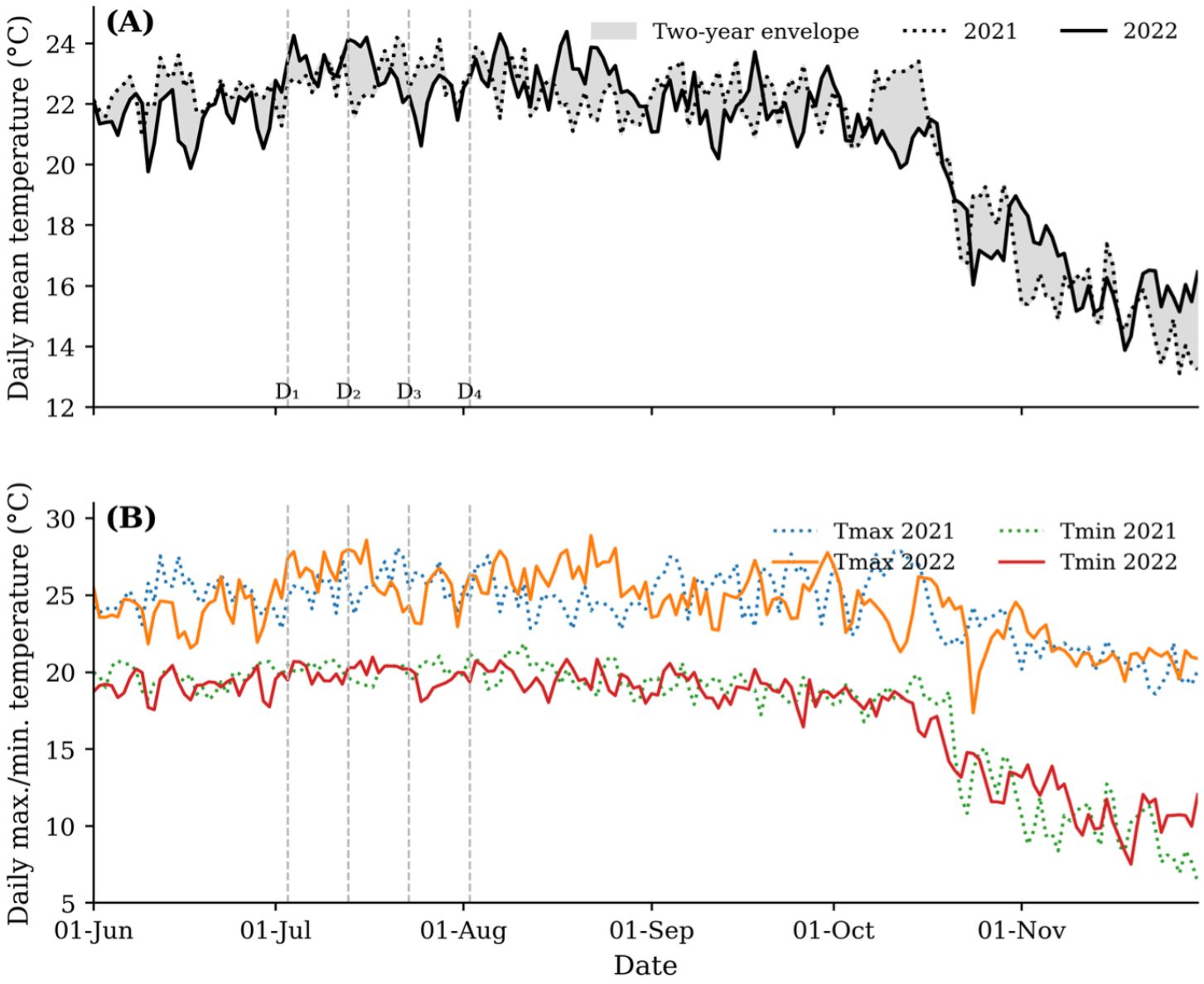


Figure 2

Seasonal temperature pattern during the 2021 and 2022 crop seasons. (A) Daily mean temperature; the gray band indicates the envelope between years. (B) Daily maximum and minimum temperature. Vertical dashed lines indicate the four transplanting dates.

