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Contrasting Phosphorus and Potassium Responses to Tillage and Straw Return in a Wheat–Maize Rotation: Associations with Soil Microbial Communities

Siddique Ahmad

siddiqueb284@gmail.com

Henan Agricultural University https://orcid.org/0009-0001-6552-007X

Wenjing Song

Lingling Ma

Siying Wang

Junying Chen

Shuping Xiong

Zhiyong Zhang

Xiaochun Wang

Huiqiang Li

Xinming Ma

Yihao Wei

https://orcid.org/0000-0001-9897-0571

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Abstract

Background and Aims:

Straw return strengthens nutrient recycling in cereal rotations, yet its effects on phosphorus (P) and potassium (K) acquisition under contrasting tillage remain unclear. **Method**: A two-year split-plot experiment in northern China compared rotary tillage (RT) and moldboard plowing (MP) under no, half, full, and double straw return in a winter wheat–summer maize rotation. Soil and crop measurements covered four harvests; topsoil microbial communities were assessed after both maize harvests. **Results**: Full and double return increased grain yield and aboveground P accumulation in both crops, with higher maize yield under MP. Wheat K accumulation increased with straw return, whereas maize K accumulation showed no significant overall tillage or straw return effect. Estimated from additional uptake, apparent straw P recovery was higher under MP, while apparent K recovery increased with return rate. Maize P accumulation increased between years as K accumulation declined. MP and higher straw inputs generally increased topsoil organic matter, available P (AP), and available K (AK). Between maize harvests, AP increased while AK declined, indicating contrasting trajectories. AP correlated positively with maize P accumulation in both years (R^2 = 0.61–0.62), and AK with K accumulation in both crops. Microbial richness increased between years; combined analysis detected modest treatment differentiation for fungi but no significant differentiation for bacteria. Nutrient-associated taxa varied between years, providing candidates for functional investigation. **Conclusion**: Findings support separate P and K monitoring when integrating straw return with tillage; recommending double over full return requires evidence of additional agronomic and economic benefits.

1. Introduction

Sustaining crop productivity while preserving soil fertility remains a major challenge in intensive cereal systems. The winter wheat-summer maize rotation is a major grain production system in North China, but its sustainability is increasingly constrained by soil degradation, inefficient residue management, and declining nutrient-use efficiency (Wang et al. 2015; Yang et al. 2023). Returning crop straw can recycle nutrients, increase organic carbon inputs, stimulate microbial activity, improve soil physicochemical properties, and support productivity (Turmel et al. 2015; Fu et al. 2021; Chen et al. 2021; Cui et al. 2022). However, its effectiveness depends on residue amount and tillage, which influence residue placement, soil disturbance, decomposition, and nutrient redistribution (Xu et al. 2019; Li et al. 2019). Clarifying this interaction is important for sustaining nutrient cycling and productivity in wheat-maize rotations.

Phosphorus (P) and potassium (K) are essential macronutrients, yet substantial proportions occur in forms that are not readily available for plant uptake (Damon et al. 2014; Rawal et al. 2022; García-Berumen et al. 2025; Zhao et al. 2025). Straw incorporation may increase available phosphorus (AP) and available potassium (AK) through residue-derived inputs, organic matter (OM) turnover, and changes in soil conditions during decomposition (Li et al. 2024a; Xu et al. 2025). A key management question is whether increases in soil AP and AK under straw return are accompanied by consistent increases in crop

P and K accumulation and grain yield across successive wheat and maize harvests, and how these relationships vary with tillage and residue input (Damon et al. 2014; Rawal et al. 2022; Li et al. 2024a). Their vertical distribution is also important because enrichment in the 0–20 cm layer may differ from that in deeper soil and influence crop access (Xu et al. 2019; Li et al. 2019).

Soil microbial communities contribute to residue decomposition, OM turnover, and nutrient transformation under straw return (Guo et al. 2018; Chen et al. 2023; Liu et al. 2024). Residue-derived carbon and nutrients can reshape bacterial and fungal communities, while tillage-induced changes in soil structure may further influence microbial habitats and community composition (Chen et al. 2023; Liu et al. 2024). Microbial groups associated with AP and AK may serve as ecological indicators of nutrient status or as co-occurring responders to altered soil conditions (Guo et al. 2018; Liu et al. 2024). However, these associations do not demonstrate that individual taxa directly mobilize, solubilize, or mineralize P and K without functional validation. It remains unclear whether microbial responses to combined straw return and tillage management co-vary with soil AP and AK, crop nutrient accumulation, and productivity.

Previous field experiments in wheat–maize rotations have demonstrated that straw-return strategies influence soil properties and grain yield, with responses depending on whether wheat straw, maize straw, or both are retained (Cui et al. 2022). Long-term experiments have also examined how tillage and straw management affect crop P and K accumulation and internal nutrient-use efficiency, supporting the joint evaluation of nutrient acquisition and grain production (Huang et al. 2025). Furthermore, residue type and return rate can alter bacterial and fungal communities and their relationships with soil nutrient conditions (Su et al. 2020). Building on this evidence, an important management question is whether soil P and K availability, crop nutrient accumulation, and yield respond consistently across successive crops under contrasting tillage and straw inputs. Evaluating these responses together can identify situations in which improved soil nutrient availability is accompanied by limited crop uptake or yield benefits and help distinguish the management implications of P and K within the rotation.

Therefore, a two-year field experiment was conducted in a winter wheat-summer maize rotation to compare rotary tillage (RT) and moldboard plowing (MP) under no, half, full, and double straw return. Soil measurements from the 0–20 and 20–40 cm layers were combined with grain yield and aboveground P and K accumulation across four successive harvests, while bacterial and fungal communities were characterized after maize harvest in both years. The objectives were to (i) determine how tillage and straw-return rate affected soil P and K availability across depths and harvests; (ii) assess whether changes in nutrient availability corresponded to crop P and K accumulation and grain yield, and whether these relationships differed between crops and years; and (iii) identify microbial community responses and taxa associated with AP and AK. The study thus evaluates the consistency of soil and crop nutrient responses within the same management experiment. This approach provides evidence for coordinating residue management with crop nutrient requirements and separate P and K monitoring, while identifying microbial associations for subsequent functional investigation.

2. Materials and Methods

2.1 Study site and cropping sequence

A two-year field experiment covering four successive wheat and maize harvests was conducted in Jian'an District, Xuchang City, Henan Province, China (34°08'01.5" N, 113°48'14.9" E) (Fig. 1a). The cropping sequence comprised winter wheat in 2023–2024, summer maize in 2024, winter wheat in 2024–2025, and summer maize in 2025. The experimental soil was a fluvo-aquic sandy loam developed from alluvial deposits. Initial soil properties were determined before treatment application in the 0–20 and 20–40 cm layers (Table 1). Air temperature and rainfall were recorded using an automatic agrometeorological station and summarized as monthly mean temperature and cumulative precipitation (Fig. 1b).

Table 1
Initial physical and chemical properties of the experimental soil before treatment application.

