Global pattern and drivers of soil soluble organic nitrogen

Tianjing Ren,[1,2] Tiantian Miao,[1] Xiaofei Li,[3] Wenju Zhang,[4] Bożena Smreczak,[2] Aleksandra Ukalska-Jaruga,[2] Yu'e Li,[1] and Andong Cai[1,*]

*Correspondence: caiandong@caas.cn

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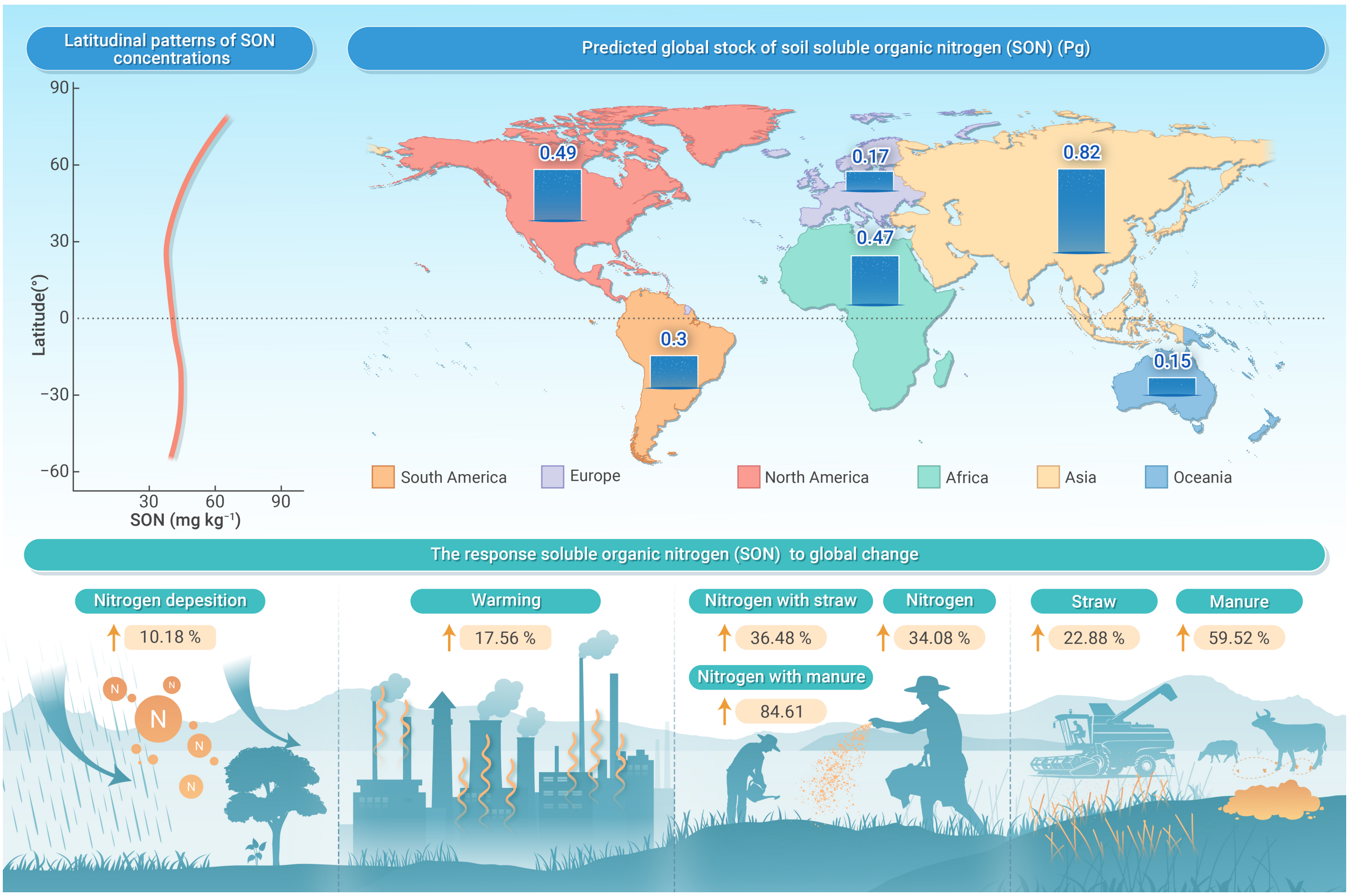
GRAPHICAL ABSTRACT



PUBLIC SUMMARY

- Soil soluble organic nitrogen (SON) is a key but poorly mapped nitrogen pool globally.
- We compiled 5,782 topsoil samples and used machine learning to map SON worldwide.
- Elevation, parent material, and precipitation emerged as the dominant SON drivers.
- Global SON stock in top 30 cm soils is estimated at 2.4 (Pg N).
- Most global changes, except drought, biochar, and no-tillage, increased SON levels.

ARTICLE

Global pattern and drivers of soil soluble organic nitrogen

Tianjing Ren,[1,2] Tiantian Miao,[1] Xiaofei Li,[3] Wenju Zhang,[4] Bożena Smreczak,[2] Aleksandra Ukalska-Jaruga,[2] Yu'e Li,[1] and Andong Cai[1,*]

[1]Institute of Environment and Sustainable Development in Agriculture, Chinese Academy of Agricultural Sciences, Beijing 100081, China

[2]Institute of Soil Science and Plant Cultivation–State Research Institute, Department Soil Science and Environmental Analyses, Puławy 24-100, Poland

[3]State Key Laboratory of Estuarine and Coastal Research, East China Normal University, Shanghai 200241, China

[4]Institute of Agricultural Resources and Regional Planning, Chinese Academy of Agricultural Sciences, Beijing 100081, China

*Correspondence: caiandong@caas.cn

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Soil soluble organic nitrogen (SON) is a central component of the terrestrial nitrogen cycle, acting as both a precursor to inorganic nitrogen via mineralization and a product of microbial assimilation of inorganic forms. Due to its high solubility and mobility, SON also represents a critical pathway for nitrogen loss and is a key contributor to nitrogen pollution and eutrophication in downstream aquatic ecosystems. Despite its ecological significance, the global distribution and environmental drivers of SON remain poorly understood, largely due to a lack of spatially explicit data. To address this gap, we compiled a comprehensive global SON dataset comprising 5,782 topsoil samples (0-30 cm depth) from 379 published studies, including detailed information on geographic location, climate, and soil properties. Overall, the global SON concentrations ranged from 0.04 to 1034 mg kg^{-1}, with an average concentration of 41.36 mg kg^{-1}. The random forest model could explain 82% of the variations in SON concentrations. Elevation, parent material, and mean annual precipitation emerged as the most influential predictors. Machine learning was used to quantify environmental contributions to SON and predict its global stock, estimated at 2.4 Pg N. The resulting global SON map revealed a distinct latitudinal gradient, with SON concentrations increasing toward higher latitudes. In addition, meta-analysis showed that except for reduced precipitation, biochar, and no-tillage, other global changes increased global SON to varying degrees (-4.45% – 70.71%). This study provides the first global map of SON distribution and identifies key biophysical and environmental controls of SON dynamics.

INTRODUCTION

Nitrogen (N) is a fundamental nutrient for life and a key regulator of biogeochemical processes, including soil fertility, water eutrophication, and atmospheric pollution.[1-3] While most research on nitrogen cycling has focused on inorganic forms such as nitrate and ammonium due to their direct bioavailability to plants, soil soluble organic nitrogen (SON) represents a dynamic yet understudied component of the terrestrial nitrogen pool. SON encompasses organic N compounds dissolved in the soil aqueous phase, operationally categorized as extractable organic nitrogen (EON) — obtained through chemical extractants (e.g., K_2SO_4 or KCl), or dissolved organic nitrogen (DON)—isolated from in situ soil solution using physical methods (e.g., lysimeters or centrifugation).[4,5] Although SON generally constitutes less than 10% of total soil N, it plays a disproportionate role in ecosystem nitrogen dynamics.

