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Research Article

Large-scale farming enhances soil health contrasting with conventional management of smallholders: Insights from a field survey

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ABSTRACT

As an effective approach to achieving sustainable utilization of arable land resources, large-scale farming has been promoted to improve agricultural production efficiency and economic benefits with intensive advanced management practices. However, further evaluation is needed to determine whether large-scale farming can effectively improve soil health without increasing soil contamination. Soil health under large-scale farming was compared with smallholder management with 39 physical, chemical, biological, and environmental indicators. Large-scale farms under the commercial organic compost application and conventional fields in southeastern China were chosen in the field survey. Results showed that aggregate stability, soil organic matter (OM), available nutrients, and microbial biomass under large-scale management were significantly higher. Large-scale farming with organic compost altered microbial community and structure with a higher ratio of Fungi to Bacteria (F/B) and a lower ratio of Gram-positive bacteria to Gram-positive bacteria (G+/G-). The soil fertility index and biological index were respectively 36.5% and 24.2% higher in large-scale farms than in conventional fields. However, there was no significant difference in soil environmental indices between the two management modes. Edaphic indicators of bulk density, penetration resistance, mean weight diameter, soil OM, DOC, earthworm biomass, gram-negative bacteria, and bacteria were identified by network analysis as key indicators of soil health assessment. The

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soil health index based on these indicators of large-scale farming was 23.4% higher than that of conventional management by smallholders, with higher structural stability, total and active organic carbon, and quantities of soil fauna and microorganisms. Similarly, the farmland quality index and soil health index based on all indicators under large-scale management were respectively 4.2% and 38.3% higher than those under conventional management. Overall, large-scale farming was cost-effective in enhancing soil health by improving soil fertility and microbial biomass without increasing soil pollution risks with specific commercial organic compost. This emphasized the advantages of large-scale farming in sustainable agriculture production through organic inputs.

Key Words: earthworms, microbial community, minimum data set, soil function, soil organic carbon

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INTRODUCTION

Global society has achieved tremendous success in increasing agricultural production and ensuring food security over the past half-century. However, the growth of food production relied heavily on the extensive use of external substances, which led to soil degradation. Previous studies showed that long-term application of chemical fertilizers led to soil acidification or salinization, resulting in soil structure degradation and biodiversity reduction (Rotchés-Ribalta *et al.*, 2023). Besides, excessive application of fertilizers and pesticides could lead to heavy metal contamination. Inorganic phosphate fertilizers and pesticides might contain potentially heavy metal elements and long-term use of these agricultural inputs could result in the risk of heavy metal accumulation (Zhou *et al.*, 2021). Given that China is still dominated by smallholder farms, land fragmentation exacerbates the risk of soil degradation in small-scale farming (Cao *et al.*, 2022). Hence, Achieving the optimal utilization of land resources has become a significant challenge in Chinese sustainable agricultural production.

Recently, large-scale farming by agricultural land transfers has become increasingly common in China since its high production efficiency and economic incomes (Wang *et al.*, 2021). It was defined as “the highly mechanized and commercial cropping activities that take place in privately owned or rented land by an individual farmer, company or family enterprise” (Tittonell *et al.*, 2020). As a critical pathway towards modernization and sustainable agriculture production, large-scale farming has a positive impact on the farmers’ income and labor efficiency (Muller *et al.*, 2017). It also emphasizes natural and environmentally friendly practices instead of synthetic inputs such as pesticides, fertilizers, and genetic modifications. Previous studies showed that organic agriculture could increase soil organic matter (OM) and improve soil structure while maintaining crop productivity of high-quality organic agricultural products through the application of organic fertilizers combined with a legume rotation system (Cai *et al.*, 2019; Li *et al.*, 2023). Moreover, organic management has been proven to enhance many soil functions, such as carbon sequestration, nutrient cycling, biodiversity maintenance, and soil erosion control (Tscharntke *et al.*, 2005; Wittwer *et al.*, 2021). However, the use of increased tillage to control weeds in organic agriculture could enhance organic matter loss and soil erosion. Another main factor determining soil health under organic farming was the quantity and quality of organic amendment input (Seufert and Ramankutty, 2017). Additionally, long-term application of organic fertilizers may lead to the accumulation of soil contamination (such as heavy metals, antibiotics, etc.) (Zhou *et al.*, 2015; Albero *et al.*, 2018). These divergent findings indicate that the impact of organic management in large-scale farming on soil health remains uncertain.

Soil health is a comprehensive understanding of soil physical, chemical, and biological characteristics that are regulated by both inherent soil properties and management practices (Lehmann *et al.*, 2020). Most studies quantified it as a soil health index (SHI) to explore the impact of management practices and land use types on soil health. It includes three steps: selection of indicators to construct a minimum data set (MDS), quantification of indicators using a scoring approach, and integration of scores into the SHI (Rinot *et al.*, 2019). Nevertheless, the current methods to evaluate soil health lack uniformity because soil health assessment is based on specific soil properties, which may not provide an accurate representation of overall soil health. To gain more accurate results, soil biological indicators have been gradually applied in calculating SHI (Bonilla-Bedoya *et al.*, 2023). Nevertheless, most soil health assessment studies emphasized microbial biomass, soil respiration, enzyme activity, and earthworms, with limited consideration given to the quantity and community structure of microorganisms (Bünemann *et al.*, 2018). Additionally, only a limited number of studies incorporated environmental indicators into quantification, which may not reflect the impact of management measures on soil environmental health (Lehmann *et al.*, 2020). Incorporating environmental indicators into soil health assessment would help identify the most effective management strategies for maintaining soil health while minimizing environmental risks.

Eastern China is an important production region for grain crops. To meet the demand for high-quality agricultural products, many cooperative organizations have transitioned to organic management practices from conventional management practices for higher economic benefits (Shen *et al.*, 2013). It is important to assess the performance of this large-scale organic farming in soil health enhancement since it is a current and widespread management practice. Nevertheless, little information is available on the impact of this shift in the farming system on soil health, considering soil fertility, environmental quality, and microbial community. To investigate the effect of large-scale farming, we compared the soil health of large-scale farms with neighboring conventional farms in eastern China. We hypothesized that (1) large-scale farming could improve soil health by increasing total and active carbon, nutrient availability, and microbial biomass because of the high inputs of organic matter; and (2) Several years of application of organic fertilizers under large-scale farming might cause the accumulation of heavy metal elements and antibiotics. These results may serve as a reference for guidance in the promotion of large-scale farming in efficient and sustainable agricultural production.

MATERIALS AND METHODS

Study site and experimental description

The study sites are located on Chongming Island in Shanghai (121°09′30″~121°54'00"E, 31°27'00"~31°51'15"N), which is located in the middle and lower reaches of the Yangtze River. The mean annual temperature and mean annual precipitation in this area are 16.5 ℃ and 1129 mm, respectively. The island is formed by alluvial sedimentation and reclamation and has a total area of approximately 1200 square kilometers. The parent materials are weathered alluvial deposits. The soil texture is between light loam and medium loam (Gao *et al.*, 2010). Since the 1850s, land reclamation continued apace and the island area continued to increase. Agriculture is the leading industry of Chongming Island, and farmland in the study area predominantly consists of paddy fields and vegetable plots. The soils in our study were classified as Hapli-Stagnic Anthrosols in World Reference Base (WRB) and Aquents (Entisols) in USDA Soil Taxonomy, which developed on fluvial deposits of the Yangtze River under similar biogeographic conditions.