Soil physicochemical properties	**Soil layers**	
	0–20 cm	**20–40 cm**
Texture	Sandy loam	Sandy loam
Bulk density (g cm^{-3})	1.38	1.48
pH	7.85	8.05
OM (g kg^{-1})	16.5	11.8
TN (g kg^{-1})	0.88	0.65
TP (g kg^{-1})	0.65	0.5
TK (g kg^{-1})	19.2	18.8
AP (mg kg^{-1})	5.2	3.8
AK (mg kg^{-1})	105	85

Values describe soil conditions in the 0–20 and 20–40 cm layers before the experiment began. OM, organic matter; TN, total nitrogen; TP, total phosphorus; TK, total potassium; AP, available phosphorus; AK, available potassium.

2.2 Experimental design and field management

A randomized split-plot experiment comprised three blocks, with rotary tillage (RT) and moldboard plowing (MP) assigned to main plots and no (NS), half (HS), full (FS), and double (DS) straw return assigned to subplots. Nominal return levels were 0, 0.5, 1.0, and 2.0 times the straw produced within each subplot at the preceding harvest, respectively. The eight treatment combinations comprised 24 permanent subplots, with assignments maintained across both rotations (Fig. 1c). Cultivars were Fengdecunmai-5 (wheat) and Denghai-1875 (maize). Treatments began after maize harvest in 2023,

following uniform crop management. After each harvest, NS, HS, and FS retained none, half the measured mass, and all subplot straw, respectively. For wheat 2023–2024, DS retained its own maize straw plus straw removed from NS. Subsequently, supplementary subplots outside the experimental layout, planted with the preceding crop and managed under FS, supplied wheat straw for maize in 2024 and 2025 and maize straw for wheat 2024–2025. Wheat straw was distributed before direct maize sowing. Following maize harvest (2023), the designated straw was incorporated before wheat sowing using RT model 1GKN-230K, operating at a depth of 15 cm, and MP model 1LFK-435, operating at a depth of 30 cm. Seasonal fertilization was identical across treatments: wheat received 264.75 kg N ha^{-1}, 76.4 kg P ha^{-1}, and 48.6 kg K ha^{-1}; maize received 250.5 kg N ha^{-1}, 49.1 kg P ha^{-1}, and 93.4 kg K ha^{-1}. Part of the N was applied as urea at wheat jointing and before maize tasseling. Irrigation, weed control, and pest management were uniform across treatments.

2.3 Crop sampling, yield, and nutrient accumulation

At physiological maturity, wheat and maize plants were harvested from each subplot and separated into grain and straw. Grain and straw yields were expressed on a dry-matter basis and calculated from the harvested mass and corresponding sampling area (Begizew et al. 2020):

$$Grain\ or\ straw\ yield\ \left(kg\ ha^{-1}\right) = \frac{Harvested\ dry\ mass\ \ (kg)}{Corresponding\ harvested\ area\ \ (m^2)} \times\ 10000$$

Representative grain and straw subsamples were oven-dried at 65°C to constant mass and ground to pass through a 0.15-mm sieve. Approximately 0.3–0.5 g of ground material was digested with concentrated H_2SO_4-H_2O_2. Phosphorus (P) concentration was determined by molybdenum-blue colorimetry, and potassium (K) concentration by flame photometry (Chapman and Pratt 1962; Jones Jr 2001). Concentrations were expressed in g kg^{-1} of dry matter. Laboratory determinations were performed in triplicate, with reagent blanks included in each analytical batch.

Total aboveground accumulation of nutrient (x), representing P or K, was calculated as (Yimer et al. 2024):

$$U_x = \frac{Y_g C_{x,g} + Y_s C_{x,s}}{1000}$$

where U_x is total aboveground nutrient accumulation (kg ha^{-1}); Y_g and Y_s are grain and straw dry-matter yields (kg ha^{-1}); and $C_{x,g}$ and $C_{x,s}$ are the corresponding nutrient concentrations (g kg^{-1}). Nutrient accumulation in grain and straw was calculated separately before summation. Replicate-level data on straw and grain P and K concentrations, nutrient accumulation, and yields are provided in (Tables S1–S2).

2.4 Apparent P and K recovery associated with straw return

The apparent recovery ratio (ARR) was calculated as the additional crop nutrient accumulation relative to NS, expressed as a percentage of the nutrient input supplied by the preceding crop's returned straw:

$$ARR_{x,j,t} = \frac{U_{x,j,t} - U_{x,NS,t}}{I_{x,j,t-1}} \times 100$$

where $ARR_{x,j,t}$ is the apparent recovery ratio (%) of nutrient x under straw return treatment (*j*) during crop season (*t*). The terms $U_{x,j,t}$ and $U_{x,NS,t}$ represent total aboveground nutrient accumulation (kg ha^{-1}) under straw return and the corresponding NS treatment, respectively, matched within the same block, tillage system, and receiving crop season. The term $I_{x,j,t-1}$ represents the nutrient input (kg ha^{-1}) from straw produced in the preceding crop season.

Straw nutrient input was calculated as:

$$I_{x,j,t-1} = \frac{B_{returned,j,t-1} \times C_{x,straw,t-1}}{1000}$$

where $B_{returned,j,t-1}$ is the dry mass of straw actually returned (kg ha^{-1}), and $C_{x,straw,t-1}$ is its nutrient concentration (g kg^{-1}).

Calculations covered maize 2024, wheat 2024–2025, and maize 2025, using nutrient inputs from wheat 2023–2024, maize 2024, and wheat 2024–2025 straw, respectively. ARR was not calculated for NS because its straw nutrient input was zero. Negative values were retained and indicated lower crop nutrient accumulation than in the corresponding NS treatment. Values exceeding 100% indicated that additional crop uptake exceeded the nutrient input from the most recent straw application. ARR is an uptake-based index that does not directly quantify straw decomposition or distinguish nutrient contributions from the most recently returned straw, soil, fertilizer, and earlier residue inputs. Replicate-level apparent P and K recovery values (%) are provided in (Table S3).

2.5 Soil sampling and physicochemical analyses

Soil was sampled after each harvest at depths of 0–20 and 20–40 cm. Three cores collected within each subplot were combined separately by depth to obtain one composite sample per layer. Samples for physicochemical analysis were air-dried, ground, and sieved. Organic matter (OM) was determined by potassium dichromate oxidation with external heating. Total nitrogen (TN) was measured by the semi-micro Kjeldahl method following concentrated H_2SO_4 digestion (Bremner 1965). Total phosphorus (TP) was determined by molybdenum-blue colorimetry after acid digestion, and total potassium (TK) by flame photometry after total digestion (Murphy and Riley 1962; Liu and Yu 2009). Available phosphorus (AP) was extracted with 0.5 mol L^{-1} $NaHCO_3$ and determined colorimetrically using the Olsen method (Kuo 1996). Available potassium (AK) was extracted with 1 mol L^{-1} NH_4OAc and measured by flame photometry (Schollenberger and Simon 1945). The replicate-level soil physicochemical data are provided in Supplementary Table S4. Initial soil texture was determined by particle-size analysis, bulk density by

the core method, and pH in a 1:2.5 soil-to-water suspension. Soil nutrient concentrations were expressed on an oven-dry mass basis.