Functionally, SON acts as both a precursor and product of inorganic N transformation: it is mineralized into inorganic N and also regenerated through microbial uptake and turnover.[6,7] Beyond its biogeochemical transformations, SON plays a central role in ecosystem-scale nitrogen retention and loss, contributing to runoff, leaching, and carbon-nitrogen coupling.[1,5,8,9] In undisturbed South American forests, for example, SON accounts for up to 70% of annual nitrogen runoff, highlighting its mobility and ecological relevance.[10,11] As a mobile and reactive nitrogen pool, SON serves as a rapid interface between biotic and abiotic processes, especially under global change drivers such as warming, drought, and nitrogen deposition.[12] Its high solubility also makes SON a key contributor to watershed nitrogen export and aquatic eutrophication.[13,14] Recent advances in molecular ecology reveal that SON comprises a diverse array of low-molecular-weight compounds including amino acids, peptides, and nucleic acids that are readily assimilated by soil microbes and even directly by plants.[15-17] These compounds respond rapidly to climatic and land-use changes, positioning SON as both a sensitive indicator and driver of biogeochemical feedback in a changing environment.[18]

Although SON concentrations have been well studied at the site scale,[19,20] its global distribution patterns and environmental drivers remain poorly characterized. This persistent knowledge gap limits our ability to fully model the terrestrial nitrogen cycle and predict ecosystem responses under future climate and land-use scenarios.

The concentrations of SON are contingent on the dynamic balance between the formation (e.g., decomposition of soil organic matter, secretions of plant roots, microbial metabolic products, and applied organic fertilizers) and consumption (e.g., direct plant uptake, microbial mineralization, adsorption and fixation in soil, and loss through leaching).[8,19] This balance is regulated by a complex interplay of environmental drivers, including climate, vegetation, parent material, and the physical, chemical, and biological properties of soils.[4,21] For instance, elevation modulates SON indirectly by shaping local temperature and precipitation regimes. Cooler temperatures at high altitudes suppress microbial decomposition and slow the mineralization of organic nitrogen, thereby promoting SON accumulation.[22] Simultaneously, increased precipitation at higher elevations enhances primary productivity, leading to greater litter inputs and root exudation, which are the primary precursors of SON.[23] Vegetation types further influences SON levels by altering the quantity and chemical quality of litter and root residues, as well as the rate of humification and microbial turnover.[7,19] Parent materials, through their distinct mineral compositions, control the soil's adsorption capacity and affect the retention and transformation of organic N.[24] Although prior studies have revealed relationships between SON and individual environmental factors, most analyses are constrained to local or regional scales. A systematic, global-scale assessment of SON drivers is still lacking, limiting our ability to predict its spatial distribution or to embed SON dynamics within Earth system models. Such limitations hinder our capacity to understand how SON responds to global environmental change.

Developing a high-resolution global map of SON concentrations is therefore critical. This would not only provide a spatial baseline of SON patterns across biomes, but also offer a benchmark for modeling ecosystem responses to global change. Over recent decades, human-driven global change factors — such as climate warming,[25] altered precipitation patterns, atmospheric nitrogen deposition,[26] and diverse agricultural management practices,[27,28] — have increasingly influenced terrestrial ecosystems, often in subtle yet significant ways.[18,29] These disturbances influence SON turnover by modifying microbial activity, organic matter decomposition, and nitrogen availability. For example, climate warming accelerates the decomposition of available carbon by microorganisms to maintain stability, which leads to the accumulation of SON.[30,31] Increased precipitation can exacerbate SON leaching into water bodies, while drought may suppress SON formation by limiting microbial activity.[32,33] Meanwhile, atmospheric nitrogen deposition alters soil nitrogen inputs, sometimes amplifying SON accumulation.[14,33,34] Agroecosystems, in particular, represent a hotspot for SON variability due to intensive land management. SON turnover in agroecosystems directly influences nitrogen use efficiency by regulating reactive N availability and minimizing losses. Practices such as fertilizer addition, organic amendment, no-tillage, straw return, and biochar application can markedly influence SON dynamics.[35,36] For example, the application of nitrogen and organic fertilizers increases the potential nitrogen supply, directly elevating SON accumulation,[27,37] while no-tillage practices reduce soil disturbance, helping to mitigate SON loss.[27,36] As a mediator of microbial C:N balance and decomposition feedbacks, SON also contributes to soil carbon retention and climate–carbon interactions. However, SON responses to global change factors vary substantially across ecosystems and continents, reflecting heterogeneity in environmental conditions, land use, and soil types. Without accurate global SON maps, it remains

Table 1. Variable data of topsoil soluble organic nitrogen (0–30 cm) across global terrestrial ecosystems. n/a refers to not applicable values.

Variables	Description	Unit	Number	Range	Mean
No.	Unique identification number	n/a	5782	1 to 5781	2891
Latitude	Latitude of study site	°	5782	-64.82 to 78.17	36.78
Longitude	Latitude of study site	°	5782	-155.40 to 175.95	68.83
MAT	Mean annual temperature	°C	4362	-10.9 to 27.5	10.24
MAP	Mean annual precipitation	mm	4576	30 to 4200	1007
Elevation	Altitude of study site	m	2736	4 to 5201	1077
Ecosystems	dominant plant species	n/a	6	n/a	n/a
Fine particle	Silt plus clay content	%	1153	3 to 98	51
Soil depth	Mean depth of soil sample	cm	5782	0.5 to 30.0	11.14
SOC	Soil organic carbon	g kg^{-1}	3379	0.30 to 527	44.73
Soil pH	Measure by 1:2.5 H_2O,	n/a	3267	2.80 to 10.98	6.49
BD	Soil bulk density	kg m^{-3}	1307	0.21 to 1.81	1.20
Date	Observation month of DOC	month	5782	1 to 12	6.50
RockType	Parent material	n/a	12	n/a	n/a
SON	Soil soluble organic nitrogen	mg kg^{-1}	5782	0.04 to 1034	41.36
TN	Soil total nitrogen	g kg^{-1}	3201	0.01 to 29.86	3.24
MBN	Microbial biomass nitrogen	mg kg^{-1}	2628	0.16-542	50.81
Urease	Nitrogen cycling enzymes	mg kg^{-1} h^{-1}	626	0.27-2398	244.70
AN	Soil available nitrogen	mg kg^{-1}	354	0.75 to 287	68.40
NO_3-N	Soil nitrate nitrogen	mg kg^{-1}	2932	0.01 to 502	14.21
NH_4-N	Soil ammonium nitrogen	mg kg^{-1}	2819	0.00 to 460	11.23

challenging to assess how SON contributes to nitrogen cycling and ecosystem resilience under future global change scenarios. A data-driven, spatially explicit understanding of SON distribution is urgently needed to inform large-scale nitrogen models and climate–soil feedback analysis.

To address this gap, we compiled a comprehensive global dataset of SON derived from 379 published studies, encompassing 5,782 topsoil samples (0-30 cm). Using machine learning techniques, we quantified the relative contributions of environmental predictors and generated high-resolution spatial predictions of global SON concentrations. In parallel, we compiled a dataset of 2,440 paired observations to evaluate SON responses to multiple global change drivers including climate warming, nitrogen deposition, altered precipitation (increase/reduction), and agricultural management practices such as no-tillage, biochar application, chemical fertilizers, organic amendments, straw return, and combined applications of nitrogen with organic or straw inputs. Specifically, we aim to: (1) identify the primary drivers of global SON concentrations, map their global distribution and estimate global SON stocks; and (2) quantify the magnitude and direction of SON responses to major global change factors.

