Supplementary Materials

Table S1. Seasonal nutrient inputs by source and cumulative P_2O_5 and K_2O inputs over O1–O3 in the rice–rapeseed rotation

Part A. Seasonal N, P_2O_5, and K_2O inputs by source (kg ha^{-1})

Rapeseed 2021–2022 (O1)

Treatment	Product rates[1]	Manure-derived[2]	Mineral-derived[2]	Total[2] (see note)	Table 2 total[2]
CK	0/0/0/0	0.000/0.000/0.000	0.000/0.000/0.000	0.000/0.000/0.000	0/0/0
CF	Not recalculated	0.000/0.000/0.000	174.000/68.000/68.000	174.000/68.000/68.000	174/68/68
OF	0/378/438/191	0.000/0.000/0.000	173.880/52.560/114.600	173.880/52.560/114.600	174/53/115
T1	4336/321/293/159	26.016/17.344/19.078	147.660/35.160/95.400	173.676/52.504/114.478	174/52/115
T2	8671/265/147/128	52.026/34.684/38.152	121.900/17.640/76.800	173.926/52.324/114.952	174/52/115
T3	14674/189/0/85	88.044/58.696/64.566	86.940/0.000/51.000	174.984/58.696/115.566	174/59/115
M1	4336/321/438/191	26.016/17.344/19.078	147.660/52.560/114.600	173.676/69.904/133.678	174/70/134
M2	8671/265/438/191	52.026/34.684/38.152	121.900/52.560/114.600	173.926/87.244/152.752	174/87/153
M3	14674/189/438/191	88.044/58.696/64.566	86.940/52.560/114.600	174.984/111.256/179.166	174/111/179

Rice 2022 (O2)

Treatment	Product rates[1]	Manure-derived[2]	Mineral-derived[2]	Total[2] (see note)	Table 2 total[2]
CK	0/0/0/0	0.000/0.000/0.000	0.000/0.000/0.000	0.000/0.000/0.000	0/0/0
CF	Not recalculated	0.000/0.000/0.000	210.000/68.000/68.000	210.000/68.000/68.000	210/68/68
OF	0/456/500/149	0.000/0.000/0.000	209.760/60.000/89.400	209.760/60.000/89.400	210/60/90
T1	5336/388/322/110	32.016/21.344/23.478	178.480/38.640/66.000	210.496/59.984/89.478	210/60/90
T2	10672/319/143/70	64.032/42.688/46.957	146.740/17.160/42.000	210.772/59.848/88.957	210/60/90
T3	17676/228/0/19	106.056/70.704/77.774	104.880/0.000/11.400	210.936/70.704/89.174	210/71/90
M1	5336/388/500/149	32.016/21.344/23.478	178.480/60.000/89.400	210.496/81.344/112.878	210/81/113
M2	10672/319/500/149	64.032/42.688/46.957	146.740/60.000/89.400	210.772/102.688/136.357	210/103/136
M3	17676/228/500/149	106.056/70.704/77.774	104.880/60.000/89.400	210.936/130.704/167.174	210/131/167

Rapeseed 2022–2023 (O3)

Treatment	Product rates[1]	Manure-derived[2]	Mineral-derived[2]	Total[2] (see note)	Table 2 total[2]
CK	0/0/0/0	0.000/0.000/0.000	0.000/0.000/0.000	0.000/0.000/0.000	0/0/0
CF	Not recalculated	0.000/0.000/0.000	174.000/68.000/68.000	174.000/68.000/68.000	174/68/68
OF	0/378/438/191	0.000/0.000/0.000	173.880/52.560/114.600	173.880/52.560/114.600	174/53/115
T1	4336/321/293/159	26.016/17.344/19.078	147.660/35.160/95.400	173.676/52.504/114.478	174/52/115
T2	8671/265/147/128	52.026/34.684/38.152	121.900/17.640/76.800	173.926/52.324/114.952	174/52/115
T3	14674/189/0/85	88.044/58.696/64.566	86.940/0.000/51.000	174.984/58.696/115.566	174/59/115
M1	4336/321/438/191	26.016/17.344/19.078	147.660/52.560/114.600	173.676/69.904/133.678	174/70/134
M2	8671/265/438/191	52.026/34.684/38.152	121.900/52.560/114.600	173.926/87.244/152.752	174/87/153
M3	14674/189/438/191	88.044/58.696/64.566	86.940/52.560/114.600	174.984/111.256/179.166	174/111/179

[1] Pig manure/urea/SSP/KCl. [2] N/P_2O_5/K_2O. Note: Fertilizer application rates and nutrient inputs are expressed in kg ha^{-1}. Fertilizer products are listed in the order pig manure/urea/single superphosphate (SSP)/potassium chloride (KCl), and nutrient inputs in the order N/P_2O_5/K_2O. The fertilizer schedule used in this experiment was also described for the same rice–rapeseed rotation in Ref. [27]. Pig manure rates are expressed on a fresh-weight basis, with N, P_2O_5, and K_2O contents of 0.60%, 0.40%, and 0.44%, respectively. For OF and T/M, mineral-fertilizer contributions were calculated using 46% N for urea, 12% P_2O_5 for SSP, and 60% K_2O for KCl. Product rates include basal and topdressing applications where applicable. For OF and T/M, total nutrient inputs are the sums of the manure- and mineral-fertilizer-derived contributions before rounding. For CF, which received no pig manure, the nutrient input values follow those reported in main-text Table 2; product-rate conversion was not repeated. The Total column contains calculated values for OF and T/M and transcribed source values for CF; the adjacent column reproduces Table 2. These distinctions should be retained when comparing the two sets of values. For rapeseed-season T1, the calculated P_2O_5 input is 52.504 kg ha^{-1}, compared with 52 kg ha^{-1} in Table 2; this discrepancy is retained and is not attributed to rounding.

Table S1, Part B. Cumulative P_2O_5 and K_2O inputs by source over O1–O3 (kg ha^{-1})

Treatment	Manure-derived P_2O_5	Mineral-derived P_2O_5	Total P_2O_5	Manure-derived K_2O	Mineral-derived K_2O	Total K_2O
CK	0.00	0.00	0.00	0.00	0.00	0.00
CF	0.00	204.00	204.00	0.00	204.00	204.00
OF	0.00	165.12	165.12	0.00	318.60	318.60
T1	56.03	108.96	164.99	61.64	256.80	318.44
T2	112.06	52.44	164.50	123.26	195.60	318.86
T3	188.10	0.00	188.10	206.91	113.40	320.31
M1	56.03	165.12	221.15	61.64	318.60	380.24
M2	112.06	165.12	277.18	123.26	318.60	441.86
M3	188.10	165.12	353.22	206.91	318.60	525.51

Note: Cumulative inputs cover the two rapeseed seasons (2021–2022 and 2022–2023) and the intervening rice season (2022), corresponding to O1–O3. Both rapeseed seasons followed the same fertilizer schedule. For each nutrient source, cumulative input was calculated as twice the rapeseed-season input plus the rice-season input. Total P_2O_5 and K_2O inputs are the sums of the respective manure- and mineral-fertilizer-derived contributions. Cumulative inputs for CF were obtained from the seasonal values reported in main-text Table 2; those for OF and T/M were calculated from the source-specific inputs in Part A. Cumulative values are presented to two decimal places.

Abbreviations: SSP, single superphosphate; KCl, potassium chloride.

