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## Research Article

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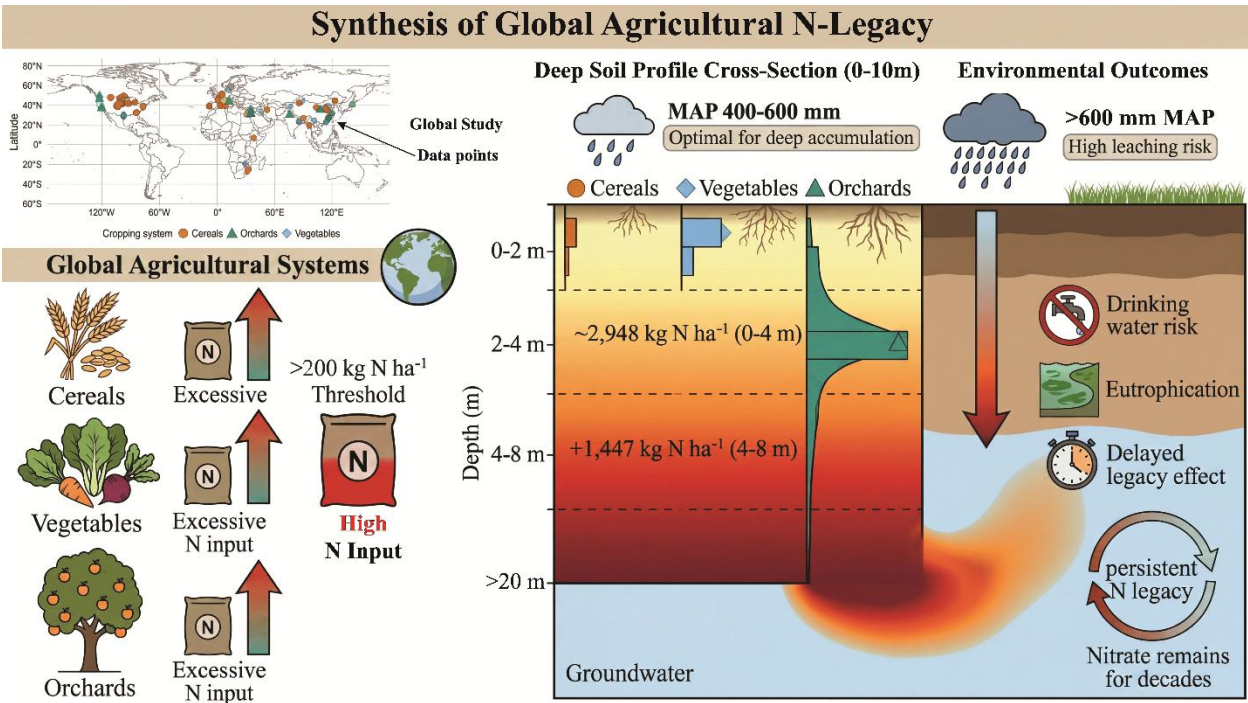
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## Abstract

Excessive nitrogen (N) inputs in agricultural systems have raised concerns regarding nitrate accumulation and associated environmental risks; however, most assessments remain limited to shallow soil profiles. In this study, we conducted a global synthesis to quantify the magnitude, depth distribution, and key drivers of nitrate accumulation in deep soil profiles across major agricultural land uses, including cereals, vegetables, and orchards, with soil profiles extending to depths of 0–10 m. We compiled depth-measured nitrate data and examined the effects of total N input rates, mean annual precipitation (MAP), and N surplus on nitrate accumulation patterns. Across all systems, substantial nitrate accumulation was detected well below the rooting zone, indicating widespread nitrate leaching into deep soil layers. Land use type strongly modulated nitrate accumulation, with orchards exhibiting the largest and deepest nitrate pools, vegetables showing high surface accumulation but limited deep storage, and cereals displaying comparatively lower accumulation across all depths. Nitrate stocks increased nonlinearly with rising N inputs, with pronounced accumulation occurring once inputs exceeded approximately 200 kg N ha<sup>-1</sup>, particularly in the 2–4 m and >4 m soil profiles. MAP exerted nonlinear control on nitrate redistribution, with moderate precipitation (400–600 mm) promoting nitrate accumulation in the 2–4 m layer, whereas high precipitation (>600) reduced deep soil (>4 m) accumulation, which is consistent with enhanced leaching beyond the sampled depth. N surplus alone explained only a limited proportion of the variability, highlighting the importance of interacting management and climatic controls. Our results demonstrate that deep soil nitrate accumulation represents a widespread and persistent N legacy in global agroecosystems. Therefore, mitigating nitrate leaching losses requires strategies that reduce N surplus and limit downward nitrate transport,

emphasizing the need to incorporate deep soil processes into N management and environmental risk assessments.

# Graphical abstract



**Keywords:** Soil NO<sub>3</sub><sup>-</sup>-N, deep layers, key factors, global assessment, legacy nitrate, land use

## Introduction

Nitrogen (N) fertilization has increased dramatically over the past six decades, with global agricultural fertilizer consumption exceeding 100 million tons annually and continuing to increase in response to intensifying food production demands (Ludemann et al., 2024; Tufail et al., 2024; Martre et al., 2024). This increase has been particularly pronounced in rapidly developing agricultural economies, such as China and India, shifting the global hotspot of reactive nitrogen (Nr) pollution from historically industrialized regions toward Asia and other emerging economies

(Bijay & Craswell, 2021; Singh, 2025; Lee et al., 2025). Although N fertilization is essential for sustaining crop productivity, its inefficient use has resulted in severe environmental challenges. Globally, less than 50% of the applied N fertilizer is recovered by crops, whereas the remainder is retained in the soil or lost to the surrounding environment through volatilization, runoff, denitrification, and leaching (Udvardi et al., 2021; Govindasamy et al., 2023; Rehman et al., 2025). Consequently, excessive N application has become a major source of Nr pollution and ecosystem degradation. By 2010, the global quantifiable N surplus reached approximately 100 Tg N yr<sup>-1</sup>, contributing substantially to soil acidification, eutrophication, and environmental degradation (Ascott et al., 2017; Stevens, 2019; Raza et al., 2020).

Among the N loss pathways, nitrate leaching is one of the most environmentally concerning processes because of the high solubility and mobility of nitrate in soil-water systems. Once N inputs exceed plant demand, surplus N can migrate downward beyond the rooting zone and accumulate within deeper soil layers and vadose zones, forming long-term deep-N reservoirs. This process is increasingly recognized as a major, but underappreciated, component of agricultural N cycling (Follett & Hatfield, 2001). Field-based evidence demonstrates the scale of these issues. For example, excessive N application in intensive agricultural systems results in nitrate losses ranging from 59.3 kg N ha<sup>-1</sup> yr<sup>-1</sup> in fertilized potato systems to 6.1 kg N ha<sup>-1</sup> yr<sup>-1</sup> in unfertilized perennial systems (Shrestha et al., 2023). Similarly, vadose-zone monitoring in an Oregon sweet corn field showed that nearly 29% of the applied N leached below 3 m depth, whereas 27% remained stored in the soil profile as accumulated N (Weitzman et al., 2022). These findings indicate that nitrate transport below the root zone contributes to significant but poorly quantified deep-soil N storage.

Recent advances have highlighted the vadose zone as a major global reservoir of Nr. A global synthesis of 280 deep soil profiles (2 to 205 m) estimated that deep soil nitrate pools contain approximately 15.2 Pg N, which is an increase of nearly 16% from previous global soil N storage estimates (Almaraz et al., 2025). These findings challenge conventional paradigms that primarily consider N storage within shallow soils and indicate that current N budgets may substantially underestimate deep N accumulation. Supporting regional evidence from intensively cultivated systems further demonstrates the magnitude of this phenomenon. In the semi-humid croplands of China, extensive surveys (>7,000 samples) have reported nitrate accumulation of 453, 1191, and 2155 kg N ha<sup>-1</sup> in cereals, vegetable, and orchard systems, respectively, within the upper 0–4 m of soil, with similarly large nitrate pools observed below 4 m depth (Zhou et al., 2016).

Deep-soil nitrate accumulation has major environmental implications because these deep-soil N pools may persist for decades and act as delayed sources of groundwater and aquatic ecosystem contamination. In the Mississippi River Basin, legacy N stored in soils and aquifers continues to contribute substantially to riverine N export despite reductions in fertilizer use, indicating a prolonged lag between improved management and water quality recovery (Metaxoglou & Smith, 2025). Similar patterns of groundwater nitrate contamination exceeding drinking water thresholds have been documented across Europe, with subsurface hydrological properties strongly influencing nitrate transport and persistence (Zhan et al., 2024; Jayasekera et al., 2025). Because deep nitrate storage can remain isolated from biological uptake and denitrification processes, these reservoirs represent long-term “legacy nitrogen” pools capable of sustaining environmental pollution for decades after the initial accumulation.

The magnitude and redistribution of nitrate accumulation in soil profiles are strongly regulated by the interactions among N inputs, land use intensity, and hydroclimatic conditions.