In this study, eight large-scale farms were selected (i.e., xinping farm, wanhe farm, mingyue farm, chunrun farm, fanxin farm in Gangxi Town, fanxin farm in Bao Town, jiangfan farm, and beihu farm) (Fig. 1). On these farms, commercial organic compost has been applied instead of chemical fertilizers or pesticides. The farms have implemented these organic management practices for a minimum of three years. The annual organic fertilizer compost for the farms was 3~18.3 t ha^{-1} (mean: 12.2 t ha^{-1}), and all the organic fertilizers in the farms were customized by Shanghai Lianye Agricultural Science and Technology Co., Ltd and recommended by the local agricultural department. The organic compost was produced by high-temperature fermentation and harmless treatment of a mixture of organic waste and straw. The price of organic compost was 110 USD t^{-1} (including 80 USD t^{-1} from large-scale farmers and 30 USD t^{-1} financial subsidies from the local agricultural department). The N, P_2O_5, and K_2O content in the organic compost were 5.5%, 3.5%, and 3.5%, respectively, and the organic matter content was over 60%. Manual weeding was adopted in large-scale farms instead of herbicides. All organic farms except xinping farm were cultivated under a rice-green manure rotation system. Detailed information on the cropping system and fertilization management is shown in Table SI (see Supplementary Material for Table SI). Three neighboring field blocks under smallholder management near each large-scale farm were selected as controls. All the conventional field blocks were cultivated under a double rice rotation system. The paddy soils were treated with chemical fertilizers and pesticides over the past five years. The annual nutrient application rate for conventional management was 225~675 kg N ha^{-1} (mean: 375 kg N ha^{-1}), 90~300 kg P_2O_5 ha^{-1} (mean: 175 kg P_2O_5 ha^{-1}), and 100~275 kg K_2O ha^{-1} (mean: 195 kg K_2O ha^{-1}). The prices of urea, diammonium phosphate, and potassium sulfate were 350, 550, and 595 USD t^{-1}.

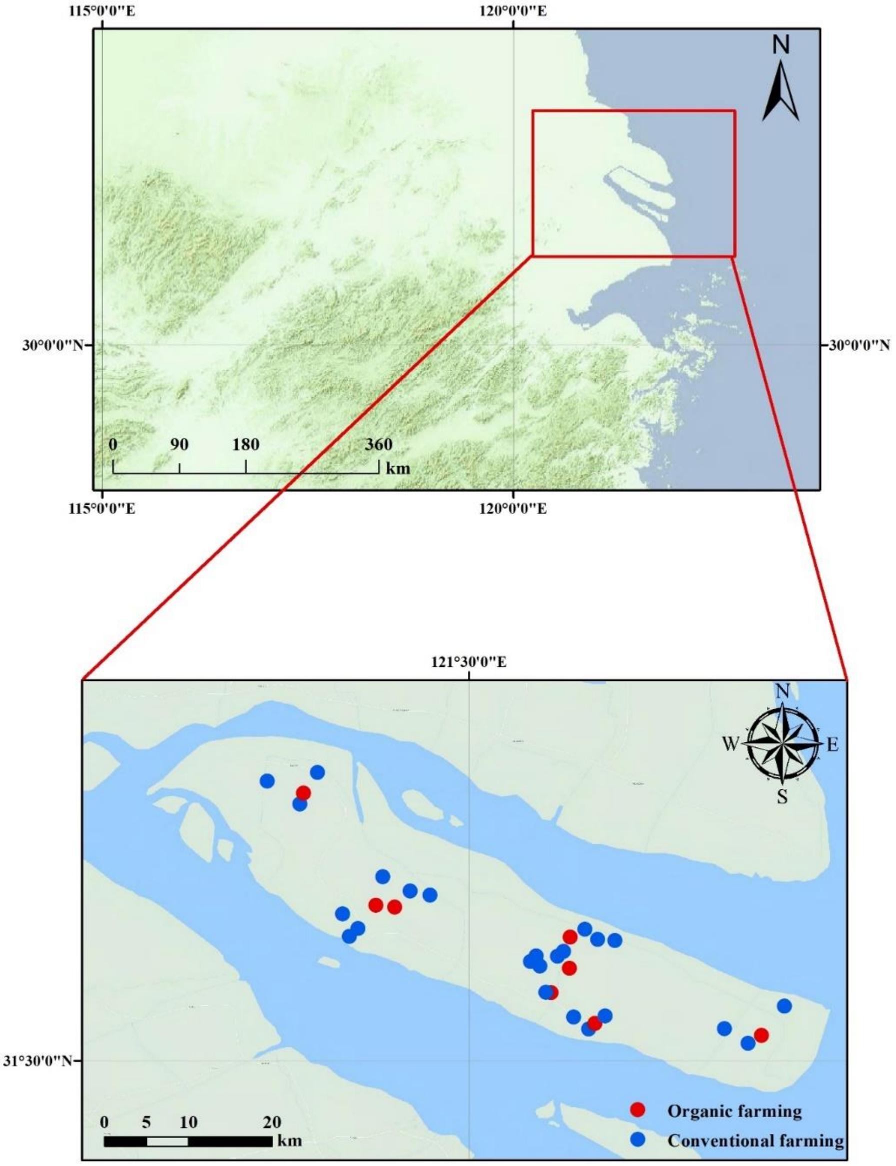

Fig. 1 The spatial distribution of the studied farms under large-scale farming and smallholder management. The red nodes represent large-scale farming sites and the blue nodes represent smallholder management sites.

Field survey

A field survey was conducted on large-scale farms and field blocks in November 2022, including profile characteristics and management level. The terrain of the farmland was determined by small and medium topographic units, and all farms were located on plains. The irrigation capacity and drainage capacity were determined through irrigation water sources, irrigation amount, drainage methods, and drainage facilities. Soil texture, texture profile configuration, and effective soil layer thickness were obtained by analyzing soil profiles and field soil texture measurements (Vos *et al.*, 2016). The farmland shelter rate was determined by the surrounding woodland belts of the field blocks. The obstacle type of farmland was determined based on the texture profile configuration, soil type, and parent material. The biodiversity of microorganisms and fauna was assessed by combining field surveys with empirical knowledge and soil microbial biomass carbon (MBC) in laboratory determination. Penetration resistance (PR) and bulk density (BD) were measured by a penetrometer (Spectrum SC-900, USA) and the core method, respectively. Earthworm density and biomass in the surface layer were determined by the amount and biomass weight considering 20×20×20 cm^3 soil cores (Tsiafouli *et al.*, 2015).

Soil sampling and analysis

During the field survey, surface soil samples (0-20cm) were collected from all the field sampling plots after the crop was harvested and fields were drained for more than two weeks in November 2022. There were 8 large-scale farms and 24 smallholder fields (3 neighbored each large-scale farm) were included in this study. The areas of large-scale farms and nearby conventional fields selected were from 20-80 ha and 2-8 ha each, respectively. Three plots with an area of 300 m^2 as replicates (10m × 10m per plot) from each farm were randomly chosen for soil sample collection. Ten soil cores were randomly sampled from each plot and mixed thoroughly to obtain one soil sample, which means there were 24 soil samples for large-scale farms and 72 samples for smallholder-managed fields. Fresh samples were packed in an icebox and immediately brought indoors. Subsequently, plant residues and stones were removed, and the soils were mixed thoroughly to achieve homogenized samples before sieving. A portion of each soil sample was gently broken by hand to pass the 8mm sieve and then air-dried indoors at room temperature for the determination of water-stable aggregates. We used air-dried soil samples to determine water-stable aggregates to characterize the difference in aggregate stability between organic agriculture and conventional agriculture for paddy soil, which was affected by water-logging/draining cycling. The other samples were sieved through a 2-mm sieve and divided into three subsamples. One subsample was stored at a 4 °C refrigerator for the determination of microbial biomass. One subsample was stored at a -80 °C ultra-low temperature freezer for the determination of microbial community and structure. The remaining subsamples were air-dried indoors to measure soil physical and chemical properties (Wang *et al.*, 2023).

Soil physical properties examined were water-stable aggregates (WSA) and mean weight diameter (MWD). Soil chemical properties determined were pH, soil OM, total nitrogen (TN), available phosphorus (AP), available potassium (AK), available copper (ACu), available zinc (AZn), dissolved organic carbon (DOC), total soluble nitrogen (TDN). Soil biological properties analyzed included soil microbial biomass carbon (MBC), soil microbial biomass nitrogen (MBN), fungi, bacteria, Gram-positive (G^+) bacteria, Gram-negative (G^-) bacteria, actinomycetes, arbuscular mycorrhizal fungi (AMF), bacteria/fungi ratio (F/B ratio), Gram-positive/Gram-negative ratio (G^+/G^- ratio), Shannon index, Simpson index, and Pielou index. Methods for more detailed measurements of these properties are shown in Tables SII and SIII (see Supplementary Material for Tables SII and SIII). The MWD was calculated based on aggregate size fractions according to Equation (1) (He *et al.*, 2020).

$$MWD = \sum_{i=1}^{n} X_i W_i \tag{1}$$

where X_i is the mean weight diameter of aggregates in each particle size (mm); W_i is the weight percentage of particle size aggregates (%).