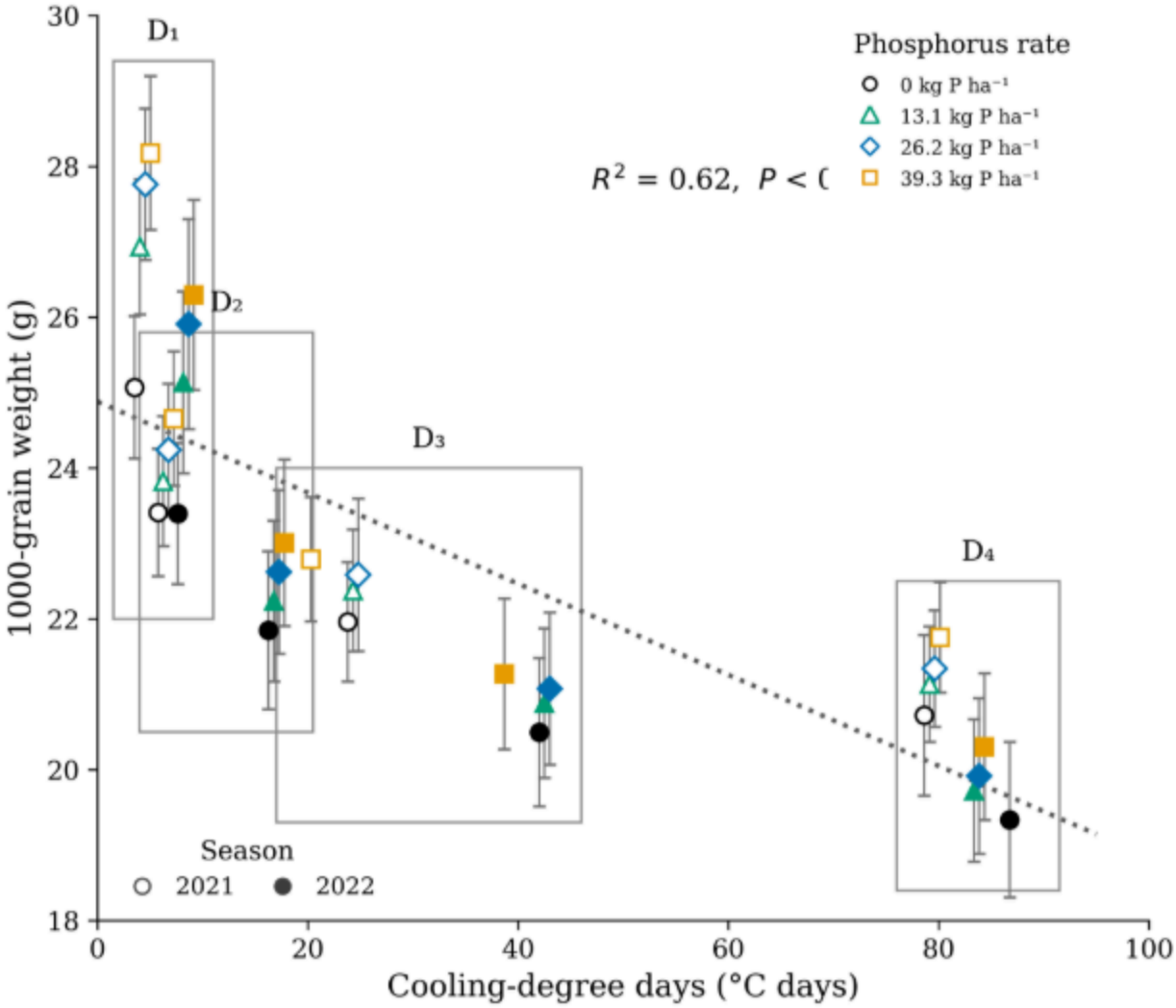


Figure 3

Relationship between cooling-degree days accumulated from 15 d before to 7 d after the directly recorded flowering date and 1000-grain weight under four transplanting dates and four phosphorus rates during 2021 and 2022. Cooling-degree days were calculated as $\Sigma(22 - T_{mean})$ for days with mean temperature below 22 °C and zero otherwise. Symbols represent treatment means and error bars indicate SE (n = 3); open symbols denote 2021 and filled symbols denote 2022. The dotted line shows the pooled linear regression.