Intensive agricultural systems, such as vegetable and orchard cultivation, typically receive substantially greater N inputs than cereal systems and are therefore associated with elevated nitrate accumulation and leaching risks (Weitzman et al., 2024; Wang et al., 2025). Land-use conversion and agricultural intensification can further alter N redistribution within soil profiles, with cropland expansion increasing nitrate accumulation at depths of 100–600 cm in converted tropical ecosystems (Popin et al., 2026). Climatic variability also exerts an important control on nitrate mobility. Increased precipitation enhances nitrate transport through soil profiles, although this relationship is often nonlinear and mediated by seasonal rainfall distribution, evapotranspiration, and soil hydraulic conditions (Wang et al., 2025). Furthermore, drought-rewetting cycles may accelerate N mineralization and remobilization, thereby increasing the vulnerability of stored N to episodic leaching (Pool et al., 2022; Shakoor et al., 2023).

Despite the increasing recognition of deep-soil nitrate storage as a globally important environmental issue, substantial knowledge gaps remain regarding its magnitude, vertical distribution, and controlling mechanisms across agricultural systems. Existing studies are often geographically constrained, focused on shallow soil depths, or limited to single cropping systems, preventing a comprehensive assessment of how nitrate accumulation varies among land-use types and climatic conditions at the global scale. More importantly, the interactions between N inputs, agricultural land use, and precipitation in the regulation of depth-dependent nitrate redistribution remain poorly understood.

Our study presents a global synthesis of nitrate accumulation across agricultural soils to a depth of 0–10 m, including cereals, vegetables, and orchards. The main aims are to (i) quantify the magnitude and depth-dependent distribution of nitrate accumulation across global agricultural soils, (ii) determine how land-use type influences nitrate storage and vertical migration, and (iii)

evaluate the role of precipitation in regulating nitrate retention versus downward transport. We hypothesized that (1) N surplus generated by excessive fertilization drives nitrate accumulation below the root zone (<1 m) and increases deep-soil legacy N reservoirs; (2) land-use type regulates the magnitude and vertical distribution of nitrate storage, with vegetable and orchard systems exhibiting greater accumulation than cereal systems owing to higher N inputs; and (3) mean annual precipitation (MAP) exerts nonlinear control over nitrate redistribution by facilitating downward nitrate transport and deep-soil accumulation. By linking N management, hydroclimatic conditions, and land-use effects to deep-soil nitrate storage, this study advances the understanding of agricultural N cycling and provides new insights into the environmental risks associated with legacy nitrogen accumulation.

## **Materials and methods**

### **Literature search and study selection**

A global dataset of soil nitrate accumulation in agricultural systems was compiled from peer-reviewed studies sourced from ISI Web of Science (Thomson Reuters, New York, NY, USA), Google Scholar (Google Inc., Mountain View, CA, USA), and China National Knowledge Infrastructure (CNKI). The literature search included studies until September 30, 2025.

The search was conducted using combination of terms related to soil nitrate accumulation, nitrogen management, soil-profile characteristics, hydrological processes, and agricultural land use. Search terms included “soil nitrate” OR “soil nitrate accumulation” OR “nitrate storage” OR “ $\text{NO}_3^-$ -N” OR “nitrogen” OR “nitrogen management” OR “agriculture lands/systems” OR “nitrate leaching” OR “total N inputs” OR “soil profile nitrate” OR “soil depths” OR “vadose/unsaturated/critical zone” OR “key drivers/factors” OR “cereals/vegetables/orchards”. Duplicate records were removed before screening. Studies were subsequently evaluated for inclusion according to the following criteria: (1) the study was conducted under

field conditions on agricultural land, whereas greenhouse and pot experiment were excluded; (2) the study covered at least one growing season; and (3) soil nitrate storage or sufficient information to calculate soil nitrate storage was available from soil profile sampling. Following screening and removal of duplicate or unsuitable studies, 101 studies were retained for global synthesis. The geographical distribution of the study sites included in the global synthesis is presented in Figure 1. The sites represented cereal, vegetable, and orchard systems distributed across a range of climatic and soil conditions.

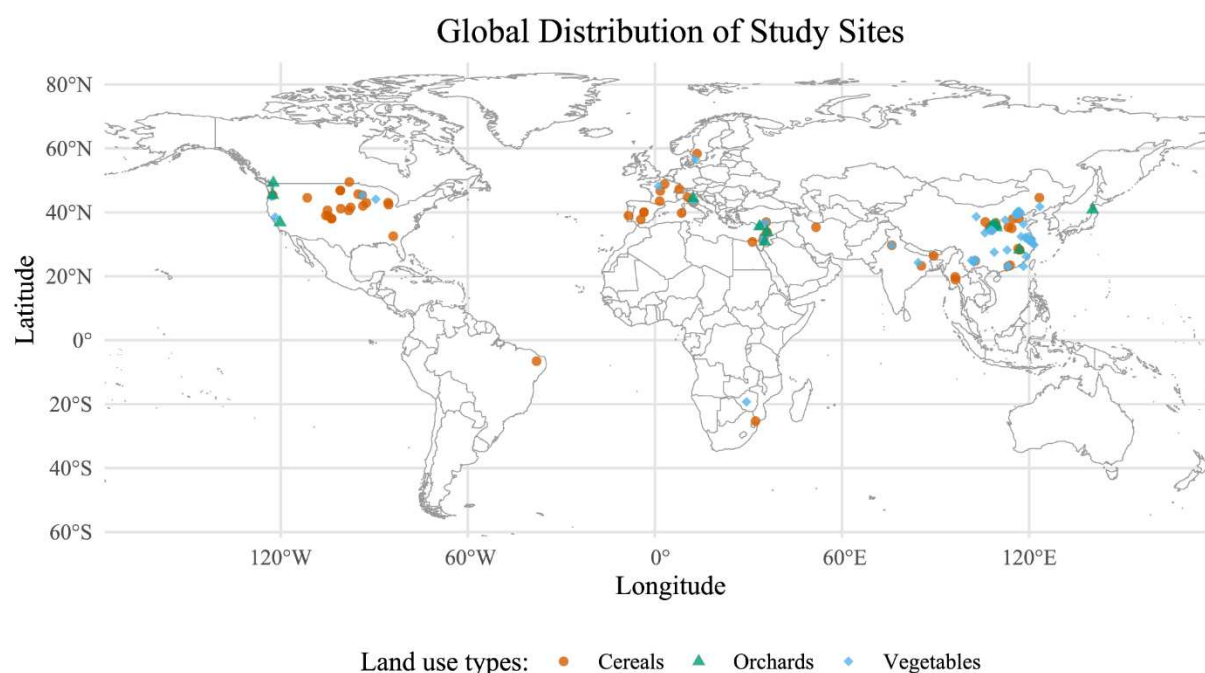


**Fig. 1** The global distribution of the study sites included in this analysis assessed soil nitrate accumulation across diverse land use types. Distinct colors and shapes represent different agricultural land-use types, including cereals (orange), vegetables (green), and orchards (blue)

Data extraction and database construction

Data were extracted from tables, supplementary materials, and figures of the selected publications. When numerical values were available only in the figures, the data were digitized using Get-Data Graph Digitizer version 2.22 (<http://getdata-graph-digitizer.com>). For each study, information was extracted on experimental location, agricultural land-use type, soil-profile nitrate concentration or accumulation, soil sampling depth, and total N input. Where available, additional management, climatic, and soil variables were recorded, including mean annual precipitation (MAP), mean annual temperature (MAT), irrigation, evapotranspiration (ET), soil pH, soil total nitrogen (TN), soil organic carbon (SOC), soil carbon-to-nitrogen ratio (C:N), and soil available phosphorus (AP) content. Total N input included mineral fertilizer + organic and inorganic N sources, where such information was reported in the original study.

Data harmonization and calculation

To quantify the magnitude and depth-dependent distribution of soil nitrate accumulation, data were grouped according to land use type (cereals, vegetables, and orchards), soil depth (0–2, 2–4, 4–6, 6–8, and 8–10 m), total N input (<100, 100–200, 200–300, 300–500, and >500 kg N ha<sup>-1</sup>), and MAP (<400, 400–600, 600–800, and >800 mm).

All soil nitrate data were converted to comparable units prior to analysis. When a study directly reported soil nitrate accumulation, the reported values were used. When only soil nitrate-N concentration was available, soil nitrate accumulation was calculated for individual soil layers using Eq. (1) (Wang et al., 2024)

$$SNA = \sum SNC \times BD \times T \times 10^{-1} \dots\dots\dots (1)$$

where SNA, SNC, BD, and T represent soil nitrate accumulation ( $\text{kg N ha}^{-1}$ ), soil nitrate concentration ( $\text{mg N kg}^{-1}$ ), soil bulk density ( $\text{g cm}^{-3}$ ), and soil layer thickness (cm), respectively.