The PLFA analysis was conducted to determine soil microbial community and structure. Different biomarkers were used to represent bacteria (including Gram-positive bacteria and Gram-positive bacteria), fungi, and actinomycetes (Orwin *et al.*, 2018). Shannon index, Simpson index, and Pielou index of fatty acids were calculated based on the relative abundance and total number of fatty acids, which were calculated as follows (Zornoza *et al.*, 2009; Zhao *et al.*, 2014):

$$Shannon\ index = -\sum P_i \times lnP_i \tag{2}$$

$$Simpson\ index = H/lnN \tag{3}$$

$$Pielou\ index = \sum_{i=1}^{N} P_i^2 \tag{4}$$

where H represents Shannon index, P_i represents the relative abundance of each fatty acid in the total sum, and N is the number of detected fatty acids.

Soil environmental properties were also tested including soil heavy metals and antibiotics. Copper (Cu), zinc (Zn), lead (Pb), arsenic (As), chromium (Cr), cadmium (Cd), available lead (APb), available cadmium (ACd), available chromium (ACr), and available arsenic (AAs) were determined. Five types of antibiotics, including tetracyclines, fluoroquinolones, sulfonamides, macrolides, and chloramphenicol (including oxytetracycline, chlortetracycline, norfloxacin, ciprofloxacin, enrofloxacin, sulfathiazole, sulfamethazine, sulfamonomethoxine, sulfamethoxazole, chloramphenicol, and tylosin) were measured.

Farmland quality and soil health assessment

Farmland quality assessment was conducted according to the Chinese national standard "Cultivated land quality grade" (GB/T 33469-2016). Several indicators were used to evaluate farmland quality under different management systems, including soil organic matter, AP, AK, BD, pH, irrigation capacity, drainage capacity, topographic position, soil texture, obstacle type, texture profile configuration, effective soil thickness, forest network ratio, biodiversity, and cleanliness. The weights and quantifications of the indicators were calculated based on the standard. The farmland quality index (FQI) was calculated based on Eq. (5):

$$FQI = \sum_{i=1}^{n} W_i \times S_i \tag{5}$$

where FQI is the farmland quality index (0~1), W_i is the weight of each indicator, S_i is the score of each indicator, and n is the number of indicators.

Thirty-eight measured indicators in this study were used to construct MDS (Fig. S1, see Supplementary Material for Fig. S1). The data on soil health indicators under organic farming and a random conventional farming field block were defined as a training set to select key indicators. The remaining data served as a test set for the MDS validation. In this study, the network analysis method was applied to form MDS according to the complex interactions between soil properties (Raiesi and Beheshti, 2022). Spearman correlation coefficients between indicators were used as the basis for constructing the network, where nodes represent soil health indicators and edges represent the correlations between indicators ($R \geq |\pm 0.4|$, $P<0.01$). Then, eigenvector centrality was calculated to represent the significance of indicators in the network, which was determined by the number of connected nodes and the importance of the neighboring nodes, which was calculated according to Eq. (6):

$$CE(N_i) = X_i = c \sum_{j=1}^{g} a_{i,j} x_j \tag{6}$$

where Xi and Xj are the importance of nodes i and j respectively, c is a proportional constant, and g is the total number of the nodes connected to node i; $a_{i,j}= 1$ if and only if i is connected to j, otherwise $a_{i,j}= 0$.

Indicators were grouped through network analysis. In each group, we chose the indicators with high eigenvector centrality in each group, which were defined as the absolute value within 10% of the highest eigenvector centrality. Pearson correlation coefficients of the indicators in each group were calculated. If there were two high eigenvector centrality indicators in a group, the one with a higher eigenvector centrality was chosen. When there were multiple high eigenvector centrality indicators characterized by high correlation within a group, we chose the indicators with the highest correlation sum (Li *et al.*, 2020).

The calculation of soil health index based on the minimum data set (SHI-MDS) was conducted by the soil health index area (SHI-area) method (Kuzyakov *et al.*, 2020). The indicators were standardized using the following formula (6) and then calculated according to formula (7):

$$stP_i = \frac{X_i}{X} \tag{7}$$

where stP_i represents the standardized indicator. For “more is better” indicators such as Soil OM and TN, X_i and X represent the measured value of the indicator under and the maximum among them, respectively. For “less is better” indicators such as PR, X_i, and X represent the minimum value and measured value, respectively. As for “optimum” indicators such as BD and pH, X_i and X represent the measured value and optimal value of the indicator according to related reference thresholds (Wei *et al.*, 2022).

$$SHI = 0.5 \times \sum_{i}^{n} {stP_i}^2 \times \sin\left(\frac{2\times\pi}{n}\right) \tag{8}$$

where n is the total number of indicators and π (3.14)

In this research, soil health supports not only crop production but also biological population regulation and maintaining environmental quality. Soil health index was calculated based on the total data set (SHI-TDS) considering three aspects, i.e. (i) soil fertility index (SFI) for crop production, (ii) soil biological index (SBI) for biological population regulation, and (iii) soil environmental index (SEI) for maintaining environmental quality. These three indices were quantified using Eqs (6) and (7) (Fig. S1). Indicators including BD, PR, WSA, MWD, pH, soil OM, TN, AP, AK, AFe, AZn, DOC, TDN, soil MBC, and MBN were used in SFI quantification. Earthworm density, earthworm biomass, G^+, G^-, bacteria, fungi, AMF, actinomycetes, total PLFAs, F/B ratio, G^+/G^- ratio, Shannon index, Simpson index, and Pielou index were used to calculate the SBI (Li *et al.*, 2023). Total Cu, Zn, Pb, Cd, Cr, As, APb, ACd, and AAs were used to calculate the SEI. Soil ACr was not detected in both management systems. Similarly, most soil antibiotics were not detected, and the measured values of a few antibiotics were lower than 100 μg kg^{-1} (i.e. the threshold of ecological toxicity set by the Veterinary International Conference of Harmonization) (Table SIV, see Supplementary Material for Table SIV). Therefore, soil antibiotics and ACr were not incorporated into the assessment. Based on the three indices, SHI-TDS was calculated using the SHI-area method.

Statistical analysis

Significant differences in soil physical, chemical, biological properties, farmland quality, and soil health between different management systems were tested using the Welch's t-test at $P<0.05$. Welch's t-test, correlation analysis, and linear regression analysis were performed in R software v 3.62 (R Core Team, Vienna, Austria). Network analysis was conducted using Gephi 0.92. Other statistical analyses were performed through SPSS 22.0 (IBM Corp., Armonk, NY, USA). All figures were generated with R software version 3.6.2 and Origin 2022 (OriginLab Inc., Northampton, MA, USA). The spatial distribution of sampling sites was visualized by ArcGIS 10.6 (ESRI, Redlands, CA, USA).

RESULTS

Soil health indicators under different management systems

Soil physical, chemical, and biological properties were improved by large-scale farming with the application of commercial organic compost. Organic management significantly ameliorated soil physical properties by increasing WSA and MWD while reducing BD. The soil OM and TN of large-scale farms were significantly higher than those of smallholder fields. Additionally, significantly higher AP, AK, and AFe of large-scale management were observed compared to conventional management significantly (Table I). Soil MBC and MBN under large-scale organic farming were 453.2 mg·kg^{-1} and 49.5 mg·kg^{-1}, which is significantly higher than that of conventional farming (Table II). The earthworm density under large-scale management was also significantly higher than that under smallholder management. Microbial community and structure differed significantly among different management systems. A higher F/B ratio and a lower G^+/G^- ratio were observed in large-scale farms. The PLFA contents of bacteria, fungi, and actinomycetes under smallholder management were significantly lower than those under large-scale management by 20.6%, 32.7%, and 18.9%, respectively. Organic management in large-scale farming significantly increased the diversity of fatty acids, with a higher Shannon index, Simpson index, and Pielou index.