2.6 Microbial DNA extraction, sequencing, and taxonomic profiling

Soil samples collected from the 0–20 cm layer after maize harvest in 2024 and 2025 were used to characterize bacterial and fungal communities. One composite sample was analyzed from each of the 24 permanent subplots at each cropping season, providing three block replicates per treatment combination and 48 samples across both years. The collected samples were immediately transported on ice from the field and stored at − 80°C until DNA extraction. DNA extraction, amplicon sequencing, and initial sequence processing were performed by Shanghai Majorbio Bio-Pharm Technology Co., Ltd. (Shanghai, China). Total genomic DNA was extracted from 0.5 g of soil using the FastDNA Spin Kit for Soil (MP Biomedicals, USA) according to the manufacturer's instructions. The bacterial 16S rRNA gene V3–V4 region was amplified using primers 338F (5'-ACTCCTACGGGAGGCAGCAG-3') and 806R (5'-GGACTACHVGGGTWTCTAAT-3'). The fungal ITS1 region was amplified using forward (5'-TCCGTAGGTGAACCTGCGG-3') and reverse (5'-GCTGCGTTCTTCATCGATGC-3') primers. Amplicons were sequenced on an Illumina NextSeq 2000 platform using paired-end 2 × 300-bp reads. Raw reads were quality-filtered using fastp and merged using FLASH (Magoč and Salzberg 2011; Chen et al. 2018). Sequences were clustered into operational taxonomic units (OTUs) at 97% similarity using UPARSE (Edgar 2013). Bacterial taxonomy was assigned against SILVA v138.2 using the RDP classifier at a 70% confidence threshold, and fungal taxonomy was assigned against UNITE v10 (Wang et al. 2007; Abarenkov et al. 2024). Sequence libraries were rarefied to the minimum sequencing depth before diversity estimation, and Chao1 richness was calculated for each sample. Taxonomic profiles were summarized at the genus level, retaining the available higher-level labels for taxa without genus assignments. Chao1 richness, β-diversity distance matrices, mean relative abundances of the 20 most abundant bacterial and fungal taxa, and abundance profiles of selected taxa associated with AP and AK after the maize harvests in 2024 and 2025 are provided in (Tables S5–S8), respectively.

2.7 Statistical analyses

Analyses used R packages *lme4*, *lmerTest*, and *emmeans* (Bates et al. 2015; Kuznetsova et al. 2017). Mixed-effects models included tillage, straw return, temporal factors, and all interactions, with random intercepts for block, main plot within block, and permanent subplot within main plot. Soil, crop, Chao1, and apparent recovery models were fitted separately by depth, crop, microbial group, and nutrient, respectively. Temporal factors were rotation year and crop season for soil properties, year for crop variables and Chao1, and cropping season (maize 2024, wheat 2024–2025, maize 2025) for recovery; recovery analyses excluded NS. Type III F-tests used Kenward–Roger degrees of freedom. Residual-versus-fitted and normal Q–Q plots assessed assumptions. Marginal-mean comparisons used Tukey adjustment, except tillage and year contrasts for yield, which used Holm adjustment.

Bray–Curtis dissimilarities from complete genus-level relative-abundance profiles were visualized by principal coordinates analysis (PCoA) in OmicStudio (Lyu et al. 2023). Analysis of similarities (ANOSIM) in *vegan* compared eight treatment combinations separately for bacteria and fungi using 9,999 restricted permutations: main plots within blocks and subplots within main plots, keeping paired 2024–2025 observations together. ANOSIM did not separately test year or interactions. Multivariate dispersion was assessed using *betadisper* and permutation tests with identical restrictions. Blocked factorial models tested paired centered log-ratio (CLR) differences (pseudocount 0.5), with Benjamini–Hochberg false discovery rate (FDR) correction across 20 genera per term (Benjamini and Hochberg 1995). Within-year Spearman correlations related AP and AK to selected taxa (n = 24 subplots), with the same correction applied separately by nutrient, year, and microbial group. Linear regressions related topsoil AP and AK to total aboveground P and K accumulation, respectively, and OM to AP and AK (n = 24 per crop season); R^2 summarized fit. Significance was set at 0.05, using adjusted P values where applicable. Treatment summaries were means ± SE (n = 3 blocks); laboratory triplicates were technical replicates.

3. Results

3.1 Grain yield, P and K accumulation, and apparent straw nutrient recovery

Observed grain yields were higher under FS and DS than NS in both crops (Fig. 2a). Wheat grain yield was higher under MP at the higher straw return rates (i.e., MP-FS and MP-DS), whereas differences between tillage treatments at these straw return rates narrowed in 2024–2025. Maize grain yield was generally higher under MP than RT, but declined by 15.9% from 2024 to 2025 when averaged across all treatments. Straw return also increased straw yield in both crops, with maize straw yield generally higher under MP than RT (Fig. S1). Total aboveground P and K accumulation in wheat increased with straw return, with the highest values under MP-FS in 2023–2024 and MP-DS in 2024–2025. In maize, P accumulation generally increased with straw return rate and was higher under MP than RT, reaching its maximum under MP-DS in both years. From 2024 to 2025, maize P accumulation increased across all treatments, whereas K accumulation declined. Neither tillage nor straw return had a significant overall effect on maize K accumulation (Fig. 2b,c). Apparent straw P recovery was generally higher under MP than RT, particularly under FS and DS during the maize seasons. Under MP, apparent P recovery was lowest in the 2024–2025 wheat season, while MP-DS produced the highest values in both maize seasons, with the overall maximum in 2024 (Fig. 2d). Apparent K recovery increased from HS to DS under both tillage systems and declined between the two maize seasons, with no significant overall difference between MP and RT (Fig. 2e).

3.2 Soil nutrient dynamics across depths and sampling seasons

Across the four harvests, OM, TN, TP, AP, and AK concentrations were generally higher at 0–20 cm than at 20–40 cm. In the topsoil, tillage significantly affected OM, AP, and AK, while straw return rate affected OM, TK, AP, and AK ($P < 0.05$; Supplementary Table S9). These properties were generally higher under FS and DS than NS, with OM, AP, and AK also higher under MP than RT. Neither factor had a significant main effect on TN or TP. Topsoil TP was generally lower after maize harvest in 2025 than after wheat harvest in 2023–2024. AP increased between maize harvests, whereas AK declined, with a larger interannual reduction after wheat than maize (Fig. 3). In the 20–40 cm layer, tillage significantly affected OM, TN, TP, and AK, with generally higher concentrations under MP, but had no significant main effect on AP or TK. Straw return generally increased all six properties, with a stronger OM response under MP. AP and TK were generally highest after maize harvest in 2025, whereas AK declined between maize harvests, particularly under RT (Fig. S2). Significant year × sampling-season interactions occurred for AP and AK at both depths. AK responses additionally depended on management, including a straw return rate × year × sampling-season interaction at both depths and a tillage × year × sampling-season interaction in the subsoil. Topsoil AK also showed a significant tillage × sampling-season interaction, indicating that the difference between MP and RT varied with crop season. The subsoil OM response also exhibited a significant tillage × straw return rate interaction (Supplementary Table S9).

