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SoilHealthDB-V2: An updated and standardized global database of soil health under conservation management

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Abstract. Field-based measurements of soil health under various conservation management practices have been compiled into the global Soil Health Database (*SoilHealthDB*), supporting comprehensive analyses of the effects of systems such as cover cropping, no-tillage, agroforestry systems, and organic fertilization on soil health. To support more effective soil health assessments and related analyses, it is essential to maintain updated and standardized datasets. In response to this need, the existing database of *SoilHealthDB* has been updated and standardized as *SoilHealthDB*-V2. All soil health indicators were harmonized to improve consistency, traceability, and analytical accuracy. The number of observations increased from 5,907 to 8,874, expanding global spatiotemporal coverage and improving representation across diverse climate regions. Several new variables related to cover crop management have been introduced, including cover crop termination date, cash crop planting date, cover crop termination method and residue return method, cover crop irrigation and fertilization practices. These additions enable more detailed assessments of best management practices. Furthermore, the inclusion of experiment duration-related data allows for more robust investigations of temporal trends in soil health outcomes. New indicators related soil carbon pools further enhance the database's utility for evaluating the effects of conservation practices on carbon cycling. Overall, *SoilHealthDB*-V2 offers a robust, globally relevant foundation for soil health assessment and provides critical support for developing evidence-based conservation management strategies.

1 Introduction

Soil health has emerged as a central topic in contemporary agricultural research and practice (Lehmann et al., 2020). It refers to the ability of soil to function as a biodiverse ecosystem that sustains plants, animals, and humans (USDA-NRCS, 2019). Soil health is a comprehensive concept that considers the holistic integration of physical, chemical, and biological properties of soil (Kibblewhite et al., 2008; Stewart et al., 2018). With increases in the intensity and extent of farmland use, the pressure on agricultural production has intensified, resulting in issues that threaten soil health and crop yields such as declining soil fertility, imbalanced pH levels, and increased soil erosion (Kibblewhite et al., 2008; Lal, 2016). Against the backdrop of global climate change, preserving soil health is also critical for maintaining ecosystem functions and ensuring long-term food security (Bradford et al., 2016; McBratney et al., 2014).

Conservation management practices, such as cover crops (which is a primary focus in both *SoilHealthDB* and *SoilHealthDB*-V2), no-tillage, organic fertilizer, agroforestry systems and straw return, are essential approaches for promoting soil health (Cárceles Rodríguez et al., 2022; Pheap et al., 2019; Teng et al., 2024). To facilitate the assessment of these practices, the Soil Health Database (*SoilHealthDB*) was developed as the first comprehensive global database integrating the effects of various conservation management approaches on soil health, including both background information and soil health indicators (Jian et al., 2020a). Background details include paper information (such as author, journal, and publication year), location (i.e., longitude, latitude, altitude), climate (e.g., annual precipitation, and average annual temperature), soil properties (e.g., pH, organic carbon, and nitrogen), and conservation management practices (e.g., tillage type, cover crop, and cash crop). Soil health indicators include soil physical properties (such as bulk density, soil water content, and soil aggregation), chemical properties (e.g., soil organic carbon, nitrogen, phosphorus, and micronutrient content), biological factors (e.g., weed diversity, fauna, and microbial biomass), environmental states and fluxes (e.g., nitrous oxide and methane), and agronomic responses (including cash crop yield and biomass). *SoilHealthDB* has supported numerous meta-analyses, including the effects of cover cropping on soil organic carbon (Jian et al., 2020b), the influence of conservation practices on erosion and runoff (Du et al., 2022), and their impacts on crop yield (Ren et al., 2023). Nonetheless, limitations in data standardization and accessibility continue to constrain the utility of *SoilHealthDB* for in-depth and systematic analyses.

Over the decades, numerous experiments on conservation management have been conducted globally, and generating a wealth of soil data (Bradford et al., 2016; Teng et al., 2024). However, at the global scale, there is still no clear consensus on how the duration of conservation management practices influences various soil indicators (Qiu et al., 2024; Shi et al., 2025; Wang et al., 2021). Moreover, it remains uncertain whether these measured soil properties can reliably reflect overall soil health, and if soil health should be interpreted differently based on specific management practices (Pheap et al., 2019; Xue et al., 2019). Therefore, compiling soil properties into a standardized data framework is crucial to support comprehensive analyses and accurately assess soil health conditions under different conservation management practices.

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In the original *SoilHealthDB*, only a few soil health indicators have standardized units (such as soil organic carbon, cash crop yield, erosion and runoff), and many other indicators have not been standardized, making it difficult to conduct in-depth and comprehensive analyses of these indicators (Jian et al., 2020a). Data availability for certain key variables, such as soil quality index and ecosystem services, remains insufficient for comprehensive meta-analysis. In addition, most papers used in the database did not provide experiment ID comments or pairing information that clearly identified the control-treatment pairs and described differences in site, year, soil depth, or conservation practice, making it difficult to organize and verify the data. Moreover, the *SoilHealthDB* does not include experiment start year, end year, or the year that soil samples were taken, making it impossible to study the combined short- and long-term effects of different conservation management practices on soil health (Blanco-Canqui and Ruis, 2020; Shi et al., 2025). While background information about individual soils is crucial for conservation management, the *SoilHealthDB* includes only soil organic carbon and omits other important indicators such as nitrogen, phosphorus, and potassium (Scavo et al., 2022). Additionally, the lack of information related to cover crop management (e.g., termination methods, interval between termination of cover crop and planting of subsequent cash crops) makes it hard to conduct research on the impact of cover crop management on soil health (Acharya et al., 2017; Tian et al., 2015; Wayman et al., 2015). Therefore, it is essential to update the *SoilHealthDB* and optimize its structure.

Here, we present a substantial update to the existing *SoilHealthDB*—now revised and released as *SoilHealthDB*-V2 (Table S1). The primary improvements including the following: (1) supplementation of the experiment ID for all papers to clarify the specific information for different processing methods, enhancing the input specifications; (2) inclusion of duration-related information; (3) addition of soil background information, cover crop management practices, and details about conservation management types; (4) standardization of all soil health indicators, unification of units across indicators, and incorporation of data source information; and (5) inclusion of more carbon-related indicators. We anticipate that these improvements will enhance the usability and interoperability of *SoilHealthDB-V2*.

2 Methods

2.1 Updates of background information in *SoilHealthDB*-V2

We restructured the *SoilHealthDB* into a new version (*SoilHealthDB*-V2) to facilitate data collection and enhance quality control (Fig. S1). We added several background information, including cover crop management practices, experiment ID comments, soil background information, duration-related information, and conservation type information (Table 1).

In *SoilHealthDB-V2, EID_Comments* was added to identify the distinguishing details of *Experiment ID*, which typically consist of pairs of control and treatment information, including soil depth, tillage, cover crop and all other criteria that can effectively distinguish *Experiment ID*. Recording the duration of experiment is beneficial for understanding the short-term and long-term effects of different conservation management practices. Therefore, we have added two columns *Start_year* and *End_year*. Soil

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background information is essential for conservation management practices. In addition to background organic carbon (*Background_SOC*) in *SoilHealthDB*, we have also added five columns related to soil nutrient availability: background nitrogen (*BG_N*), background available nitrogen (*BG_AN*), background phosphorus (*BG_P*), background available phosphorus (*BG_AP*), background potassium (*BG_K*) and background available potassium (*BG_AK*). On the other hand, we deleted some columns, such as "*Others*" and the "*Conservation_Description*" as these columns are either rarely recorded or have been covered by the newly added columns.

To study the impact of cover crop management practices on soil health, we added several columns, including the year of cover crop planting (*CC_plant_year*), the day of the year of cover crop planting (*CC_plant_DOY*), the day of the year of cover crop termination (*CC_termination_DOY*), the days of cover crop grow (*CC_growth_day*, which can also be calculated as *CC_termination_DOY* - *CC_plant_DOY*), the method of cover crop termination (*CC_termination_method*), the method of cover crop return (*CC_return_method*), the irrigation applied to cover crop (*CC_irrigation*), the fertilization applied to cover crop (*CC_fertilization*), the day of the year of cash crop plating (*Crop_plant_DOY*), and the days of cover crop residue retain in soil/surface before planting cash crop (*CC_retain_day*, which can also be calculated as *Crop_plant_DOY* - *CC_termination_DOY*). The original *SoilHealthDB* only included treatment-specific information on conservation management type (*Conservation_Type*) and description (*Conservation_Description*), but did not provide information on paired control and treatment and their differences. Therefore, we added two columns, *Conservation_C* and *Conservation_T*, to specify the respective practices used in the control and treatment, and revised *Conservation_Type* to reflect the differences between them.