TABLE I

Soil physical and chemical properties under large-scale farming and smallholder management.

Soil physical-chemical indicators	Large-scale farming	Smallholder management
BD (g·cm^{-3})	1.22±0.01b	1.25±0.01a
PR (kPa)	1116.93±38.85	1161.09±52.89
WSA (%)	65.92±2.14a	53.54±1.50b

MWD (mm)	1.85±0.06a	1.17±0.04b
pH	7.87±0.04	7.95±0.03
Soil OM (g·kg^{-1})	31.75±0.99a	28.90±0.75b
TN (g·kg^{-1})	1.81±0.05	1.75±0.05
AP (mg·kg^{-1})	35.52±3.48a	22.14±1.79b
AK (mg·kg^{-1})	133.75±6.35a	110.57±2.75b
AFe (mg·kg^{-1})	6.75±0.14b	8.49±0.32a
AZn (mg·kg^{-1})	1.89±0.17	1.90±0.21
DOC (mg·kg^{-1})	294.25±7.57a	256.37±2.13b
TDN (mg·kg^{-1})	36.02±1.79a	27.58±5.56b

Data represent the means ± standard error (n=24 for large-scale farming and n=72 for smallholder management). Significant differences are denoted by different letters (P <0.05). BD, bulk density; PR, penetration resistance; WSA, water stable aggregate; MWD, mean weight diameter; Soil OM, soil organic matter; TN, total nitrogen; AP, available phosphorus; AK, available potassium; AFe, available iron; AZn, available zinc; DOC, dissolved organic carbon; TDN, total dissolved nitrogen.

TABLE II

Soil biological indicators under large-scale farming and smallholder management.

Soil biological indicators	Large-scale farming	Smallholder management
Soil MBC (mg·kg^{-1})	453.20±38.27a	327.52±21.98b
Soil MBN (mg·kg^{-1})	49.50±3.05a	36.62±1.30b
Earthworm density (Ind·(20·20·20) cm^{-3})	1.54±0.49a	0.54±0.16b
Earthworm biomass (g·(20·20·20) cm^{-3}))	0.17±0.14	0.01±0.01
G^+ (nmol·g^{-1})	19.07±1.21a	14.90±0.67b
G^- (nmol·g^{-1})	28.48±1.62a	20.67±1.01b
Bacteria (nmol·g^{-1})	58.79±3.53a	46.69±1.82b
Fungi (nmol·g^{-1})	11.09±0.55a	8.36±0.24b
AMF (nmol/g^{-1})	3.19±0.14a	2.62±0.07b
Actinomycetes (nmol·g^{-1})	12.72±0.78a	10.32±0.36a
total PLFAs (nmol·g^{-1})	108.20±4.09a	91.51±2.04b
F/B ratio	0.19±0.02a	0.18±0.02b
G^+/ G^- ratio	0.66±0.01b	0.73±0.01a
Shannon index	3.15±0.01a	3.10±0.00b
Simpson index	0.91±0.00a	0.90±0.00b
Pielou index	0.85±0.00a	0.82±0.00b

Data represent the means ± standard error (n=24 for large-scale farming and n=72 for smallholder management). Significant differences are denoted by different letters (P <0.05). Soil MBC, soil microbial biomass carbon; Soil MBN, soil microbial biomass nitrogen; G^+, Gram-positive; G^-, Gram-negative; AMF, arbuscular mycorrhizal fungi; F/B ratio, bacteria/fungi ratio; G^+/ G^- ratio, Gram-positive/Gram-negative ratio.

Management systems significantly influenced soil heavy metals. The application of organic compost in large-scale farms resulted in lower Zn, Cd, Cr, and AAs and higher Pb compared with smallholder farming (Table SV, see Supplementary Material for Table SV). However, there were no significant differences in other heavy metals between the two management modes. All total heavy metals under the two agricultural systems were lower than the risk values according to the Chinese national standard “Soil environmental quality-risk control standard for soil contamination of agricultural land” (GB 15618-2018), indicating that organic compost inputs did not result in an accumulation of heavy metals under large-scale management.

The indicators in the minimum data set

All the indicators were used in the selection of key indicators through network analysis. The network consisted of 38 nodes (indicators) and 412 edges (Fig. S2, see Supplementary Material for Fig. S2). All the indicators in the network were identified as eight modules (groups), as shown in Table SVI (see Supplementary Material for Table SVI). The eigenvector centrality of soil MBC was the highest among all the indicators, with a value of 1.00. The sole indicators in the first and second groups were BD and PR, respectively, which were directly chosen in the MDS. There were two highly correlated indicators in the third and fifth groups, and MWD and DOC were selected in the MDS, with higher eigenvector centrality in each group. In the fourth group, soil OM, TN, and soil MBC were high eigenvector centrality indicators. The correlation sum of soil OM was the highest, which was 2.81 (Table SVI). Therefore, it was chosen to be included in the MDS. Likewise, bacteria and G^- with the highest correlation sums in the sixth and seventh groups were selected, respectively. In the eighth group, the eigenvector centralities of earthworm density and biomass were the same. Since earthworm biomass could simultaneously represent earthworm density, it was chosen to be one of the key indicators of the MDS.

The indicators in the MDS were BD, PR, MWD, soil OM, DOC, earthworm biomass, G^-, and bacteria. The SHI-MDS in the training set showed a significant positive correlation with both SHI-TDS and FQI, and R^2 values were 0.73 and 0.36, respectively (Fig. 2). Furthermore, the linear regression results for SHI-MDS, SHI-TDS, and FQI based on the test set also showed a significant positive correlation. The positive correlations between the indices showed good accuracy and representativeness of these indicators in characterizing soil health.