3.3 Bacterial and fungal richness and community structure

Chao1 richness increased overall from 2024 to 2025 for both bacteria and fungi (Fig. 4a,c). Averaged across years, bacterial richness was higher under MP than RT, whereas straw return had no significant overall effect. The largest observed increase in bacterial richness occurred under MP-DS, while values under RT-DS changed little. Fungal richness responded differently to straw return under the two tillage systems: RT-DS maintained the lowest values in both years, whereas MP-HS showed the largest increase and the highest richness in 2025 (Fig. 4c). PCoA based on Bray-Curtis dissimilarities showed visual separation between samples collected in 2024 and 2025 for bacterial (Fig. 4b) and fungal (Fig. 4d) groups. When both years were analyzed together, bacterial communities showed no significant differentiation among treatments (ANOSIM: $R = 0.030$, $P = 0.239$), whereas fungal communities exhibited modest but significant treatment differentiation ($R = 0.128$, $P = 0.012$).

3.4 Microbial taxonomic composition and associations with soil AP and AK

Taxa affiliated with *Vicinamibacteraceae* and *Vicinamibacterales* were among the most abundant bacterial groups across both years. Their relative abundances declined from 2024 to 2025, together with that of *Sphingomonas*, whereas *Nitrospira*, *Arthrobacter*, and *Rubrobacter* increased (Fig. 5a). Among fungi, *Mortierella* remained prominent but declined overall, while *Talaromyces*, *Fusarium*, and *Trichoderma* increased. These temporal changes were significant in the analysis of CLR abundances following FDR correction ($q < 0.05$; Fig. 5a). Significant positive bacterial associations with both AP and AK involved RB41 and *Luteolibacter* in 2024 (Fig. 5b) and *Cellulomonas* and *Flavobacterium* in 2025 (Fig. 5c).

Additional positive associations with AK occurred for *Chthoniobacter* and *Candidatus Udaeobacter* in 2024, and *Arthrobacter* and *Pantoea* in 2025 (Fig. 5b,c). Among the selected fungal genera, *Aspergillus*, *Coprinellus*, and *Sagenomella* were positively correlated with both nutrients in 2024 (Fig. 5b). In 2025, only *Aspergillus* showed a significant positive association with AK, while neither of the displayed fungal genera was significantly associated with AP (Fig. 5c).

3.5 Soil AP and AK in relation to organic matter and crop nutrient accumulation

Higher soil AP was associated with greater total aboveground P accumulation in maize in both years (R^2 = 0.61–0.62). The corresponding relationship in wheat was significant in 2023–2024 but weak and nonsignificant in 2024–2025 (Fig. 6a). Higher soil AK was associated with greater total aboveground K accumulation in both wheat and maize across the two years (Fig. 6b). Higher soil OM was associated with higher AP across all four harvests (Fig. S3a). A positive OM-AK relationship was also evident after both maize harvests and the 2023–2024 wheat harvest, but was weak and nonsignificant after the 2024–2025 wheat harvest (Fig. S3b).

4. Discussion

4.1 Contrasting P and K accumulation in wheat and maize

The contrasting temporal responses of P and K highlight the need to distinguish nutrient acquisition from grain production. Increased maize P accumulation alongside lower yield underscores the distinction between P acquisition and internal utilization (Veneklaas et al. 2012), while balanced nutrient uptake remains important for realizing yield potential (Setiyono et al. 2010). Concurrent declines in soil AK and maize K accumulation support evaluating P and K separately under straw management, but do not establish whether K availability or other seasonal factors caused the yield decline. For K, substantial retention in cereal straw means that total aboveground accumulation reflects vegetative biomass and tissue K concentrations as well as grain production, allowing nutrient accumulation and grain yield to respond differently (Carciochi et al. 2025). Residue P composition and placement could contribute to differences in apparent P recovery between crops and tillage systems by influencing nutrient transfer into pools accessible to roots (Noack et al. 2012, 2014). However, the apparent recovery index measures additional crop uptake relative to the nutrient input, and treatment differences can include changes in uptake from soil and fertilizer sources alongside the contribution from residues (Noack et al. 2014). Seasonal variation in apparent recovery may therefore reflect changes in crop nutrient demand and acquisition as well as residue nutrient supply, without directly demonstrating differences in decomposition rate (Setiyono et al. 2010; Noack et al. 2014).

4.2 Tillage and straw return shape soil P and K availability

The fertility benefit of straw return depends on where nutrients accumulate and how readily they enter plant-available pools (Liu et al. 2021; Wang et al. 2025). Differences in residue distribution offer a plausible explanation for the subsoil enrichment under MP, because deeper incorporation can extend carbon and nutrient inputs below the surface layer and alter their distribution within the cultivated profile (Liu et al. 2021). The OM-AP association is consistent with organic inputs supporting P turnover, as straw can supply phosphate and stimulate organic P mineralization (Damon et al. 2014; Wang et al. 2025). Released phosphate subsequently undergoes microbial immobilization and mineral retention, which regulate the proportion remaining available for plant uptake (Hinsinger 2001; Damon et al. 2014). Sorption and precipitation could therefore buffer the subsoil AP response to tillage even where total P concentrations differ, providing a possible explanation for the contrasting responses of these pools (Hinsinger 2001). For K, residue and fertilizer inputs replenish available and slowly available pools, but continued crop uptake can offset this replenishment (Zhao et al. 2014). The decline in AK across rotations is therefore compatible with a drawdown of readily available K despite partial replenishment through straw return, as observed in long-term wheat-maize experiments (Zhao et al. 2014). Sustaining soil P and K availability consequently requires residue management that combines appropriate nutrient placement with continued replenishment of the available pools depleted during cropping (Zhao et al. 2014; Liu et al. 2021; Wang et al. 2025).

4.3 Microbial community responses and associations with soil P and K availability

Straw return creates a changing microbial habitat through substrate inputs, while tillage modifies the spatial accessibility of these resources (Shamshitov et al. 2025). The bacterial richness response should therefore be interpreted in the context of nutrient supply and management duration, which can modify the effects of straw inputs (Zhang et al. 2024). Fungal community differentiation is mechanistically plausible because hyphal growth and extracellular enzymes facilitate residue colonization and decomposition, processes influenced by residue placement and physical disturbance (Treseder and Lennon 2015; Shamshitov et al. 2025). Changes in residue composition during decomposition could also contribute to the temporal turnover of microbial taxa (Shamshitov et al. 2025). Selected nutrient associations have a plausible biochemical basis: the PafA phosphatase characterized in *Flavobacterium johnsoniae* releases phosphate during the utilization of phosphorylated carbohydrates, linking microbial carbon acquisition with organic P mineralization (Lidbury et al. 2022). Similarly, experimental K release by an *Aspergillus fumigatus* isolate demonstrates a mineral-weathering pathway that could contribute to the association between *Aspergillus* and AK (Lian et al. 2008). These mechanisms remain hypotheses for the present field conditions because genus-level associations can reflect shared environmental responses and cannot establish functional activity (Louca et al. 2018; Carr et al. 2019). The microbial evidence therefore identifies candidate biological links between residue management and nutrient availability, providing a focused basis for testing P mineralization and K mobilization through enzyme assays and mineral-solubilization experiments (Lian et al. 2008; Lidbury et al. 2022).