In cases where studies did not report BD values, we estimated BD using soil SOC with the following Eq. (2) (Khan et al., 2025)

$$\text{BD} = 1.377 \times \text{Exp}(-0.0048 \times \text{SOC}) \dots\dots\dots (2)$$

Nitrogen surplus was calculated using Eq. (3) (Zhang et al., 2015)

$$\text{N surplus} = \text{N input} - \text{Harvested N} \dots\dots\dots (3)$$

Where N input represents the total amount of applied nitrogen and harvested N represents total N uptake by aboveground biomass harvested at crop maturity. For consistency throughout this study, N surplus was treated as an N-budget indicator representing the imbalance between the reported total N input and crop N removal rather than as a direct measurement of nitrate remaining in the soil profile.

## Statistical analyses

A Random Forest model was used as an exploratory variable importance analysis to identify the major management, climatic, and soil factors associated with nitrate accumulation. Key predictors included total N input, soil depth, MAT, MAP, soil pH, ET, irrigation, TN, SOC, C:N ratio, and AP according to data availability. Random Forest analyses were conducted for overall dataset and separately for each land use types. The importance of each predictor was evaluated using the percentage increase in the mean squared error (%IncMSE). Based on their overall random forest importance and mechanistic relevance to nitrate supply, hydrological

transport, and vertical distribution, total N input, MAP, and soil depth were selected for subsequent detailed analyses of nitrate accumulation and redistribution in soil profile.

Depth-dependent nitrate accumulation was summarized as the mean  $\pm$  standard error (SE). Vertical distribution patterns were visualized using line-point plots, whereas variations in total N inputs and nitrate accumulation among soil depth intervals and land-use types were illustrated using box-and-whisker.

The relationship between N surplus and soil nitrate accumulation was evaluated using linear regression for the overall dataset and separately for each land use type. Model performance was assessed using the coefficient of determination ( $R^2$ ), and statistical significance was evaluated at  $p < 0.05$ . Statistical analyses and graphical visualizations were performed using R, Origin Pro 2024, and Microsoft Excel 2024.

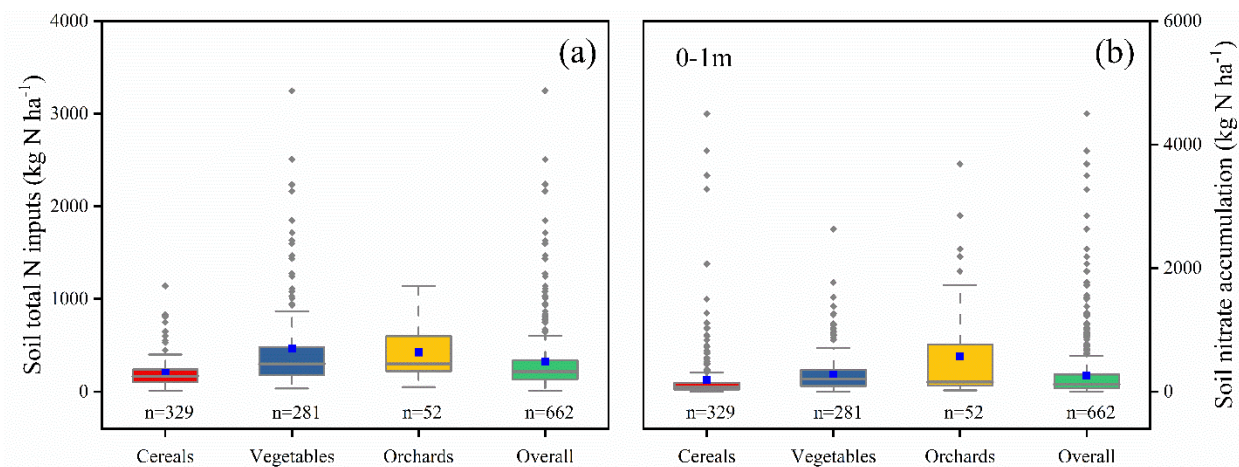


**Fig. 2** Box-and-whisker plots illustrating (a) total N input and (b) soil nitrate accumulation (0-1 m) soil profile. In each panel, the box denotes the interquartile range (IQR; 25th-75th percentiles), representing the central 50% of the observations. The thick horizontal line within the box indicates

the median, and open squares represent the mean values. Whiskers extend to the most extreme observations within  $1.5 \times \text{IQR}$  from the lower (Q1) and upper (Q3) quartiles, whereas solid diamond symbols indicate outliers beyond this range. The colors correspond to the land-use types: cereals (red), vegetables (blue), orchards (yellow), and overall (green). The figure highlights the vertical distribution, variability, and comparative magnitude of nitrate accumulation with respect to N inputs across different agricultural systems

## Results

### Magnitude and vertical distribution of nitrate accumulation in soil profile

The distribution of total N inputs and soil nitrate accumulation exhibited substantial variation across different agricultural land use types (Fig. 2). Orchard systems showed the highest N inputs and nitrate accumulation, whereas cereal systems generally recorded the lowest. Vegetable systems displayed an intermediate response. Depth-dependent comparison further highlighted notable differences in nitrate storage across the soil profile (Fig. 3). The most substantial nitrate accumulation was observed in orchard, particularly at depths of 0–2 and 2–4 m, followed by a decline in deeper layers. Conversely, cereal and vegetable systems maintained relatively lower nitrate stocks throughout the profile.

The synthesis further revealed substantial nitrate accumulation throughout the 0–10 m soil profile in global agricultural lands, with substantial stocks extending well below the root zone (Fig. 4a). The average nitrate accumulation in the 0–4 m profile was  $2948 \pm 483 \text{ kg N ha}^{-1}$  across all land uses, with an additional  $1447 \pm 329 \text{ kg N ha}^{-1}$  stored between 4–8 m, indicating extensive deep-soil nitrate storage. Orchard systems consistently exhibited the highest nitrate accumulation at all depths, with  $7461 \pm 1131 \text{ kg N ha}^{-1}$  in the 0–4 m layer, which was more than five times

higher than that in cereal and vegetable systems (Fig. 4b and Table S1). Notably, peak nitrate accumulation in orchards occurred below the shallow soil (2–4 m), whereas cereals and vegetables displayed more moderate and vertically distributed nitrate profiles.

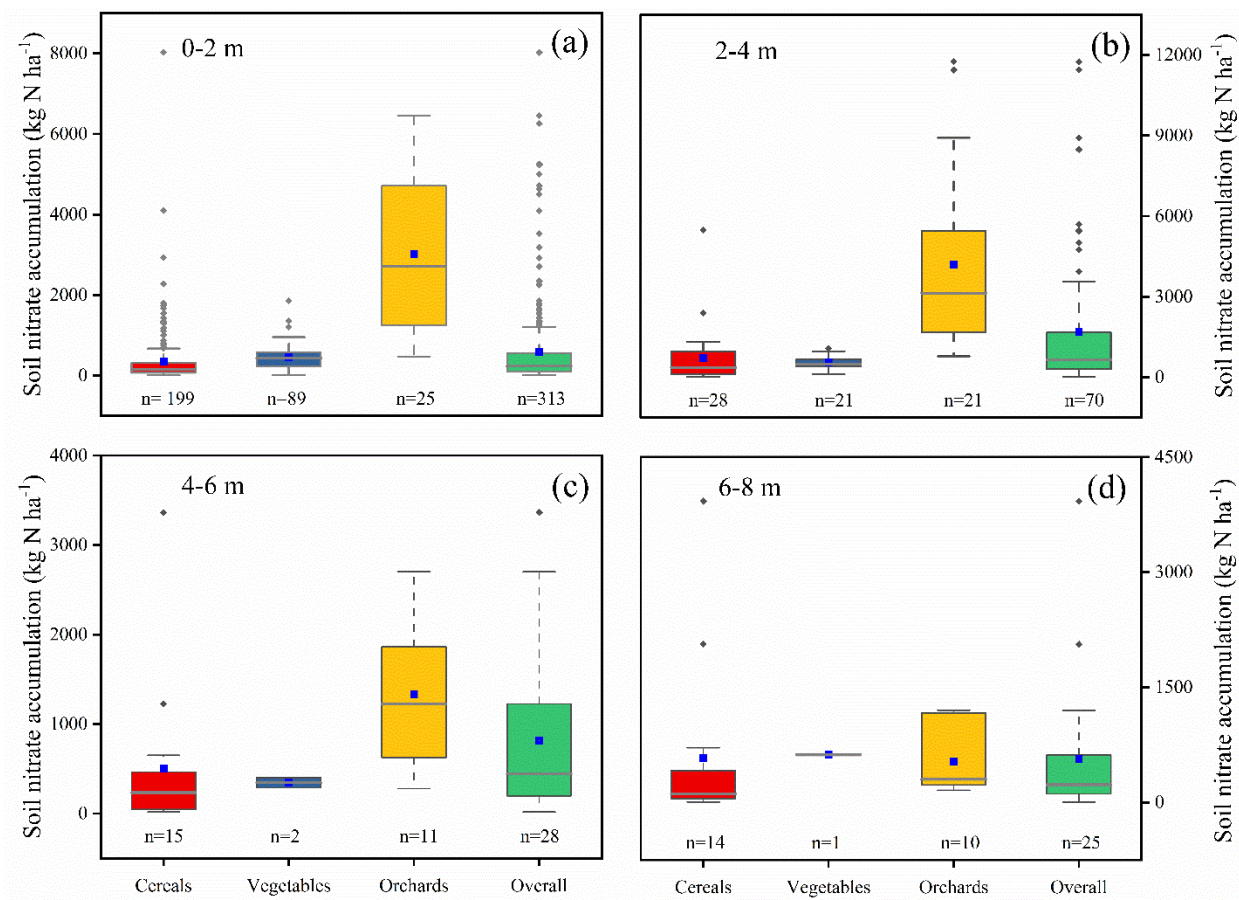


**Fig. 3** Box-and-whisker plots illustrating soil nitrate accumulation across different soil depths. Panels represent (a) 0–2 m, (b) 2–4 m, (c) 4–6 m, (d) 6–8 m, soil profile. In each panel, the box denotes the interquartile range (IQR; 25th–75th percentiles), representing the central 50% of the observations. The thick horizontal line within the box indicates the median, and the open squares represent the mean values. Whiskers extend to the most extreme observations within  $1.5 \times \text{IQR}$  from the lower (Q1) and upper (Q3) quartiles, whereas solid diamond symbols indicate outliers beyond this range. The colors correspond to the land-use types: cereals (red), vegetables (blue),