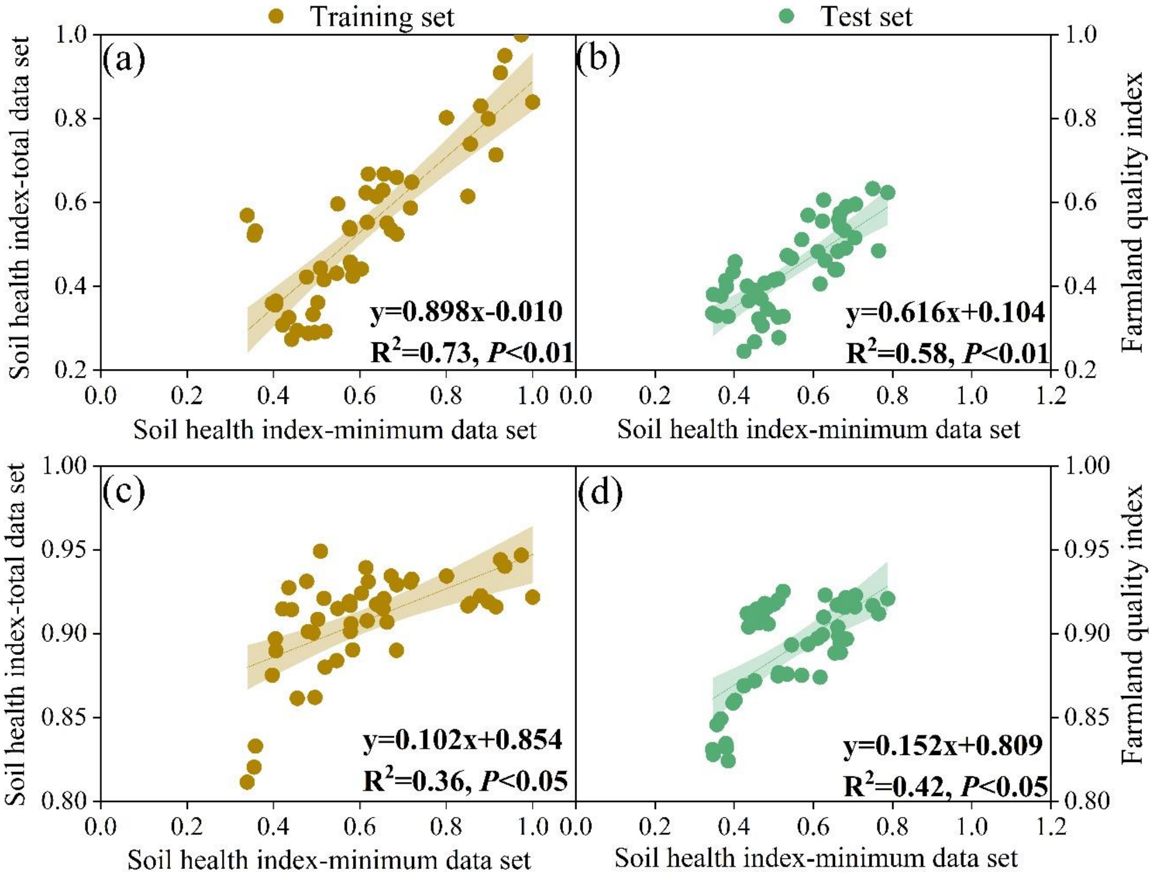

Fig. 2 Linear regressions between soil health index based on the minimum data set and soil health index based on the total data set and farmland quality index in the training set (a, c) and test set (b, d).

Effects of management systems on SHI

Large-scale organic farming has significantly changed the SHI. The SHI-TDS under large-scale management was 0.65, which was 38.3% higher than that under smallholder management (Fig. 3). Concretely, the SFI and SBI of large-scale farms were significantly higher, with values of 0.74 and 0.70, respectively. However, there was no significant difference in the SEI between the two systems. The trend of FQI was consistent with that of SHI-TDS, which showed the significant effect of large-scale farming on soil health enhancement by organic inputs. The SHI-MDS of the large-scale farms was 23.4% higher than that of the conventional fields (Fig. 4). Specifically, SHI-MDSs of all large-scale farms, except fanxin farm in Gangxi Town, were significantly higher than that of conventional farms. Among alllarge-scale farms, the SHI-MDSs of beihu farm, wanhe farm, and fanxin farm in Bao Town were 44.1%, 44.9%, and 53.6% higher than those of smallholder fields, which showed the most significant improvement.

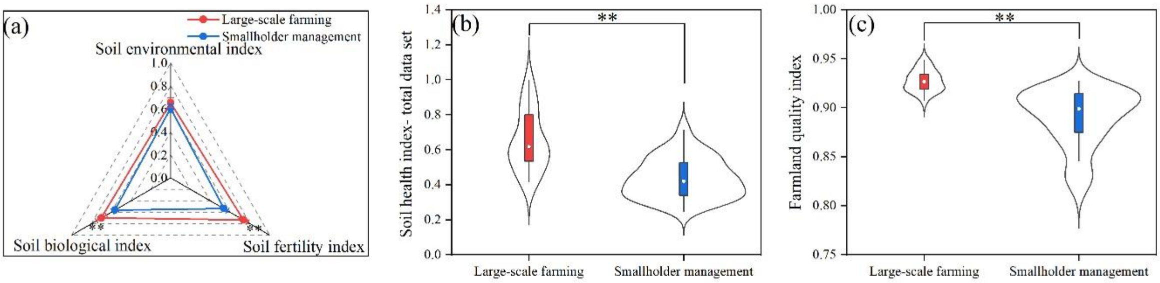

Fig. 3 Soil health index based on the total data set (a, b), and farmland quality index (c) under large-scale farming and smallholder management systems. Data represent the means ± standard error (n=24 for large-scale farming and n=72 for smallholder management). Soil health index-total data set was calculated by soil fertility index, soil biological index, and soil environmental index. Significant differences are denoted by * (*P* <0.05) and ** (*P* <0.01). The graphical shape of the violin plot represents data distribution; the box boundaries indicate the upper and lower quartiles; the white square indicates the mean; the whisker indicates 1.5 times the interquartile range.

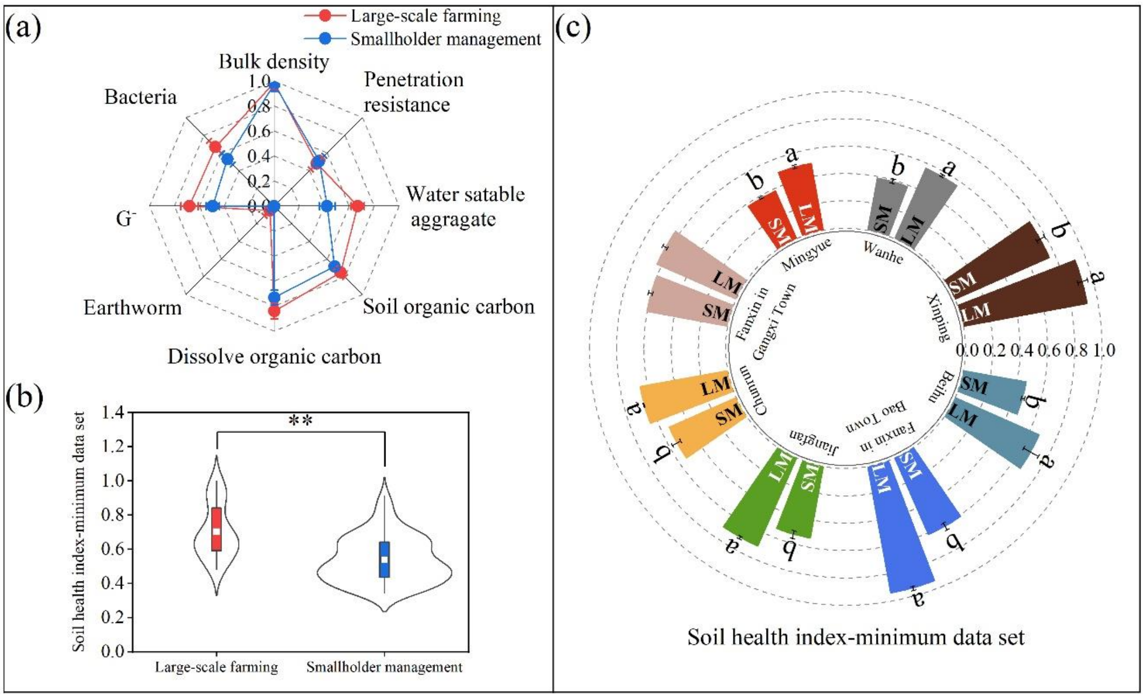

Fig. 4 Soil health index based on the minimum data set under large-scale farming and smallholder management (a, b) and under each large-scale farms and compared smallholder fields (c). LM, large-scale management; SM, smallholder management. Data represent the means ± standard error (n=24 for large-scale farming and n=72 for smallholder management; n=3 for large-scale farms and n=9 for smallholder fields). Significant differences are denoted by * (*P* <0.05) and ** (*P* <0.01). The graphical shape of the violin plot represents data distribution; the box boundaries indicate the upper and lower quartiles; the white square indicates the mean; the whisker indicates 1.5 times the interquartile range.

DISCUSSION

Effects of large-scale farming on soil health indicators

Large-scale farming integrates organic compost application with rational crop rotation systems, resulting in the modification of soil physical, chemical, and biological properties. The amelioration of the soil health indicators by large-scale management was mainly caused by the amount and quality of organic compost. Previous studies have demonstrated that organic systems could reduce bulk density, alter porosity, and improve soil aeration and water-holding capacity (Li and Zhang, 2007; Guo *et al.*, 2016). Our finding also revealed that soil aggregate structure under organic compost application was significantly improved, which was caused by the promoting effect of abundant organic binding materials in organic compost on the formation of water-stable aggregates (Di Prima *et al.*, 2018; Steinberger *et al.*, 2023). Additionally, large-scale farming accelerated the formation of particle organic matter by promoting the activity of microorganisms in the rhizosphere, thus improving aggregation stability with compost (Huang *et al.*, 2010). Besides, organic fertilizers could provide more organic matter and slow-release nutrients compared to chemical fertilizers, resulting in significantly higher soil organic matter and nutrients (Ma *et al.*, 2011; Si *et al.*, 2023). Meanwhile, organic inputs could enhance microbial activity to stimulate nutrient release and utilization for crop growth (Xiao *et al.*, 2021). Except for xinping farm, the selected farms adopted green manure rotation, which increased soil nutrients through green manure incorporation into soils. Moreover, humic substances and low molecular organic matter derived from green manure could have affected the organic carbon mineralization process, increasing soil OM (Sharma *et al.*, 2017). Above all, large-scale farming significantly improved total carbon and active carbon and promoted the formation of macro-aggregates, which were significant contributors to carbon stock. This inferred that it promoted carbon stock by increasing organic inputs.