Table 1. Summary of background information update in *SoilHealthDB-V2* compared with the *SoilHealthDB*

Column	Description	Comments
Others	Other soil health indicators need to make comments	Deleted in *SoilHealthDB*-V2
EID_Comments	Details about how experiments ID was determined	Added in *SoilHealthDB*-V2
Start_year	Experiment start year	Added in *SoilHealthDB*-V2
End_year	Experiment end year	Added in *SoilHealthDB*-V2
BG_N	Background soil total nitrogen	Added in *SoilHealthDB*-V2
BG_AN	Background soil available nitrogen	Added in *SoilHealthDB*-V2
BG_P	Background soil total phosphorus	Added in *SoilHealthDB*-V2
BG_AP	Background soil available phosphorus	Added in *SoilHealthDB*-V2
BG_K	Background soil total potassium	Added in *SoilHealthDB*-V2
BG_AK	Background soil available potassium	Added in *SoilHealthDB*-V2
CC_plant_year	Year that cover crops were planted	Added in *SoilHealthDB*-V2
CC_plant_DOY	DOY that cover crops were planted	Added in *SoilHealthDB*-V2
CC_termination_DOY	DOY of killing cover crop	Added in *SoilHealthDB*-V2
CC_growth_day	How many days cover crop grow before samples taken, *CC_termination_DOY* - *CC_plant_DOY*	Added in *SoilHealthDB*-V2
CC_termination_method	Method of killing cover crop, such as mechanical, biological, integrated	Added in *SoilHealthDB*-V2
CC_return_method	How to treat crop cover biomass, such as	Added in *SoilHealthDB*-V2

	incorporated, surface, removed	
CC_irrigation	Irrigation (mm) cover crop received	Added in *SoilHealthDB*-V2
CC_fertilization	Fertilization cover crop received	Added in *SoilHealthDB*-V2
Crop_plant_DOY	DOY that cash crops were planted	Added in *SoilHealthDB*-V2
CC_retain_day	How many days crop cover residue retain in soil/surface before plan cash crop, *Crop_plant_DOY - CC_termination_DOY*	Added in *SoilHealthDB*-V2
Conservation_Description	Description on conservation	Deleted in *SoilHealthDB*-V2
Conservation_C	Agriculture management of control, usually is conventional management (CK)	Added in *SoilHealthDB*-V2
Conservation_T	Including cover crop (CC), No-tillage (NT), organic fertilizer (OF), straw return (SR) etc.	Added in *SoilHealthDB*-V2
Conservation_Type	Conservation management difference between control and treatment.	Revised in *SoilHealthDB*-V2

2.2 Standardization and soil health indicators in *SoilHealthDB*-V2

We standardized the soil health indicators and added new columns to ensure each indicator has six columns in *SoilHealthDB*-V2 (Table 2). In the *SoilHealthDB*, only a few indicators (including soil organic carbon, cash crop yield, erosion and runoff) had standardized unites, limiting the ability to perform in-depth and comprehensive analyses. To address this, *SoilHealthDB*-V2 provides six columns for each indicator: *Index_C*, *Index_T*, *Index_C_SD*, *Index_T_SD*, *Index_units* and *Index_Comments*. All indicators are standardized to a common unit of measurement wherever feasible. The *Index_Comments column* includes the index name, unit information, and data source to facilitate data verification, validation, and traceability, thereby enhancing the reliability and usability of the dataset of data.

Table 2. Overview of standardized soil health indicators in *SoilHealthDB*-V2

Column	Description
Index_C	Value of control for a certain index
Index_T	Value of treatment for a certain index
Index_C_SD	Standard deviation of control for a certain index
Index_T_SD	Standard deviation of treatment for a certain index
Index_units	Unit of index
Index_Comments	Comments on the index, including index name, unit information, data source

With a deeper understanding of the carbon cycle, an increasing number of studies have focused on different carbon pools. In response, we added four columns: total carbon and inorganic carbon (*TCIC*), fast carbon (*FastC*), slow carbon (*SlowC*) and passive carbon (*PassiveC*). The latter three indicators describe soil carbon turnover and residence time. Fast carbon includes active carbon, dissolved organic carbon, and easily oxidizable organic carbon. slow carbon encompasses light fraction carbon and particulate organic carbon, while passive carbon consists of heavy fraction carbon and microbial-associated organic matter (Sherrod et al., 2019). We also added the columns Crop water use amount (*WUA*) and Crop water use efficiency (*WUE*), which extend the database perspective from soil water status to crop water utilization and production efficiency, thereby facilitating

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a more comprehensive assessment of the effects of conservation management practices on water cycling and agricultural productivity. To streamline related indicators, we removed substrate-induced respiration (*SIR*) and CO_2Bust, merging them into the broader categories of microbial biomass carbon (*MBC*) and carbon mineralization (*Cmineralization*). Additionally, in response to the growing emphasis on soil microbial studies, microbial biomass phosphorus (*MBP*) was also added in this update. Finally, the column *Microelement* was revised to *NutrientElement* to encompass both macro- and micronutrients of the soil.

Table 3. Summary of soil health indicators updates in *SoilHealthDB*-V2 compared with the old version *SoilHealthDB*

Column	Description	Comments
SIR	Substrate induced respiration	Merging into *MBC* in *SoilHealthDB*-V2
CO2Bust	CO_2 burst test respiration	Merging into *Cmineralization* in *SoilHealthDB*-V2
TCIC	Total carbon and inorganic carbon	Added in *SoilHealthDB*-V2
FastC	Fast carbon	Added in *SoilHealthDB*-V2
SlowC	Slow carbon	Added in *SoilHealthDB*-V2
PassiveC	Passive carbon	Added in *SoilHealthDB*-V2
WUA	Crop water use amount	Added in *SoilHealthDB*-V2
WUE	Crop water use efficiency	Added in *SoilHealthDB*-V2
MBP	Microbial biomass phosphorus	Added in *SoilHealthDB*-V2
NutrientElement	Macro- and micronutrient	Revised in *SoilHealthDB*-V2

2.3 Data sources and quality control

Building on the 321 papers included in *SoilHealthDB*, we expanded the database by adding new studies that were cited in previous meta-analyses and review papers, but not yet incorporated into *SoilHealthDB*. Specifically, we included original research papers that were cited in the meta-analyses or review papers conducted by Garba et al. (2022), Lu (2020), Mbava et al. (2020), Wang et al. (2021), and Yu et al. (2021). Additional relevant papers were also selected based on the original inclusion criteria of *SoilHealthDB*. In *SoilHealthDB-V2*, approximately 81 % of the sources were published in English, with 19 % in Chinese. Publications in other languages were rarely included. Peer-reviewed journal articles constituted the majority of data sources, though academic theses and conference papers were also included.

To ensure data quality and consistency, we first employed an R script developed by Jian et al. (2020a) for automated validation. For example, geographic coordinates were checked to ensure latitude and longitude values fell within valid ranges, with warnings triggered for invalid entries. Detailed information on the data constraints applied to each column in *SoilHealthDB-V2* can be found in the "https://github.com/jianjinshi/SoilHealthDB-V2", which is available via the GitHub repository and included in every database release. This script is also executed for all pull requests to the Github repository, allowing us to detect and address data quality issues before any updates are merged into the database. Secondly, we recorded the data sources from the original paper in the comment column for each indicator (Table 2), which enables users to find the data quickly and perform quality checks. Finally, one team member was assigned to data collection, while another experienced individual was

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responsible for conducting data quality checks to ensure the accuracy and integrity of the data recorded in the database.