orchards (yellow), and overall (green). The figure highlights the vertical distribution, variability, and comparative magnitude of nitrate accumulation with respect to N inputs across different agricultural systems

Across different regions and land use types, agricultural systems in China showed substantially higher soil nitrate accumulation than the global average (Table S2 and S3). Specifically, orchard systems in China accumulated ( $7858 \pm 1150 \text{ kg N ha}^{-1}$ ), which is over 30 times greater than the accumulation observed in other countries ( $257 \pm 98 \text{ kg N ha}^{-1}$ ), despite only 2–3-fold higher total N inputs. In cereal systems, China recorded an accumulation of ( $1413 \pm 362 \text{ kg N ha}^{-1}$ ), nearly ten times the accumulation found in other countries ( $153 \pm 14 \text{ kg N ha}^{-1}$ ). Furthermore, vegetable systems in China also showed increased nitrate accumulation ( $440 \pm 27 \text{ kg N ha}^{-1}$ ) compared to other countries ( $260 \pm 56 \text{ kg N ha}^{-1}$ ), which aligns with the higher N inputs (Table S3).

#### Key drivers of soil nitrate accumulation in agricultural lands

Land use types and different regions have substantial effects on the soil nitrate accumulation at different soil depths. To further identify the key factors that drive nitrate from shallow soil to deeper soil, we tested the effect of total N input rates, mean annual precipitation and N surplus on soil nitrate accumulation.

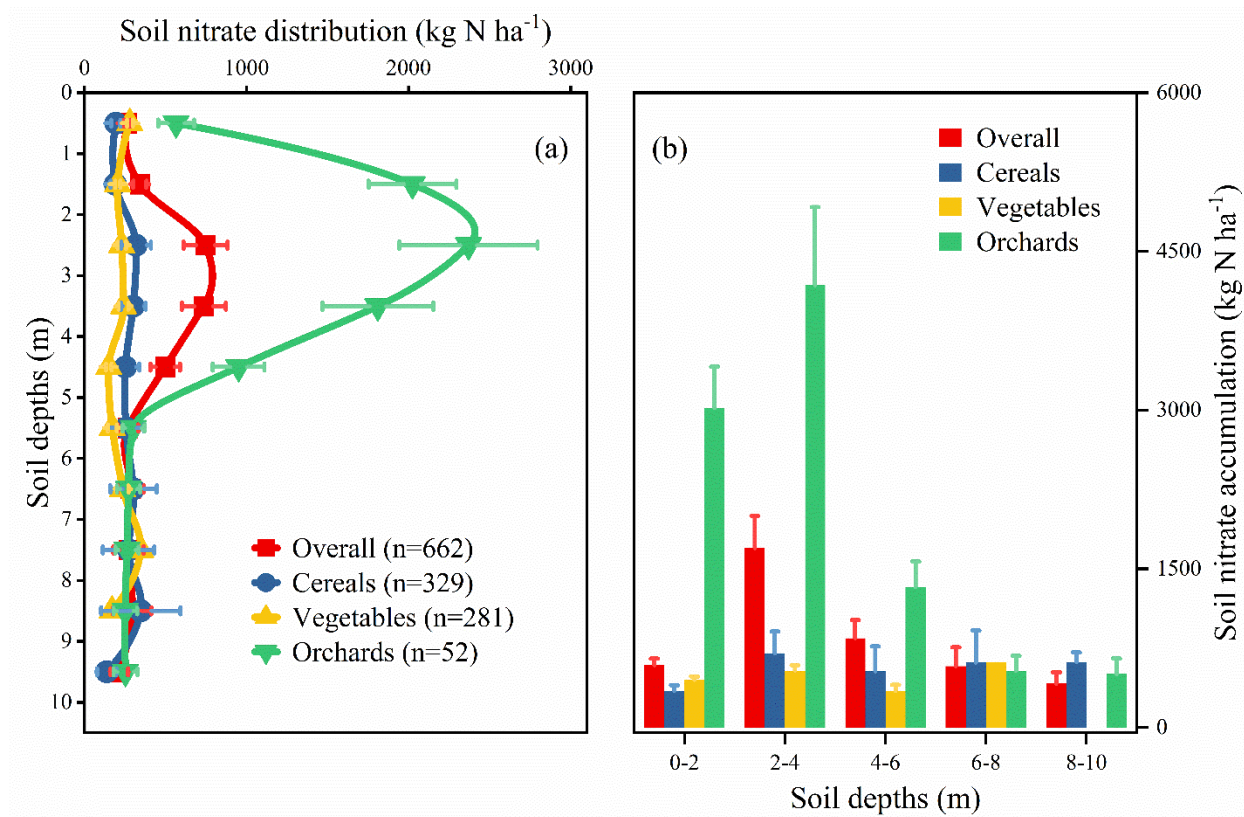


**Fig. 4** Patterns of soil nitrate distribution and accumulation across soil profiles in global agricultural systems. (a) The vertical distribution of soil nitrate concentration in the soil profile (0–10 m) is presented as mean trends with individual data points (line + point). (b) Soil nitrate accumulation was sub-grouped into five depth intervals (0–2, 2–4, 4–6, 6–8, and 8–10 m), illustrated using bar charts to emphasize depth-dependent storage

## Total N inputs

Total N inputs exerted a strong effect on both the magnitude and vertical distribution of soil nitrate accumulation across agricultural land use types (Fig. 5). Across all agricultural land uses, nitrate accumulation within the 0–2 m soil profile increased from  $292 \pm 32$  kg N ha<sup>-1</sup> at N inputs of less than 100 kg N ha<sup>-1</sup> to  $1873 \pm 319$  kg N ha<sup>-1</sup> at inputs greater than 500 kg N ha<sup>-1</sup>, accompanied by a substantial increase in 2–4 m soil profile ( $4031 \pm 760$  kg N ha<sup>-1</sup>). A distinct

threshold response was observed at approximately 200–300 kg N ha<sup>-1</sup>, beyond which nitrate accumulation intensified sharply and extended below the root zone (Fig. 5a and Table S4).