Table S2. Fertilizer product application rates by treatment and application stage in the rice–rapeseed rotation (kg ha^{-1}).

Part A. Rapeseed seasons (2021–2022 and 2022–2023)

Treatment	Pig manure (basal)	Urea (basal)	Urea (topdressing)	SSP (basal)	KCl (basal)	KCl (topdressing)
CK	0	0	0	0	0	0
CF	0	228	150	563	115	60
OF	0	228	150	438	131	60
T1	4336	171	150	293	99	60
T2	8671	115	150	147	68	60
T3	14674	39	150	0	25	60
M1	4336	171	150	438	131	60
M2	8671	115	150	438	131	60
M3	14674	39	150	438	131	60

Part B. Rice season (2022)

Treatment	Pig manure (basal)	Urea (basal)	Urea (topdressing)	SSP (basal)	KCl (basal)	KCl (topdressing)
CK	0	0	0	0	0	0
CF	0	304	152	731	146	0
OF	0	304	152	500	89	60
T1	5336	236	152	322	50	60
T2	10672	167	152	143	10	60
T3	17676	76	152	0	0	19
M1	5336	236	152	500	89	60
M2	10672	167	152	500	89	60
M3	17676	76	152	500	89	60

Notes for Parts A and B: Rates are fertilizer product amounts (kg ha^{-1}), not nutrient totals. Pig manure rates are on a fresh-weight basis. The two rapeseed seasons used the same schedule. Single superphosphate (SSP) was applied only as basal fertilizer. In rice, urea topdressing combines tillering and panicle applications; the original records do not separate the two amounts. Conventional fertilization (CF) followed local practice; optimized fertilization (OF) followed the Fertilizer Recommendation Card for Major Crops in Feidong County. KCl = potassium chloride.

Part C. Cumulative differences in fertilizer product and nutrient inputs between paired T and M treatments over O1–O3

Manure N substitution rate (%)	Δ Pig manure	Δ Urea	Δ SSP	Δ KCl	ΔN	ΔP_2O_5	ΔK_2O
15%	0	0	468	103	0	56.16	61.80
30%	0	0	939	205	0	112.68	123.00
50%	0	0	1376	342	0	165.12	205.20

Note: All values represent cumulative differences (M−T) over O1–O3 and are expressed in kg ha^{-1}. Cumulative application rates were calculated as twice the rapeseed-season rate plus the 2022 rice-season rate. Pig manure and urea inputs were identical within each paired T/M treatment. SSP and KCl denote single superphosphate and potassium chloride, respectively. Nutrient differences were calculated using the product nutrient contents specified in Table S1.

Table S3. Fixed-effect tests for seven soil chemical indicators and the soil chemical fertility index (SQI).

Part A. Nine fertilization treatments (27 plots, 81 plot–occasion records).

Note: Each cell reports F, the numerator and Satterthwaite denominator degrees of freedom in parentheses, and P. Each plot was the repeated-measures subject, with one observation at each of O1–O3: 81 records from 27 independent plots. Block was a fixed effect. ARH(1) was used for pH and TP, and AR(1) for the remaining indicators and SQI. No separate plot-level random intercept was fitted. Occasion and Treatment were categorical factors.

Indicator	Occasion	Block	Treatment	Occasion × Treatment
pH	112.093 (2, 20.647) P<0.001	2.270 (2, 21.148) P=0.128	4.055 (8, 13.436) P=0.012	0.750 (16, 20.647) P=0.718
SOM	3210.513 (2, 36.004) P<0.001	0.038 (2, 16.034) P=0.962	155.373 (8, 16.145) P<0.001	88.402 (16, 36.004) P<0.001
TN	24.348 (2, 38.097) P<0.001	1.215 (2, 21.948) P=0.316	72.727 (8, 21.193) P<0.001	3.433 (16, 38.097) P<0.001
TP	65.888 (2, 25.591) P<0.001	4.531 (2, 19.812) P=0.024	32.848 (8, 19.147) P<0.001	1.111 (16, 25.591) P=0.395
TK	1267.459 (2, 36.794) P<0.001	0.063 (2, 19.144) P=0.939	47.345 (8, 18.906) P<0.001	18.058 (16, 36.794) P<0.001
AP	457.990 (2, 36.025) P<0.001	1.216 (2, 16.115) P=0.322	61.415 (8, 16.291) P<0.001	12.236 (16, 36.025) P<0.001
AK	99.751 (2, 35.399) P<0.001	1.443 (2, 15.720) P=0.266	17.300 (8, 15.973) P<0.001	0.507 (16, 35.399) P=0.926
SQI	1727.782 (2, 35.718) P<0.001	0.056 (2, 16.883) P=0.946	127.341 (8, 17.052) P<0.001	19.540 (16, 35.718) P<0.001

Note: Each cell reports F, the numerator and Satterthwaite denominator degrees of freedom in parentheses, and P. Each plot was the repeated-measures subject, with one observation at each of O1–O3: 81 records from 27 independent plots. Block was a fixed effect. ARH(1) was used for pH and TP, and AR(1) for the remaining indicators and SQI. No separate plot-level random intercept was fitted. Occasion and Treatment were categorical factors.

Table S3, Part B. T/M factorial subset (18 plots, 54 plot–occasion records).

B1. Main effects.

Indicator / structure	Occasion	T/M	Rate
SQI AR(1)	1346.273 (2, 24.030) P<0.001	52.165 (1, 11.014) P<0.001	51.398 (2, 11.014) P<0.001
pH ARH(1)	63.009 (2, 14.622) P<0.001	0.489 (1, 8.893) P=0.502	1.576 (2, 8.893) P=0.259
SOM AR(1)	5483.880 (2, 23.820) P<0.001	412.438 (1, 10.058) P<0.001	332.627 (2, 10.058) P<0.001
TP CS	85.331 (2, 24.000) P<0.001	14.722 (1, 10.000) P=0.003	9.707 (2, 10.000) P=0.005
TN AR(1)	28.077 (2, 25.274) P<0.001	6.038 (1, 13.416) P=0.028	28.039 (2, 13.416) P<0.001
TK ARH(1)	1218.952 (2, 15.992) P<0.001	14.770 (1, 11.304) P=0.003	15.147 (2, 11.304) P<0.001
AP AR(1)	315.856 (2, 24.012) P<0.001	31.532 (1, 10.109) P<0.001	13.608 (2, 10.109) P=0.001
AK AR(1)	44.363 (2, 22.905) P<0.001	7.491 (1, 9.685) P=0.022	22.536 (2, 9.685) P<0.001

B2. Interaction effects.