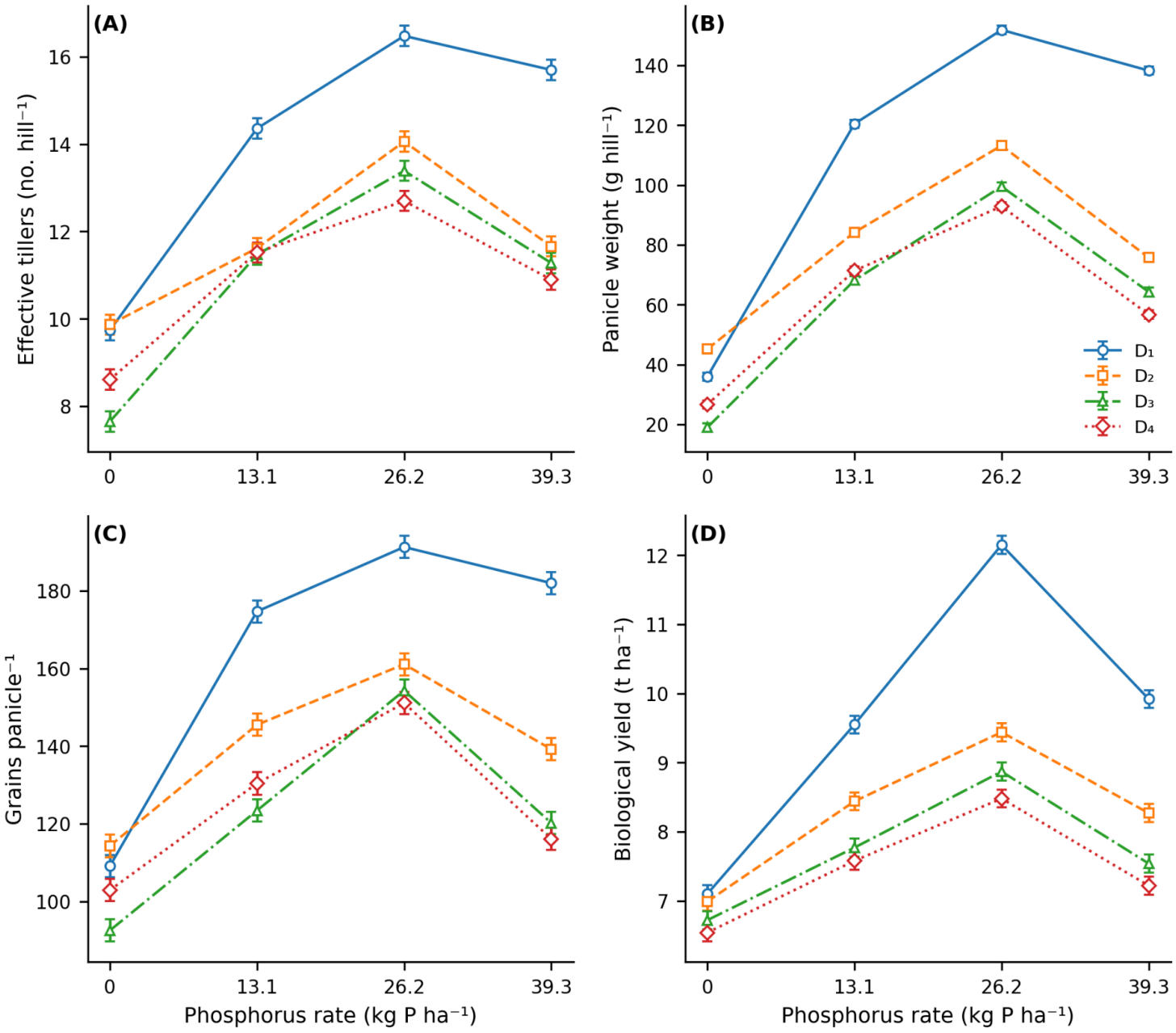


Figure 4

Pooled interaction effects of transplanting date and phosphorus rate on (A) effective tillers, (B) panicle weight, (C) grains per panicle and (D) biological yield. Error bars are SE for comparing P levels within a transplanting date.

