### A global soil health database for soil health assessment

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### Abstract

Field studies have been performed for decades on cropland conservation management, but the data from historical papers are not integrated to serve future cropland soil quality management. Reliable soil health database is essential to investigate cash crop yield, soil physical, chemical, and biological properties when cropland alter from traditional management to conservation management. Here, we collect, extracted, and integrated a global soil health database (SoilHealthDB) based on published ﬁeld measurements. We extracted 5,241 entries of data from 281 published studies for four main cropland conservation management methods: cover crop, no-tillage, agro-forestry systems, and organic farm. Data are from 324 geographic sites (location with different latitude and longitude) in 45 countries around the world. The SoilHealthDB includes 42 soil health indicators and 45 background indicators. Our database provides a common data-frame-work for sharing soil health measurements in the future. For some soil health indicators with abundance of comparisons, meta-analysis can be applied to analyze its dynamic under conservation management. SoilHealthDB could also support a comprehensive analysis of soil health changes related to cropland conservation management, therefore supporting a soil health calculator developing.

|  |  |
| --- | --- |
| Design Types | data integration objective |
| Measurement Type(s) | 42 soil health indicators (details please see table 2) |
| Technology Type(s) | data extracted from published papers |
| Factor Type(s) |  |
| Sample Characteristic(s) | Cover crop, no-tillage, organic farm, soil health, soil quality |

### Background & Summary

Cropland soil degradation due to natural vegetation removal, unsuitable agricultural activities, and erosion are among the main factors causing soil quality and crop yield decrease. According to a recent report from the Food and Agriculture Organization of the United Nations (FAO), one-third of soils in the world are infertile due to unsustainable land-use management practices1. Cropland conservation management practices, including the use of cover crops within rotations, change from traditional tillage to no-tillage, have been proposed as a way to increase soil carbon and soil health. Many on-site experiments have been conducted to identify the effects of conservation management (e.g., cover crops and no-tillage) on soil properties. Despite the concept of conservation management has been proposed for decades, there is little consistency in what indicators should be measured and how to actually quantify the soil quality improvement after conservation management. In addition, contradictions exist among studies. For example, introducing cover crop as rotation during fallow season usually enhances soil organic carbon2, yet sometimes does not3–5.

In order to average means across different individual studies with heterogeneous variation, systematic review and meta-analysis were conducted in the past to evaluate the effects of cover crops6, no-tillage7,8, organic farm9, and agroforestry systems10 on crop yield and soil properties. However, there are still many challenges in understanding the factors impacting soil health at global scale largely owing to lack of global observation-based dataset of soil health with corresponding information on soil health indicators, background information, and management practices. Therefore, it is essential to collect the historical published data and integrate them together to support a comprehensive quantitative assessment on soil quality improvement by converting management from traditional to conservation.

We collected studies which compared agricultural production with traditional management and conservational management. Publications that meet the criteria were digitized and the data were integrated into a global soil health database (SoilHealthDB). This dataset is available and can be continuously updated by including newly publication. Such a global soil health dataset based on ﬁeld measurements can be used for providing statistical analysis (e.g., meta-analyses) on a specific soil health indicator. For example, the SoilHealthDB including soil erosion, runoff, and nutrient leaching indicators, provides an opportunity to evaluate the non-point pollution, which is a major water contaminant in the globe, under traditional and conservational management. In addition, SoilHealthDB provides a common soil health framework for sharing and integrating new field measurements and related information, to better explore factors impacting soil health and cash crop yield. Lastly, our soil health data can be potentially upscaled to a global observation-based soil health calculator that would provide valuable information for farmers to determine future cropland management planning.

### Methods

**Data collection**

We designed a soil health data framework, hereafter named SoilHealthDB, which include 46 background indicators (Table 1), and 42 soil health indicators (Table 2). We conducted a systematic literature search of studies on field comparisons between traditional and conservational management. Currently, we targeted four major conservational management methods: cover crop (CC), no-tillage (NT), organic farm (OG), and agro-forestry systems (AFS).

Publications were searched and collected from three sources: (1) previous soil health related tools such as the “Research Landscape Tool” that compiles soil health results into a searchable database and includes publication and research projects; (2) citied papers from previous meta-analysis or review papers 6,9,11,12; and (3) a literature search using ISI Web of Science, Google scholar, and the China National Knowledge Infrastructure (CNKI). We used the key words “Soil health” or “soil quality” and “conservation management” (we also replaced the term “conservation management” with “cover crop”, “no-till”, “organic farm”, “agroforestry systems”) in ISI Web of Science, Google scholar, and the CNKI to search published papers. Papers from peer reviewed journals, conference collections, theses, and dissertations were included. No other restriction was considered on the language, publication data, and other filtering criteria. We collected a total of more than 500 papers, we then read through articles and used the following criteria to determine whether the publication would be included in this study: (1) experiments were conducted in the field or research station; (2) the publications reported comparison between control (traditional management) and treatment (conservational management); (3) publications provide at least one comparison between control and treatment of soil health indicators (Table 2). Within these constraints, 281 papers were extracted and integrated into the SoilHealthDB.