MATERIALS AND METHODS

Data sources and processing

In conducting the literature search for this dataset, we utilized three databases: Google Scholar, Web of Science, and the China National Knowledge Infrastructure (CNKI). The specific keyword combinations used for searches included (soluble organic nitrogen OR dissolved organic nitrogen OR extractable organic nitrogen OR dissolved organic matter OR "SON" OR "DON" OR "EON" OR "DOM") AND soil, with the search period ending in December 2022. Figure S1 provides a detailed overview of the screening process at various stages. To ensure consistency and reduce bias in the dataset, we adhered to the following inclusion criteria: (1) Only studies that directly measured SON concentrations or related indicators in terrestrial ecosystems were included, while studies on marine or riverine systems were excluded; (2) Duplicate results appearing in multiple publications were recorded only once; (3) While agricultural soils influenced by anthropogenic activities (e.g., cultivation and fertilization) were included, industrial and urban soils were excluded; (4) Only primary research articles were considered; reviews, editorials, and conference abstracts were excluded to ensure that the dataset comprised original and empirical research results. For data that was presented only in graphical form, we extracted the values using the digitization tool in Origin 2019 software. Based on these criteria, we compiled 6,296 soil SON observations from 379 publications, of which 5,782 (92%) were from the 0-30 cm topsoil layer and 514 (8%) from subsoil layers (> 30 cm) (Figure S2). To ensure model consistency, we excluded these observations from model training and global mapping. A detailed rationale for this decision is provided in Text S1.1 & S1.4. Furthermore, most environmental covariates used in the model (e.g., vegetation, climate, soil properties) were only available for topsoil conditions, making it difficult to control for depth-related confounding effects. All subsoil data have been retained in the published database for transparency and future use by the scientific community. Supplementary information collected included the precise locations of the study sites, climate conditions, vegetation types, and the physical and chemical attributes of the soils (Table 1). For cases where variable values were missing in the original publications, we extracted the missing information from publicly available gridded datasets based on the geographical coordinates of each observation site. For example, soil parent material was derived from the OpenLandMap database, and missing climate variables were filled using WorldClim data at 1 km resolution. A complete list of variables, data sources, and spatial resolutions is provided in Table S1.

Additionally, to systematically assess the impacts of global change factors, we compiled a dataset of 2,440 paired observations from 183 publications covering multiple global change factors — including climate warming, nitrogen deposition, altered precipitation (increase/reduction), and agricultural management practices including no-tillage, biochar application, chemical fertilizers, organic amendments, straw return, and combined applications of nitrogen with organic or straw inputs. Meta-analysis statistical technique used for the systematic and quantitative analysis of independent experimental results with a specific research objective was employed to analyze the compiled data.[38] The data processing for this meta-analysis was conducted using the Meta-Win 2.1 software (https://www.metawinsoft.com/), with the specific formula provided in Text S1.1 & S1.2. To assess potential publication bias, we performed Egger's regression test and Begg's rank correlation test for each treatment group included in the meta-analysis (Table S3).

Data standardization

SON is broadly defined as the pool of organic nitrogen that exists in the aqueous phase of soil and is readily mobile or leachable. Operationally, SON encompasses two primary components based on extraction methodology: EON and DON. EON refers to the organic nitrogen fraction extracted from soils using chemical solutions (e.g., 0.5 mol L^{-1} K_2SO_4, 1 mol·L^{-1} KCl, 10 mmol L^{-1} $CaCl_2$, or 1/15 mol L^{-1} phosphate buffer), following procedures involving "shaking–extracting–filtering".[4] In contrast, DON is derived from physical extraction methods such as vacuum lysimeter, centrifugation, or in situ leaching, representing the organic N naturally present in soil solutions.[5] While these two pools—EON and DON—are obtained through different approaches and may differ in their molecular compositions and concentrations, they represent overlapping operational fractions of mobile soil organic nitrogen. Importantly, due to the lack of a universally accepted chemical demarcation,[27,39] we treated both EON and DON as components of SON for the purposes of global synthesis. To ensure methodological consistency across studies, we applied a standardization protocol to harmonize physically extracted DON values with chemically extracted SON values. Specifically, DON concentrations (mg L^{-1}) obtained through physical methods were converted into equivalent soil-based SON concentrations (mg g^{-1}) using the following equation:[40]

$$SON_{soil} = \frac{SON_{solution} \times V \times 1000}{W} \times \frac{1}{V \times (1 - W) \times BD \times 1000000} \quad (1)$$

where, SON_{soil} represents the soil SON concentration determined by chemical methods (mg g^{-1}); $SON_{solution}$ is the concentration measured by physical methods (mg L^{-1}); W denotes the volumetric soil moisture (m^3 m^{-3}); V is the volume of the soil column for solution extraction (m^3); and BD is the soil bulk density (g cm^{-3}). The factor 1000 converts m^3 to L, and 1000000 converts m^3 to cm^3 following the protocol established by Guo.[40] Over 80% of the SON was determined using chemical techniques, which highlighted their reliability. This standardization allowed for a consistent comparison and analysis of SON data across various studies.

Predictive modeling and global son mapping

The driving factors behind SON concentrations were categorized into four groups: climate, ecosystem, soil properties, and observation time. The soil properties included physical attributes (e.g., parent materials, fine particles, bulk densities, soil horizons, and chemical attributes (e.g., soil organic carbon (SOC) and pH). The observation times were recorded in months. Climate factors encompassed the mean annual temperature (MAT), mean annual precipitation (MAP), and elevation. Ecosystem types include wetlands, forests, shrublands, tundra, grasslands, and croplands. In the extrapolative models, some predictors may exhibit redundancy, which could lead to an underestimation of their relative importance. Thus, the total nitrogen (TN), silt content, and aridity index were excluded from the analysis due to their correlation with soil organic carbon, sand proportion, and mean annual precipitation, respectively (Figure S3). Additionally, some less frequently reported variables, such as iron and aluminum oxides, were also excluded from the analysis.

To develop and optimize the predictive models for SON, various regression methods were employed, including three linear and four nonlinear methods (Table S2). The linear regression methods included Least Absolute Shrinkage and Selection Operator, Elastic Net, and standard Linear Modeling, which were aimed at identifying the most important predictors in the regression models, while minimizing the risk of overfitting. The nonlinear regression methods consisted of Random Forest, Boosted Trees, Bagged Trees, and Cubist models. Each model had its own internal feature selection mechanism and was optimized to improve prediction accuracy and manage model complexity. The RF was constructed using 500 decision trees (ntree = 500) and three randomly selected variables at each split (mtry = 3). Variable importance was assessed by enabling the importance = TRUE option, and the trained forest was retained for subsequent analysis (keep.forest = TRUE). The more details of hyperparameter optimization settings and performance metrics for all tested models are provided in section S1.2. The RF model distinguished itself with the lowest RMSE within a standard deviation range, which was then selected for subsequent analyses focusing on variable importance (Table S2 & Figure S4). For evaluating the sensitivity analysis of model predictions, the Sobol method, a variance of based global sensitivity analysis method, was used to assess how model input parameters impact output results. The total-effect Sobol indices decompose the total variance of model predictions into contributions from individual predictor variables and their combinations. Higher Sobol total-effect values reflect greater importance of the respective variable in shaping SON predictions (Figure S5). To investigate the interactions among key environmental and soil predictors influencing soil soluble organic nitrogen (SON) concentration, we employed the SHapley Additive exPlanations (SHAP) methodology. SHAP provides a robust interpretability framework for machine learning model outputs, quantifying both the individual (main) effects of each predictor and the interactive (pairwise) contributions among predictors. Specifically, we utilized the TreeExplainer algorithm to generate SHAP interaction values from our Random Forest model. These interaction values explicitly represent how predictor pairs jointly influence model predictions beyond their individual contributions, thus offering transparent insights into complex ecological interactions that underpin SON dynamics. The relative importance of the factors driving the SON and the global SON distribution map were the results of the Random Forest model. The SON dataset was combined with global climate, vegetation, and soil raster data (Table S1) to generate global maps of soil SON distribution and prediction uncertainties (Figure S7). Utilizing eleven key predictors, factor maps were created to derive detailed global spatial SON distributions. The specific mapping process is outlined in Text S1.3.