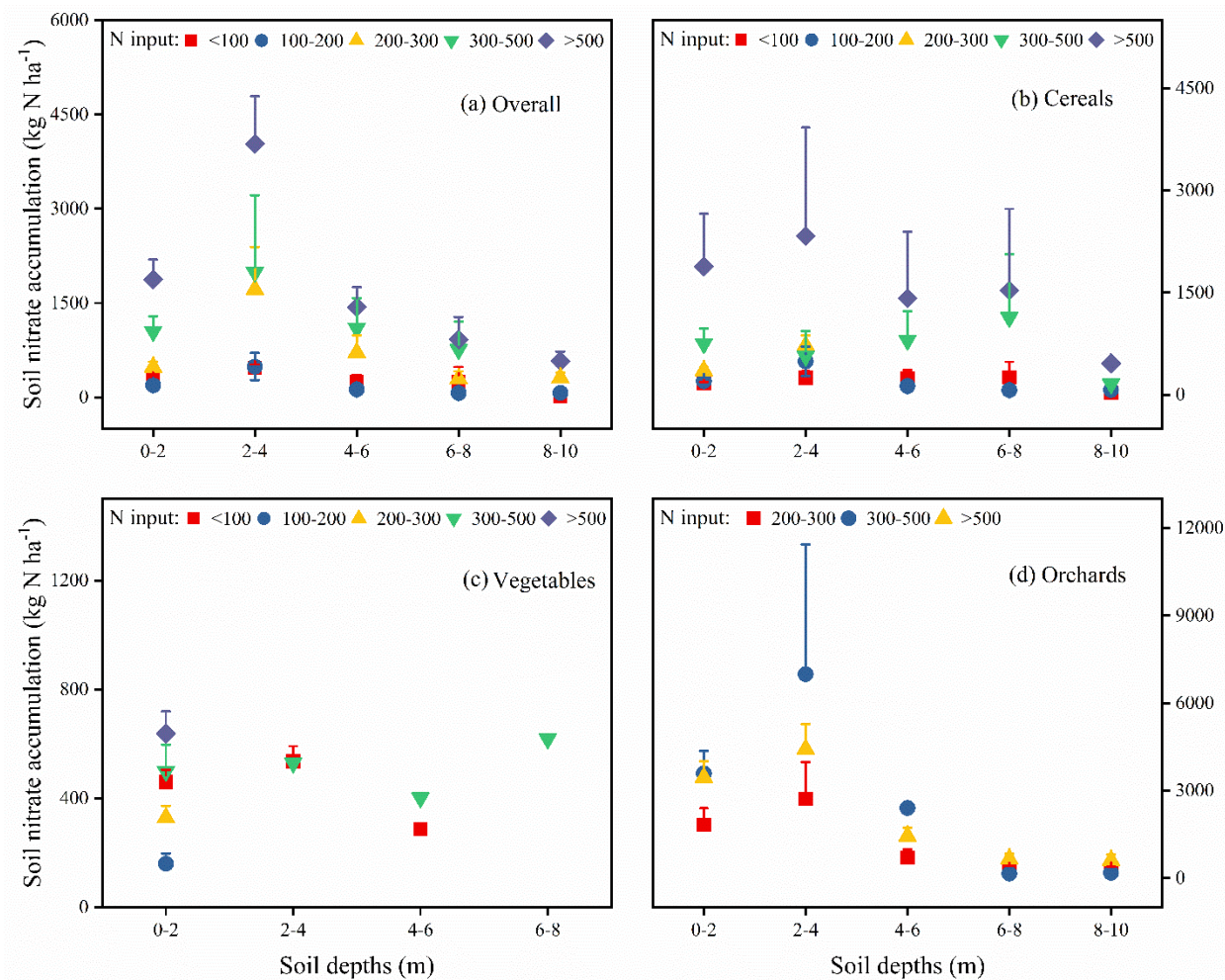


**Fig. 5** Depth-dependent effects of total N input rates on soil nitrate accumulation across different agricultural land use types. The mean soil nitrate accumulation is shown for distinct soil depth intervals across different land use types (a) overall, (b) cereals, (c) vegetables, and (d) orchards. Increasing total N input rates are associated with greater nitrate accumulation and pronounced differences in land-use type in the magnitude and depth of nitrate storage

Among different land use types, cereal systems demonstrated a gradual yet consistent increase in nitrate accumulation with elevated N inputs across depths, with 0–2 m nitrate stocks increasing from  $169 \pm 20$  to  $1884 \pm 773$  kg N ha<sup>-1</sup> between the lowest and highest N input, accompanied by a substantial rise in subsoil nitrate storage (2–4 m: up to  $2332 \pm 1594$  kg N ha<sup>-1</sup>; (Fig. 5b; Table S5). Vegetable systems displayed high sensitivity in both the shallow and subsoil layers (0–2 m: up to  $638 \pm 82$  kg N ha<sup>-1</sup>) but showed comparatively limited deep-soil accumulation (Fig. 5c, Table S6). Orchard systems exhibited the most pronounced nonlinear response, with exceptionally large nitrate pools forming below 2 m (up to  $6994 \pm 4450$  kg N ha<sup>-1</sup> in 2–4 m layer) even with moderate N inputs (Fig. 5d; Table S7). Overall, increasing N inputs amplified both the magnitude and vertical redistribution of soil nitrate, particularly in the perennial systems.

#### Nitrogen surplus

Soil nitrate accumulation was observed to increase with N surplus across global agricultural lands; however, the magnitude of this relationship varied among land use types (Fig. 6). When all agricultural lands were considered collectively, nitrate accumulation exhibited a positive correlation with N surplus ( $R^2 = 0.083$ ,  $p < 0.001$ ), although the N surplus accounted for only a modest proportion of overall variability.

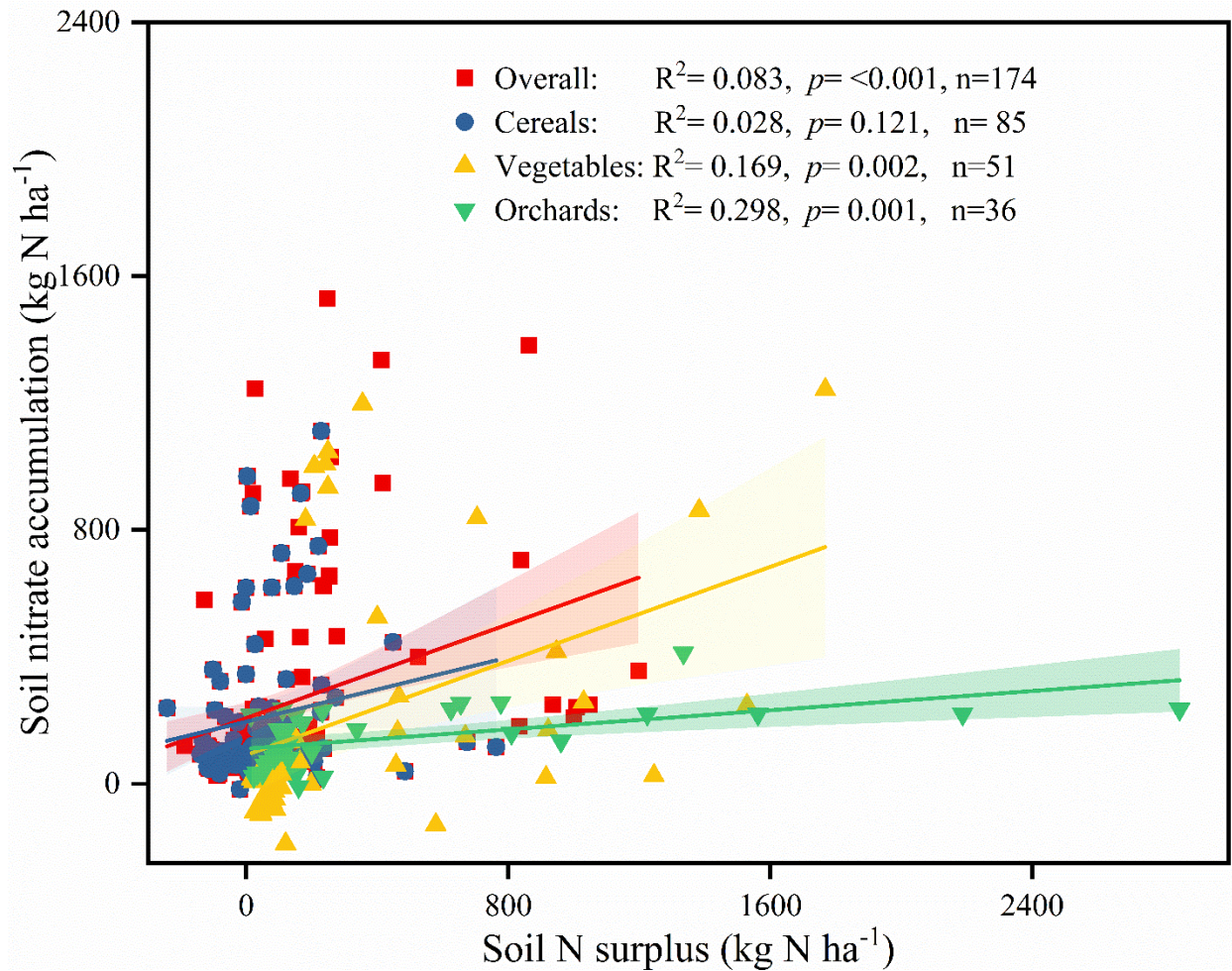


**Fig. 6** Relationship between N surplus and soil nitrate accumulation across different agricultural land-use types. Points represent individual observations, and solid lines indicate fitted linear regressions with shaded areas representing the 95% confidence intervals. The results are shown: overall (red) and cereals (blue), vegetables (yellow), and orchards (green) systems. The reported statistics denote the coefficient of determination ( $R^2$ ), significance level ( $p$ ), and sample size ( $n$ )

Land-use type regressions revealed contrasting results. In cereal systems, the relationship was weak and not statistically significant ( $R^2 = 0.028$ ,  $p = 0.121$ ), suggesting limited nitrate buildup

despite an increase in the N surplus. Conversely, the vegetable systems demonstrated a significant positive response ( $R^2 = 0.169$ ,  $p = 0.002$ ), with nitrate accumulation increasing consistently as the N surplus increased. The most pronounced response was observed in orchard systems, where nitrate accumulation increased sharply with N surplus ( $R^2 = 0.298$ ,  $p = 0.001$ ), underscoring their high susceptibility to the buildup of nitrate legacy. Collectively, these findings suggest that N surplus alone is insufficient to predict soil nitrate accumulation, and that land-use type processes play a crucial role in regulating nitrate storage and retention.