Indicator	Occasion × T/M	Occasion × Rate	T/M × Rate	Occasion × T/M × Rate
SQI	0.044 (2, 24.030) P=0.957	0.251 (4, 24.030) P=0.906	0.110 (2, 11.014) P=0.897	0.368 (4, 24.030) P=0.829
pH	1.489 (2, 14.622) P=0.258	0.375 (4, 14.622) P=0.823	0.476 (2, 8.893) P=0.636	0.732 (4, 14.622) P=0.584
SOM	72.605 (2, 23.820) P<0.001	8.457 (4, 23.820) P<0.001	1.587 (2, 10.058) P=0.252	1.136 (4, 23.820) P=0.363
TP	2.728 (2, 24.000) P=0.086	0.898 (4, 24.000) P=0.480	0.251 (2, 10.000) P=0.782	0.530 (4, 24.000) P=0.715
TN	5.592 (2, 25.274) P=0.010	1.965 (4, 25.274) P=0.131	0.032 (2, 13.416) P=0.969	0.163 (4, 25.274) P=0.955
TK	13.057 (2, 15.992) P<0.001	0.536 (4, 15.992) P=0.712	0.063 (2, 11.304) P=0.939	0.677 (4, 15.992) P=0.618
AP	40.949 (2, 24.012) P<0.001	11.241 (4, 24.012) P<0.001	1.862 (2, 10.109) P=0.205	12.199 (4, 24.012) P<0.001
AK	0.880 (2, 22.905) P=0.428	0.527 (4, 22.905) P=0.717	0.247 (2, 9.685) P=0.786	0.033 (4, 22.905) P=0.998

Note: Each cell reports F, (df_1, df_2), and P; df_2 was approximated using the Satterthwaite method. The 54 records are repeated observations at O1–O3 from 18 independent plots. Block was a fixed effect, and Occasion and Rate were categorical factors. No separate plot-level random intercept was fitted. AR(1), ARH(1), and CS denote first-order autoregressive, heterogeneous first-order autoregressive, and compound symmetry covariance structures, respectively.

Table S4. Descriptive classification of T/M management labels: performance metrics and confusion matrices.

Part A. Performance of the classifiers and the constant baseline.

Evaluation dataset	Model	AUC	CA	F1	MCC	Correct / tested
Internal O1–O3	Logistic regression	0.852	0.796	0.795	0.603	43/54
Internal O1–O3	Linear SVM	0.834	0.704	0.697	0.427	38/54
Internal O1–O3	Random forest	0.829	0.759	0.757	0.528	41/54
O4 (post-rice harvest, 2024)	Logistic regression	0.938	0.833	0.833	0.671	15/18
O4 (post-rice harvest, 2024)	Linear SVM	0.951	0.833	0.833	0.671	15/18
O4 (post-rice harvest, 2024)	Random forest	0.691	0.500	0.458	0.000	9/18
O5 (2024–2025 rapeseed)	Logistic regression	0.654	0.667	0.667	0.333	12/18
O5 (2024–2025 rapeseed)	Linear SVM	0.654	0.611	0.610	0.224	11/18
O5 (2024–2025 rapeseed)	Random forest	0.321	0.444	0.308	−0.243	8/18
O4 + O5 pooled	Logistic regression	0.796	0.750	0.750	0.501	27/36
O4 + O5 pooled	Linear SVM	0.799	0.722	0.722	0.444	26/36
O4 + O5 pooled	Random forest	0.546	0.472	0.393	−0.080	17/36
All datasets	Constant	0.500	0.500	0.333	0.000	See note

Note:Internal evaluation used three-fold cross-validation grouped by block (54 records from 18 plots). O4 and O5 each comprised one later observation from each of the same 18 plots represented in the O1–O3 training data. The pooled dataset contained 36 plot–occasion records from 18 plots, not 36 independent plots. O4 refers to the post-rice-harvest sampling occasion in 2024, and O5 refers to the post-rapeseed-harvest sampling occasion in May 2025. CA = classification accuracy; F1 was weighted by class size. The constant baseline had 50% accuracy in each balanced dataset.

Part B. Confusion matrices and class-specific classification performance.

Evaluation dataset	Model	T→T	T→M	M→T	M→M	Sensitivity	Specificity	Correct
Internal O1–O3	Logistic regression	24	3	8	19	0.704	0.889	43/54
Internal O1–O3	Linear SVM	23	4	12	15	0.556	0.852	38/54
Internal O1–O3	Random forest	23	4	9	18	0.667	0.852	41/54
O4 (2024 rice)	Logistic regression	8	1	2	7	0.778	0.889	15/18
O4 (2024 rice)	Linear SVM	8	1	2	7	0.778	0.889	15/18
O4 (2024 rice)	Random forest	7	2	7	2	0.222	0.778	9/18
O5 (2024–2025 rapeseed)	Logistic regression	6	3	3	6	0.667	0.667	12/18
O5 (2024–2025 rapeseed)	Linear SVM	5	4	3	6	0.667	0.556	11/18
O5 (2024–2025 rapeseed)	Random forest	8	1	9	0	0.000	0.889	8/18
O4 + O5 pooled	Logistic regression	14	4	5	13	0.722	0.778	27/36
O4 + O5 pooled	Linear SVM	13	5	5	13	0.722	0.722	26/36
O4 + O5 pooled	Random forest	15	3	16	2	0.111	0.833	17/36

Note: Confusion matrices were calculated from the observed management labels and model-predicted classes. M (unreduced mineral P/K fertilization) was designated as the positive class, and T (reduced mineral P/K fertilization) as the negative class. T→T and M→M represent correct classifications, whereas T→M and M→T represent misclassifications. Sensitivity was calculated as M→M/(M→M + M→T), and specificity as T→T/(T→T + T→M). Correct indicates the number of correctly classified observations relative to the total number evaluated. Internal validation included 54 observations from 18 plots. O4 and O5 each included 18 observations from the same 18 plots, yielding 36 observations in the pooled evaluation.

Table S5. Temporal repeatability and treatment rankings for the seven soil indicators

Indicator	ICC[1]	Residual ICC[2]	ρ, O1–O3	ρ, six treatments in later seasons	Nominally significant occasions (of 5)
pH	0.407	0.000	0.57–0.92	−0.14–0.89	0
SOM	0.965	0.949	0.98–1.00	0.83–1.00	5
TN	0.859	0.096	0.88–0.98	0.54–1.00	2
TP	0.815	0.130	0.88–0.98	0.77–1.00	3
TK	0.678	0.390	0.73–0.95	0.89–1.00	3
AP	0.982	0.922	1.00	0.71–0.94	3
AK	0.975	0.835	1.00	0.94–1.00	3

Note: [1] Plot-level ICCs for O1–O3 after subtracting Occasion means; [2] residual repeatability after further subtracting Treatment × Occasion means, with negative estimates reported as zero. Both measures were based on 27 plots sampled on three occasions, excluding O4 and O5. ρ denotes the range of Spearman correlations between sampling occasions, calculated from treatment means. Counts of nominally significant sampling occasions were based on the confidence intervals in Table S7, without adjustment for multiple testing, and are reported only as an exploratory summary.

Table S6. Sensitivity analysis of treatment rankings based on SQI

Comparison scenario	Spearman ρ
Pairwise comparisons among the three sampling occasions (O1–O3)	0.983 / 0.983 / 1.000
Entropy weighting vs. equal weighting	0.983–1.000
Global min–max bounds vs. fixed O1 reference bounds	0.967–0.983
Omitting one indicator at a time (LOO)	0.967–1.000
Omitting TK (LOO; O1/O2/O3)	1.000 / 0.983 / 0.967
Rankings at O4 and O5 vs. the training-period reference ranking for the six treatments	1.000 / 0.943

Note: Rows 1–5 use means for the nine treatments at O1–O3. Row 1 compares the original SQI rankings between sampling occasions. Rows 2–5 compare each scoring variant with the original scoring scheme at the same occasion. Row 6 includes only the six T/M treatments at O4 and O5, compared with the reference order shared by O1–O3: T1 < T2 < M1 < T3 < M2 < M3. The mean SQI differences (M−T) at O4 and O5 were 0.114 and 0.094, respectively.