2.4 Data coverage

To assess the spatial and climatic representativeness of *SoilHealthDB*-V2, we linked each site to the Köppen climate classification (at 0.5° × 0.5° resolution) using its latitude and longitude. Based on this linkage, all sites were assigned to one of four major climate types: arid, equatorial, snow, and temperate.

Similarly, we also extracted mean annual temperature (MAT) and mean annual precipitation (MAP) for each site in *SoilHealthDB*-V2 using a global climate dataset from the Center for Climate Research at the University of Delaware (also at 0.5° × 0.5° resolution). These MAT and MAP values were then compared with global distributions to evaluate how well the database represents global farmland climate conditions. A close match between the *SoilHealthDB*-V2 and global distributions would indicate that the database provides broad and representative coverage of global agricultural soils.

To further explore regional differences, we combined Köppen climate types with MAT and MAP data, allowing for a climate-specific comparison between *SoilHealthDB*-V2 and global patterns. As the database continues to expand, we anticipate improved coverage and representativeness relative to its predecessor, *SoilHealthDB*.

2.5 Overview of soil health indicators

Understanding how different conservation management practices impact soil health is essential for guiding agricultural production. Following the Cornell Soil Health Framework, soil texture in *SoilHealthDB*-V2 was categorized into three classes: coarse (sand, loamy sand, sandy loam), medium (sandy clay loam, loam, silt loam, silt), and fine (clay, sandy clay, clay loam, silty clay, silty clay loam). For sites lacking soil texture information in the original publications, we derived texture classes by linking site coordinates to the SoilGrids database (250 m × 250 m resolution). The proportions of sand, silt, and clay were extracted, and soil texture was determined using the "soiltexture" R package.

To evaluate data coverage and reporting frequency, we quantified the number and proportion of studies that reported each soil health indicator and compared these values between *SoilhealthDB* and *SoilhealthDB*-V2. In addition, we analyzed the sub-indictors reported under each major soil health indicator to improve database usability and transparency. The relative proportions of these sub-indicators were documented to capture the richness and diversity of the data. This step also helped to identify patterns and potential biases in how soil health indicators are measured and reported in current papers.

2.6 Correlation analysis among soil health indicators

For each soil health indicator, the natural logarithm of the response ratio (lnRR) was first calculated based on pairwise comparisons between treatment and control groups.

$$RR_x = \ln{(X_T/X_C)} \tag{1}$$

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where X_T is the parameter value under the conservation management practice, and X_C is the value under the conventional management practice.

It should be noted that not all studies reported all 48 soil health indicators, some indicators do not have enough data to support the correlation analysis. Therefore, we only conducted pairwise Pearson correlation analyses between indicators with more than 14 overlapping data to identify the relationships, and correlation coefficients and corresponding p-values were calculated and presented in this study. Specific parameters analyzed included: 1) *BiomassCash* (cash crop biomass); 2) *Yield* (cash crop yield; 3) *BD* (bulk density); 4) *OC* (soil organic carbon); 5) *TCIC* (total carbon or inorganic carbon); 6) *OC_seq* (soil organic carbon sequestration rate compare with beginning of experiments); 7) *FastC* (soil fast carbon); 8) *SlowC* (soil slow carbon); 9) *PassiveC* (soil passive carbon); 10) *N* (soil nitrogen); 11) *P* (soil phosphorus); 12) *K* (soil potassium); 13) soil *pH*; 14) *CEC_Cation* (soil cation exchange capacity); 15) *EC* (soil electricity conductivity); 16) *BS_ToS* (soil base saturation); 17) *Aggregate* (soil aggregate stability); 18) *Porosity* (soil porosity); 19) *Penetration* (soil penetration resistance); 20) *Infiltration* (soil infiltration rates); 21) *Ksat* (saturated hydraulic conductivity); 22) *Erosion*; 23) *Runoff*; 24) *Leaching*; 25) *ST* (soil temperature); 26) *SWC* (soil water content); 27) *AWHC* (available water holding capacity); 28) *WUA* (crop water use amount); 29) *WUE* (water use efficiency); 30) *Weed*; 31) *Diseases*; 32) *Pests*; 33) *SoilFauna* (soil fauna); 34) *Fungal* (fungal and bacteria); 35) *MicrobialOther* (other microbial indicators); 36) *Enzyme*; 37) *Cmineralization* (carbon mineralization); 38) *Nmineralization* (nitrogen mineralization); 39) *N2O*; 40) CO_2; 41) CH_4; 42) *MBC* (microbial biomass carbon); 43) *MBN* (microbial biomass nitrogen); 44) *MBP* (microbial biomass phosphorus); 45) *NutrientElemen*t (Macro- and micronutrient); 46) *SQI* (soil quality index); 47) *ESS* (ecosystem services); and 48) *Texture*.

2.7 Effects of duration on soil health indicators under cover crop management

To investigate the influence of conservation management duration on soil health, we used cover crops as a representative example. Our initial approach involved classifying field experiments into short-, medium-, and long-term categories based on the durations reported in the source literature. However, we found that the criteria for these temporal classifications were inconsistent across studies, with no established standard. To establish a robust data-driven classification framework, we conducted a systematic compilation of review and meta-analysis articles from the Web of Science. We searched for publications using key terms including "cover crop*", "no till*", "organic farm", "agroforestry system*", or "straw return" and "duration". We then extracted the reported duration threshold for medium- and long-term experiments. We then applied a nonparametric bootstrap resampling technique (Hesterberg, 2011) to estimate the mean duration and its 95% confidence intervals for each category. This analysis established the mean for medium-term experiments at 4.63 (±0.33) years, and for long-term experiments at 10.25 (±0.62) years (Fig. S2). Based on these results, we defined rounded thresholds of 5 and 10 years to categorize all experiments within *SoilHealthDB*-V2. Consequently, experiments were classified as follows: short-term (1–4 years), medium-term (5–9 years), and long-term (≥10 years) categories.

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For each pairwise comparison between the treatment (T; with cover crops) and control (C; without cover crops) across short-term, medium-term, and long-term categories, we calculated the natural logarithm response ratio (lnRR) for a suite of soil health indicators. To estimate the 95 % confidence intervals, we employed a nonparametric bootstrap resampling technique with 5,000 iterations applied to the original RR values. The mean effect sizes and their associated confidence intervals were then used to assess the influence of cover crop management on soil health indicators for each temporal category.

3 Results

3.1 Data coverage

SoilHealthDB-V2 comprises data from 591 study sites worldwide that investigated various conservation management practices (Fig. 1). Among these, cover cropping (283 sites) was the most extensively studied practice, with the United States dominating in terms of site representation, followed by China, Europe, and parts of Africa. No-tillage (59 sites) and organic fertilizer application (63 sites) were also primarily concentrated in North America, Europe, and China. Agroforestry system (42 sites) was mainly distributed across Africa and Southeast Asia. Straw return (66 sites) was predominantly practiced in East Asia, particularly in China. The "Other" category (22 sites), which includes interplanting, plastic film mulching, ridging, rotation, and stubble, was mostly concentrated in China. Sites involving two or more practices (TOM, 56 sites) were notably clustered in East Asia and Australia. Although a diverse range of conservation practices has been studied globally, research efforts remain disproportionately concentrated in North America, China, and Europe, with notable gaps in Africa, South America, and other underrepresented regions.