4.4 Management implications and study limitations

Under conditions comparable to this site, FS represents a practical management option that combines yield improvement with recycling of field-produced residues, avoiding the additional straw procurement required for DS. Adoption of DS should depend on longer-term evidence that its additional yield benefits justify the costs of straw collection, transport, and incorporation, consistent with evaluating profitability through both production benefits and management inputs (J. Li et al., 2024). Higher maize yield under MP supports considering this tillage system where soil conditions and machinery permit, recognizing that tillage was applied before wheat within the rotation. The contrasting AP and AK trends support separate nutrient monitoring, complemented by accounting for fertilizer inputs, imported straw, and nutrient exports in grain and removed residues, particularly when assessing K replenishment (Zhao et al. 2014). Because fertilizer rates were identical across treatments, specific fertilizer replacement rates remain to be tested. Given the two-year, single-site design, wider recommendations require validation across environments and economic assessment. Environmental evaluation is also necessary because soil carbon benefits can coincide with increased reactive nitrogen losses under straw return (Xia et al. 2018). Microbial associations require functional validation, while repeated sampling across both crop seasons would help distinguish management responses from seasonal variation.

5. Conclusions

This two-year wheat–maize experiment identified contrasting P and K responses to tillage and straw management. FS and DS generally increased grain yield and P accumulation, while MP favored maize performance. Between maize harvests, AP and maize P accumulation increased, whereas AK, maize K accumulation, and grain yield declined. These contrasting responses support assessing soil nutrient availability, crop acquisition, and grain production together. For comparable production conditions, the findings support evaluating full straw return with locally appropriate tillage and monitoring P and K separately. DS requires assessment of its additional benefits and costs, and fertilizer replacement rates remain to be tested. Microbial associations provide targets for functional validation.

Declarations

Authorship contribution statement

SA: Writing – original draft. XM and YW: Supervision. All authors: Writing – review & editing. All authors approved the final version of the manuscript for submission.

Competing interest

the authors declare no competing interests.

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Data availability

The replicate-level raw data supporting the findings of this study are provided in the supplementary material.

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Figures

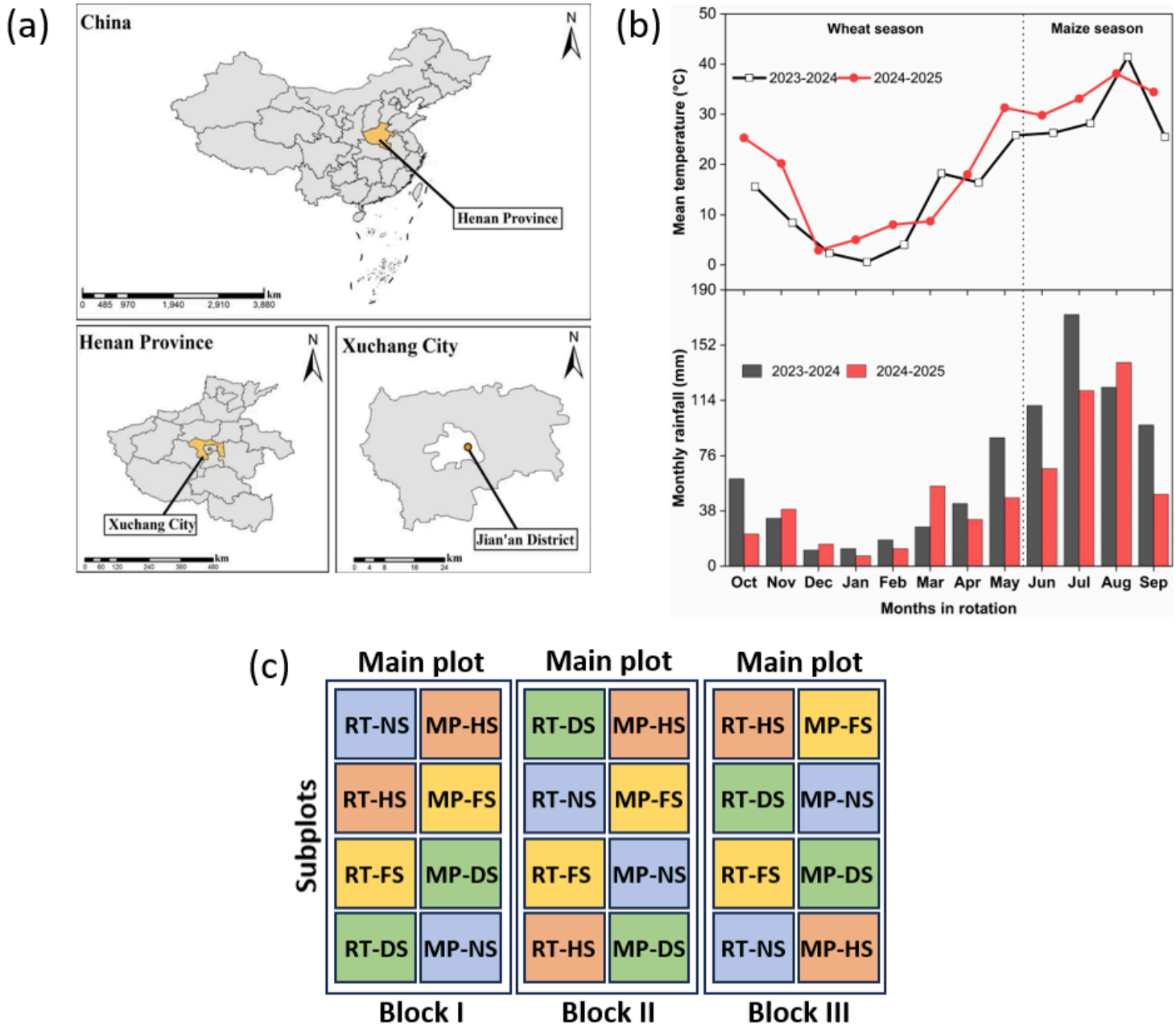


Figure 1

Study location, climate and experimental design. (a) Experimental site in Jian'an District, Henan Province, China. (b) Monthly mean air temperature and total monthly precipitation during the two wheat-maize rotations. (c) Split-plot design with three blocks, each containing two tillage main plots, with four straw

return subplots per main plot. Treatments remained unchanged throughout the experiment. Treatment abbreviations: RT, rotary tillage; MP, moldboard plowing; NS, no straw return; HS, half straw return; FS, full straw return; DS, double straw return.