Table S7. Adjusted M−T differences and 95% confidence intervals at each sampling occasion

Indicator	O1	O2	O3	O4	O5
pH	−0.13 [−0.46, 0.20]	+0.17 [−0.05, 0.39]	+0.15 [−0.03, 0.33]	−0.04 [−0.15, 0.06]	+0.16 [−0.10, 0.43]
SOM	+0.97 [+0.85, +1.09]	+0.96 [+0.82, +1.10]	+0.74 [+0.58, +0.89]	+3.76 [+1.99, +5.54]	+2.03 [+1.05, +3.00]
TN	+0.10 [+0.06, +0.13]	+0.00 [−0.06, +0.06]	+0.02 [−0.03, +0.07]	+0.01 [−0.03, +0.06]	+0.13 [+0.08, +0.17]
TP	+0.05 [+0.03, +0.08]	+0.01 [−0.03, +0.04]	+0.04 [+0.02, +0.07]	+0.06 [+0.01, +0.10]	+0.04 [−0.01, +0.08]
TK	−0.02 [−0.29, +0.24]	+0.86 [+0.36, +1.35]	+0.91 [+0.43, +1.39]	+0.36 [+0.10, +0.63]	+0.43 [−0.18, +1.05]
AP	+1.73 [+1.05, +2.42]	+1.77 [+1.08, +2.47]	+1.08 [+0.53, +1.63]	+0.43 [−0.52, +1.38]	+0.11 [−1.19, +1.41]
AK	+5.0 [−0.2, +10.2]	+4.9 [+1.4, +8.5]	+7.0 [+3.3, +10.7]	+3.6 [−3.9, +11.0]	+6.6 [+2.6, +10.7]

Note: An additive model was fitted at each sampling occasion, including Block, Rate as a continuous covariate (15, 30, and 50), and accounting strategy, without interactions. Confidence intervals were not adjusted for multiple testing across seven indicators × five sampling occasions; the results are exploratory. pH is dimensionless; SOM, TN, TP, and TK are expressed in g kg^{-1}, and AP and AK in mg kg^{-1}. This model differs from the full factorial repeated-measures model in Table S3, Part B, in which Rate was treated as a categorical variable. These occasion-specific additive models were used for exploratory comparisons and did not replace the categorical-rate factorial models used for the primary analysis.

Table S8. Tests of fixed effects for rapeseed yield over two seasons.

Part A. Nine fertilization treatments (27 plots, 54 plot–season records).

Fixed effect	df_1	df_2	F statistic	P value
Block	2	16.263	0.792	0.470
Season	1	18.263	5.620	0.029
Treatment	8	18.263	11.883	<0.001
Season × Treatment	8	18.263	1.482	0.231

Part B. T/M factorial subset (18 plots, 36 plot–season records).

Fixed effect	df_1	df_2	F statistic	P value
Block	2	10.119	0.378	0.695
Season	1	12.118	4.222	0.062
Rate	2	12.118	8.604	0.005
P and K accounting strategy	1	12.118	13.119	0.003
Season × Rate	2	12.118	3.416	0.067
Season × P/K	1	12.118	0.284	0.604
P/K × Rate	2	12.118	0.467	0.638
Season × P/K × Rate	2	12.118	1.750	0.215

Note: Both models used a DIAG covariance structure without a separate plot-level random intercept. Season denotes the 2021–2022 and 2022–2023 rapeseed seasons; Rate is a categorical variable with three levels; and P/K denotes the joint P and K accounting strategy (T/M). df_2 denotes the denominator degrees of freedom approximated using the Satterthwaite method. The mean yield across the nine treatments was 2226.6 kg ha^{-1} in 2021–2022 and 2110.4 kg ha^{-1} in 2022–2023 (estimated marginal means).

Part C. Sensitivity of the paired yield contrast to the residual covariance structure.

Structure	M−T (kg ha^{-1})	95% CI (kg ha^{-1})	P	AIC	Residual correlation
DIAG	212.0	84.6–339.5	0.003	274.5	0 (fixed)
UN	212.0	85.2–338.9	0.003	276.5	−0.071

Note: Both models used the same T/M factorial fixed-effects structure and the same 18 plots (36 plot–season records). DIAG permits different residual variances by season and fixes the residual covariance at zero; UN estimates both variances and their covariance. Values are the sensitivity results reported in the main Results section.

Table S9. Two-season mean rapeseed yields and descriptive input and yield differences for OF and the six T/M treatments.

Treatment	Mean yield (kg ha^{-1})	ΔP_2O_5 (kg ha^{-1})	ΔK_2O (kg ha^{-1})	Δyield (kg ha^{-1})	Δyield (%)
OF	2042	—	—	—	—
T1	2082	—	—	—	—
T2	2348	—	—	—	—
T3	2146	—	—	—	—
M1	2227	+17.40	+19.20	+145	+7.0
M2	2555	+34.92	+37.80	+207	+8.8
M3	2430	+52.56	+63.60	+284	+13.2

Note: Input differences are per rapeseed season and were calculated from the product-rate differences in Table S2 and the nutrient contents in Table S1 before rounding. Yield differences are based on the two-season estimated marginal means and rounded to whole kilograms per hectare. Δ denotes M minus its matched T at the same substitution rate; OF has no paired treatment. Dashes indicate not applicable. Model-based rate-specific yield contrasts and confidence intervals are reported in main-text Table 3. Input quantities are not monetary costs.

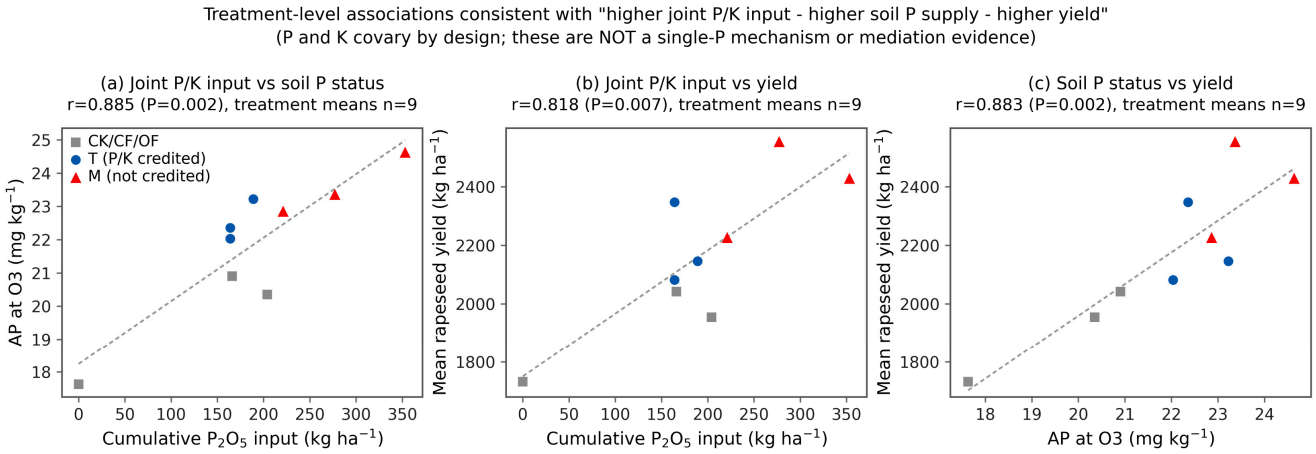

Figure S1. Treatment-mean correlations among cumulative P_2O_5 input, soil AP, and rapeseed yield.