Data are digitized from tables and figures. The software Data Thief was used to read the data from figures (version III, http://datathief.org/). Background information was extracted from the publication and fit into 46 background indicators (Table 1). When latitude and longitude were not reported in the literature, they were collected from https://www.findlatitudeandlongitude.com based on the site’s name. When elevation was missing from the original paper, it was identified by latitude and longitude in https://www.freemaptools.com/elevation-finder.htm. The extracted data from 281 papers resulted in 5241 comparisons across the globe (Figure 1), approximately 20 comparisons in one study, and some of the comparisons are not independent. We allocate a unique experiment ID to a comparison if the cover crop group, cash crop group, site, tillage, fertilization, soil depth, termination, or rotation is different within a comparison (Figure 2). This process resulted in a total of 1177 experiments. We assume experiments are independent of each other.

**Data processing**

After the location information is carefully checked, sites’ climate region can be identified according to climate Koppen classification (http://koeppen-geiger.vu-wien.ac.at/) using sites’ latitude and longitude (please see the supplemental R code). The missing MAT and MAP values were filled by a global air temperature and precipitation data from the Center for Climate Research at the University of Delaware 14. The MAP and MAT were calculated based on the monthly precipitation and temperature between 1961 and 2015. Soil texture was grouped into coarse (sand, loamy sand, and sandy loam), medium (sandy clay loam, loam, silt loam, and silt), and fine (clay, sandy clay, clay loam, silty clay, and silty clay loam) based on The Cornell Framework of Soil Health Manual 15.

The cash crops were grouped into corn, soybean, wheat, other monoculture, corn-soybean rotation (CS), corn-soybean-wheat rotation (CSW), and other rotation of more than two cash crops (ROT). The cover crops were grouped into broadleaf, grass, legume, mixed of more than two legumes (LL), mixed of legume and grass (LG), and other mixtures of more than two cover crops (MTT). Soil sampling depths were grouped into 0-10cm, 0-20cm, 0-30cm, and 30-100cm (Figure 3). It should be noted that the user can regroup the cash crop, cover crop, and soil sampling depth according to the detailed cash crop, cover crop, and soil sampling depth information according to their research objectives.

The number of replication and SD were integrated from the publication when possible. For the publication reported a standard error (SE), coefficient of variation (CV), or confidence interval (CI), SD was calculated according to the following equations:

(1)

(2)

(3)

Where is Z score for a given level of signiﬁcance is equal to 1.96 when α = 0.05 and 1.645 when α = 0.10.

For the SOC data, if background SOC stocks were reported [or can be calculated based on SOC concentration and soil BD, equation (4)], SOC sequestration can be calculated by equation (5). If background SOC stocks were not available, SOC sequestration can be calculated by equation (6):

(4)

(5)

(6)

Where SOC and SOC% represent soil organic carbon stock (Mg/ha) and soil organic concentration (%), respectively. represents SOC sequestration rate (Mg/ha/yr). SOCcc SOCbackground, and SOCnc are soil carbon stocks under CCs, background soil carbon stock, and NC, respectively (Mg/ha). h represents soil sampling depth (meter), BD represents soil bulk density (Mg/m3), and n represents years after CCs.

**Code availability**

All the data processing and data visualization were conducted under R (version 3.5.1)16. The source code is available on the Open Science Framework. The code is detailed with instructions for users. The intent of the code is to illustrate how some missing background information was filled in based on other data sources. The code also intends to check data quality, and to explain how some soil health indicators are grouped based on the basic information. The code and the SoilHealthDB are available for individual, academic, research, and commercial usage, but it could not be repacked or sold without written permission.

### Data Records

Data records are reported in a single table including 5241 rows and 268 columns. Each row corresponds to as many as 42 comparisons (if all soil health indicators have data), and each column corresponds to one detail of background information or one soil health indicator. The names, attributes, and description of the background information and soil health indicators are shown in Table 1 and Table 2, respectively. Background information columns are grouped by categories further denoted as “ID” (Table 1). Detailed description on each background information and soil health indicator can be found in Table 1 and Table 2.