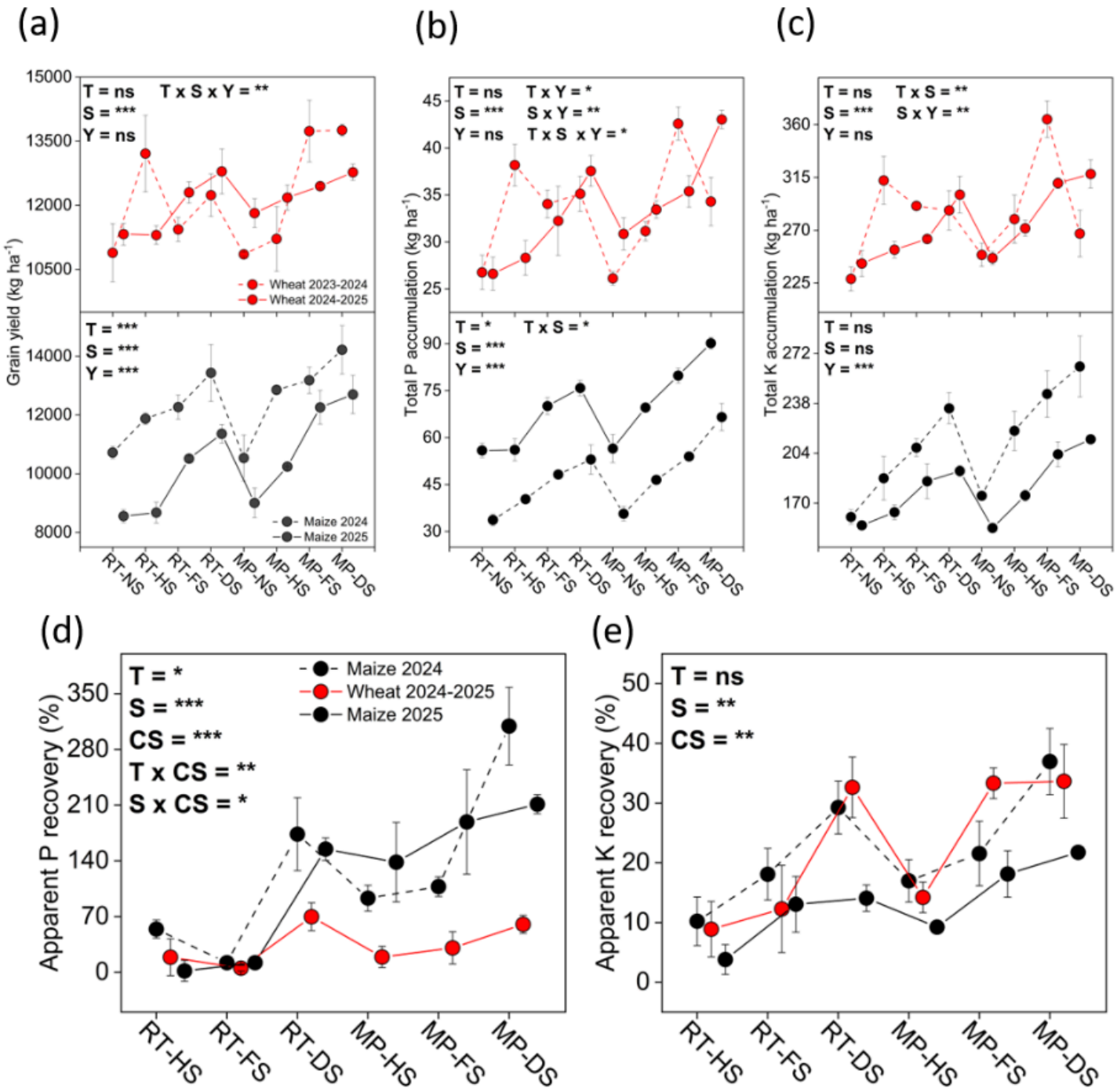


Figure 2

Grain yield, total aboveground phosphorus (P) and potassium (K) accumulation, and apparent straw P and K recovery under different tillage and straw return treatments. Panels show grain yield (a), total P accumulation (b), total K accumulation (c), apparent P recovery (d), and apparent K recovery (e). Values are means ± SE (n = 3 blocks). Colors differentiate crops, while dashed and solid lines indicate cropping

seasons. Annotations show Type III Kenward–Roger F-tests from repeated-measures mixed models: T, tillage; S, straw return; Y, year; CS, cropping season. *, P < 0.05; **, P < 0.01; ***, P < 0.001; ns, not significant. Treatment abbreviations follow (Fig. 1).

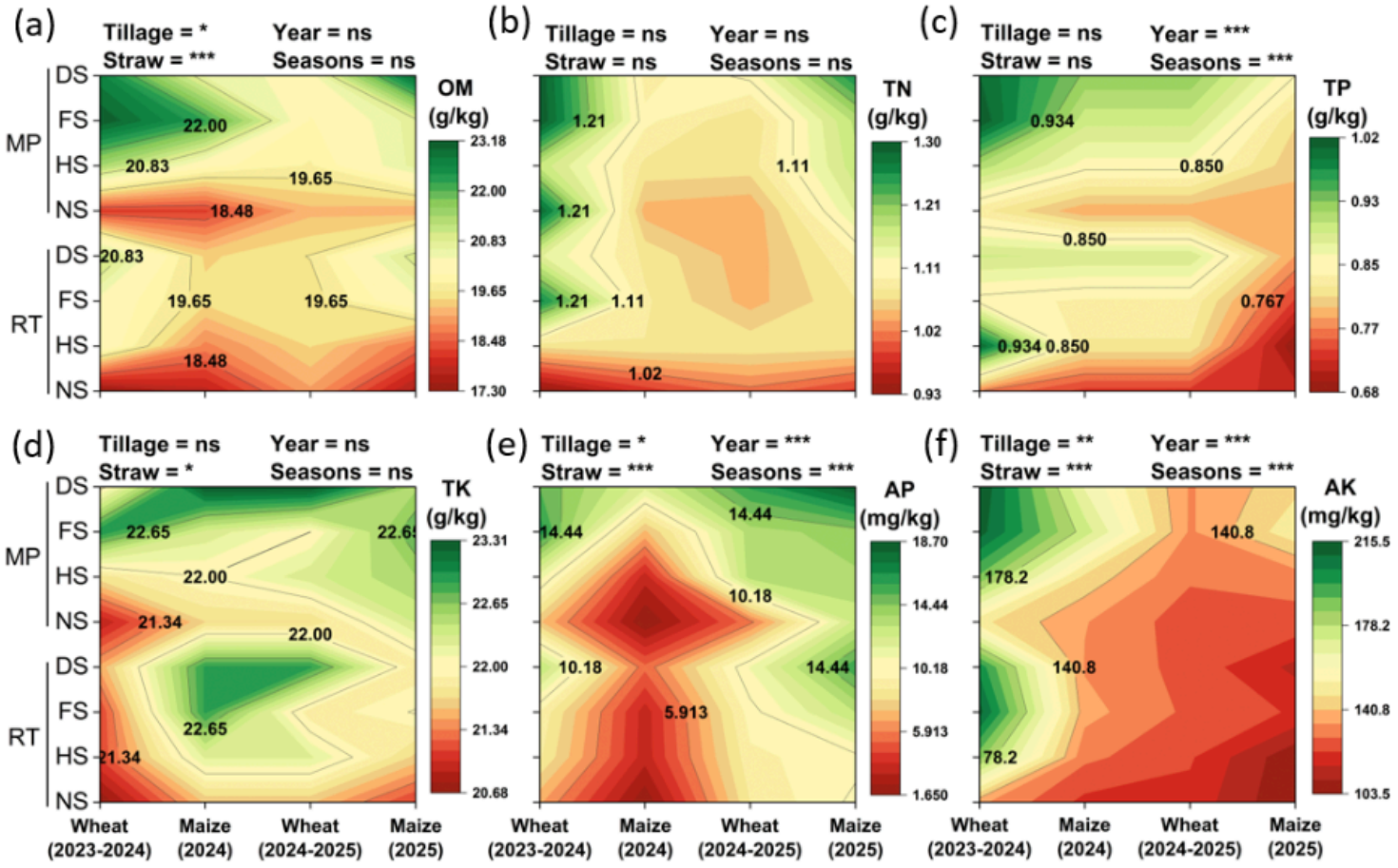


Figure 3

Topsoil organic matter and nutrient concentrations across two wheat-maize rotations. Panels show organic matter (a), total nitrogen (b), total phosphorus (c), total potassium (d), available phosphorus (e) and available potassium (f) in the 0–20 cm layer at four successive harvests. Contours represent interpolated treatment means (n = 3 blocks per treatment and harvest). Annotations show Type III F-tests for tillage, straw return, rotation year and sampling season. *, P < 0.05; **, P < 0.01; ***, P < 0.001; ns, not significant. Treatment abbreviations follow (Fig. 1).