Note: n = 9 treatment means. P input represents cumulative P_2O_5 inputs over the first three crop seasons. P and K inputs covaried with N sources across treatments; these correlations therefore cannot isolate individual nutrient effects and do not establish mediation pathways or validate mechanisms. CF inputs follow the source values in main-text Table 2, whereas OF and T/M inputs were calculated from product rates as described in Table S1.

Table S10. Estimated marginal means and pairwise occasion contrasts for pH, total phosphorus (TP), and total potassium (TK) in the nine-treatment model

Part A. pH

Estimated marginal means

Occasion	EMM	SE	df	95% CI
O1	7.986	0.070	12.611	7.835–8.137
O2	7.008	0.036	17.361	6.932–7.084
O3	7.057	0.030	19.640	6.995–7.119

Pairwise occasion comparisons

Contrast	Mean difference (I−J)	SE	df	Sidak P	95% CI
O1−O2	0.979	0.065	19.890	<0.001	0.808–1.149
O1−O3	0.930	0.072	19.958	<0.001	0.742–1.117
O2−O3	−0.049	0.037	20.268	0.490	−0.145–0.047

Part B. Total phosphorus (TP)

Estimated marginal means

Occasion	EMM (g kg^{-1})	SE	df	95% CI
O1	0.505	0.010	17.077	0.484–0.525
O2	0.595	0.006	17.267	0.582–0.609
O3	0.628	0.005	17.323	0.618–0.639

Pairwise occasion comparisons

Contrast	Mean difference (I−J)	SE	df	Sidak P	95% CI
O1−O2	−0.091	0.011	23.699	<0.001	−0.118–−0.063
O1−O3	−0.124	0.011	26.723	<0.001	−0.151–−0.096
O2−O3	−0.033	0.008	23.720	<0.001	−0.052–−0.014

Part C. Total potassium (TK)

Pairwise occasion comparisons within each fertilization treatment

Treatment	Contrast	EMM at I	EMM at J	Mean difference (I−J)	SE	df	Sidak P	95% CI
CK	O1−O2	11.033	11.833	−0.800	0.226	36.757	0.003	−1.365 to −0.235
CK	O1−O3	11.033	11.500	−0.467	0.279	36.757	0.276	−1.164 to 0.230
CK	O2−O3	11.833	11.500	0.333	0.226	36.757	0.384	−0.232 to 0.898
CF	O1−O2	11.533	14.500	−2.967	0.226	36.757	<0.001	−3.532 to −2.402
CF	O1−O3	11.533	14.517	−2.984	0.279	36.757	<0.001	−3.681 to −2.287
CF	O2−O3	14.500	14.517	−0.017	0.226	36.757	1.000	−0.582 to 0.548
OF	O1−O2	11.667	15.867	−4.200	0.226	36.757	<0.001	−4.765 to −3.635
OF	O1−O3	11.667	15.333	−3.666	0.279	36.757	<0.001	−4.363 to −2.969
OF	O2−O3	15.867	15.333	0.534	0.226	36.757	0.069	−0.031 to 1.099
T1	O1−O2	11.600	15.133	−3.533	0.226	36.757	<0.001	−4.098 to −2.968
T1	O1−O3	11.600	15.587	−3.987	0.279	36.757	<0.001	−4.684 to −3.290
T1	O2−O3	15.133	15.587	−0.454	0.226	36.757	0.148	−1.019 to 0.111
T2	O1−O2	12.233	15.667	−3.434	0.226	36.757	<0.001	−3.999 to −2.869
T2	O1−O3	12.233	16.172	−3.939	0.279	36.757	<0.001	−4.636 to −3.242
T2	O2−O3	15.667	16.172	−0.505	0.226	36.757	0.092	−1.070 to 0.060
T3	O1−O2	12.267	16.267	−4.000	0.226	36.757	<0.001	−4.565 to −3.435
T3	O1−O3	12.267	16.755	−4.488	0.279	36.757	<0.001	−5.185 to −3.791
T3	O2−O3	16.267	16.755	−0.488	0.226	36.757	0.108	−1.053 to 0.077
M1	O1−O2	11.400	16.100	−4.700	0.226	36.757	<0.001	−5.265 to −4.135
M1	O1−O3	11.400	16.583	−5.183	0.279	36.757	<0.001	−5.880 to −4.486
M1	O2−O3	16.100	16.583	−0.483	0.226	36.757	0.113	−1.048 to 0.082
M2	O1−O2	12.067	16.533	−4.466	0.226	36.757	<0.001	−5.031 to −3.901
M2	O1−O3	12.067	17.003	−4.936	0.279	36.757	<0.001	−5.633 to −4.239
M2	O2−O3	16.533	17.003	−0.470	0.226	36.757	0.128	−1.035 to 0.095
M3	O1−O2	12.567	17.000	−4.433	0.226	36.757	<0.001	−4.998 to −3.868
M3	O1−O3	12.567	17.646	−5.079	0.279	36.757	<0.001	−5.776 to −4.382
M3	O2−O3	17.000	17.646	−0.646	0.226	36.757	0.021	−1.211 to −0.081

Notes: O1 denotes sampling after the May 2022 rapeseed harvest, O2 denotes sampling after the 2022 rice harvest, and O3 denotes sampling after the May 2023 rapeseed harvest. EMM, estimated marginal mean; SE, standard error; CI, confidence interval. pH is dimensionless, whereas TP and TK are expressed in g kg^{-1}. Mean differences are calculated as I−J; negative values indicate higher values at occasion J.

For pH and TP, occasion comparisons were based on the overall EMMs averaged across the nine fertilization treatments because the Occasion × Treatment interaction was not significant. Pairwise P values and confidence intervals were adjusted using the Sidak procedure.

For TK, the Occasion × Treatment interaction was significant; therefore, occasion comparisons were conducted separately within each treatment. The TK contrast standard errors and confidence intervals were calculated from the final AR(1) covariance parameter estimates (residual variance $\sigma^2 = 0.159387$ and correlation coefficient $\rho = 0.519514$), with three plots per treatment. The contrast standard error was calculated as $SE = \sqrt{[2\sigma^2(1-\rho^d)/3]}$, where $d = 1$ for adjacent occasions and $d = 2$ for O1 versus O3. The Satterthwaite denominator degrees of freedom were 36.757, and Sidak adjustment was applied to the three occasion comparisons within each treatment. Mean differences were calculated from unrounded EMMs and are presented to three decimal places.

Table S11. Part A Occasion-specific estimated marginal means of SQI and paired M−T contrasts in the T/M treatment subset

Occasion	T EMM	M EMM	M−T	SE	df	95% Sidak-adjusted CI	Sidak-adjusted P
O1	0.391	0.493	0.102	0.016	17.746	0.060–0.143	<0.001
O2	0.689	0.787	0.098	0.016	17.746	0.056–0.140	<0.001
O3	0.764	0.863	0.098	0.016	17.746	0.056–0.140	<0.001

Note: EMM, estimated marginal mean; SE, standard error; CI, confidence interval. SQI is dimensionless. O1 denotes sampling after the May 2022 rapeseed harvest, O2 after the 2022 rice harvest, and O3 after the May 2023 rapeseed harvest. T and M denote the mineral P and K reduction and non-reduction strategies, respectively. EMMs under each strategy were averaged across the three N substitution rates (15%, 30%, and 50%) and experimental blocks. M−T denotes the estimated difference between the two accounting strategies. The repeated-measures model included Block as a fixed effect, plot as the repeated-measures subject, and an AR(1) covariance structure. Denominator degrees of freedom were approximated using the Satterthwaite method. Sidak adjustment was applied across the three occasion-specific M−T contrasts for both P values and 95% confidence intervals. Means and contrasts were rounded separately from the unrounded estimates; differences between displayed means may therefore differ from the displayed contrasts by one unit in the last decimal place.