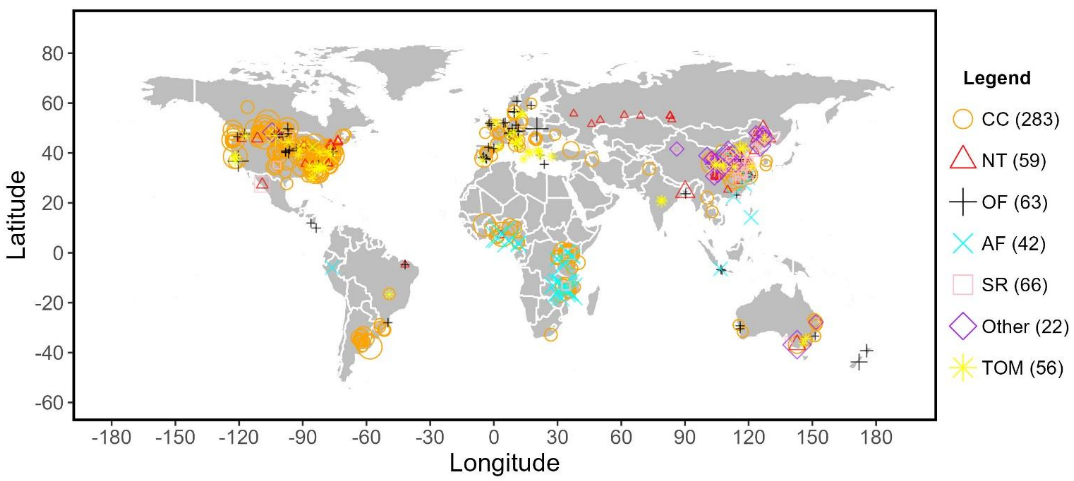

Figure 1. Global distribution of study sites included in *SoilHealthDB*-V2. Different symbols representing different conservation management practices: cover crops (CC), no-tillage (NT), organic fertilizer (OF), agroforestry systems (AF), straw return (SR), other practices (e.g., interplanting, plastic film mulching, ridging, rotation, and stubble), and two or more practices combined (TOM). Numbers in parentheses indicate the number of sites for each practice. Symbol sizes represent the number of comparisons at each site.

Most study sites in *SoilHealthDB*-V2 are located in temperate (48 %) and snow (29 %) climate zones, with fewer sites in equatorial (14 %) and arid (9 %) regions (Fig. 2a). The distributions of MAT and MAP in *SoilHealthDB*-V2 differ slightly from global distributions, likely reflecting the climatic conditions most suitable for crop growth (Fig. 2b and 2c). Globally, MAT spans a wide range, from below 0 °C in colder regions to above 30 °C in hot zones, with a peak near 26 °C. In contrast, MAT values in *SoilHealthDB*-V2 are primarily concentrated between 5 °C and 25 °C, with prominent peaks around 10 °C and 15 °C, forming an approximately normal distribution. Similarly, MAP values in the database are primarily distributed between 500-1500 mm, while the global dataset spans a broader range, particularly in arid regions (<500 mm) and tropical zones (>2000 mm). These patterns suggest that most conservation studies focus on regions with moderate temperature and precipitation conditions, which likely correspond to optimal environments for crop growth.

To further explore these differences, we compared MAT and MAP distributions between *SoilHealthDB*-V2 and global distributions across the four major Köppen climate zones (Fig. 2d and 2e). In equatorial (20-30 °C) and temperate (10-20 °C) regions, the MAT distributions in *SoilHealthDB*-V2 closely align with global patterns. However, in snow and arid regions, substantial discrepancies are observed. The global MAT distribution shows extremes, with prominent peaks at both high (20-30 °C for Arid) and low (−10-5 °C for Snow) temperature ranges, while *SoilHealthDB*-V2 data are mainly concentrated between 0 and 15 °C for both arid and snow (Fig. 2d). For MAP, *SoilHealthDB*-V2 aligns well with global dataset in snow (300–1000 mm) and temperate (500–1300 mm) zones. In contrast, the global MAP exhibits greater variability in arid (<500 mm) and equatorial (>1500 mm) regions. These findings suggest that conservation practices documented in *SoilHealthDB*-V2 are largely implemented in regions with moderate temperature and precipitation, likely reflecting both the environmental suitability for crop production and a research bias toward agriculturally favorable climates.

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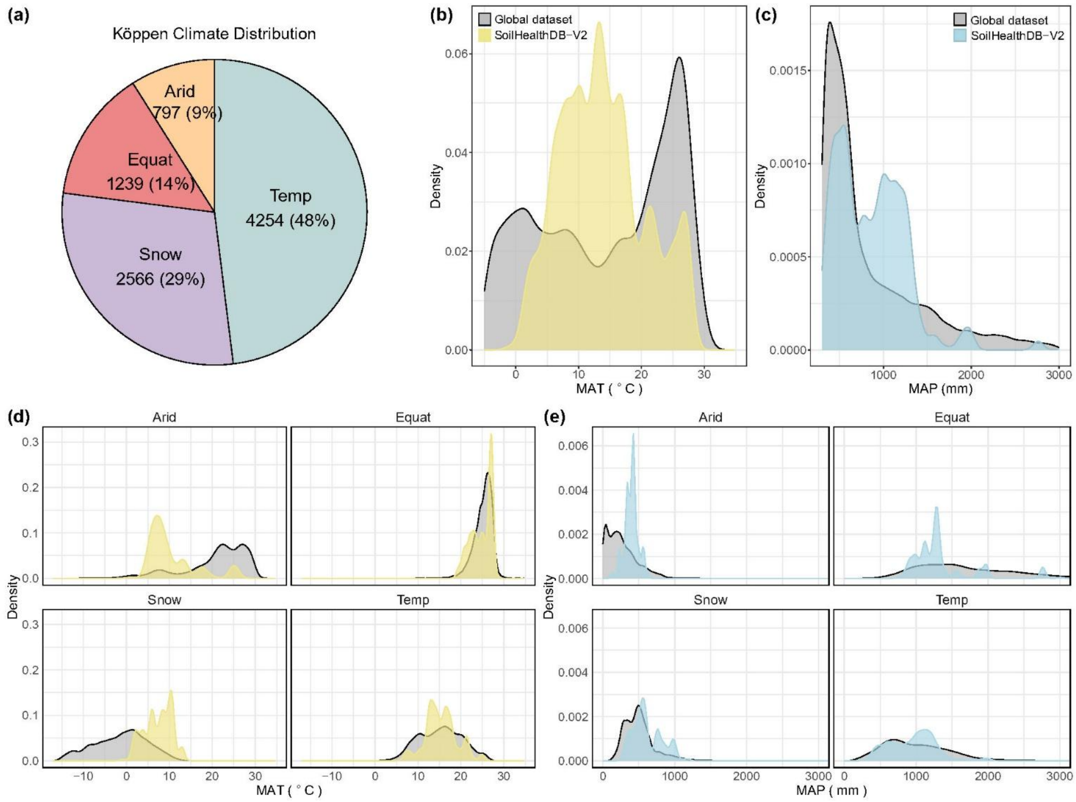

Figure 2. Climate representation of *SoilHealthDB*-V2 samples compared to global climate distributions. (a) Distribution of *SoilHealthDB*-V2 samples across major climate types. (b) Mean annual temperature (MAT) and (c) mean annual precipitation (MAP) distributions for *SoilHealthDB*-V2 (in color) versus global reference data (in gray) from the Harmonized World Soil Database v1.2. (d) MAT distributions within each climate type; (e) MAP distributions within each climate type. Note: Equat = Equatorial, Temp = Temperate. Yellow and blue areas represent *SoilHealthDB*-V2 samples; gray areas represent global data.

3.2 Representativeness of soil types

A total of 12 soil texture classes were represented across the studies compiled in *SoilHealthDB*-V2 (Fig. 3). The most frequently reported soil textures were loam and silt loam, which accounted for the highest number of study sites, followed by sandy loam and clay loam. In contrast, soil textures such as silt, silty clay, and sandy clay were among the least represented. For broader analysis, soil textures were grouped into three categories: coarse-, medium-, and fine-textured soils. Medium-textured soils were the most dominant, represented in over 150 studies, while coarse- and fine-textured soils appeared in approximately 90 studies each. This distribution indicates a research preference toward medium-textured soils, likely due to their favorable physical and hydraulic properties for crop production and experimental management.