RESULTS

Global distribution of son concentrations

Figure 1 presents a comprehensive global assessment of SON concentrations based on a dataset (following a normal distribution) that covered 5,782 topsoil samples (0-30 cm) across six continents under various climates and terrestrial ecosystems (Figure 1B). The global SON concentrations ranged from 0.04 to 1034 mg kg^{-1}, with an average concentration of 41.36 mg kg^{-1} (Figure 1 & Table 1). Substantial geographic variation in SON was observed. High SON concentrations (> 100 mg kg^{-1}, shown in dark red) were concentrated in specific regions of North America, Eastern Europe, and certain regions of Asia. In contrast, low SON concentrations were more frequently observed in tropical forests and subtropical deserts (Figure 1A). The scatter plot illustrates the relationship between the SON concentrations and climate variables across different biomes (Figure 1C). Among terrestrial ecosystems, shrubland soils exhibited the highest average SON concentrations (71.98 mg kg^{-1}), while tundra soils had the lowest (30.23 mg kg^{-1}, Table 2). Intermediate values were observed for wetlands (63.84 mg kg^{-1}), grasslands (54.68 mg kg^{-1}), croplands (41.32 mg kg^{-1}), and forests (33.76 mg kg^{-1}). Among various parent materials, soils derived from mixed sedimentary rock (SM) had the highest mean SON concentration (55.07 mg kg^{-1}), whereas intermediate plutonic substrates (PI) supported the lowest (8.77 mg kg^{-1}) (Table 3).

Environmental drivers of son concentrations

The random forest model explain 82% of the variations in SON concentrations (Figures 2 & S4), outperforming other tested models in terms of predictive accuracy (lowest RMSE, Table S2). Elevation played the most important predictor for soil SON prediction among the selected 11 variables, followed by parent material, MAP and soil bulk density (BD) (Figure 2). The relative importance of SOC, MAT, month, and soil pH was gradually diminishing. Sensitivity analysis using Sobol indices further confirmed that SOC, BD, fine particles, and soil depth were the most influential variables driving model output uncertainty (Figure S5). Partial dependence plots revealed relationships consistent with Pearson correlation results: SON increased with elevation and SOC but decreased with higher BD (Figures 3 & S6). SHAP-based interaction analysis uncovered key pairwise interactions that modulate SON dynamics (Figure 4). The most notable interaction was between elevation and MAT (absolute SHAP interaction = 9.05), followed by elevation × fine particle content (4.21)

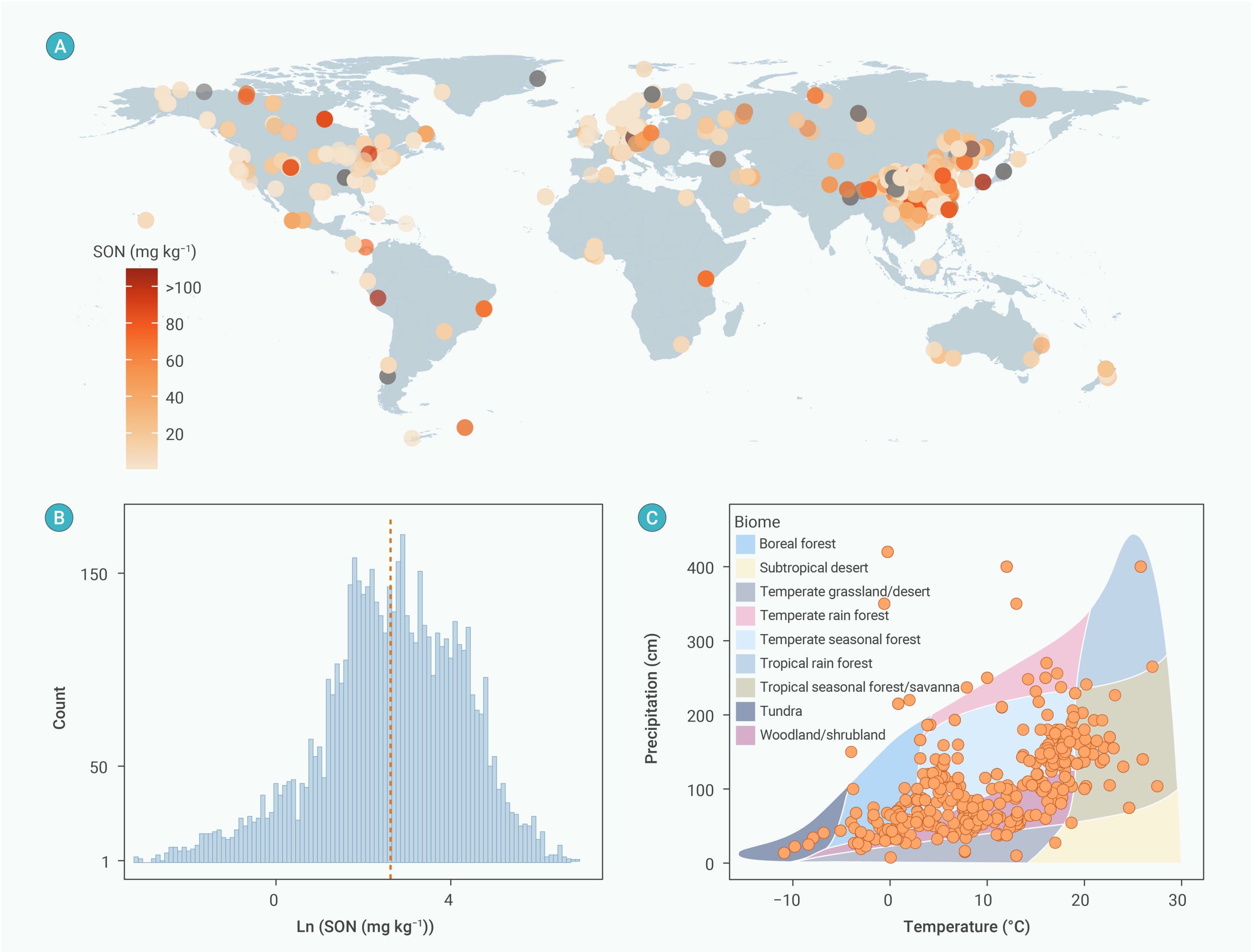

Figure 1. Global distribution of soluble organic nitrogen (SON) concentrations in soils according to our site-level dataset The dataset contains 5782 sets of data (A, B), which cover major terrestrial biomes (C). The dashed red line within the subplot (B) signifies the average SON concentration (41.36 mg kg^{-1}).

Table 2. Global soil soluble organic nitrogen concentrations (mg kg^{-1}) for major terrestrial ecosystems. 25% and 75% represent the 25th and 75th percentiles of one group, respectively. SD, Standard deviation; SE, Standard error.

Ecosystems	Mean	SD	SE	Skewness	Kurtosis	25%	Median	75%
Shrubland	71.98	49.11	3.42	0.87	1.00	34.86	61.78	106.95
Wetland	63.84	122.28	9.49	5.27	34.35	3.65	35.03	76.75
Tundra	30.23	69.13	7.21	4.57	24.83	1.62	7.99	20.96
Forest	33.76	60.26	1.26	3.64	19.80	2.96	9.51	34.92
Grassland	54.68	122.29	4.84	4.14	18.13	7.81	17.54	40.14
Cropland	41.32	67.16	1.37	3.82	18.03	6.99	17.56	48.65

and MAT × MAP (5.58). These interactions suggest that soil texture and structure shape how climatic variables influence SON retention and turnover. In contrast, ecosystem type and parent material showed comparatively weaker interactions with other predictors, indicating that their influence may be more context-specific or operate through main effects rather than synergistic interactions.