Significant differences in soil biological indicators were observed under different management modes, which were crucial for assessing soil health status (Table II). Soil MBC and MBN under large-scale management were significantly higher, corresponding to most studies showing that organic fertilizer application could significantly increase microbial biomass (Li *et al.*, 2020; Huang *et al.*, 2021). Microbial community and structure were significantly altered under the application of organic compost. Higher bacteria, fungi, actinomycetes, G^+, G^-, and total PLFAs under large-scale farming demonstrated that organic inputs and the restriction of pesticides could significantly increase microbial abundance and activity (Wei *et al.*, 2017; Wołejko *et al.*, 2020). The higher F/B ratio and the lower G^+/G^- ratio in cooperative farms could be mainly attributed to the application of organic amendments. Organic matter inputs might increase the proportion of fungi in microorganisms due to its relatively high C/N ratio, resulting in a shift towards a predominantly fungal composition (Wang and Zed, 2024). Microbial communities dominated by fungi are more conducive to carbon accumulation and stability, showing that organic agriculture helps improve soil carbon stock (Yang *et al.*, 2024). Gram-negative bacteria are more likely to grow under conditions with sufficient nutrients, so the addition of compost usually tends to result in a higher proportion (Bray *et al.*, 2012; Wang *et al.*, 2020). Our results also demonstrated that the application of organic compost in large-scale management and crop rotation could regulate the soil microbial community and structure with higher organic matter contents, better nutrient supply, and a more suitable environment (Lin *et al.*, 2019).

Differences in Zn, Pb, Cd, Cr, and AAs were found under the two agricultural systems. The inorganic phosphate fertilizers and agrochemicals (herbicides, pesticides, and fungicides) can contain Cd, Cu, Pb, Zn, and Cr as contaminants, which might lead to higher heavy metals in conventional management systems. In contrast, organic compost in large-scale farming improved organic matter content and microbial activity, reducing heavy metals by affecting the transformation and migration (Karlsson *et al.*, 2006). The contents of As, Pb, Cd, and Cr of organic compost were lower than 15, 50, 3, and 150 mg kg^{-1}, respectively. The Cd and Cr in both management systems were higher than the background values and mean values of this area in 2009, while Pb and As were lower. This increase in Cd and Cr might be caused by years of fertilizer input and atmospheric deposition. The latter might be the major exogenous input factor of heavy metals in agricultural soils (Sun *et al.*, 2010). However, all the total heavy metals under the two management systems were lower than the risk values of agricultural land. Besides, large-scale farming has replaced herbicides with manual weeding, which reduced potential heavy metal inputs from herbicides. In our study, the concentrations of antibiotics in the soil under both management modes were below the threshold values of ecological toxicity (according to the Veterinary International Conference of Harmonization). The organic compost was produced from organic waste and straw, which were treated harmlessly through continuous high-temperature fermentation. This might explain why the use of commercial organic compost did not lead to an increase in antibiotics (Spielmeyer, 2018). The raw materials and properties of organic fertilizers were important factors affecting the soil environmental pollution risks (Zhou *et al.*, 2015; Zhou *et al.*, 2021). Further studies are needed to investigate the long-term effect of organic fertilizer types, application rate, and duration on soil environmental pollution risks in large-scale farming.

Indicators in the Minimum data set

In our study, BD, PR, MWD, soil OM, DOC, earthworm biomass, G-negative bacteria, and bacteria were included in the MDS. The MDS reflected different aspects of soil health, including physical, chemical, and biological properties. The significant positive correlation between SHI-MDS and SHI-TDS indicated that network analysis had high accuracy in constructing the MDS (Fig. 2). Bulk density is a commonly used physical indicator that reflects soil structure, aeration, and water-holding capacity. Penetration resistance comprehensively reflects the thickness of the plough layer and soil water content, which affect the absorption of water and nutrients by crop roots (Arvidsson and Håkansson, 2014). Mean weight diameter reflects the stability of soil aggregation structure and resistance to soil erosion (He *et al.*, 2020). soil OM plays a crucial role in various soil processes and is a key indicator of soil health evaluation, which frequently appears in the MDS (Bünemann *et al.*, 2018). It helps to preserve soil structure stability, increase soil nutrient levels and availability, improve water retention, and promote the amount and activity of microorganisms (Schmidt *et al.*, 2011). Generally, the change in soil OM is a relatively slow process. As such, in the literature, most studies focus on the most active organic carbon pools to investigate soil carbon dynamics. Among these pools, DOC is an important intermediate substance in the formation and turnover process of organic carbon, which has high activity and plays an important role in the transformation of nutrients as well as in microbial growth and metabolism in soils (McDowell, 2003). As such, we considered DOC in the MDS.

An increasing number of studies have called for including biological indicators in soil health assessments to elucidate soil functions. Meanwhile, many biological indicators were considered to be sensitive to agro-management practices (Zwetsloot *et al.*, 2022). Earthworms showed sensitivity to changes in soil health, effectiveness, and practicability (Willoughby *et al.*, 2023). In our study, the large coefficients of variation of earthworm biomass under large-scale management resulted in no significant difference in earthworm biomass between the two agricultural management modes. It is commonly used in the context of field-based soil health assessment. Bacteria account for over 70% of the total amount of soil microorganisms and play a crucial role in nutrient cycling and organic matter transformation (De Vries *et al.*, 2006); Gram-negative bacteria, as typical r-strategy microorganisms, are superior in growth and reproduction under favorable environments and sufficient nutrient, which can reflect soil nutrient conditions and environment (Bray *et al.*, 2012). These biological indicators were accurate in evaluating soil health status. Total and available heavy metals were not included in the MDS, which might be due to the relatively small variation in these indicators among the different agro-management practices.

Improvement of soil health under large-scale management

For the past twenty years, the integration of rapid urbanization and expansion of farm sizes has created new demands for modern agricultural practices. Large-scale farming has been rapidly expanding in China to enlargement of agricultural operations (Wu *et al.*, 2018; Duan *et al.*, 2021). Organic management was promoted in large-scale management for a win-win effect for economic benefits and soil health by organic fertilizer application with rational crop rotation systems. Our study revealed that large-scale management significantly improved soil health through the application of organic compost, the incorporation of green manure, and the usage of green manure without herbicides and pesticides (Figs. 3 and 4). Previous studies reported that organic fertilizers could promote plant growth, increase plant-derived carbon input, improve nutrient availability, and provide suitable environments for microbial growth, which enhanced carbon cycling, nutrient cycling, and biodiversity maintenance functions, resulting in a general soil health enhancement (Lazcano *et al.*, 2013; Li *et al.*, 2023). Crop rotation with green manure could also enhance soil fertility by increasing organic carbon storage, accelerating soil mineralization, and promoting nutrient release (Liu *et al.*, 2023). It is believed that the application of herbicides and pesticides reduces the abundance and activity of soil biota (Bardgett and Van Der Putten, 2014). Organic farming could avoid the decrease of soil microorganisms and fauna through a ban on the usage of synthetic compounds for pest, disease, and weed control. In our study, large-scale farming is a key pathway to modernizing agricultural management and ensuring sustainable utilization of croplands.