Part B. Overall M−T contrast for the seven-indicator SQI and the index excluding total K.

Index	M EMM	T EMM	M−T	SE	df	95% CI
Seven indicators (primary)	0.7143	0.6150	0.0993	0.0137	11.014	0.0690–0.1295
Six indicators (TK omitted)	0.7619	0.6548	0.1071	0.0155	9.814	0.0725–0.1417

Note:For the sensitivity analysis, TK was excluded and the entropy weights of pH, SOM, TN, TP, AP, and AK were recalculated using the same 81 observations. The two indices were evaluated using the same 18 T/M plots and repeated-measures model, with Block as a fixed effect and an AR(1) covariance structure. Estimates represent contrasts averaged equally across the three sampling occasions and three substitution rates. The confidence intervals quantify uncertainty in each respective M−T contrast and do not test equivalence between the two index specifications.

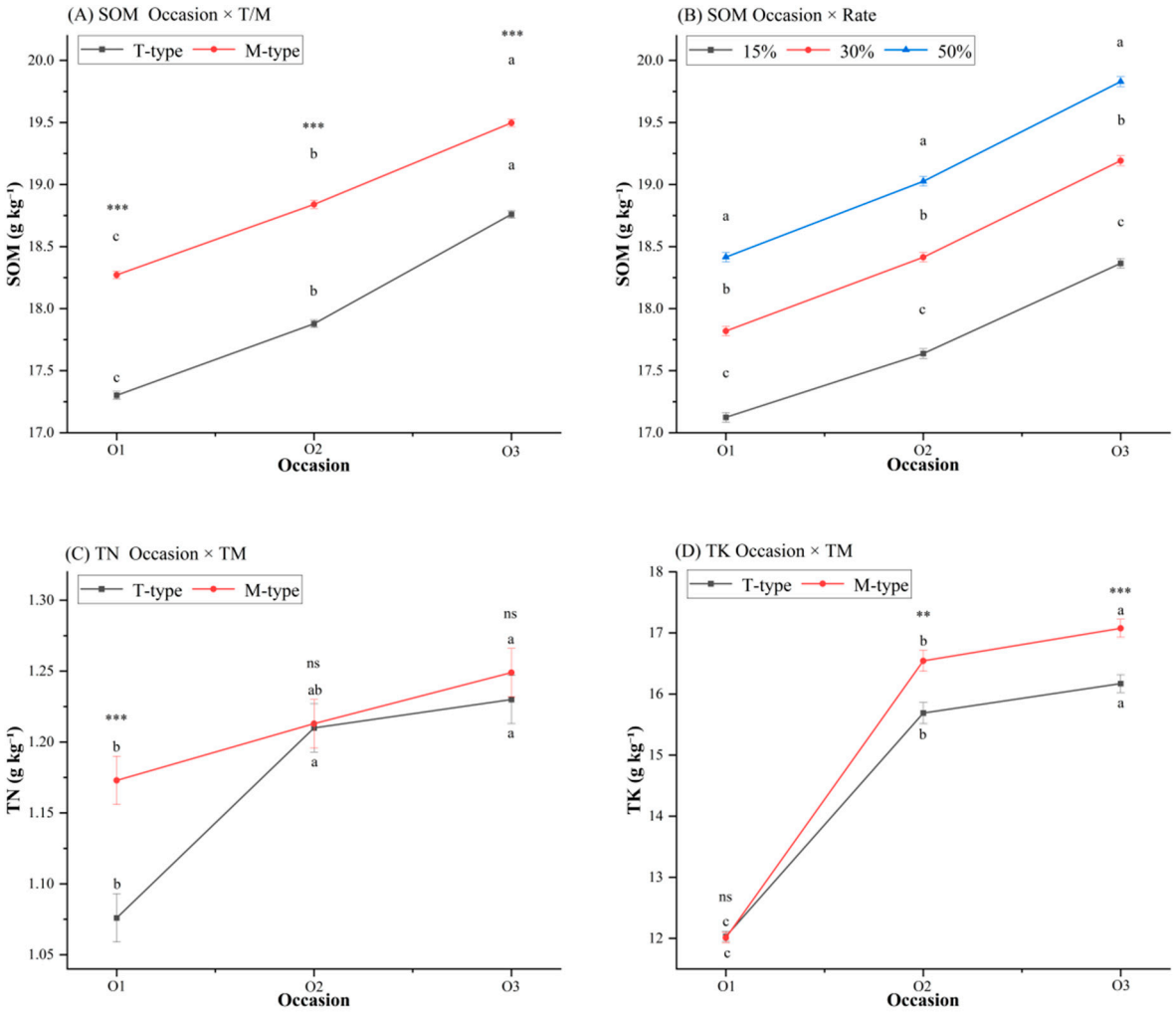

Figure S2. Interaction effects involving sampling occasion on SOM, TN, and TK

Note: Data are presented as EMM ± SE. Letters indicate Sidak-adjusted comparisons among sampling occasions within each accounting strategy in (a, c, d), and among substitution rates within each sampling occasion in (b). For T/M comparisons at the same sampling occasion, ns indicates a nonsignificant difference, while ** and *** indicate $P < 0.01$ and $P < 0.001$, respectively.

Table S12. Available phosphorus by sampling occasion and substitution rate: estimated marginal means and paired M−T contrasts.

Occasion	Rate	T EMM [95% CI]	M EMM [95% CI]	M−T [95% CI]	P
O1	15%	20.400 [19.651, 21.149]	21.167 [20.418, 21.915]	0.767 [−0.292, 1.826]	0.139
O1	30%	20.700 [19.951, 21.449]	22.867 [22.118, 23.615]	2.167 [1.108, 3.226]	<0.001
O1	50%	21.500 [20.751, 22.249]	23.767 [23.018, 24.515]	2.267 [1.208, 3.326]	<0.001
O2	15%	21.012 [20.263, 21.761]	21.802 [21.053, 22.550]	0.790 [−0.269, 1.849]	0.129
O2	30%	21.321 [20.572, 22.070]	23.553 [22.804, 24.301]	2.232 [1.173, 3.291]	<0.001
O2	50%	22.145 [21.396, 22.894]	24.446 [23.698, 25.195]	2.301 [1.242, 3.360]	<0.001
O3	15%	22.033 [21.284, 22.782]	22.861 [22.112, 23.610]	0.828 [−0.231, 1.887]	0.113
O3	30%	22.357 [21.608, 23.106]	23.364 [22.615, 24.113]	1.007 [−0.052, 2.066]	0.060
O3	50%	23.221 [22.472, 23.970]	24.634 [23.886, 25.383]	1.413 [0.354, 2.472]	0.014

Note: AP is expressed in mg kg^{-1}. EMM, estimated marginal mean; CI, confidence interval. O1 and O3 correspond to sampling after the rapeseed harvests in May 2022 and May 2023, respectively; O2 corresponds to sampling after the 2022 rice harvest. Each of the six T/M treatments included three plots. Estimates and confidence intervals were obtained from the repeated-measures model with categorical Rate and its interactions. Within each sampling occasion × substitution rate combination, M was compared with its paired T treatment. M−T denotes the estimated difference between the two accounting strategies; positive values indicate higher AP under M. The reported P values are the Sidak-adjusted pairwise values for these comparisons. No single family-wise adjustment was applied simultaneously across all nine sampling occasion × substitution rate combinations. The reported 95% confidence intervals are model-based intervals for individual estimates and contrasts and should not be interpreted as simultaneous confidence intervals across all nine combinations. The original T−M contrasts and their confidence limits were reversed to express M−T.