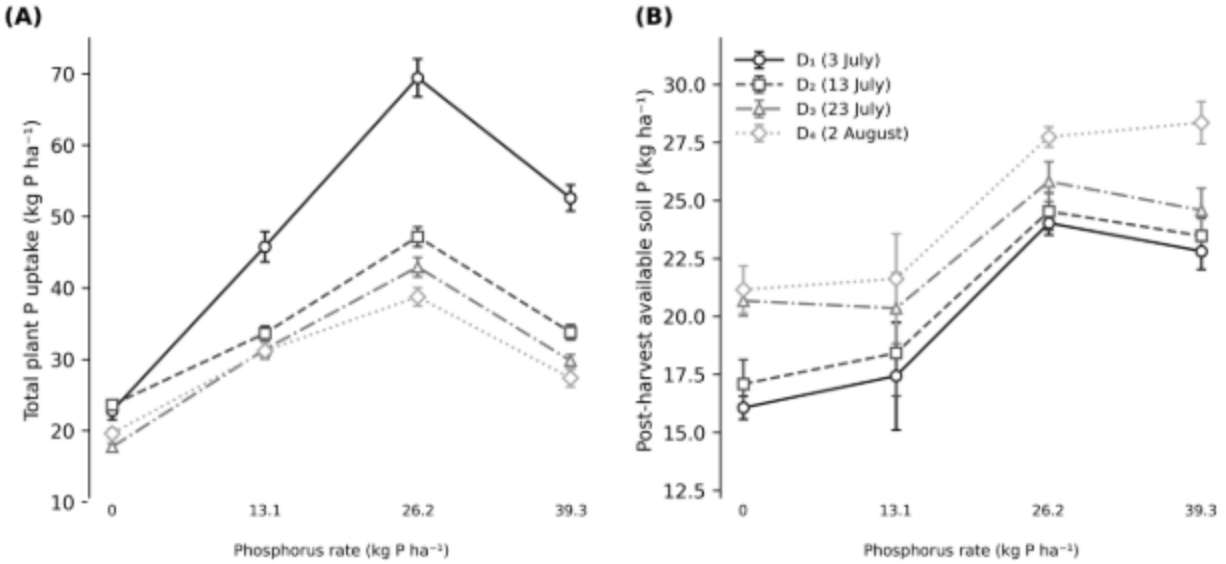


Figure 5

Response of (A) total aboveground P uptake and (B) post-harvest available soil P to phosphorus rate under four transplanting dates, pooled over 2021 and 2022. Points are treatment means and error bars are SE across six observations.