Spatial patterns of son concentration and stock

SON concentrations exhibited significant spatial heterogeneity (Figure 5A). A clear latitudinal gradient was observed which concentrations generally increased from the equator toward the North Pole and showed a unimodal pattern with latitude in the Southern Hemisphere (Figure 5B). High SON concentrations were predominantly found in the Northern Hemisphere, particularly in boreal forests, temperate regions of North America, and parts of Europe and Asia. In contrast, lower SON concentrations were common in tropical and subtropical regions, including parts of Africa, Southeast Asia, and South America. Notable exceptions were observed in high-altitude regions such as the Tibetan Plateau and Andean mountains, which exhibited elevated SON levels despite their low latitudes (Figure 5A). The predicted global average SON concentration was 42.77 mg kg^{-1}, with the highest predicted SON

Table 3. Global soil soluble organic nitrogen concentrations (mg kg^{-1}) for major parent materials. 25% and 75% represent the 25th and 75th percentiles of one group, respectively. SD, standard deviation; SE, standard error. Soil parent materials include siliciclastic sedimentary (SS), unconsolidated sediment (SU), carbonate sedimentary (SC), intermediate plutonic (PI), mixed sedimentary (SM), basic volcanic (VB), acid plutonics (PA) intermediate volcanic (VI), metamorphic (MT), pyroclastic (PY), acid volcanic (VA), and basic plutonic (PB).

Parent material	Mean	SD	SE	Skewness	Kurtosis	25%	Median	75%
SS	42.91	69.87	1.96	3.51	17.15	6.44	16.58	46.73
SU	46.10	70.80	1.66	3.04	11.03	5.89	17.78	59.48
SC	19.80	27.99	1.70	4.46	30.10	5.53	10.78	27.52
PI	8.77	7.74	0.85	3.44	11.27	5.62	7.01	7.68
SM	55.07	113.21	3.88	4.22	19.69	5.41	18.58	58.94
VB	26.62	37.70	7.00	2.35	6.38	3.35	10.90	34.60
PA	36.47	76.73	2.83	6.73	65.63	4.22	11.41	35.05
VI	27.08	26.33	2.18	4.98	39.77	14.06	21.70	33.74
MT	29.36	45.64	2.10	1.94	3.54	1.28	5.59	39.89
PY	22.64	33.92	4.21	4.95	26.13	8.34	13.84	23.46
VA	12.48	12.26	3.07	0.94	-0.02	2.22	9.52	20.78
PB	11.65	7.09	2.14	1.07	0.53	6.83	10.58	13.60

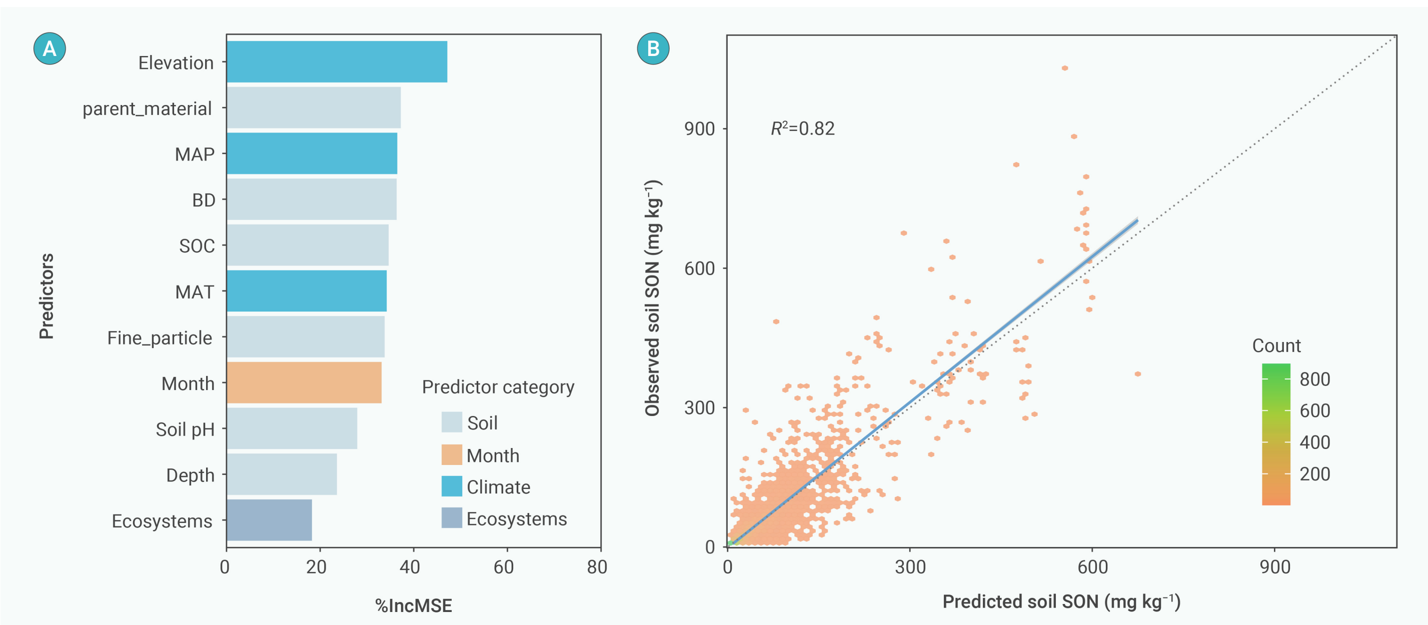

Figure 2. Results of the random forest model predicting soil soluble organic nitrogen (SON) concentrations (A) Relative importance of predictors in the random forest model. (B) Predicted vs. observed SON concentrations. Dashed line indicates the 1:1 line and blue line indicates the regression line between predicted and observed values.

concentration in North America (46.66 mg kg^{-1}) and lowest in Africa (35.38 mg kg^{-1}). The global average SON content was 18.73 g m^{-2}, with North America having the highest at 20.07 g m^{-2}. The total global SON stock in the top 30 cm of soil was 2.40 Pg N, with Asia contributing the largest share (0.82 Pg N), followed by Oceania (0.15 Pg N) (Figure 5A).

The response of son to global change

Global change drivers influenced SON concentrations in divergent ways (Figure 6). With the exception of reduced precipitation, biochar application, and no-tillage practices, all other global change factors led to varying degrees of increase in global soil SON concentrations (Figure 6). Among agricultural management practices, the sole application of organic amendments or straw resulted in SON increased by 23.01% and 53.66%, respectively. Notably, co-application of nitrogen fertilizer with straw or organic amendments further amplified SON accumulation, resulting in increases of 34.46% and 70.71%, respectively. Climate change-related factors, such as warming and nitrogen deposition, also contributed to SON accumulation, increasing concentrations by 14.96% and 16.46%, respectively (Figure 6). However, these SON responses were modulated by ecosystem type and geographic context (Figure 7). For example, nitrogen deposition significantly elevated SON in forest ecosystems by 22.51% but led to a decline of 9.24% in grasslands (Figure 7A). At the continental scale, nitrogen addition increased SON in Asia and North America, while a decline was observed in Europe soils (Figure 7B).