### Technical Validation

Quality control was performed to guarantee the quality of the data. Each paper was carefully read at least twice, and special attention was paid to the tables, figures, and method parts where most of the soil health indicator comparisons and background information are from. It should be noted that different measure objectives may be involved in the same soil health indicator (e.g., soil total nitrogen, soil organic nitrogen, or soil inorganic nitrogen maybe reported in different papers to represent the soil nitrogen indicator, ID 5 in Table 2), therefore, it is important that the measure objectives, unit, and other detailed descriptions should be recorded in the comments columns. After the data extraction, we compared the digitized data against the tables or figures from the original paper again to make sure the data were loaded correctly. Before a new paper was extracted, we first used the bibliography database manager Mendeley to check whether it is a duplicate of previous papers (for details, please see the supplemental reference document).

After the data extraction, we performed an elaborate examination of the data quality using R (version 3.5.1). The formats of each column (numerical or string) were checked to correct the mistyping in the numerical columns (e.g., all soil health indicator, and some background information columns like latitude and longitude). For each soil health indicator, we calculated the response ratio, which is the value of treatment divide by the value of control. We then plotted the frequency distribution of response ratio for each soil health indicator, and returned to the original articles to check extreme values. We also made the visualization of data distribution for the background columns that contain numeric values (e.g. latitude, elevation) and manually checked the outliers by validating them in the original papers. For the location of each site, we plotted the latitude and longitude by country and check whether there are sites from a specific country that fall outside the borderline. For those sites, we checked the extracted latitude and longitude information with location information from the original paper (latitude, longitude, site name, and country name). For some sites located nearby the coastal area, few sites fall in the sea probably due to the precision of values. For these sites, we corrected slightly the longitude and latitude to the near land if the reported coordinates are extracted correct.

### Usage Notes

In the SoilHelthDB, the measure objectives and units between each comparison (control vs. treatment within same row) will always be the same. However, each soil health indicator may have multiple measure objectives and therefore involve multiple units (e.g., researcher may measure soil total nitrogen in one site, but measure organic nitrogen in other study). Without data filtration and conversion, only the response ratio can be analysed. However, more analysis can be applied with data filtration and conversion. The detailed information about measure objectives and units will be recorded under the comments column. As a result, the user should check the measure objectives and units before data processing and data analysis. We suggest that the user play with the data using the code we provided, as the code already includes elaborate explanation and should be easy to follow. The user can contact the corresponding author whenever they have questions on understanding the code and using the data. It should also be noted that for some soil health indicators (e.g., CH4 and N2O emission), we did not extract enough comparisons from the 281 papers, thus the users have to expand the data based on the SoilHelthDB data framework before a further analysis.

### Acknowledgements

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### Author contributions

Jinshi Jian and Ryan D. Stewart conceived the design of the data framework. Jinshi Jian and Xuan Du extracted and integrated the data from papers to the SoilHealthDB. Jinshi Jian drafted the manuscript, and all authors revised and approved the manuscript.

### Competing interests

The authors declare no competing interests.

### Figures

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**Figure 1.** **The spatial distribution of sites from cover crop (CC), no-tillage (NT), organic farm (OGF), and agro-forestry system (AFS) across the globe.** The numbers in the parenthesis represent the number of sites for different conservation management method. The size of sign in the map represents the number of comparisons in each site.



**Figure 2.** **Flow chart shows the procedure of data integration (left panel), experiment ID allocation (middle panel), and use of potential the database can support (right panel).** Historical conservation papers across the globe were collected and only some met our criteria and were extracted and integrated into the dataset. To identify the experiment ID of pair comparisons, if the cash crop, site, tillage, fertilizer level, cover crop, soil sampling depth, cover crop termination, and cash crop rotation were the same, we assigned them the same experiment ID, otherwise, a different experiment ID was assigned (middle panel). The database can support systematic review, meta-analysis, soil health calculator developing, guide future experiment design, analyze conservation management’s effect on nonpoint pollution (e.g., soil erosion, runoff, and nutrient leaching), cropland management recommendation, and many other usages (right panel).