#### Mean annual precipitation

MAP showed a nonlinear influence on soil nitrate accumulation across various land uses and soil depths (Fig. 7; Tables S8–11). Overall, nitrate accumulation in shallow soils (0–2 m) increased from low MAP (<400 mm) to a peak at moderate MAP (400–600 mm;  $\sim 1038 \text{ kg N ha}^{-1}$ ) but declined under higher precipitation conditions (>600 mm; Fig. 7a). Similarly, nitrate storage in deeper soils (2–6 m) also reached its maximum at moderate MAP, indicating enhanced downward nitrate transport under moderate precipitation, whereas deep nitrate accumulation (>6 m) decreased markedly at MAP > 800 mm.

Cereal systems showed a similar response pattern to MAP across soil depths, with the highest nitrate accumulation occurring at 400–600 mm and reduced storage under high MAP (Fig. 7b). Vegetable systems consistently exhibited high nitrate accumulation in the shallow soil layers across all MAP classes but showed limited accumulation below 4 m, suggesting restricted deep nitrate penetration (Fig. 7c). Conversely, orchard systems exhibited the greatest sensitivity to precipitation, with notably large nitrate pools at moderate to high MAP and substantial nitrate accumulation extending into deeper soil layers (Fig. 7d). Overall, MAP regulated soil nitrate

accumulation through threshold-type and land-use-specific responses, with moderate precipitation (400-600 mm) promoting deep soil nitrate storage, whereas high MAP (>600 mm) likely enhances nitrate leaching beyond the sampled profile.

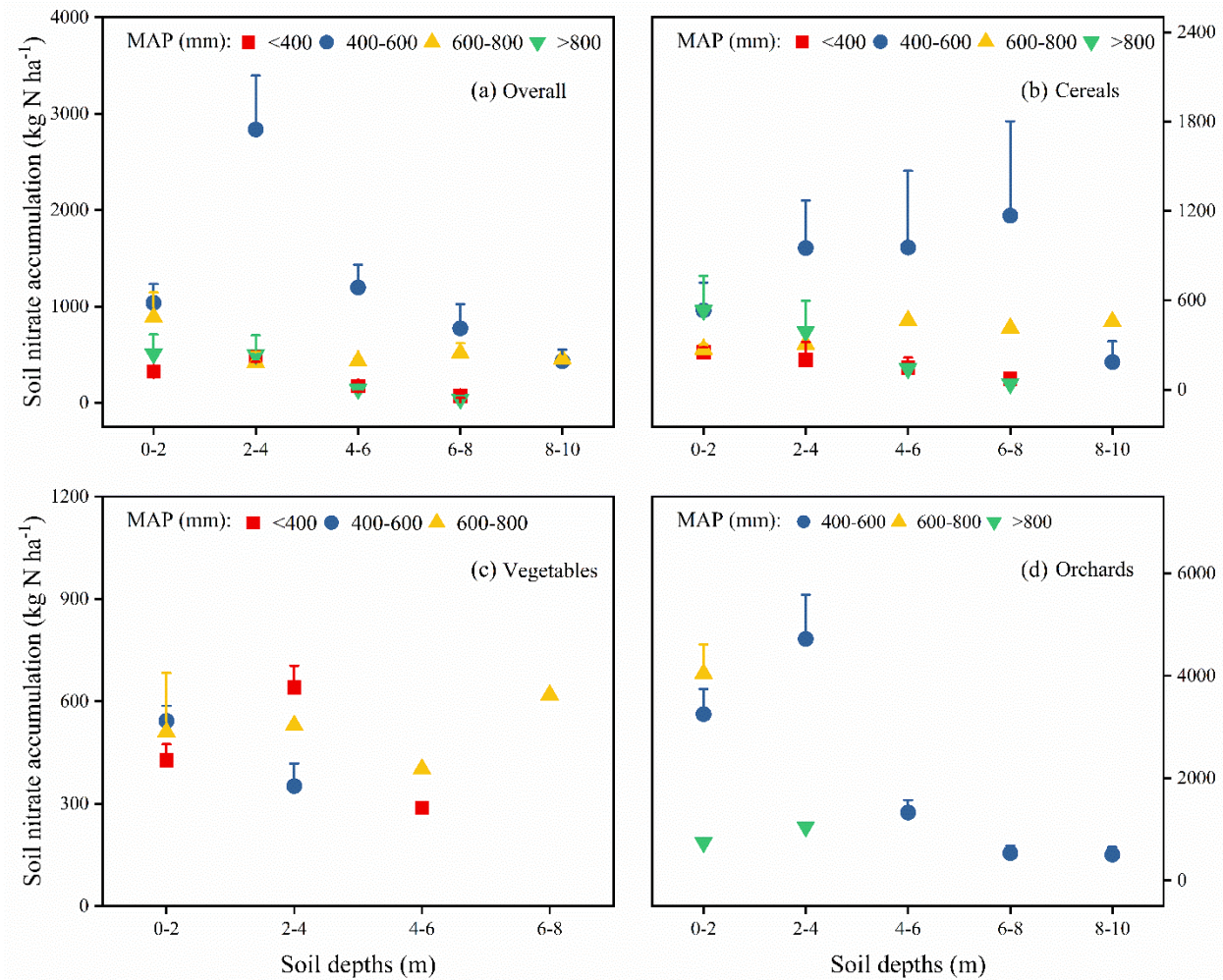


**Fig. 7** Depth-dependent effects of mean annual precipitation (MAP) on soil nitrate accumulation across agricultural land-use types. The mean soil nitrate accumulation is shown for discrete soil depth intervals across different land-use types: (a) overall land, (b) cereals land, (c) vegetables,

and (d) orchards. Soil nitrate accumulation peaks under intermediate precipitation regimes and exhibits strong differences in land use types in both magnitude and vertical distribution

# Relative importance of drivers

Random Forest analysis identified total N input as the most influential predictor of soil nitrate accumulation in overall dataset, as indicated by the highest %IncMSE (Fig. 8). Soil depth and MAT also showed high variable importance, followed by MAP and pH. Other variables, including ET, irrigation, TN, and SOC, showed comparatively lower importance, whereas C:N ratio and AP contributed relatively little to the model prediction. The importance of the predictors varied among cereal, vegetable, and orchard systems. Based on their overall Random Forest importance and mechanistic relevance to nitrate supply, hydrological transport, and vertical distribution, total N input, MAP, and soil depth were selected for subsequent analyses.

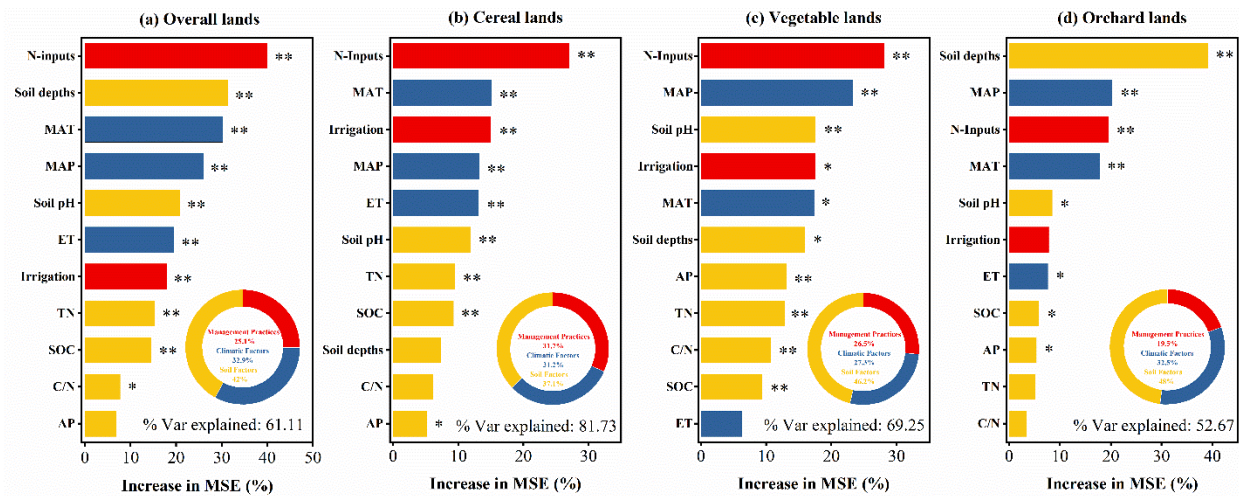


**Fig. 8** Identification of key drivers of soil nitrate accumulation across different agricultural land use types using a random forest model. Random forest analysis elucidated the complex interrelationships among management practices, climatic, and soil factors affecting soil nitrate

dynamics, emphasizing total N inputs, mean annual precipitation (MAP), and soil depth as the primary predictors selected for further analysis. (a) Overall lands, (b) cereal lands, (c) vegetable lands, and (d) orchard lands included in this study

A conceptual framework illustrating the mechanisms and outcomes of deep soil nitrate accumulation across global agricultural systems is presented in Fig. 9. The figure depicts a continuous landscape cross-section spanning three contrasting land uses: cereals, vegetables, and orchards with total N inputs (fertilizer, manure, and atmospheric deposition) entering each system from above and crop-specific rooting zones delineating the boundary between active N uptake and residual N migration. Within the soil profile (0–10 m), nitrate distributions diverge markedly among land uses: cereal systems exhibit modest, surface-confined accumulation ( $\sim 1,400 \text{ kg N ha}^{-1}$ ); vegetable systems display intense but shallow nitrate enrichment ( $\sim 440 \text{ kg N ha}^{-1}$ ) with limited downward penetration; whereas orchard systems develop an extensive deep soil legacy ( $\sim 7,500 \text{ kg N ha}^{-1}$ ) with peak accumulation at 2–4 m and persistent storage extending below 6 m. Mechanistic arrows highlight the underlying processes, including plant N uptake, nitrate leaching driven by percolating water, and limited denitrification under predominantly oxic deep soil conditions, which together prolong the nitrate residence time and sustain the legacy pool. The role of MAP was integrated into the leaching pathways, with moderate MAP (400–600 mm) promoting nitrate accumulation within the 2–4 m soil profile, whereas high MAP ( $>600 \text{ mm}$ ) promoted nitrate leaching or flushing beyond the sampled depth toward the groundwater table. Collectively, the schematic synthesizes how excess N inputs, land use type, and hydroclimatic conditions interact to generate depth-dependent nitrate legacies that pose delayed but persistent risks to groundwater quality across global agroecosystems.