DISCUSSIONS

Variations in soil SON across terrestrial ecosystems

The concentration of SON exhibited marked heterogeneity across global ecosystems. Shrublands recorded the highest SON concentrations (71.98 mg kg^{-1}), which may have been attributed to dense root systems and abundant leaf litter that led to high organic matter inputs.[41] Shrub plants is characterized by high N use efficiency, and its deep roots stimulate microbial activity and decomposition, facilitating the accumulation and transformation of organic N into soluble forms.[41,42] Wetlands also showed elevated SON concentrations (63.84 mg kg^{-1}), possibly due to persistent anaerobic condi-

Figure 3. Partial dependence of predictors from random forest algorithm Soil soluble organic nitrogen (SON, mg kg^{-1}) concentration as relates to mean annual temperature (MAT, °C), mean annual precipitation (MAP, mm), elevation (m), soil fine particle (%), soil depth (cm), soil organic carbon (SOC, g kg^{-1}), soil pH, bulk density (kg m^{-3}), month, ecosystems, and soil parent material (A, B, C, D, E, F, G, H, I, J, K, respectively). Soil parent material includes siliciclastic sedimentary (SS), unconsolidated sediment (SU), carbonate sedimentary (SC), intermediate plutonic (PI), mixed sedimentary (SM), basic volcanic (VB), acid plutonics (PA) intermediate volcanic (VI), metamorphic (MT), pyroclastic (PY), acid volcanic (VA), and basic plutonic (PB).

tions that inhibit decomposition and enhance organic matter preservation.[43,44] Grasslands maintained moderate SON levels (54.68 mg kg^{-1}), reflecting contributions from root biomass and aboveground litter, although their SON dynamics are sensitive to hydrological fluctuations. However, grassland soils are often subject to global change， such as seasonal wet-dry cycles can cause fluctuations in the decomposition and accumulation of SON.[22] Our results also show that warming increases grassland SON concentration (Figure 7A), while nitrogen deposition decreases grassland SON (Figure 7A). In contrast, agricultural soils have a lower SON concentration (41.32 mg kg^{-1}), likely due to intensive land management practices such as tillage, fertilization, and crop harvesting, which disrupt soil structures and accelerate nutrient loss.[45] Nevertheless, agronomic interventions such as organic amendments, straw return, and nitrogen fertilization—either alone or in combination—can substantially enhance SON through increased substrate availability and

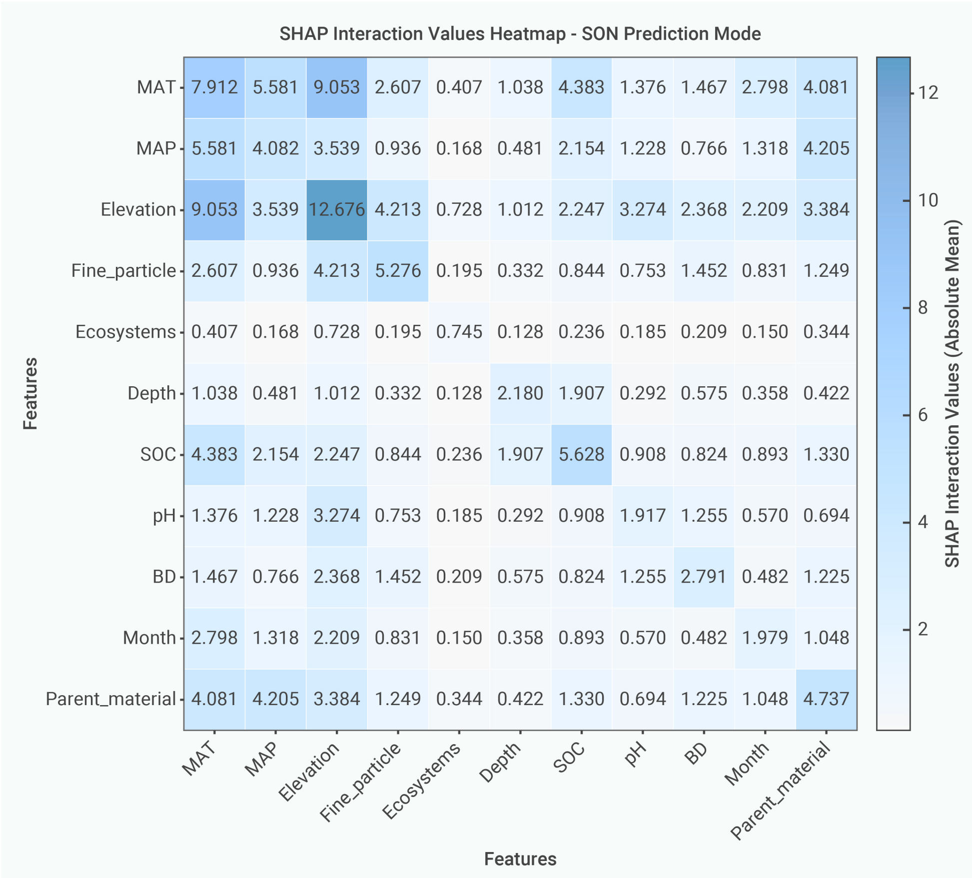

Figure 4. SHAP interaction analysis revealing key feature interactions driving soil soluble organic nitrogen (SON) concentration SHapley Additive exPlanations (SHAP) interaction values quantify how pairs of predictors jointly impact SON prediction. Predictors include mean annual temperature (MAT), mean annual precipitation (MAP), elevation, fine particle content, ecosystem type, soil depth, soil organic carbon (SOC), soil pH, bulk density (BD), sampling month, and parent material. Values in each cell indicate the absolute mean strength of interactions between corresponding predictor pairs, with darker red colors representing stronger interactive effects.

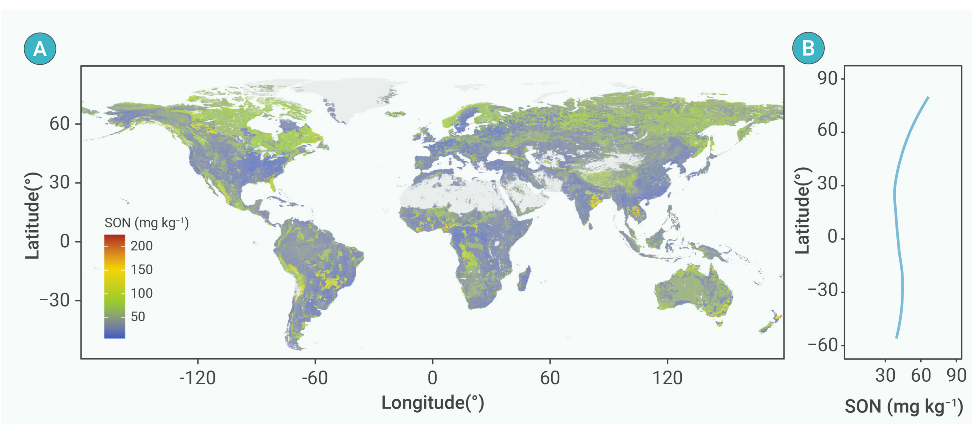

Figure 5. Prediction of soil soluble organic nitrogen (SON) concentrations in global ecosystems (A) Modeled global SON distribution map. (B) Latitudinal patterns of SON concentrations. Blue line indicates locally weighted regressions between latitudes and SON concentrations in the predicted global distribution map. Values in the predicted distribution map reflect SON concentrations within a grid cell resolution of 0.05° × 0.05°. Values in the grid are averaged from the results of the random forest model.

microbial activity (Figure 7A).[27] Forest soils possess the lowest SON concentrations (33.76 mg kg^{-1}), which may be due to SON serves as a key vector of nitrogen loss in forest ecosystems.[11] Indeed, SON has been identified as the dominant leachable form of nitrogen in certain forest types.[5,46] Interestingly, nitrogen deposition increased SON in forests, suggesting that elevated N input may exceed biological demand, leading to enhanced leaching or accumulation in soluble pools (Figure 7A). Tundra soils exhibited the lowest SON concentrations (30.23 mg kg^{-1}), constrained by cold temperatures, limited microbial activity, and sparse vegetation, all of which inhibit organic matter turnover and nitrogen mineralization.[47,48] Collectively, this global synthesis, encompassing over 5,700 observations, provides the most comprehensive spatial analysis of SON to date, filling a longstanding gap in nitrogen biogeochemistry. It highlights the critical role of biome-specific processes in shaping the SON pool and establishes a foundational benchmark for assessing ecosystem nitrogen status under global environmental change.