Soil health is deeply influenced by soil inherent properties and agricultural inputs (Li *et al.*, 2022). Inherent soil characteristics, including soil types, parent materials, and texture, were related to soil health (Bünemann *et al.*, 2018). This study was conducted on Chongming Island, which was formed by the deposition of sediments transported by the Yangtze River and extensive reclamation and transformation (Sun *et al.*, 2010). The parent materials of cropland soils are weathered alluvial deposits. The soil texture is between light loam and medium loam (Gao *et al.*, 2010). The latter indicates that the mean background values for soil nutrients and heavy metals should have been similar in our research. The difference in SHI between the two agricultural management systems could mainly be the result of agricultural inputs. Generally, agricultural income is one of the most important influencing factors of field management (Ma *et al.*, 2011). In order to increase crop yields and obtain higher economic benefits, the annual nutrient inputs of organic compost under large-scale management were much higher than chemical fertilizers under smallholder management. The average nutrient inputs of N, P_2O_5, and K_2O were 671, 427, and 427 kg ha^{-1} in large-scale farming. Higher nutrient input was also an important factor influencing the ability of large-scale farming to provide more nutrients for microorganisms and crops. Besides, more organic matter from organic compost could enhance aggregate stability, increase available nutrients, and thereby improve microbial biomass while stimulating microbial activity.

The economic feasibility of the organic compost application under large-scale farming was also compared with chemical fertilizers. The cost of organic compost and chemical fertilizers were 976 USD ha^{-1} and 726 USD ha^{-1}, respectively. According to the field survey, the annual crop yields of large-scale farming and smallholder management were 6 and 12 t ha^{-1}. The price of organic rice is much higher, with annual incomes accounting to 25000 USD ha^{-1} under large-scale management and 6667 USD ha^{-1} under conventional management, respectively. Large-scale farming could achieve synergistic improvement of soil health and economic benefits. Overall, the application of commercial organic compost instead of chemical fertilizers, herbicides, and pesticides in large-scale farms was cost-effective in enhancing soil health while not causing soil environmental pollution. This highlights the beneficial effects of large-scale farming on soil health, which should be further promoted as an effective management practice ensuring food security and farmland quality.

CONCLUSIONS

Large-scale farming altered soil physical, chemical, biological, and environmental indicators by higher organic inputs. Large-scale management obtained higher soil microbial biomass, aggregates stability, earthworm density, and microbial communities, which were highly related to increased soil organic matter resulting from the 3-7 years of application of organic compost. Therefore, large-scale farming promoted soil organic carbon accumulation and nutrient cycling by enhancing soil nutrient availability, microbial abundance, and soil structure. There was no significant difference in SEI between large-scale farming and smallholder fields in less than 7 years. The key indicators of BD, PR, MWD, soil OM, DOC, earthworm biomass, G-, and bacteria were selected from all the indicators to evaluate soil health.

The MWD, soil OM, DOC, G-, and bacteria were significantly higher in cooperative farms, indicating a higher soil health status. The FQI under large-scale management was also significantly higher than that under conventional management. Large-scale farming effectively improved soil health in intensive agricultural production without influencing soil environmental health by increasing nutrients from organic inputs. Our findings highlighted that organic management in large-scale farms was an economically feasible approach to reducing the risk of soil degradation and ensuring sustainable high-quality agricultural production.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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SUPPLEMENTARY MATERIAL

Supplementary material for this article can be found in the online version.

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Supplementary Material

Table SI

Field management practices of sampled large-scale farms.

Farm	Duration years	Rotation system	Organic compost input (t ha^{-1} yr^{-1})			Estimated nutrient inputs (kg ha^{-1} yr^{-1})		
			Commercial organic compost	Granular organic compost	Bio-organic compost	N	P_2O_5	K_2O
Xinping	3	Rice	15	0.225		837.4	532.9	532.9
Wanhe	3	Rice-rapeseed	15	3.3		1006.5	640.5	640.5
Mingyue	7	Rice-rapeseed	12	3		825.0	525.0	525.0
Chunrun	5	Rice-faba bean		3		165.0	105.0	105.0
Fanxin in Gangxi Town	4	Rice-faba bean		6.75		371.3	236.3	236.3
Fanxin in Bao Town	3	Rice-faba bean	7.5			412.5	262.5	262.5
Jiangfan	3	Rice-rapeseed	12		2.7	808.5	514.5	514.5
Beihu	4	Rice-faba bean	15	2.1		940.5	598.5	598.5

Table SII

Testing methods used for the determination of soil physical, chemical, and biological indicators.

Indicators	Methods/instruments
BD (g cm^{-3}) PR (kPa)	Core method (Lu, 1999) Compactometer (Spectrum SC-900, USA) (Jin *et al.*, 2021)
WSA (%) MWD (mm)	Wet sieving method (He *et al.*, 2020)
pH	a pH under meter 1:2.5 w:v (FE30, Mettler Toledo, Switzerland) (Lu, 1999)
Soil OM (g kg^{-1})	$K_2Cr_2O_7$ colorimetric oxidization method (Lu, 1999)
TN (g kg^{-1})	Kjeldahl method (Lu, 1999)
AP (mg kg^{-1})	Olsen method (Olsen, 1954)
AK (mg kg^{-1})	CH_3COONH_4 extraction with a flame photometer (Lu, 1999)
ACu (mg kg^{-1}) AZn (mg kg^{-1})	DTPA extraction-inductively coupled plasma mass spectrometry (ICP-MS, Agilent 7500a, USA)
DOC (mg kg^{-1}) TDN (mg kg^{-1})	2M KCl extracted solution with a C/N analyzer (multi-N/C 3100, Analytik Jena, Germany) (Wang *et al.*, 2023)
Soil MBC (mg kg^{-1}) Soil MBN (mg kg^{-1})	Chloroform fumigation-incubation method with a Multi C/N 3100 (Analytik Jena, Germany) (Wu *et al.*, 1990)
Earthworm biomass (g 20*20*30 cm^{-3}) Earthworm density (Ind 20*20*30 cm^{-3})	Amount and biomass weight from the 20×20×20 cm^3 soil core (Tsiafouli *et al.*, 2015)
Bacteria (nmol g^{-1}) Fungi (nmol g^{-1}) Actinomycetes (nmol g^{-1}) G^+ (nmol g^{-1}) G^- (nmol g^{-1}) AMF (nmol g^{-1}) F/B ratio G^+/G^- ratio Shannon index Simpson index Pielou index	Phospholipid fatty acid analysis (Frostegård *et al.*, 1991; Huang *et al.*, 2021)

Table SIII

Testing methods used for the determination of soil environmental indicators.

Indicators	Methods/instruments
Cu Zn Pb As Cr	HCl-HNO_3-$HClO_4$ digestion with inductively coupled plasma mass spectrometry (ICP-MS, Agilent 7500a, USA) (Song *et al.*, 2022)
Cd	HF-HNO_3-$HClO_4$ digestion with ICP-MS (Song *et al.*, 2022)
APb ACd ACr	DTPA digestion with ICP-MS (Zhong *et al.*, 2020)
AAs	NaH_2PO_4 extraction-atomic fluorescence spectrophotometry (Zhong *et al.*, 2020)
Tetracyclines Fluoroquinolones Sulfonamides Macrolides Chloramphenicol	High-performance liquid chromatography-tandem mass spectrometry method (Li *et al.*, 2023)

Table SIV

Soil antibiotics of eight large-scale farms. ND, not detected.