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**Figure 3. Diagram showed how soil sampling depths were separated into 0-10cm, 0-20cm, 0-30cm, and 30-90cm layer groups.**

|  |  |  |
| --- | --- | --- |
| **ID** | **Background indicator** | **Description** |
| 1 | ExperimentID | Experiment ID number, please see details in **Figure 2** |
| 2.1 | Author\_F | First author's Family name |
| 2.2 | Author\_G | First author's Given name |
| 3 | YearPublication | Paper publication year |
| 4 | SamplingYear | Sampling year, should be earlier than publication year |
| 5 | Journal | Journal name of paper published |
| 6 | SiteInfor | Site name and detailed information |
| 7 | Country | Country name of the site |
| 8 | Latitude | Latitude of the site |
| 9 | Longitude | Longitude of the site |
| 10 | Elevation | Elevation of the site |
| 11 | Tannual | Annual average air temperature |
| 12 | MAT | Mean annual air temperature reported from paper (Time span may differ from paper to paper) or from a global air temperature data 14. |
| 13 | Pannual | Annual precipitation from paper |
| 14 | MAP | Mean annual precipitation (Time span may differ from paper to paper) or from a global precipitation data 14. |
| 15 | ClimateType | Study site's climate type, obtain from climate koeppon |
| 16 | YearsAfterCoverCrop | How many years cover crop applied before taking soil samples (e.g., experiment initiated at 1991, sample take at 1995, then fill with 5) |
| 17 | Duration | How many years the whole experiment last for (e.g., experiement started at 1990 and end at 2000, duration is 11 years) |
| 18.1 | Time\_CC | Time of cover crop planted, indicate winter or summer CC |
| 19 | Time\_Comments | Comments about cover crop period |
| 20 | SoilSampling | Soil sampling depth from top to bottom, formatted as: top-to-bottom, e.g., 10-to-20. |
| 21.1 | SamplingDepth | Difference between bottom and top, e.g., 10-to-20, SamplingDepth is 10 |
| 21.2 | SoilDepthGroup | Soil depth grouped based on the sampling depth, see **Figure 2** for more details |
| 21.3 | SurfaceSubsurface | Surface or subsurface indicator, see **Figure 2** for more details |
| 22 | SoilBD | Bulk density |
| 23.1 | SandPerc | Percentage of sand |
| 23.2 | SiltPerc | Percentage of silt |
| 23.3 | ClayPerc | Percentage of clay |
| 24.1 | Texture | Soil texture |
| 24.2 | TextureGroup | Soil texture group (coarse, medium, and fine), based on the Cornell Framework of Soil Health Manual 15. |
| 25 | SoilpH | Soil pH |
| 26 | SoilTC | Soil total carbon, this is the background soil carbon information (Unit is %), note that this column is differ from OC\_C\_concentration, OC\_T in the response columns |
| 27 | SOC\_NaturalVeg | Soil organic carbon of nearby natural vegetation land use (Unit is %) |
| 28 | SoilKsat | Soil saturated conductivity |
| 29 | SoilFamily | Soil family or soil group information, it should be noted that there are many soil classification system in the word, studies from different country may use different soil classification system |
| 30.1 | CoverCrop | Cover crop type, some literature called catch crop, green manure |
| 30.2 | CoverCropGroup | Cover crop grouped by function or family of cover crop, please see more details in **the data file** |
| 31.1 | GrainCrop | Grain crop type, also called cash crop |
| 31.2 | GrainCropGroup | Grain crop grouped by function or family of grain crop, please see more details in **the data file** |
| 32 | Landuse | Landuse type |
| 33.1 | Rotation\_C | Type of rotation/crop sequence for control |
| 33.2 | Rotation\_T | Type of rotation/crop sequence for treatment |
| 33.3 | Rotation\_Diff | Whether type of rotation/crop sequence differ between control and cover crop, yes or no |
| 34.1 | Tillage\_C | Type of tillage for control |
| 34.2 | Tillage\_T | Type of tillage for cover crop |
| 34.3 | Tillage\_Diff | Whether type of tillage differ between control and cover crop, yes or no |
| 34.4 | TillageGroup\_C | Tillage method grouped to CT, RT, or NT of control, details please see **the data file** |
| 34.5 | TillageGroup\_T | Tillage method grouped to CT, RT, or NT of treatment, details please see **the data file** |
| 35.1 | Fertilization\_C | Description about fertilization for control |
| 35.2 | Fertilization\_T | Description about fertilization for treatment |
| 35.3 | Fert\_Diff | Whether control and cover crop applied different fertilizer level, yes or no |
| 36 | ControlDescription | Control description (e.g., winter fallow, summer fallow, no cover crop, bare soil) |
| 37.1 | No\_C | Number of plot in control |
| 37.2 | No\_T | Number of plot in treatment |
| 37.3 | NoSupsample | Number of subsamples |
| 38 | ExperimentDesign | CRD,RCBD, split-design etc. |
| 39 | CCFreshBiomass | Fresh biomass of cover crop (return to soil as green manure) |
| 40 | CCDryBiomass | Dry biomass of cover crop (return to soil as green manure) |
| 41 | CNOfCoverCrop | Carbon to nitrogen ratio of the cover crop dry biomass (determine quality of green manure) |
| 42 | CCTermination | Method of killing cover crop |
| 43 | Conservation\_Type | Including cover crop(CC), No-tillage(NT), organic farm(OGF), Agro-forestry ecosystem (AFS), straw mulching |
| 44 | Conservation\_Description | More details or descriptions on conservation method of cropland |
| 45 | Others | Other meta information about the publication |