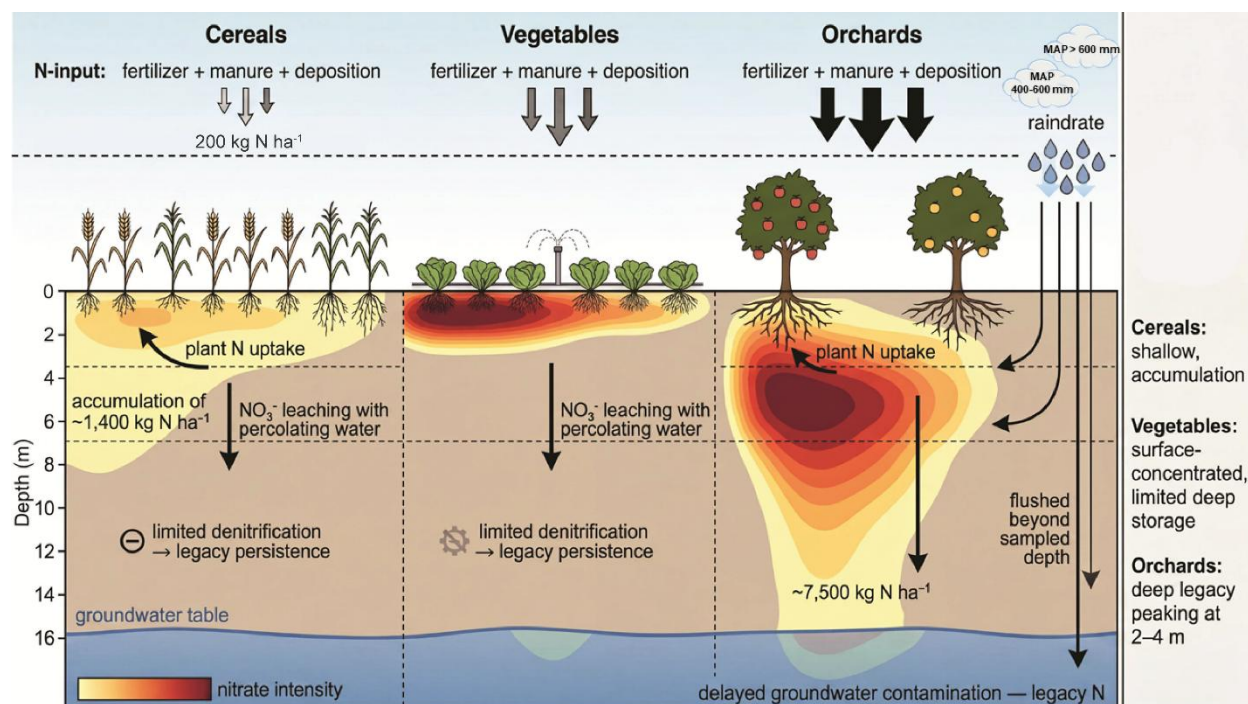


**Fig. 9** Conceptual framework showing the mechanisms and outcomes of deep soil nitrate accumulation in global agricultural systems. Excess N inputs (fertilizer, manure, and deposition) through root zone processes (crop uptake and conversion), interact with MAP under diverse land use types, regulate nitrate accumulation and downward distribution within the 0–10 m soil profile

## Discussion

### Magnitude and depth legacy of soil nitrate accumulation at large scale

Our study found that a substantial amount of nitrate stock persists well below the effective root zone across global agricultural lands (Fig. 4a–b), providing strong evidence of a widespread and enduring deep soil nitrate legacy. It suggests that a large portion of the applied N is stored in the deep vadose zone rather than being recovered by crops. This depth-dependent quantification corroborates previous regional observations of extensive subsurface nitrate storage in regions

characterized by long-term agricultural intensification and thick vadose zones (Ascott et al., 2017). Similar patterns have been documented in Chinese semi-humid croplands, where significant nitrate accumulation within the upper 4 m reflects continuous fertilizer inputs exceeding plant demand (Zhou et al., 2016), and in other intensively cultivated regions, where nitrate reservoirs extend to depths of 8–30 m (Gao et al., 2021). The mechanisms underlying deep nitrate accumulation are inherently multifactorial. Excessive N application remains the predominant driver of residual nitrate generation, which is highly mobile and prone to leaching (Zhou et al., 2016). Soil physicochemical properties, particularly texture, structure, and permeability, regulate the nitrate transport capacity, and rainfall- or irrigation-induced percolation facilitates progressive downward migration through the soil profile (Zhu et al., 2022; Wang et al., 2026). Furthermore, limited denitrification under predominantly oxic deep soil conditions prolongs the nitrate residence time (Almaraz et al., 2025), allowing the gradual accumulation of nitrate within the vadose zone. Collectively, these processes elucidate the formation of deep subsurface nitrate reservoirs that act as delayed sources of groundwater contamination and pose long-term risks to hydrogeological systems and water quality (Nakagawa et al., 2021; Borah et al., 2025). These findings suggest that a large proportion of agricultural nitrate is stored in deep soil layers, underscoring the presence of widespread nitrate legacy pools in intensively managed agricultural systems that warrant further investigation in the future.

Among the land use types, orchard systems consistently demonstrated the highest nitrate accumulation at all soil depths (Table S3). Notably, nitrate accumulation was particularly pronounced in the 2–4 m, indicating significant downward transport and long-term storage below the root zone (Fig. 4b). Similar depth-dependent patterns have been widely reported, with orchard soils, particularly below 2 m, accumulating substantially higher nitrate loads than annual cropping

systems (Zhou et al., 2016; Liu et al., 2019; Gao et al., 2021; Wang et al., 2026; Zhao et al., 2026). This pronounced deep accumulation is commonly attributed to intensive and prolonged N fertilization, coupled with the perennial growth habit of orchards, which alters root distribution, water uptake dynamics, and N demand throughout the year. The presence of such large nitrate reservoirs in deep soil layers of orchard systems represents a persistent environmental challenge, as the slow but continuous downward movement of nitrate increases the likelihood of long-term groundwater contamination. In contrast, annual cropping systems, such as cereals and vegetables, generally exhibit shallower nitrate distributions, reflecting shorter crop cycles, more frequent soil disturbance, and comparatively lower cumulative N inputs over time. However, the absence of deep-rooted perennial vegetation does not prevent nitrate loss to deeper soil profiles. Previous studies have consistently demonstrated that excessive fertilizer application rates, and mismatches between N supply and crop uptake in annual systems can result in substantial nitrate leaching below the rooting zone and into groundwater (He et al., 2023; You et al., 2024). Consequently, while nitrate accumulation in cereals and vegetables is typically less pronounced at depth than in orchards, localized hotspots and cumulative losses remain environmentally significant, particularly under intensive management or high-rainfall conditions.

Collectively, these results demonstrate that nitrate accumulation in soil profiles does not exhibit a linear relationship with total soil N inputs across different regions or land use types. Notably, orchard systems have been identified as significant hotspots of nitrate accumulation, particularly in Asia and China whereas cereal crops generally display lower nitrate storage (Tables S1 and S2). The pronounced regional contrasts suggest that the geographic context significantly influences the magnitude and redistribution of nitrate accumulation in agricultural soils.

Interactive influences of N inputs and precipitation on nitrate accumulation and redistribution.