Soil antibiotics	Xinping	Wanhe	Mingyue	Chunrun	Fanxin in Gangxi Town	Fanxin in Bao Town	Jiangfan	Beihu
Oxytetracycline (μg kg^{-1})	ND	ND	ND	61.87	31.00	2.12	26.91	0.56
Chlortetracycline (μg kg^{-1})	ND	ND	ND	1.27	0.50	2.41	0.18	1.26
Norfloxacin (μg kg^{-1})	ND	ND	ND	ND	ND	ND	ND	ND
Ciprofloxacin (μg kg^{-1})	ND	ND	ND	ND	ND	ND	ND	ND
Enrofloxacin (μg kg^{-1})	ND	ND	ND	2.84	2.62	2.67	1.96	3.73
Sulfathiazole (μg kg^{-1})	ND	ND	ND	ND	ND	ND	ND	ND
Sulfamethazine (μg kg^{-1})	ND	ND	ND	0.16	0.79	0.14	0.21	0.12
Sulfamonomethoxine (μg kg^{-1})	ND	ND	ND	ND	ND	ND	ND	0.37
Sulfamethoxazole (μg kg^{-1})	ND	ND	ND	ND	ND	ND	ND	ND
Chloramphenicol (μg kg^{-1})	ND	ND	ND	ND	ND	ND	ND	ND
Tylosin (μg kg^{-1})	ND	ND	ND	ND	ND	ND	ND	ND

Table SV

Soil total heavy metals (a) and available heavy metals (b) under large-scale farming and smallholder management, background values, and mean values in paddy soils in 2009.

Soil heavy metals	Cooperative management	Smallholder management	Soil background values	Mean values in paddy soils (2009)
Cu ($mg{\cdot}kg^{-1}$)	35.60±0.71	38.43±0.87		
Zn ($mg{\cdot}kg^{-1}$)	91.86±2.06b	98.5±0.71a		
Pb ($mg{\cdot}kg^{-1}$)	20.54±0.76a	18.2±0.34b	25.47	22.2
Cd ($mg{\cdot}kg^{-1}$)	0.27±0.02b	0.34±0.01a	0.13	0.17
Cr ($mg{\cdot}kg^{-1}$)	79.3±2.44b	88.04±1.24a	75	68.1
As ($mg{\cdot}kg^{-1}$)	8.01±2.34	7.6±1.12	9.1	8.61
APb ($mg{\cdot}kg^{-1}$)	4.62±0.20	5.36±0.24		
ACd ($mg{\cdot}kg^{-1}$)	0.09±0.03	0.07±0.01		
AAs ($mg{\cdot}kg^{-1}$)	0.02±0.00b	0.03±0.00a		

Data represent the means ± standard error (n=24 for large-scale farming and n=72 for smallholder management). Significant differences are denoted by different letters ($P < 0.05$). Available chromium (ACr) of all the treatments was not detected.

Table SVI

Eigenvector centralities and correlation sums of soil health indicators with high eigenvector centralities in each group identified by network analysis (NA).

Indicators with high eigenvector centralities	Group	Eigenvector centrality	Correlation sums
BD	1	0.001	
PR	2	0.001	
MWD	3	0.943	1.40
Simpson index	3	0.912	1.40
Soil OM	4	0.977	2.81
TN	4	0.936	2.76
Soil MBC	4	1.000	2.77
DOC	5	0.937	1.03
Total Pb	5	0.871	1.03
Soil MBN	6	0.955	3.87
G^+	6	0.955	4.45
Bacteria	6	0.978	4.50
Actinomycetes	6	0.955	4.39
AMF	6	0.996	4.26
G^-	7	0.995	2.94
Fungi	7	0.973	2.91
total PLFAs	7	0.977	3.93
Earthworm density	8	0.002	
Earthworm biomass	8	0.002	

Correlation sums of the indicators were calculated if there were more than two indicators with high eigenvector centrality in each group.

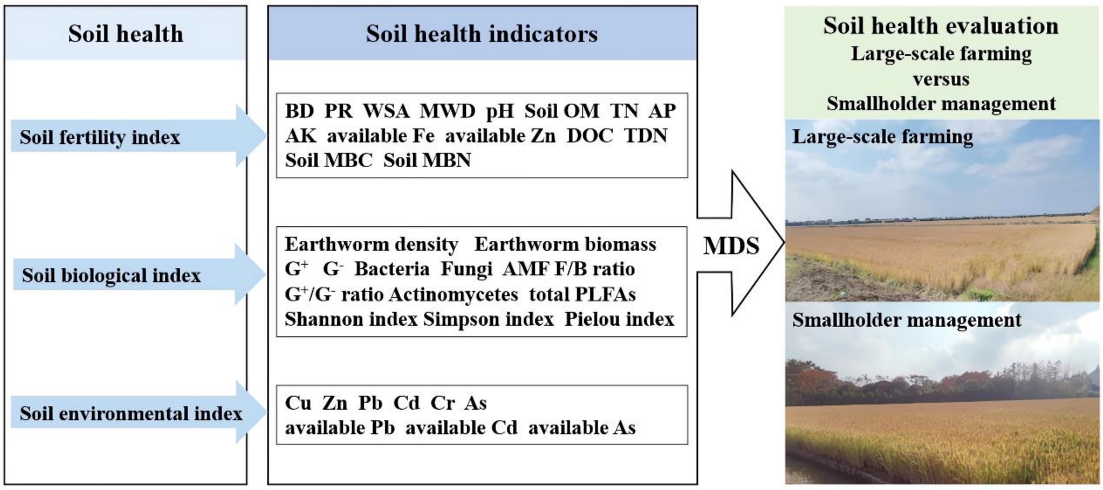

Fig. S1 Conceptual framework for soil health assessment and its application on large-scale farms and smallholder fields. BD, bulk density; PR, penetration resistance; WSA, water stable aggregate; MWD, mean weight diameter; Soil OM. soil organic matter; TN, total nitrogen; AP, available phosphorus; AK, available potassium; DOC, dissolved organic carbon; TDN, total dissolved nitrogen; Soil MBC, soil microbial biomass carbon; Soil MBN, soil microbial biomass nitrogen; G^+, Gram-positive; G^-, Gram-negative; AMF, arbuscular mycorrhizal fungi; F/B ratio, bacteria/fungi ratio; G^+/ G^- ratio, Gram-positive/Gram-negative ratio.

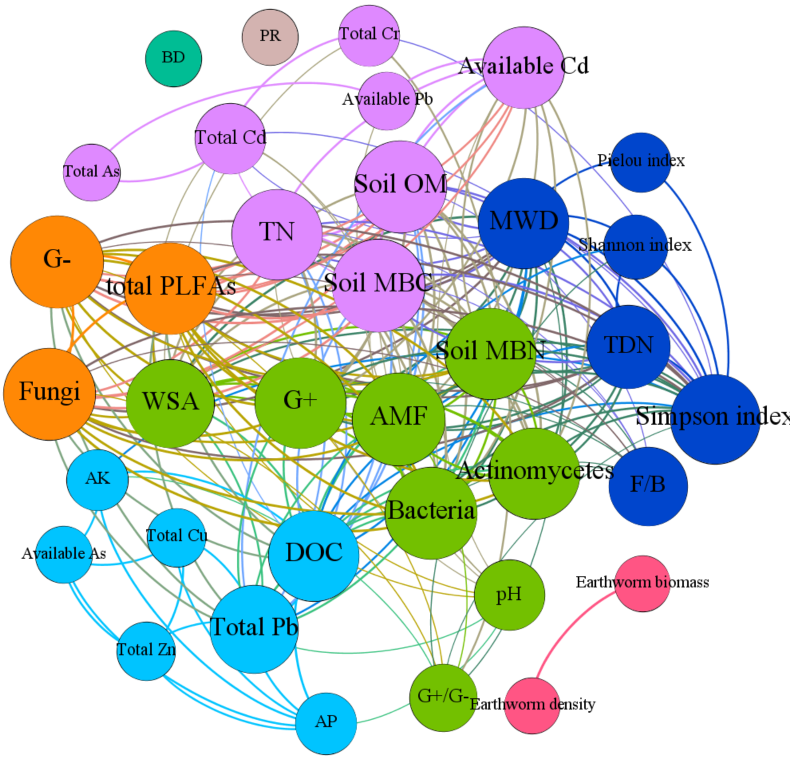

Fig. S2 A network model of soil health indicators under large-scale farming and smallholder management systems. Each node represents a soil indicator and each edge shows a significant correlation between soil indicators. Node colors reflect the soil function groups, and the size of each node reflects the value of eigenvector centrality. The thickness of each edge between two nodes represents the value of significant Spearman’s coefficients coefficient (at $P < 0.01$ corresponding to an r value >0.4).

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