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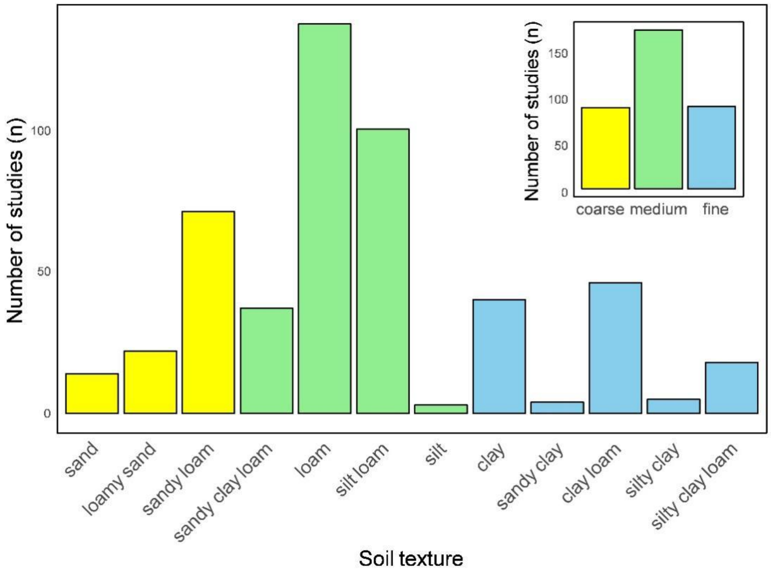

Figure 3. Distribution of study sites in *SoilHealthDB*-V2 by soil texture. The main panel shows the number of studies associated with each detailed USDA soil texture class. Bar colors represent three broader texture categories: coarse (yellow), medium (green), and fine (blue). The inset summarizes the total number of studies within each texture category.

3.3 Extent and diversity of soil indicators

The number and range of soil health indicators increased substantially in *SoilHealthDB*-V2 compared to *SoilHealthDB* (Fig. 4), although the degree of increase varied across different indicators. Newly added indicators in *SoilHealthDB*-V2 include fast carbon (*FastC*), slow carbon (*SlowC*), passive carbon (*PassiveC*) and total carbon or inorganic carbon (*TCIC*), although their representation remains limited. The most frequently reported indicators in both versions are cash crop biomass (*BiomassCash*), cash crop yield (*Yield*), bulk density (*BD*), organic carbon (*OC*), nitrogen (*N*), phosphorus (*P*), potassium (*K*), *pH*, soil water content (*SWC*) and crop water use efficiency (*WUE*), each appearing in over 50 studies. Substantial increases were observed for variables such as *Yield*, *SWC*, *N*, *WUE*, *OC*, *BiomassCash*, *K*, available water hold capacity (*AWHC*) and *P* in *SoilHealthDB*-V2. In contrast, indicators such as Base saturation or total bases (*BS_ToS*), *Diseases*, *Pests*, NO_2, CH_4 and soil quality index (*SQI*) remained underrepresented in both database versions. Overall, crop yield and soil nutrient status continue to serve as core indicators in conservation management studies, while *SoilHealthDB*-V2 expands the scope of assessment to include more functional and integrative dimensions, such as soil carbon fractions and ecosystem services.

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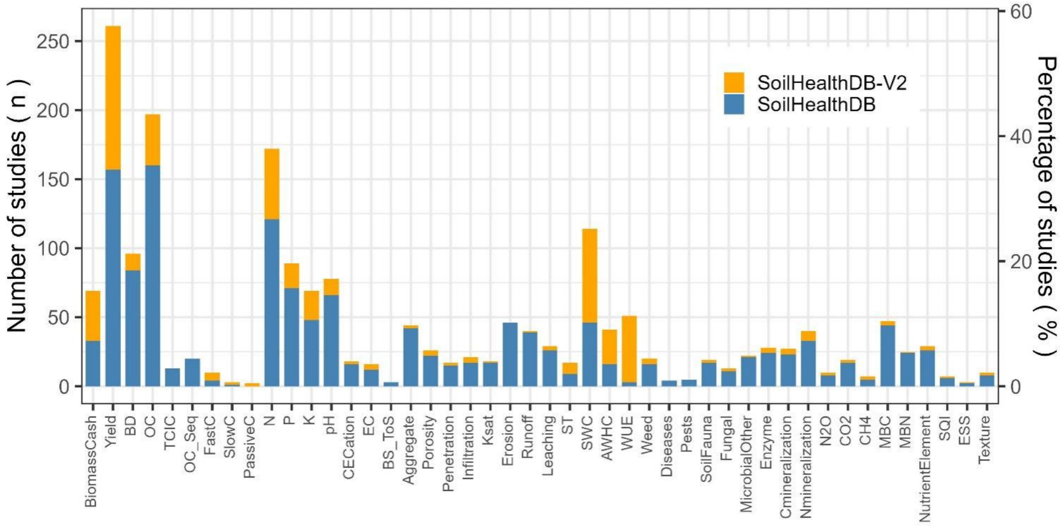

Figure 4. Comparison of soil health indicators coverage between *SoilHealthDB* and *SoilHealthDB*-V2. The bar plot shows the number of studies reporting various soil health indicators in the papers across *SoilHealthDB* (blue) and *SoilHealthDB-V2* (orange). The left y-axis represents the number of studies, while the right y-axis indicates the percentage of studies reporting each soil health indicators.

It should be noted that certain soil health indicators may encompass multiple measurement matrices. For instance, the CO_2 indicator (the 40th index in *SoilHealthDB*-V2) incorporates data such as soil respiration, basal respiration, and incubation-derived CO_2 efflux. We systematically aggregated these indices and examined the composition of their sub-indicators. Our analysis showed that most major indicators were predominantly characterized by a single dominant sub-indicator (Fig. 5). For example, soil aggregate stability (*Aggregate*) represented 85.1 % of the data under the water stable aggregates (*WAS*) category, while mean weight diameter (*MWD*) was less frequently reported. Similar dominance patterns were observed for carbon and nitrogen mineralization (*Cmineralization* and *Nmineralization*), *Porosity*, available water holding capacity (*AWHC*), and *Fungal*. However, some indicators displayed greater sub-indicator diversity. For instance, nitrogen-related measurements included total nitrogen (*TN*, 56.3 %), inorganic nitrogen (*IN*, 33.2 %), and available nitrogen (*AN*, 5.9 %). Similarly, phosphorus and potassium were recorded in both total and available forms. Enzyme indicators included C-cycling enzymes (35.4 %), microbial ecology and diversity (25 %), and N-cycling enzymes (22.9 %). Within the other microbial indicators (*MicrobialOther*), 76 % of data related to microbial community composition, and 24 % to microbial functional activity.

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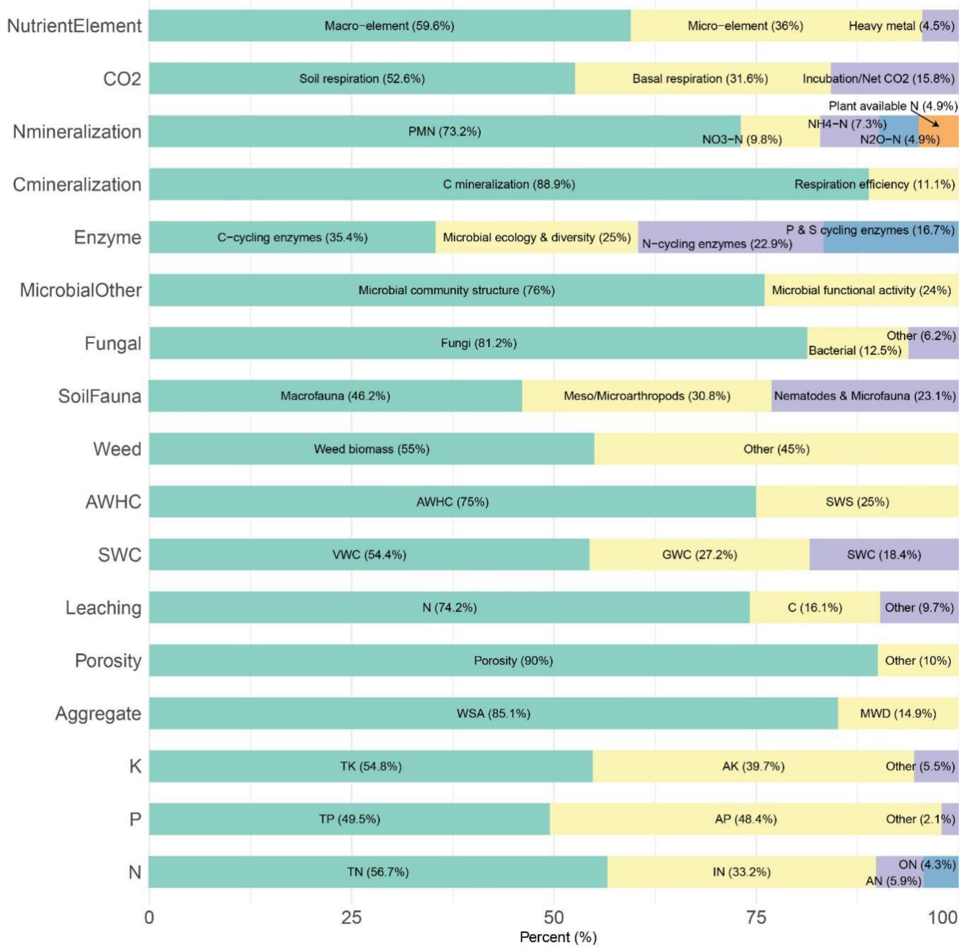