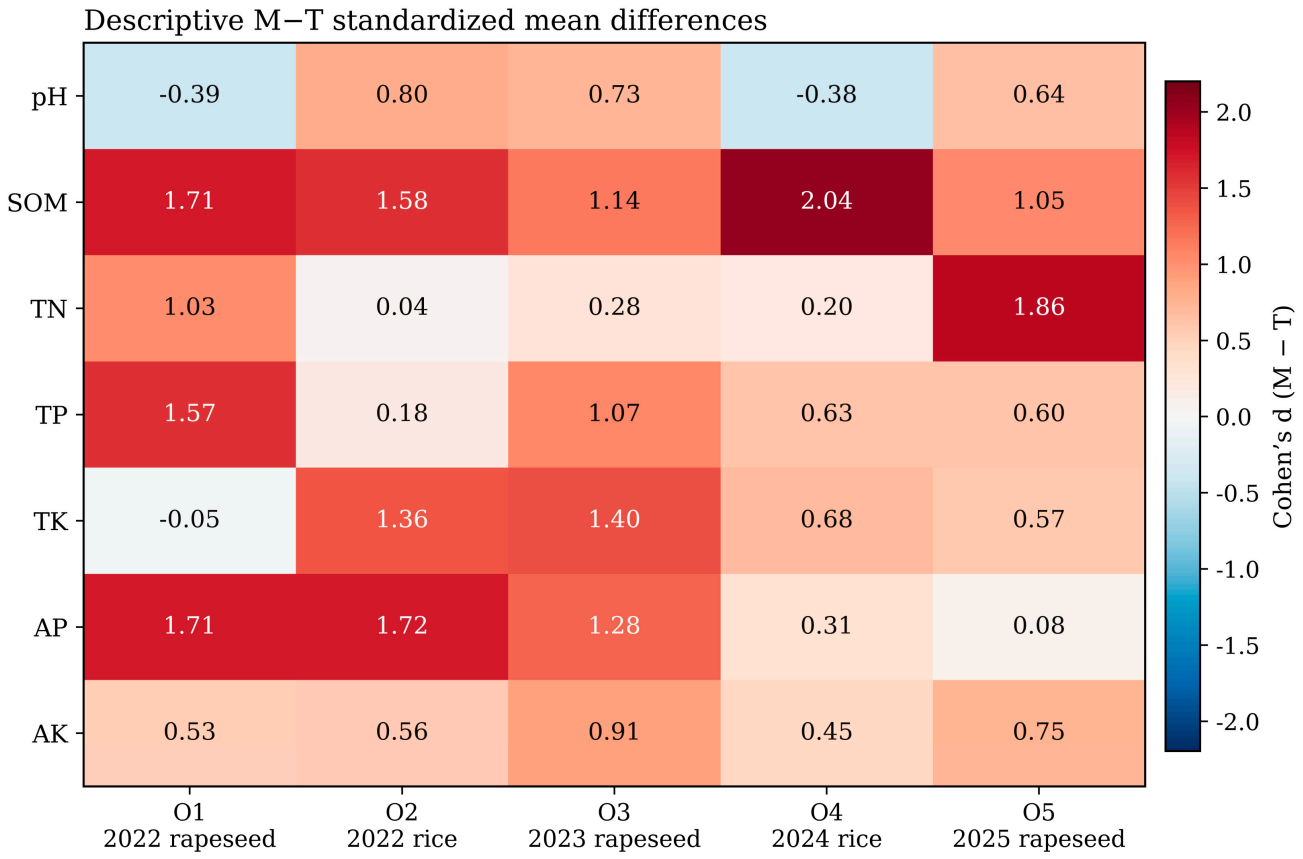

Figure S3. Standardized mean differences between T and M across five sampling occasions

Note: Cohen's d describes effect size only; positive values indicate M > T. It is not used to assess statistical significance.

Table S13. Indicator–yield associations with plot-clustered robust standard errors

Indicator	B per 1 SD	CR1 SE	95% CI (t, df = 26)	P (t)	P (normal approximation)
pH	-68.06	74.06	-220.29—84.17	0.367	0.358
SOM	203.68	102.55	-7.11—414.48	0.058	0.047
TN	-40.52	102.22	-250.63—169.59	0.695	0.692
TP	-55.13	85.11	-230.08—119.82	0.523	0.517
TK	24.10	65.03	-109.57—157.77	0.714	0.711
AP	186.60	91.52	-1.51—374.72	0.052	0.041
AK	57.08	60.79	-67.87—182.02	0.356	0.348
SQI	75.51	95.28	-120.34—271.36	0.435	0.428

Note: Each indicator was entered into a separate model adjusted for Season, Block, and Treatment (n = 54 records from 27 plots). B represents the yield difference (kg ha^{-1}) per one-standard-deviation increase in the indicator, with standard deviations calculated from the combined sample. The CR1 correction factor was $G/(G-1) \times (n-1)/(n-p)$, where G = 27 and p = 13. Primary confidence intervals and P values were based on t_{26}; normal-approximation P values were reported only as a sensitivity check. No adjustment for multiple testing across indicators was applied, and the results should not be interpreted as confirming independent predictive value.

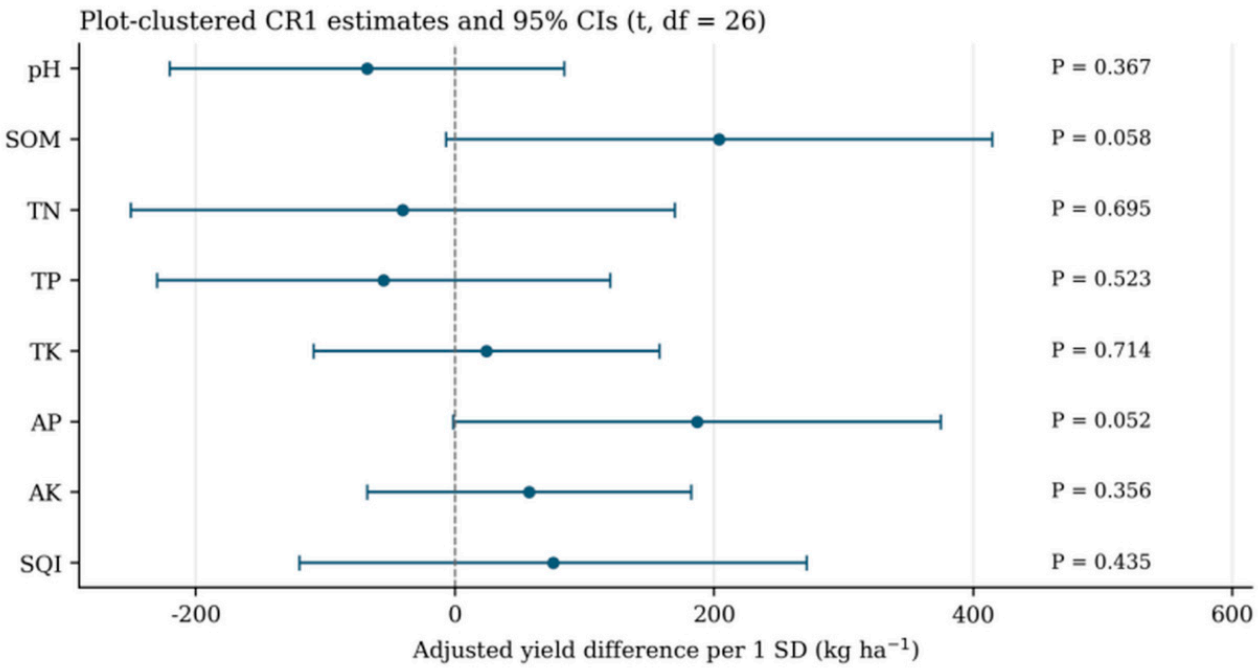

Figure S4. Adjusted indicator–yield coefficients and cluster-robust confidence intervals