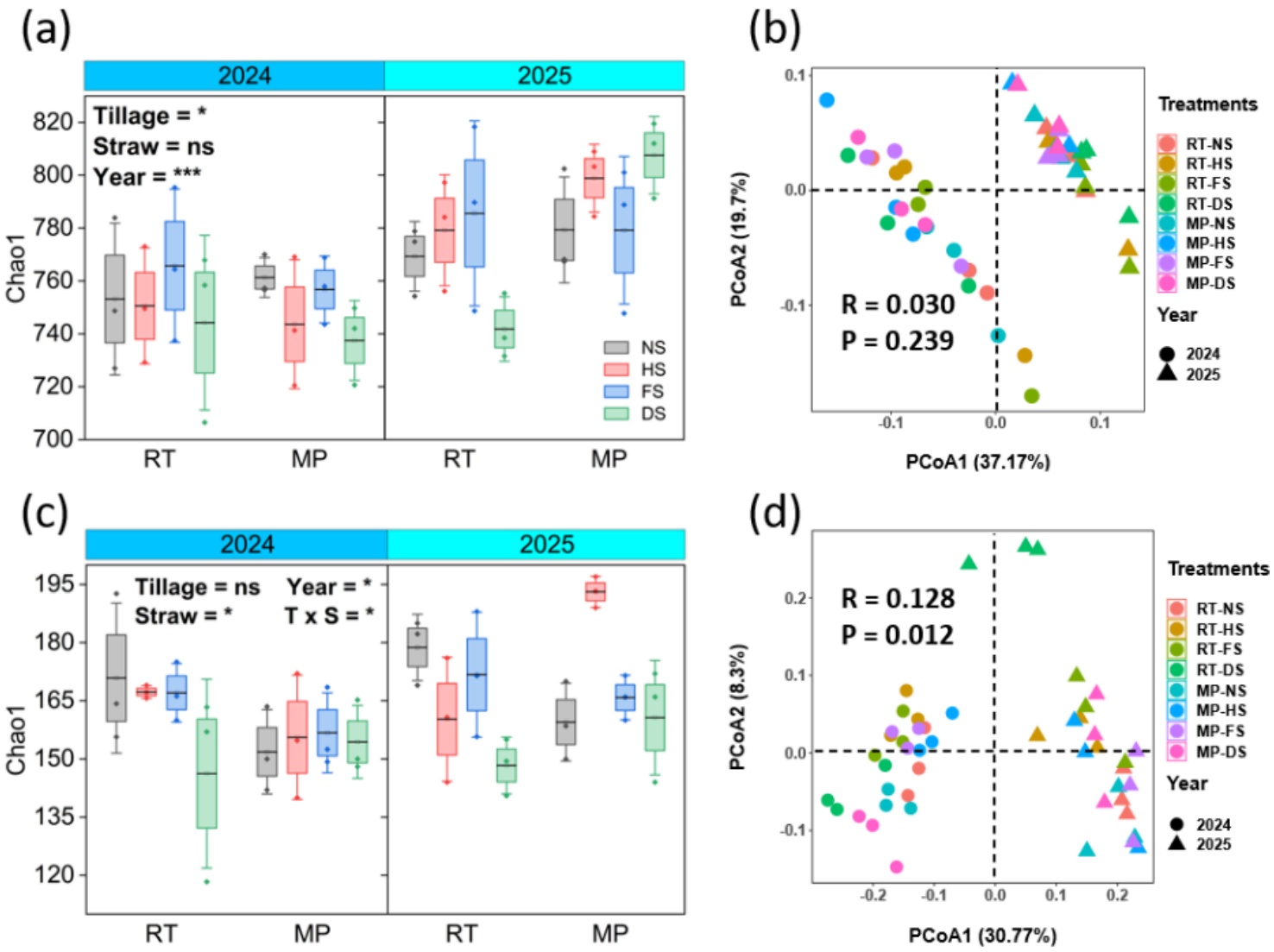


Figure 4

Soil bacterial and fungal richness and community composition after maize harvest in 2024 and 2025. Panels show bacterial Chao1 richness (a) and PCoA (b), and fungal Chao1 richness (c) and PCoA (d). Boxes represent mean ± SE, whiskers indicate mean ± SD, and points show block replicates (n = 3 per treatment–year). Chao1 annotations show Type III Kenward–Roger F-tests from repeated-measures mixed models. PCoA uses Bray–Curtis dissimilarities; colors identify treatments, and circles and triangles indicate 2024 and 2025, respectively. ANOSIM compares eight treatment combinations across both years. *, P < 0.05; **, P < 0.01; ***, P < 0.001; ns, not significant. Treatment abbreviations follow (Fig. 1).