Figure 5. Proportional distribution of sub-indicators under each soil health indicator category in *SoilHealthDB*-V2. Note: *TN* = total nitrogen, *IN* = inorganic nitrogen, *AN* = available nitrogen, *ON* = organic nitrogen, *TP* = total phosphorus, *AP* = available phosphorus, *TK* = total potassium, *AK* = available potassium, *WAS* = water-stable aggregates, *MWD* = mean weight diameter, *VWC* = volumetric water content, *GWC* = gravimetric water content, *SWC* = soil water content, *AWHC* = available water hold capacity, *SWS* = soil water storage, *PMN* = potentially mineralizable nitrogen.

3.4 Correlations among soil health indicators

The correlation analysis revealed the relationships between crop agronomic performance and soil health indicators under conservation managements (Fig. 6). Crop *Yield* was positively correlated with organic carbon (*OC*, r = 0.13, p<0.01), *N* (r = 0.30, p<0.001), *P* (r = 0.13, p<0.05), soil water content (*SWC*, r = 0.3, p<0.001) and available water hold capacity (*AWHC*, r = 0.46, p<0.001). *OC* also exhibited strong and highly significant positive correlations with *N* (r = 0.45, p<0.001), *P* (r = 0.22, p<0.001), and *K* (r = 0.12, p<0.01). Hydrological indicators showed similar patterns: *Aggregate* and *Porosity* were negatively correlated with *Runoff* (r = –0.74, p<0.001 and r = -0.61, p<0.01), *Porosity* was negatively correlated with *Erosion* (r = –0.75, p<0.001), and *Penetration* was negatively correlated with *Leaching* (r = –0.56, p<0.05), consistent with improved water movement and soil structure under conservation management. Among biological indicators, *MicrobialOther* was strongly correlated with *Cmineralization* (r = 0.3, p<0.05), and *Enzyme* activity was positively correlated with *MBN* (r = 0.45, p<0.001), reflecting high internal consistency within biological soil functions.

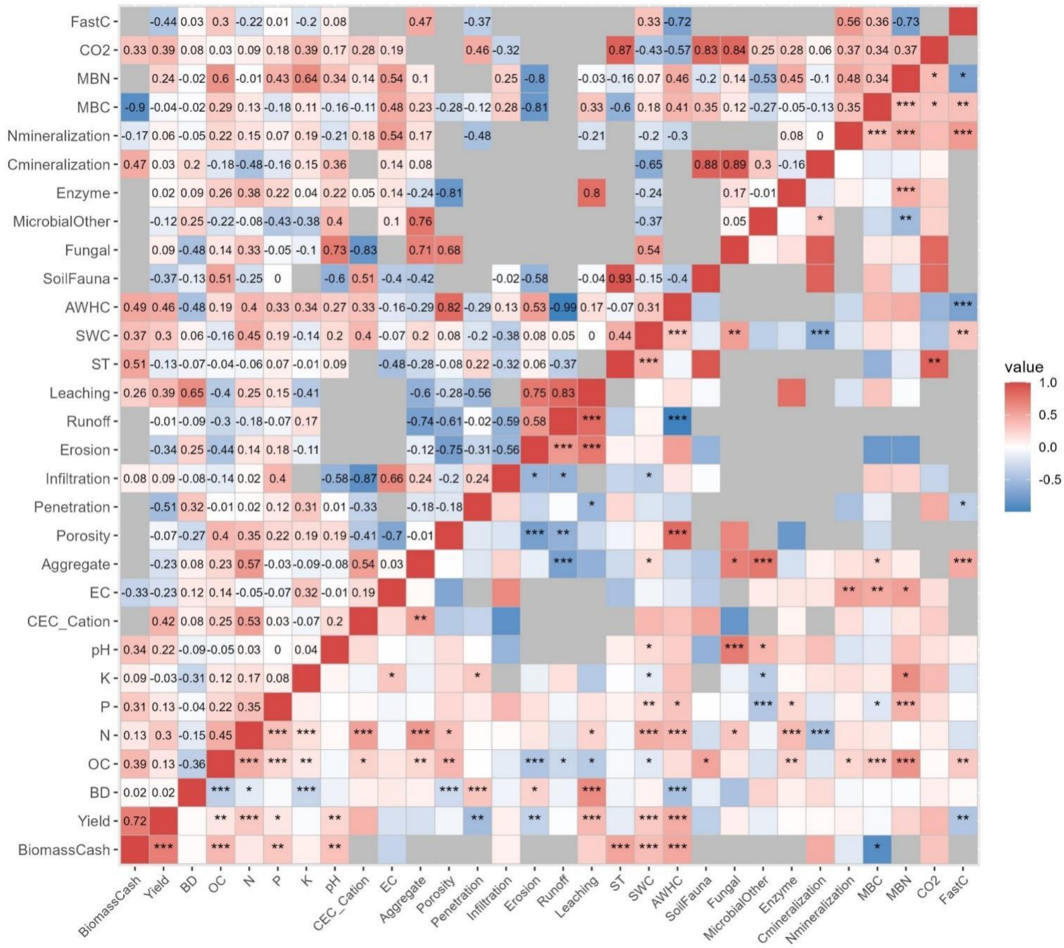

Figure 6. Correlations among soil health indicators based on log response ratios (lnRR) under conservation managements. Pearson correlation coefficients were calculated between pairs of soil health indicators using lnRR values from control and treatment conditions. Due to incomplete reporting across studies, only indicator pairs with at least 14 overlapping observations were included. Colored tiles represent the direction (red = positive, blue = negative) and strength of correlations, while asterisks indicate significance levels (* p < 0.05, ** p < 0.01, *** p < 0.001). Gray cells indicate insufficient data for correlation analysis.

3.5 Effect of duration on soil indicators under cover crop management

The mean durations of medium- and long-term experiments were 4.63 (± 0.33) and 10.25 (± 0.62) years, respectively, as summarized from the collected review and meta-analysis papers (Fig. S2). Based on these results, rounded thresholds of 5 and 10 years were defined to categorize all experiments in *SoilHealthDB*-V2. Accordingly, the experiments were classified as

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short-term (1–4 years), medium-term (5–9 years), and long-term (≥10 years). The response ratios of cover crop effects on soil indicators varied across these duration categories (Fig. 7). In the short term, significant increases were observed in *OC, Fast C*, *Aggregate*, *Infiltration* and microbial-related indicators including *SoilFauna*, *Fungal*, *MicrobialOther*, *Enzyme*, *MBC* and *MBN*. At the same time, significant reductions were found in *Weed*, *Erosion*, *Runoff*, and *Leaching*. Moderate improvements were noted in *Porosity* and *Penetration*, while indicators such as *BD* and *pH* showed no consistent trends. In the medium term, positive effects became more consistent and extended across a broader range of indicators. *SlowC*, *PassiveC*, electricity conductivity (*EC*), *Porosity* and *Penetration* showed clear and significant improvements. Microbial indicators such as *SoilFauna*, *MicrobialOther*, and *MBN* also showed continued enhancement, reflecting the cumulative benefits from continued cover crop use. In the long term, the benefits of cover crop were sustained or amplified for many key indicators. *SOC*, *Aggregate*, *Infiltration* and *Enzyme* maintained strong positive responses, while some indicators, such as *N* and soil quality index (*SQI*), showed significant improvements only in the long term. Besides, the greenhouse gas–related indicators such as N_2O, CO_2, and CH_4 showed an increasing trend at all terms, which may be related to enhanced microbial activity.