Note: Each indicator was modeled separately with adjustment for Season, Block, and Treatment; coefficients are expressed per one-standard-deviation increase in the indicator. Error bars show 95% confidence intervals calculated using the CR1-corrected covariance matrix and a t distribution with 26 degrees of freedom. The dashed line marks zero. Results are exploratory; see Table S13.

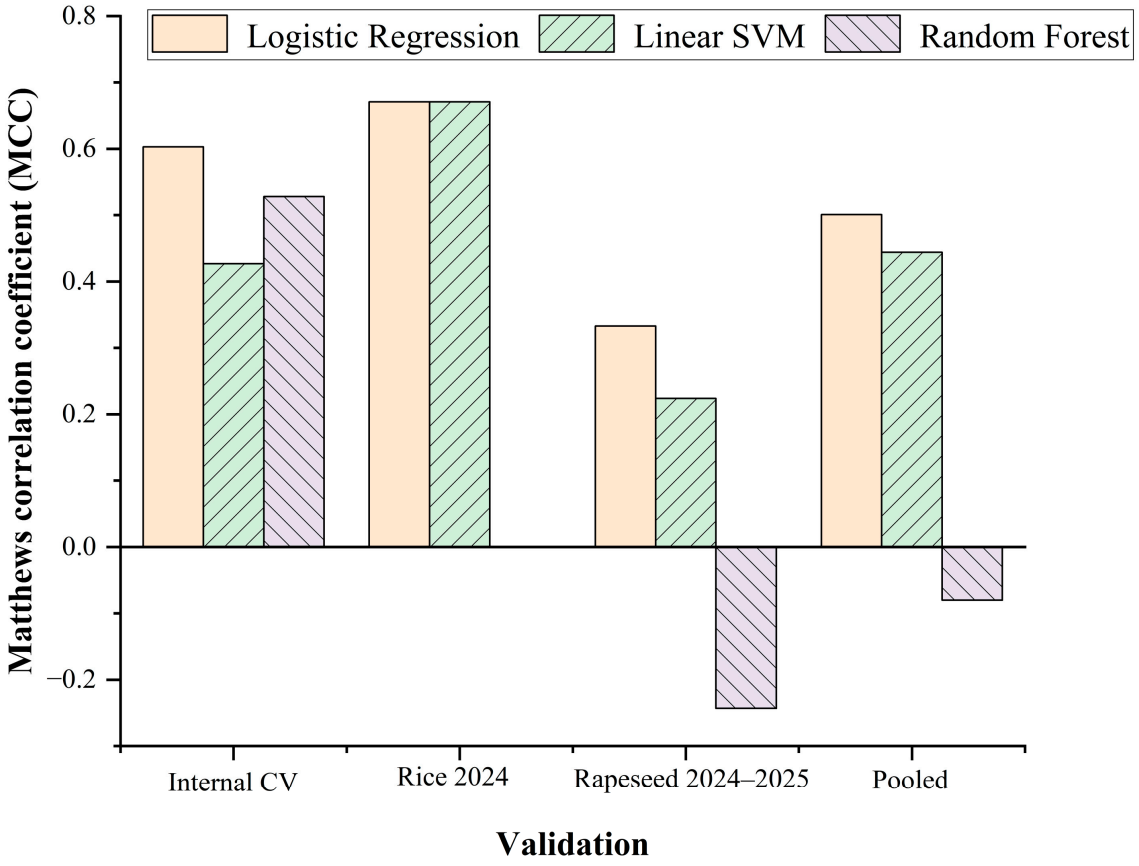

Figure S5. Matthews correlation coefficients for the three classifiers in block-grouped internal cross-validation and descriptive classification at later sampling occasions.

Note: Within each dataset, the correct/tested counts for logistic regression, linear SVM, and random forest, respectively, were 43/54, 38/54, and 41/54 internally; 15/18, 15/18, and 9/18 at O4; 12/18, 11/18, and 8/18 at O5; and 27/36, 26/36, and 17/36 in the pooled dataset. MCC ranges from −1 to 1. Internal CV denotes three-fold cross-validation grouped by block. O4 and O5 represent later sampling occasions from the same 18 plots included in the training data, and their classification results are descriptive rather than independent validation.

Table S14. Training-set feature scores for the seven soil indicators

Indicator	Information gain	ANOVA	ReliefF	Logistic regression score	Random forest score
pH	0.126	0.198	0.004	0.412	0.115
SOM	0.123	16.267	0.064	1.175	0.191
TN	0.059	2.434	0.005	0.769	0.105
TP	0.030	3.497	0.022	0.239	0.089
TK	0.078	0.951	0.038	0.370	0.118
AP	0.290	26.263	0.120	1.770	0.270
AK	0.087	4.960	−0.003	0.800	0.113

Note: Feature scores were calculated using the 54 T/M records from O1–O3, with all seven features retained. Scores should be compared only within the same method and do not represent causal contributions.

Table S15. Illustrative scenario analysis of the M−T as-threshed seed-mass yield contrast under hypothetical differences in seed moisture.

Assumed moisture content of T (%)	Assumed moisture content of M (%)	Moisture-corrected yield of T	Moisture-corrected yield of M	M−T difference
10	10	2191.9	2404.0	212.1
10	12	2191.9	2350.6	158.7
10	14	2191.9	2297.2	105.3
10	16	2191.9	2243.7	51.8
10	17.94	2191.9	2191.9	≈0

Note: Calculations were based on the two-season estimated marginal means (EMMs) of as-threshed seed-mass yield reported in the main text (T = 2,191.9 and M = 2,404.0 kg ha^{-1}). The moisture content of T was fixed at an assumed value of 10%, while that of M was varied. Yields were hypothetically adjusted to a common reference moisture content of 10% using $Y_{10} = Y_as\text{-}threshed \times (1 - m)/(1 - 0.10)$, where m represents the assumed wet-basis moisture fraction. The 10% value is used solely as an illustrative reference and does not represent measured moisture content or an asserted official standard. No plot-level seed moisture measurements were available. These calculations are illustrative scenarios rather than measured moisture values, empirical corrections, or moisture-adjusted statistical estimates. The displayed EMMs are rounded to one decimal place; their arithmetic difference is 212.1 kg ha^{-1}, whereas the model-based contrast calculated from unrounded estimates is 212.0 kg ha^{-1}.