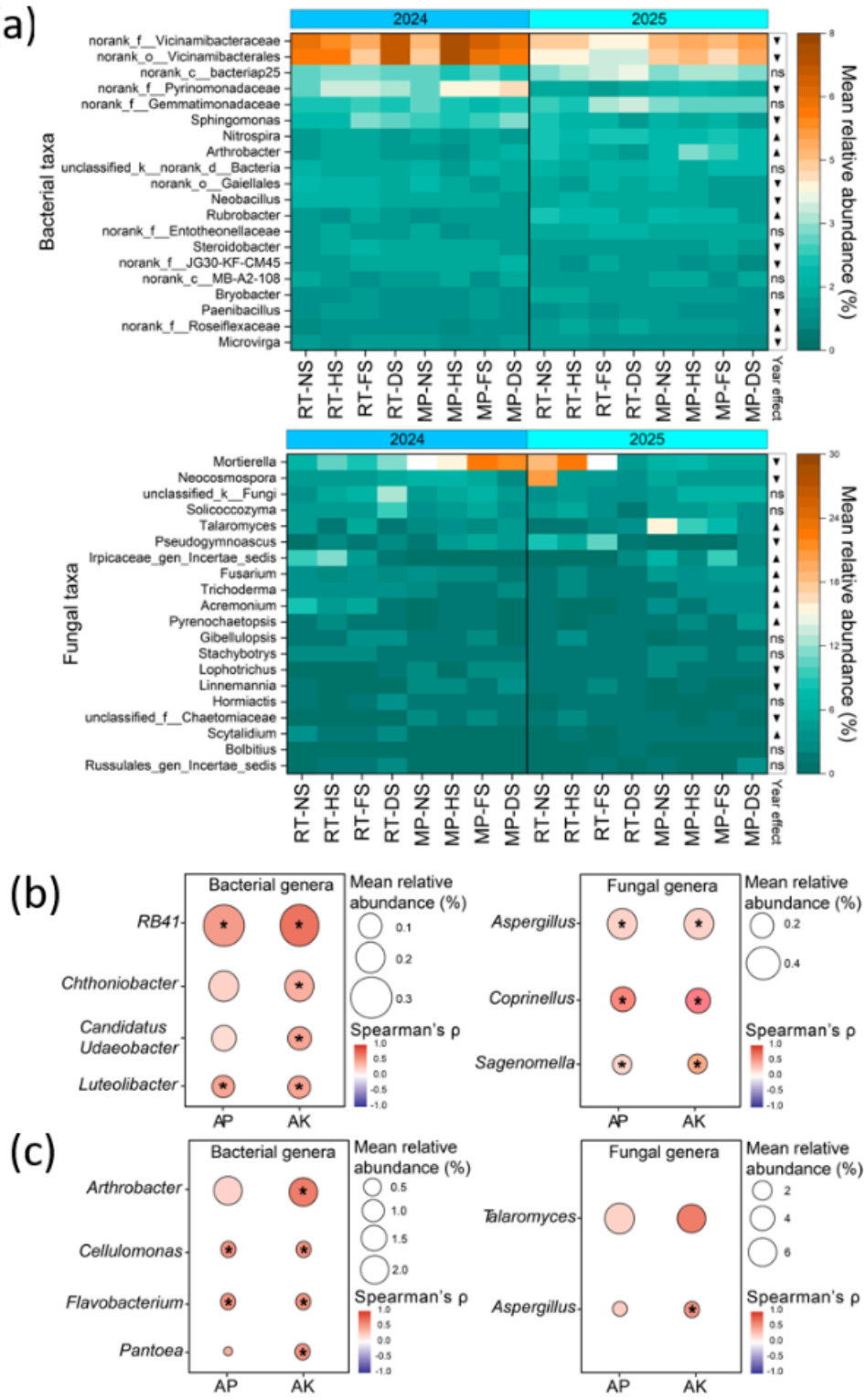


Figure 5

Microbial composition and associations with soil available phosphorus (AP) and potassium (AK). **(a)** Heatmaps of the top 20 taxa per microbial group, ranked by mean relative abundance across both years (n = 3 blocks per treatment–year). Labels indicate genera or higher taxonomic ranks where genus assignments are unavailable. ▲/▼ indicate significant increases/decreases from 2024 to 2025 based on centered log-ratio abundances (FDR q < 0.05); ns, nonsignificant. **(b, c)** Spearman correlations for

2024 and 2025, respectively (n = 24 subplots per year). Bubble color indicates ρ; size indicates mean relative abundance. *, q < 0.05 following Benjamini–Hochberg correction within each nutrient–year–microbial group. Treatment abbreviations follow (Fig. 1).

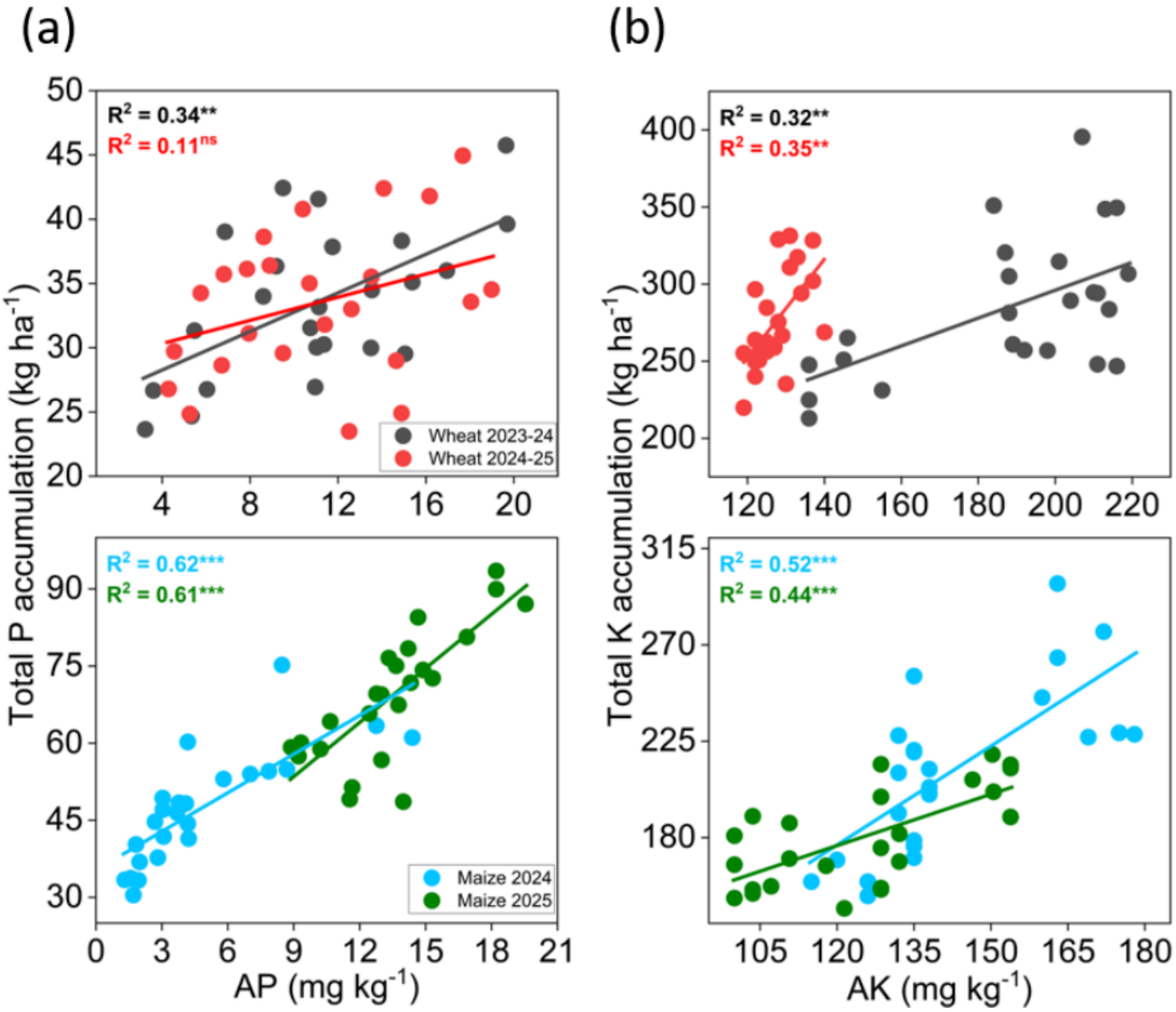


Figure 6

Relationships between soil nutrient availability and crop nutrient accumulation. Panels show available phosphorus versus total aboveground P accumulation (a) and available potassium versus total aboveground K accumulation (b) for wheat and maize. Points represent paired soil and crop measurements from individual subplots (n = 24 per crop-year). Colors distinguish growing seasons, and lines show separate linear regressions for each crop-year. R^2 values and significance levels are shown: *, P < 0.05; **, P < 0.01; ***, P < 0.001; ns, not significant.

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