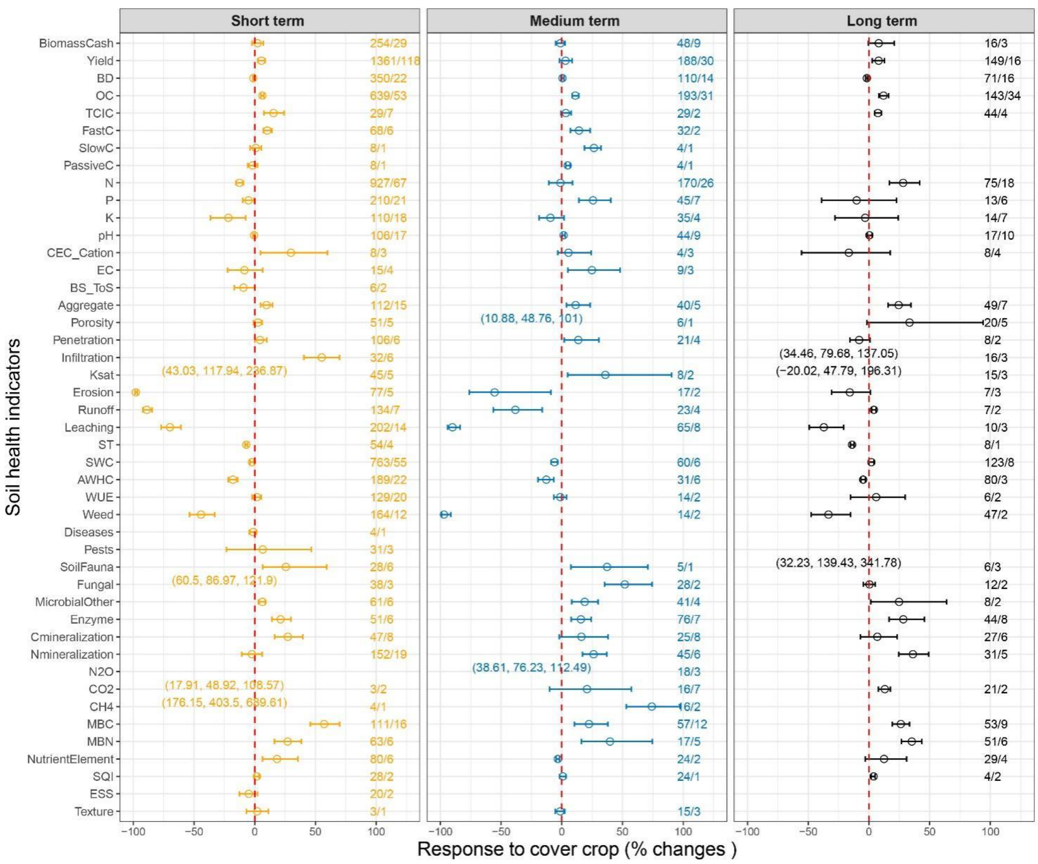

Figure 7. Soil health indicator responses to cover crop implementation over different duration. Panels represent the percentage change in soil health indicators in response to cover crop across three time periods: short-term, medium-term, and long-term. Each point with an error bar shows the overall mean log response ratio (RRx), converted to percent change, with 95 % confidence intervals. Red vertical dashed

lines indicate zero change; indicators whose confidence intervals do not cross zero are considered to show statistically significant effects. Numbers to the right of each row represent the number of observations derived from the corresponding number of studies.

4 Discussion

4.1 Enhancements and updates of *SoilHealthDB*-V2

SoilHealthDB-V2 presents a significantly expanded and standardized collection of global soil health indicators across a wide range of agricultural conservation management practices. Compared to the initial version (Jian et al., 2020a), the updated dataset includes more detailed metadata, such as experiment-specific treatments, soil depth, sampling year, and site-specific climate and soil classifications. These additions have improved the database's transparency, usability, and interoperability of the database (Jacobsen et al., 2020).

A key enhancement is the structured inclusion of Experiment ID, which addresses limitations in *SoilHealthDB* where experiment metadata were often sparse or oversimplified. In *SoilHealthDB*-V2, each Experiment ID is assigned based on consistent criteria, including soil depth, tillage, cover crop, and other relevant treatment–control distinctions. This structured format enhances the transparency of the dataset and supports more efficient data validation and quality control (Jacobsen et al., 2020). Moreover, it enables users to interpret experimental designs, such as treatment types and sampling conditions, without the need of referring back to the original publications. This feature is particularly valuable for large-scale meta-analyses and synthesis studies, where rapid interpretation of experimental contrasts is critical (Díaz-Guadarrama et al., 2024). It also facilitates more nuanced assessments of how management and environmental variables influence soil health indicators, supporting more robust modeling efforts (Maaz et al., 2023).

The standardization process in *SoilHealthDB*-V2 primarily focused on harmonizing indicator units and metadata documentation. By unifying measurement units for each soil health indicator, the database reduces dimensional inconsistencies and minimizes errors from unit conversions in subsequent analyses (Batjes et al., 2024). In addition, efforts were made to record each indicator with detailed metadata, including the index name, unit information, and data source, enhancing traceability and improving data reliability. This standardization also enables disaggregation of complex indicators into their subcomponents, such as total, inorganic, and organic N, allowing for more detailed analysis of how specific nutrient pools respond to conservation practices (Farmaha et al., 2022; Grandy et al., 2022).

Despite improvements in site and climate coverage, spatial and climatic biases persist in *SoilHealthDB*-V2, with most study sites concentrated in the Northern Hemisphere, especially in the United States, China, and Europe. These imbalances reflect disparities in agricultural research infrastructure, environmental priorities, and policy support (Bergtold et al., 2017; Vincent-Caboud et al., 2017). In the United States, cover crop studies are driven by large agricultural land and policies addressing nutrient runoff and water quality, such as the Gulf of Mexico's hypoxic 'dead zone' (Tellatin and Myers, 2018). Programs like Environmental Quality Incentives Program (EQIP) and Conservation Stewardship Program (CSP) incentivize adoption, supported by the land-grant university system and USDA research network (Wallander et al., 2021). To address these spatial biases in *SoilHealthDB*-V2, stratified analyses based on climatic zones or soil types could provide more representative insights into soil health dynamics. Additionally, the development of region- or soil-specific models could better support localized decision-making and adaptive management strategies (Maaz et al., 2023).

The analysis of sub-indicator composition revealed that most major indicators were predominantly represented by a single sub-indicator. However, nutrient-related indicators (e.g., nitrogen, phosphorus, and potassium) commonly included multiple sub-indicators. This suggests a growing recognition of the importance of different nutrient fractions—such as total, organic, inorganic, and available forms—in better understanding their roles in soil health (Cárceles Rodríguez et al., 2022; Zeng et al., 2025). Additionally, soil biology indicators (e.g., soil fauna, other microbial indicators and enzyme) exhibited substantial heterogeneity in sub-indicator composition. This diversity reflects the varied methodological approaches in soil biology research and may be due to evolving research needs or challenges in standardization.

4.2 Improvements and analyses of cover crop practice

A major advancement in *SoilHealthDB*-V2 is the inclusion of detailed cover crop management variables, which enables more context-specific analysis of soil health responses. Interval between cover crop termination and cash crop planting significant affect nutrient inputs, soil water conditions and weed control (Lamichhane and Alletto, 2022; Rosa et al., 2021). Termination methods, whether chemical or physical, impact soil health differently, with chemicals potentially harming microbial communities, while physical methods improve soil moisture retention and organic matter decomposition, though further research is needed (Bavougian et al., 2019). The return methods of cover crop residues, including incorporation and surface retention, also affect soil health and crop yield—incorporation generally boosts yield but may disturb the soil, while surface retention conserves moisture but shows inconsistent effects on yield, highlighting the need for site-specific strategies (Chahal and Van Eerd, 2023; Tian et al., 2015). Fertilization and irrigation during the cover crop phase can significantly improve soil health and crop yield, with nitrogen and phosphorus enhancing biological activity and stability, but the effects vary by cover crop type and site conditions (Fernandez et al., 2016; Gabriel et al., 2012). To better understand the specific processes and mechanisms, further systematic analysis of cover crop management practices is necessary. Key management variables such as cover crop interval, termination method, residue return strategy, and the use of fertilization and irrigation should be integrated into future meta-analyses and modeling efforts to better capture the variability and outcomes of cover crop systems across diverse agroecosystems.