The combined effects of N inputs and MAP substantially influences nitrate accumulation and vertical redistribution, revealing complex synergistic and antagonistic effects that vary with land use and soil depth. Nitrate stocks increase nonlinearly with rising N inputs, with pronounced accumulation occurring once inputs exceed approximately 200 kg N ha<sup>-1</sup>, particularly in the 2–4 m and deep soil profiles (>4 m) (Fig.5). This pattern indicates that high N inputs producing N surplus alone are sufficient to generate substantial deep-soil nitrate pools, but their ultimate fate is strongly modulated by hydrological conditions. The MAP exerts nonlinear control on nitrate redistribution along the soil profile. Moderate MAP levels (approximately 400–600 mm) favor nitrate accumulation in 2–4 m soil profiles, whereas high MAP (>600) is associated with reduced deep-soil (>4 m) nitrate storage (Fig.7), which is consistent with enhanced downward leaching. Similar patterns have been reported previously, where high N inputs combined with moderate MAP result in pronounced deep nitrate accumulation, especially in perennial systems such as orchards, whereas comparable N inputs under high MAP led to diminished deep storage owing to accelerated leaching losses (Zhou et al., 2016). Similarly, Jia et al. (2018) support our findings, that moderate precipitation facilitated nitrate accumulation in deeper soil profile by promoting downward movement without inducing extensive hydrological flushing. Furthermore, Zhu et al. (2024) also support our findings that extreme precipitation events can significantly accelerate nitrate leaching to deep soil profiles, thereby exacerbating deep soil nitrate accumulation in thick soil profiles or groundwater contamination in regions with thinner soil profiles.

The mechanisms underlying these patterns are multifactorial and involve interactions among N transformation processes and plant uptake dynamics. Deep nitrate storage is attributed

to the interplay between N surplus, hydrological dynamics, and land use management. When N input exceeds crop uptake, residual N undergoes rapid nitrification, resulting in a surplus of nitrate. This surplus nitrate is highly mobile and susceptible to downward transport beyond the shallow soil profile, especially under moderate to high precipitation levels (400–600 mm), which facilitates deep soil profile nitrate accumulation (2–4 m). In contrast, high precipitation (>600 mm) may lead to nitrate leaching beyond the sampled depths in our study, contributing to nitrate legacies in the deep soil and, over time, with periodic high-intensity rainfall to groundwater. In addition, hydrological factors, such as infiltration rates and seasonal rainfall patterns, govern the vertical redistribution of nitrate, thereby elucidating the observed depth-dependent patterns across various climatic regions. The type of land use further intensifies these dynamics: orchard systems accumulate the largest and deepest nitrate pools, vegetables concentrate nitrate in surface soils, and cereals exhibit comparatively lower accumulation. Excessive fertilization, especially in perennial systems or under hydrological conditions conducive to leaching, exacerbates deep nitrate storage and increases the risk of long-term groundwater contamination compared with seasonal cereal or vegetable crops.

Collectively, nitrate accumulation and redistribution were controlled by a nonlinear interaction between total N inputs and MAP. Excessive N contributes to N surplus, whereas MAP regulates vertical transport. Moderate MAP facilitates deep accumulation, whereas high MAP accelerates leaching beyond sampling depths, increasing the risk of groundwater contamination. These effects are particularly pronounced in perennial systems, such as orchards, where continuous N inputs enhance deep nitrate storage. Therefore, this interplay between N surplus and hydrological processes dictates the vertical movement of soil nitrate, underscoring the necessity of integrated nutrient and water-management to mitigate long-term environmental risks.

Our comprehensive global analysis revealed that nitrate is distributed throughout the 0-10 m soil profile, with an average accumulation of nearly 4,400 kg N ha<sup>-1</sup> with substantially larger stocks in perennial orchard systems (9429 kg N ha<sup>-1</sup>) within the upper 8 m (Table S3). This vertical redistribution is indicative of chronic N surpluses, where the application of N exceeds crop uptake, resulting in progressive leaching into deeper soil profiles. Identifying a fertilization threshold (>200 kg N ha<sup>-1</sup>) beyond which nitrate accumulation intensifies and penetrates below the root zone highlights the potential for nonlinear environmental degradation under ongoing intensification (Fig. 5). Furthermore, the interaction with MAP suggests that moderate MAP (400–600 mm) facilitates downward transport while retaining nitrate within the vadose zone, thereby creating hydrologically connected reservoirs that threaten groundwater quality (Fig. 7). Given the slow turnover of nitrate at depth, these stores function as delayed contamination sources, implying that improvements in water quality may be delayed even after a reduction in fertilizer N inputs. Episodic flushing, driven by extreme rainfall (>600 mm) or land use types, can further mobilize these legacy pools, increasing the risk of groundwater contamination, eutrophication, and long-term ecosystem degradation.

To address these challenges, several strategies must be employed to effectively mitigate nitrate accumulation in deep soils. First, preventing N surplus at its source is paramount; this involves maintaining N input below critical thresholds and aligning fertilizer application rates with realistic crop demands. Second, enhancing NUE through split applications, precision fertilization, and fertigation improves the synchronization between nutrient supply and crop uptake, thereby reducing residual nitrate in the soil profile. Third, complementary measures, such as the use of

enhanced-efficiency fertilizers (e.g., controlled-release products and nitrification inhibitors), cover cropping, diversified rotations, and improved irrigation scheduling, are instrumental in slowing nitrate formation, biologically capturing residual N, and minimizing percolation-driven leaching. Fourth, integrated management frameworks, including soil-crop system optimization programs (e.g., IKPS) and FAO-led Sustainable Soil Management, IPNM, and INM initiatives, demonstrate that coordinated, site-specific nutrient and water management can simultaneously reduce Nr losses and sustain productivity. Finally, embedding these practices within long-term monitoring, predictive modeling, and vadose zone process assessments is essential to link agronomic optimization with groundwater protection and to prevent further expansion of nitrate legacy in agricultural systems.

Collectively, these strategies underscore the need for systematic management rather than isolated interventions to reduce nitrate leaching. Without the coordinated adoption of optimized fertilization, enhanced-efficiency products, biological N capture, and improved irrigation, the continued N surplus will exacerbate deep soil nitrate accumulation, soil acidification, groundwater contamination, eutrophication, and long-term agroecosystem degradation.

#### Study limitations and future directions

This global synthesis offers novel insights; however, it is important to acknowledge several limitations related to the scale and nature of the analysis. The compiled datasets demonstrated considerable heterogeneity in methodologies, reporting standards, and experimental designs, which introduced variability and necessitated cautious interpretation of the synthesized results. Variations in soil sampling protocols, nitrate analytical methods, sampling depths, crop rotations, and management practices can bias estimates of nitrate accumulation, particularly when comparing

different regions and land use types. Notably, many studies have concentrated primarily on shallow layers, potentially leading to an underestimation of the total nitrate stocks in deeper soil profiles. Furthermore, the uneven spatial and temporal coverage of available studies may limit the representativeness of certain regions or production systems, thereby increasing the uncertainty when extrapolating findings beyond the sampled conditions. Although robust statistical approaches are needed to account for variability, these sources of heterogeneity remain critical when interpreting the magnitude and generality of the reported patterns.

Future research should focus on underrepresented regions and agricultural systems, particularly in rapidly developing countries, to address significant data deficiencies. Investigations should incorporate environmental, soil, and management factors, including soil properties, microbial communities, and historical N practices, to enhance our comprehension of nitrate accumulation, leaching, and legacy effects. The development of robust predictive models that integrate process-based and machine learning methodologies, calibrated across diverse pedoclimatic zones, and downscale findings to regional contexts will facilitate the formulation of tailored mitigation strategies and the development of effective policies.

## **Conclusion**

Our global analysis demonstrated that soil nitrate accumulation in agricultural soils extends substantially beyond surface soils, with considerable nitrate reserves persisting in deep soil profiles. On average, approximately 2948 kg N ha<sup>-1</sup> accumulated within the upper 0–4 m, with an additional ~1447 kg N ha<sup>-1</sup> stored between 4–8 m, thereby confirming the widespread presence of deep soil nitrate legacies globally. Orchard systems have been identified as major hotspots, particularly below 2 m, whereas cereal and vegetable systems exhibit comparatively lower but still

substantial nitrate accumulation. Notable regional variations, especially the elevated nitrate stocks observed in China, suggest that accumulation does not increase linearly with N inputs alone. N inputs were identified as the primary source, with distinct threshold responses observed above 200 kg N ha<sup>-1</sup>, which facilitated deep nitrate storage. MAP exerted a nonlinear influence, with moderate rainfall (400–600 mm) enhancing deep soil (2–4 m) nitrate accumulation, whereas high rainfall (>600 mm) accelerated leaching beyond sampling depth (10 m). Random Forest analysis further underscored the combined effects of total N input, soil depth, and climate. Overall, deep vadose zone nitrate represents a persistent legacy and delayed threat to groundwater quality, underscoring the necessity for depth-dependent N management and long-term monitoring strategies.

**Author contributions** MT: Writing—original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. MZ: Methodology, Investigation, Conceptualization. WL: Validation, Methodology, Investigation. SQ: Validation, Conceptualization. XL: Investigation, Methodology. SK: Methodology, Investigation, Data curation. MR: Methodology, Investigation, Conceptualization. ZC: Writing—review & editing, Validation, Supervision, Resources, Project administration, Methodology, Conceptualization. JZ: Writing—review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization.

**Data availability** All data used in the analyses are available in supplementary file 1.

**Declarations**

**Ethical approval** All authors have read, understood, and have complied as applicable with the statement on “Ethical responsibilities of Authors” as found in the Instructions for Authors.

**Consent to participate** Not applicable

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