Driving factors that control SON concentrations

Spatial variations in SON concentrations are controlled by complex interactions among climatic factors, soil properties, and parent material. Elevation emerged as the most important predictor in the random forest model, followed by parent material, MAP and soil BD (Figure 2A). SON levels increased with elevation, potentially due to cooler temperatures, lower microbial turnover, and enhanced retention of undecomposed organic matter.[22,49] Freeze-thaw cycles in high-altitude zones may also facilitate physical disaggregation of litter, enhancing nitrogen release. Furthermore, high-elevation ecosystems are generally less impacted by anthropogenic disturbances, limiting nitrogen loss pathways.[50] Our results also indicated higher SON concentrations in low-latitude plateaus and mountain ranges (e.g., the Tibetan Plateau, Andes, and African Highlands) (Figure 5A). The strongest interaction was observed between elevation and MAT (mean absolute SHAP interaction = 9.05), highlighting the critical role of elevation gradients in modulating temperature-driven processes influencing SON (Figure 4). Additionally, the interaction between elevation and fine particle content (4.21) underscores how physical soil characteristics vary markedly along altitudinal gradients (Figure 4), influencing nutrient retention and cycling. MAT and MAP also exhibited a substantial interactive effect (5.58) (Figure 4), emphasizing that climatic moisture and thermal regimes jointly shape the spatial distribution and transformation of SON through their impacts on microbial metabolism and organic matter decomposition.

Parent materials influences SON indirectly through its role in soil genesis and mineralogy. However, differences in SON concentrations exist between various parent materials, with SM rocks showing the highest concentrations and PI rocks the lowest (Table 3). Soils derived from SM rocks, comprising limestone, shale, and sandstone—exhibited the highest SON levels, likely due to their higher organic matter content and mineral surfaces (e.g., clay and carbonates) that promote nitrogen retention and mineralization.[24] In contrast, soils formed from PI rocks, such as diorite and syenite, had the lowest SON levels, reflecting their lower weathering rates, reduced clay content, and limited capacity for organic N adsorption.[51] Consequently, PI-derived soils have a lower N retention capacity, resulting in faster N loss rather than conversion to SON.[24] Bulk density negatively correlated with SON, as compacted soils restrict aera-

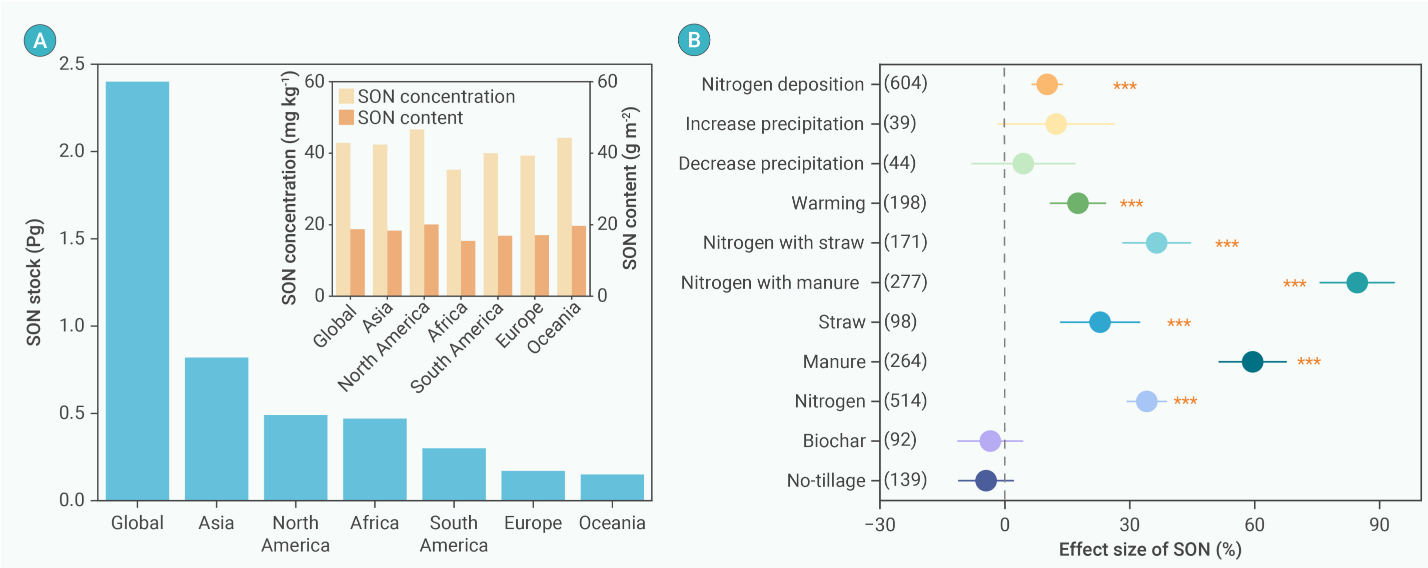

Figure 6. Analysis of the predicted global distribution map of soil soluble organic nitrogen (SON) (A) and the response to global change (B) Area-weighted average SON concentrations were calculated based on our predicted distribution map. Soil bulk density and land area were used to convert SON concentrations to SON contents. Dots and bars represent mean and 95% confidence intervals of effect size, respectively. Effect sizes are statistically significant if the 95% confidence intervals of effect size do not overlap with the vertical dashed lines. The value in parentheses represents the sample size. Asterisks denote statistical significance (***, $p < 0.001$).

tion, water infiltration, and microbial activity, thereby hindering organic matter decomposition.[52,53] SHAP analysis further revealed modest but significant interactions between BD and other variables, including fine particles (1.45), SOC (1.26), and MAT (1.47), suggesting that soil physical structure modulates the responsiveness of SON to both biotic and abiotic drivers.

While our dataset does not resolve SON molecular composition, literature suggests that molecular composition of SON may partly explain its observed spatial patterns.[16] Labile low-molecular-weight compounds (e.g., amino acids) dominate in warm and biologically active systems,[15,17] whereas high-molecular-weight fractions (e.g., humic-bound N) persist in cold, clay-rich soils due to their sportive stabilization.[54-57] Future coupling of molecular analyses with large-scale SON mapping will be crucial to disentangling the mechanistic basis of SON heterogeneity. Overall, these findings underscored the complex interactions between environmental, soil, and ecosystem variables in determining the concentrations of SON. Understanding these relationships can enhance our ability to predict changes in SON and its role in ecosystems, to provide essential scientific guidance for soil management and agricultural practices.

Global SON concentration patterns

Decreases in SON concentrations at low latitudes are a result of multiple interacting factors.[58] At lower latitudes the climate shifts from cold polar and temperate regions to warmer subtropical and tropical regions, where rising temperatures accelerate the decomposition of soil organic matter, which reduces the accumulation of SON. In high-latitude regions, vegetation in coniferous forests, tundra, and permafrost experience slower organic matter decomposition, which leads to greater SON accumulation in the soil.[59] In contrast, although tropical rainforests, savannas, and farmlands in low-latitude regions generate large quantities of plant litter, the robust microbial activities in these regions result in faster decomposition, leading to lower SON concentrations. Additionally, frequent human activities in low-latitude regions accelerate N losses, which further reduces SON concentrations. In high-latitude regions, however, anthropogenic activities are less prevalent, N cycling is slower, and SON concentrations are more stable.[13,59] Furthermore, in high-latitude regions of the Northern Hemisphere, permafrost thawing due to climate warming gradually releases accumulated nutrients, which further increases SON concentrations. Nevertheless, there is significant heterogeneity at regional and local scales. For example, compared with Eastern China, the Tibetan Plateau has higher SON concentrations (Figure 5A). This is primarily due to lower temperatures at higher altitudes that slow down microbial processes and the decomposition of organic matter, which allows organic N to accumulate in the form of SON.[22]

Our predictive model estimated a global topsoil (0-30 cm) SON stock of 2.4 Pg N, accounting for 3.6% of the total topsoil nitrogen pool.[60] SON is quantitatively comparable to the microbial N pool (2 Pg N) and roughly one-fourth of plant biomass nitrogen (10 Pg N).[60,61] Additionally, it is an order of magnitude smaller than the deep soil nitrate pool (15.2 ± 1.1 Pg N),[62] another key mobile nitrogen reservoir. Asia has the largest SON stocks (0.82 Pg N) due to its vast land area and diverse ecosystems, which range from tropical rainforests to temperate regions that contribute to significant N storage in soils. Europe and Oceania possess the smallest stocks, at 0.17 Pg N and 0.15 Pg N, respectively, which are likely due to their smaller land areas and moderate N concentrations. Global change also influences the distribution patterns of SON. For instance, nitrogen deposition increases SON concentrations in Asia and North America but reduces them in Europe (Figure 7B). Among agricultural management practices, organic fertilizer application enhances SON levels in Asia and Europe, yet shows no significant effect in North America (Figure 7B). Consequently, in the context of global change, predicting SON dynamics becomes increasingly critical.