The inclusion of variables such as *Start_year* and *End_year* allows for detailed assessment of how duration of cover cropping affects soil health over time (Blanco-Canqui and Ruis, 2020). Short-term studies (1–4 years) showed that cover crop led to significant improvements in dynamic and biologically sensitive indicators such as organic carbon, aggregate stability, and microbial-related indicators such as soil fauna, fungal, other microbial indicators, enzyme, microbial biomass carbon and

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nitrogen (Blanco-Canqui and Ruis, 2020). These early benefits were likely driven by rapid inputs of root biomass and organic residues, which stimulate microbial processes and contribute to initial improvements in soil structure (Vincent-Caboud et al., 2019). At the same time, cover crops effectively suppressed weeds and reduced erosion, runoff, and leaching—demonstrating their immediate role in soil protection (Blanco-Canqui et al., 2015). However, other indicators such as bulk density, and pH exhibited no consistent trends, reflecting the limited timeframe for more stable or structural soil changes to manifest (Blanco-Canqui and Ruis, 2020; Teng et al., 2024). Indicators like penetration resistance and porosity showed moderate responses, suggesting some early influence on physical properties. Medium-term studies (5–9 years) revealed that the effects of cover crops became more consistent and widespread across biological, chemical, and physical indicators. Clear improvements were observed in slow carbon, passive carbon, electricity conductivity, porosity, and penetration, suggesting enhanced resource availability, root development, and soil system stability (Blanco-Canqui, 2024). Biological indicators—including soil fauna, other microbial indicators and microbial biomass nitrogen—continued to show strong positive responses, highlighting the cumulative impact of sustained organic matter inputs and reduced disturbance on microbial activity and diversity (Koudahe et al., 2022; Scavo et al., 2022). Long-term studies (≥10 years) showed sustained or amplified benefits of cover crop for key indicators such as organic carbon, aggregate stability, infiltration and enzyme consistently, while indicators like total nitrogen and soil quality index showed significant positive responses only after extended implementation (Hu et al., 2023; Wang et al., 2022). Besides, greenhouse gas–related indicators such as N_2O, CO_2, and CH_4 exhibited increasing trends across all terms, likely driven by enhanced microbial activity and associated organic matter decomposition under cover crop management (Abdalla et al., 2019; Garba et al., 2022; Wang et al., 2022). These findings underscore the importance of long-term experiments and time-series data in evaluating conservation outcomes (Blanco-Canqui et al., 2023; Shi et al., 2025). Continued investment in medium- and long-term studies is critical for improving understanding of temporal dynamics and informing durable, evidence-based soil health management strategies (Basche et al., 2016; Olson et al., 2014).

4.3 Correlations among soil health indicators

Correlations among different indicators showed that crop yield was significantly and positively associated with soil nutrient and moisture indicators, underscoring the importance of nutrient and water availability in supporting crop growth and agricultural productivity (Daigh et al., 2014; Scavo et al., 2022). This association emphasizes the need for integrated nutrient and water management strategies under cover cropping systems to enhance crop yield and sustain productive systems (Qiu et al., 2024; Wang et al., 2021). Hydrological indicators exhibited similar trends: porosity was negatively correlated with runoff and erosion (Du et al., 2022). These patterns suggest that well-structured soils not only facilitate water retention and movement but also effectively resist surface runoff, soil loss, and degradation (Blanco-Canqui, 2024; Blanco-Canqui and Ruis, 2020). Such relationships highlight the multiple benefits of maintaining and improving soil physical properties, particularly under increasing climate variability and land-use pressures (Blanco-Canqui et al., 2015; Bradford et al., 2016). Strong correlations

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were also observed among biological indicators, indicating internal consistency within soil biological functions (Fernandez et al., 2016; Liang et al., 2014). This coherence suggests that different biological metrics often respond synergistically to environmental and management factors, reflecting the tightly coupled nature of soil biological processes (Fernandez et al., 2016; Pheap et al., 2019). Overall, these findings demonstrate complex interrelationships among soil biological, chemical, and physical properties, reinforcing the view of soil as a dynamic and interconnected system (Lehmann et al., 2020). The observed interdependencies underscore the need for a systems-based, multidimensional assessment framework to inform strategies aimed at enhancing soil resilience, productivity, and long-term sustainability (Cárceles Rodríguez et al., 2022).

4.4 Potential applications and perspective

Several issues identified in *SoilHealthDB* have been addressed, resulting in improved standardization and accessibility in *SoilHealthDB*-V2. The updated database supports a wide range of analyses related to conservation management and soil health, including the following:

(1) All soil health indicators have been standardized to facilitate meta-analyses and systematic reviews.

(2) The impact of experiment duration—classified as short, medium and long-term—on soil health indicators can be studied.

(3) The effects of cover crop management practices on soil health indicators and cash crop yields can be analyzed in greater detail.

(4) The effects of single and multiple conservation management practices on soil health indicators can be investigated.

SoilHealthDB-V2 is designed to generate new insights in soil science and contribute to addressing global challenges related to food production, soil security and health, climate change mitigation, and land degradation.

4.5 Limitations and future improvements

Although *SoilHealthDB*-V2 can support the studies and analyses mentioned above, there is still a need for continuous updates and optimizations of the database.

(1) The current update primarily focuses on cover crops; however, future efforts will include the collection of additional data on agricultural conservation practices such as no-tillage, organic fertilizer, and biochar to further enrich the database (Chahal et al., 2021).

(2) Data on certain indicators (such as soil carbon pool related) remains limited, which is insufficient for conducting meta-analyses or systematic reviews. Therefore, it is imperative to collect additional relevant data in the future.

(3) Data from regions such as Sub-Saharan Africa and South America remain sparse; collecting region-specific studies—including those published in local languages or regional journals—will be essential to improve geographic representation.

(4) The new database currently includes only agricultural conservation management practices. In the future, we could expand it to include soil health indicators under other land uses and consider integrating socio-economic and management factors.

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Overall, future efforts should prioritize data collection from underrepresented regions, standardization of soil health indicators, and the integration of other factors. Additionally, incorporating remote sensing data, long-term monitoring, and machine learning approaches could further enhance the utility of the database for prediction and decision-making (Zeng et al., 2025). Continued collaboration across disciplines and institutions will be essential to expand, refine, and apply the database for comprehensive global soil health assessments.

5 Code and data availability

All data and code in this study can be found at https://doi.org/10.5281/zenodo.17565204 (Jian, 2025).

6 Conclusions

By significantly expanding data coverage and standardizing indicator formats, *SoilHealthDB*-V2 marks a major advancement in global soil health research infrastructure. Compared to *SoilHealthDB*, the updated version expands spatial coverage and improves the representativeness of study sites across different climates and regions. The standardization of soil health indicators in V2 greatly enhances data interoperability and reusability, facilitating broader applications such as meta-analyses, modeling, and decision support. These enhancements provide a stronger foundation for more accurate and comprehensive soil health assessments. Additionally, the inclusion of detailed cover crop management variables offers critical support for identifying and optimizing best management practices tailored to specific environmental and agronomic contexts. Despite these improvements, the database will continue to be refined and expanded to include greater representation of different regions of the globe and management practices, along with new types of data (such as remote sensing products and socio-economic information).

Author contributions

JJ and PX designed the new version of the global Soil Health Database (*SoilHealthDB*-V2). JJ conducted the search, downloaded relevant papers, and compiled the meta-information. JJ, YG, BZ, YZ, and PX contributed to data collection; JJ and QS provided technical support for data analysis; JJ and XZ provided valuable suggestions while working on the outline and structure of the manuscript; JL, XZ and RDS provided feedback and insights throughout all phases of the project. PX wrote the manuscript in close collaboration with all authors.

Competing interests

The contact author has declared that none of the authors has any competing interests.

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