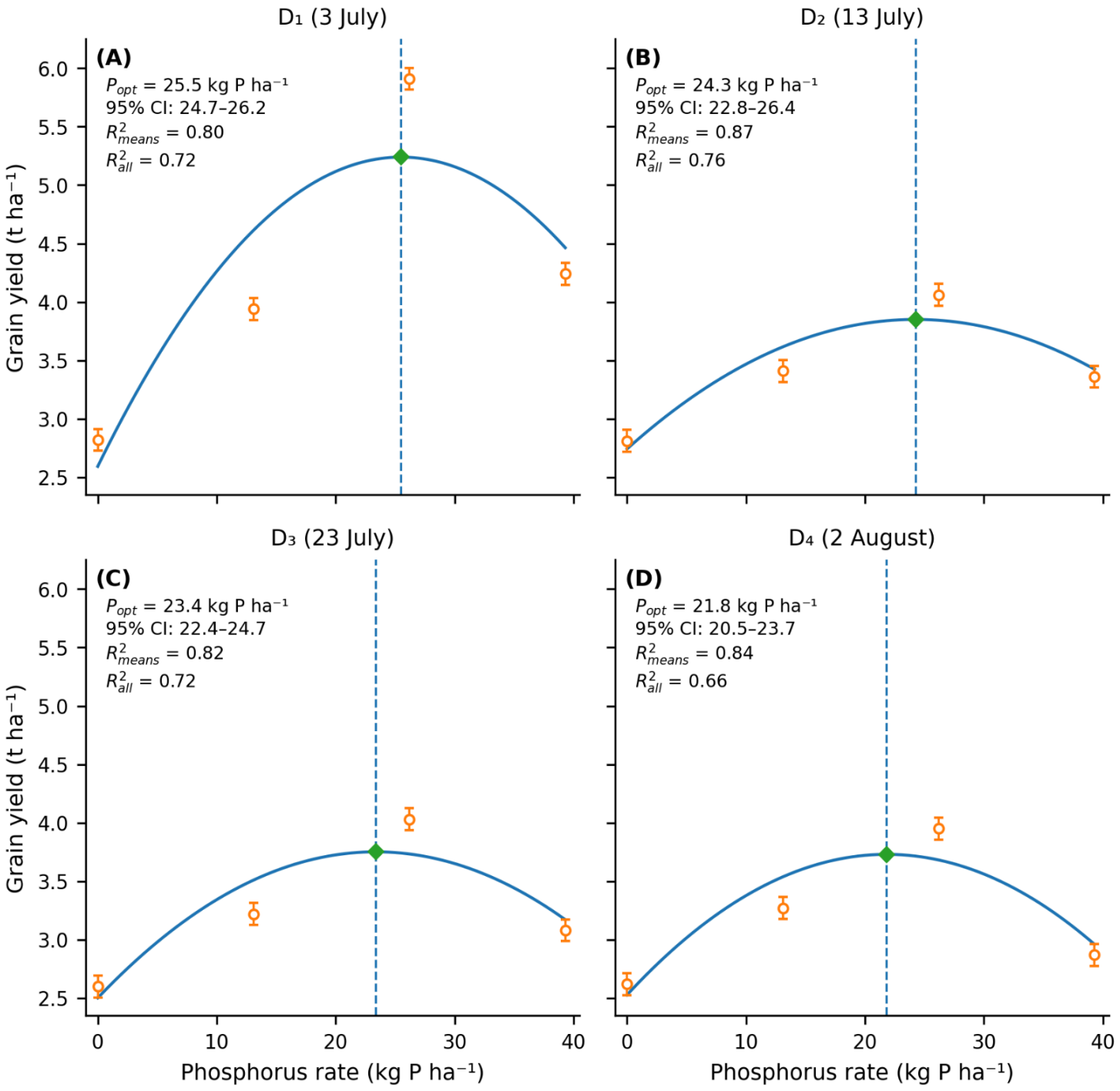


Figure 6

Date-specific quadratic grain-yield response to phosphorus rate, pooled over 2021 and 2022. Open circles are treatment means, error bars are SE for comparing P levels within a date, dashed lines indicate the point estimate of Popt and filled diamonds indicate the fitted yield at Popt. Bootstrap 95% confidence intervals for Popt are reported in Table 8.