The predictive model adopted in this study demonstrated a high level of accuracy in estimating global soil SON stocks, with an explanatory power of up to 82% (Figure 2). This high precision was attributed to two key factors. First, the availability of a rich and comprehensive dataset established a solid foundation for the prediction of global scale SON. Second, by comparing various linear and nonlinear models, the most suitable model for global SON prediction was selected. SON distribution map can inform targeted management interventions, such as optimizing fertilizer timing or reducing N losses in vulnerable areas, and serve as key inputs for policy frameworks addressing nonpoint source pollution (e.g., SDG 6, 15, EU Nitrate Directive).[63] In conclusion, SON mapping offers a science-based tool for linking soil process knowledge with practical policy interventions under global change.

Limitations and predictive uncertainties

Despite compiling a comprehensive global dataset of SON concentrations, identifying key drivers, and conducting global predictions, our study had several limitations. Firstly, some ecosystems remained underrepresented, as the current data were still heavily concentrated in croplands and forests, which accounted for 81% of the dataset, while other ecosystems collectively represented only 19%. This underrepresentation may have reduced the predictive accuracy for certain ecosystems. Secondly, although we gathered data on SON concentrations from a global perspective, certain regions (particularly Africa, South America, remote mountainous, and polar areas), remained under sampled. Thirdly, although subsoil data (> 30 cm) were initially collected, we ultimately excluded them from model training and global mapping due to their sparse availability and limited spatial representativeness. Subsoil observations constituted only 8% of the dataset and were predominantly concentrated in East Asia, particularly China, with minimal coverage of other continents and major biomes. Moreover, subsoil SON

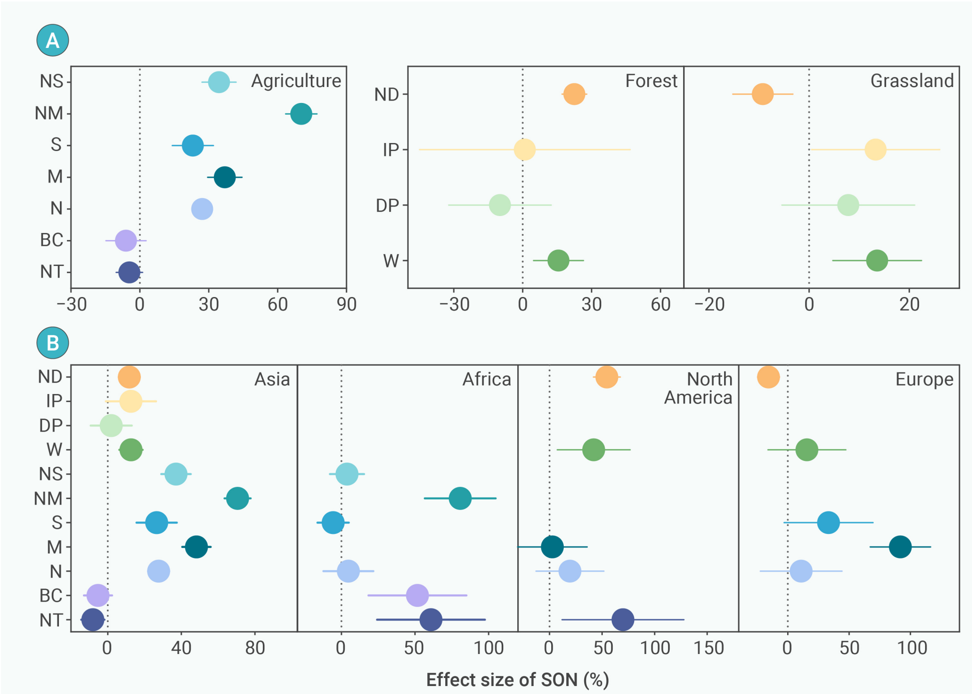

Figure 7. Response of soil soluble organic nitrogen (SON) to global change among different ecosystems (A) and continents (B) Dots and bars represent mean and 95% confidence intervals of effect size, respectively. Effect sizes are statistically significant if the 95% confidence intervals of effect size do not overlap with the vertical dashed lines. NS, nitrogen combined with straw; NM, nitrogen combined with manure; S, straw; M, manure; N, nitrogen; BC, biochar; NT, no-tillage; ND, nitrogen deposition; IP, increase precipitation; DP; decrease precipitation; W, warming.

dynamics are governed by distinct processes — such as reduced organic inputs, altered microbial communities, and different mineral interactions — that are not adequately captured by current global-scale predictors. For transparency, all subsoil SON data have been made publicly accessible, and we encourage future studies to expand subsoil sampling and develop depth-specific predictive frameworks.

CONCLUSION

Global SON exhibited significant variability across climates, ecosystems, vegetation types, and soil properties. Among predictive models, the random forest model performed best, explaining 82% of SON variability, with elevation, parent material, and bulk density as the key drivers. The RF-predicted global average SON concentration was 41.36 mg kg^{-1}. The estimated global SON stock in topsoil (0-30 cm) reached 2.4 Pg N, and the model successfully captured latitudinal trends from the equator to the poles. Meta-analysis revealed that most global change factors increased SON (−4.45% to +70.71%), except for reduced precipitation, biochar application, and no-tillage practices. The findings enhance the understanding of terrestrial nitrogen dynamics, support sustainable nitrogen management, and improve biogeochemical modeling under global change. The comprehensive dataset provides a foundation for assessing nitrogen-related environmental risks and optimizing ecosystem resilience. Moving forward, we recommend three key directions for future research: (1) investigating SON in deeper soil layers (below 30 cm), which are essential for long-term nutrient dynamics but poorly represented in current data; (2) elucidating microbial functional mechanisms, including extracellular enzyme production and microbial nitrogen use strategies that govern SON turnover; and (3) addressing data gaps in underrepresented ecosystems such as tropical wetlands, arid zones, and alpine tundra, to improve model predictions and ecological generality. Collectively, these efforts will refine global nitrogen models and enhance understanding of SON's role in ecosystem resilience under changing climates."

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AUTHOR CONTRIBUTIONS

Andong Cai designed this study. Tianjing Ren collected the data. Tianjing Ren and Andong Cai discussed analyzing methods. Andong Cai conducted the analysis. Tianjing Ren drafted the manuscript. All authors discussed the results and contributed to the manuscript. All authors contributed to the manuscript and approved the final version.

DECLARATION OF INTERESTS

The authors declare no competing interests.

DATA AND CODE AVAILABILITY

The global soil SON in this study and raw dataset of driving factors can be downloaded at https://doi.org/10.6084/m9.figshare.27048991.

SUPPLEMENTAL INFORMATION

It can be found online at https://doi.org/10.59717/j.xinn-geo.2025.100151