**Table 1. Description and attributes of background information in the SoilHealthDB.**

|  |  |  |  |
| --- | --- | --- | --- |
| **ID** | **Indicator** | **Description** | **Comments** |
| 1 | Biomass | Biomass of cash crop except for yield (e.g., stem, leave, root) | Unit varied, unit is kg/hm2 if without explanation |
| 2 | Yield | Yield of grain(cash) crop | Unit: kg/hm2 if without explanation |
| 3 | BD | Soil Bulk density | Always g/cm3 |
| 4.1 | SOC\_Conc | Soil organic carbon concentration (in unit of %) | SOC = SOM/1.72 |
| 4.2 | SOC\_Stock | Soil organic carbon stock (in unit of Mg/ha) | When not reported, it can be calculated by equation (4) |
| 4.3 | SOC\_SEQ | Soil organic carbon sequestration rate (in unit of Mg/ha/cm/yr) | Can be calculated by either equation (5) or (6) |
| 5 | N | Soil Nitrogen | Unit varied |
| 6 | P | Soil Phosphorus | Unit varied |
| 7 | K | Soil Potassium | Unit varied |
| 8 | pH | Soil pH | No unit |
| 9 | CEC | Soil cation exchange capability | Unit varied |
| 10 | EC | Soil electric conductivity | Unit varied |
| 11 | BS | Soil base Saturation | Unit varied |
| 12 | Aggregate | Soil aggregation | There are multiple ways to measure soil aggregation, the unit varied |
| 13 | Porosity | Soil porosity | Unit varied |
| 14 | Penetration | Soil penetration resistance | Unit varied |
| 15 | Infiltration | Soil infiltration rate | Unit varied |
| 16 | Ksat | Field saturated hydraulic conductivity | Unit varied |
| 17 | Erosion | Soil erosion or wind erosion | Unit varied |
| 18 | Runoff | Runoff | Unit varied |
| 19 | Leaching | Soil nutrient leaching | Unit varied |
| 20 | ST | Soil temperature | ℃ |
| 21 | SWC | Soil water content | Unit varied |
| 22 | AWHC | Available water hold capacity | Unit varied |
| 23 | Weed | Weed of the cropland | Unit varied |
| 24 | Diseases | Diseases of the cropland | Unit varied |
| 25 | Pests | Pests of cropland | Unit varied |
| 26 | SoilFauna | Earthworm, authors, nematode (soil should benefit from their exists) living in the soil | Unit varied |
| 27 | Fungal | Bacterial, fungal, mycorrhizal in the soil | Unit varied |
| 28 | O-Microbial | Other microbial indicators | Unit varied |
| 29 | Enzyme | Enzyme activity specifically beta-glucosidase activity and phenol oxidase | Unit varied |
| 30 | Cmin | Soil mineralizable carbon | Unit varied |
| 31 | Nmin | Soil mineralizable nitrogen | Unit varied |
| 32 | N2O | Soil N2O efflux | Unit varied |
| 33 | SIR | Soil substrate-induced respiration | Unit varied |
| 34 | CO2BTest | Soil CO2 burst test respiration | Unit varied |
| 35 | CO2 | Soil respiration (some literature called CO2 efflux, CO2 flux) | Unit varied |
| 36 | CH4 | Soil CH4 emission | Unit varied |
| 37 | MBC | Microbe Biomass Carbon | Unit varied |
| 38 | MBN | Microbe Biomass Nitrogen | Unit varied |
| 39 | Microelement | Mn, Zn, Cu etc. | We do not record the actual data yet, instead, we labelled with 9999 if a paper reported Microelement |
| 40 | SQI | Soil quality indicator, soil health indicator | We do not record the actual data yet, instead, we labelled with 9999 if a paper reported SQI |
| 41 | ESS | Ecosystem services indicator | We do not record the actual data yet, instead, we labelled with 9999 if a paper reported ESS |
| 42 | Texture | Cover crop effect on soil texture compare with control | We do not record the actual data yet, instead, we labelled with 9999 if a paper reported Texture |
|  | Notes | Other notes, comments |  |

**Table 2. Description and attributes of soil health indicators in the SoilHealthDB.** Note that in the data sheet, each indicator has 5 columns, recording information for control, treatment, standard deviation (SD) for control, SD for treatment, and comments, respectively.

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