Soil Respiration Dynamics and Carbon Mineralization under Organic Farming Systems

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Received: 20 Dec 2023
Revised: 06 Jan 2023
Accepted: 22 Jan 2024
Published: 08 Feb 2024

E-ISSN: 2989-5340
DOI: https://doi.org/10.54660/jafi.2024.4.1.49-54

ABSTRACT

Background: Soil respiration is one of the major components of the terrestrial carbon cycle, as it shows the general contribution of the roots and the activity of heterotrophic microorganisms; this process is responsible for carbon accumulation and release of carbon dioxide into the atmosphere. Carbon mineralization, which entails the utilization of organic materials by microorganisms, regulates both access of nutrients and capacity for accumulation of soil organic carbon. It is suggested that organic farming changes these processes in comparison to conventional practices, but a limited amount of research findings exist.

Objective: The goal of this paper is to analyze the soil respiration dynamics and carbon mineralization rates in organic farming, concerning conventional agricultural practices.

Method: Randomized complete block field study comparison of the four treatments, farmyard manure, vermicompost, green manure, and biochar, with unamended and conventional fertilization was carried out over a year, with the help of the alkali absorption method for measuring soil respiration, laboratory incubation for measuring carbon mineralization, and chloroform fumigation-extraction for determining microbial biomass carbon and with subsequent determination of total SOC, enzyme activity, moisture content, and soil bulk density analyzed through ANOVA.

Result: Treatment with organic fertilizers turned out to be useful in terms of soil respiration and carbon conversion in comparison with no treatment and traditional fertilization. The best result in respiration was achieved for vermicompost (1.93 mg CO_2-C/kg/hour), and the best treatment for SOC was biochar (16.3 grammatical). Microbial biomass carbon and dehydrogenase activity correlated with the rate of carbon transformation ($r > 0.80$, $p < 0.01$), and PCA showed that organic fertilizers treated plots have distinct features in terms of biological processes.

Conclusion: Organic fertilizers provide favorable conditions for biological carbon cycling in soils while storing carbon, which shows that the application of the right kind of organic fertilizers may lead to the balancing of the process of carbon release with carbon sequestration.

Keywords: Soil respiration, Carbon mineralization, Organic farming, Soil organic carbon, Microbial biomass carbon

1. Introduction

Soil constitutes the largest terrestrial reservoir of organic carbon, storing more carbon than the atmosphere and vegetation combined, and even modest proportional changes in this pool exert disproportionate influence on atmospheric CO_2 concentrations. Soil respiration, the release of CO_2 from root and microbial metabolism, is widely used as an integrative indicator of soil biological activity because it responds rapidly to changes in substrate availability, moisture, temperature, and management. Carbon mineralization, the enzymatic conversion of organic compounds into simpler mineral forms, underlies both this respiratory flux and the release of plant-available nitrogen, phosphorus, and sulfur, linking carbon and nutrient cycles inseparably.

Organic farming systems are built on the principle of returning organic residues, animal manures, and biologically derived amendments to soil rather than relying on synthetic fertilizers, and this practice is widely reported to enhance microbial abundance, diversity, and enzymatic capacity. The resulting shift in substrate quality and quantity can alter both the rate and temperature sensitivity of decomposition, with implications for whether organic systems function as net carbon sinks or sources over agronomically relevant timescales.

Given accelerating climate variability and the urgent need for agricultural systems that simultaneously maintain productivity and mitigate greenhouse gas emissions, a mechanistic understanding of how organic inputs govern respiration and mineralization is essential. However, much existing evidence is derived from short-term incubations or single-amendment comparisons, leaving a gap in field-validated, multi-amendment assessments that integrate respiration, mineralization kinetics, and soil quality indicators within a unified experimental framework. This study addresses that gap by quantifying these processes across several organic amendments relative to conventional management under consistent field conditions.

2. Related Work

Long-term field trials have repeatedly demonstrated that organically managed soils accumulate more SOC than conventionally fertilized counterparts, an effect attributed to greater carbon input rather than intrinsically slower decomposition [1]. Meta-analyses spanning multiple continents confirm consistently elevated microbial biomass and enzymatic activity under organic management, reinforcing the role of substrate supply in sustaining biological activity [2]. Paired comparisons across cropping systems further indicate that enhanced topsoil carbon stocks under organic regimes persist even after accounting for differences in yield and residue return [3].

Mechanistic studies emphasize that microbial necromass, rather than plant residue directly, forms a substantial share of stabilized SOC, implicating microbial carbon-use efficiency as a central determinant of sequestration outcomes [4, 5]. Field-scale nitrogen and carbon balance studies in rice-wheat systems show that combined organic-inorganic fertilization sustains SOC better than either input alone [6], while reduced tillage interacts with organic carbon inputs to further modify aggregate stability and carbon protection [7].

Reviews of soil quality frameworks identify respiration, microbial biomass, and enzyme activity as core biological indicators sensitive to management change [8], and studies in semi-arid and karst systems show that land-use conversion alters respiration primarily through shifts in microbial metabolic efficiency rather than biomass alone [9]. Nitrogen fertilization meta-analyses reveal that enzyme responses to management are strongly mediated by substrate carbon-to-nitrogen ratios [10], a pattern corroborated by community-level shifts in bacterial and fungal composition under organic versus inorganic fertilization [11, 12].

Amendment-specific research indicates that compost effects on microbial biomass depend on particle size and native soil fertility [15], while biochar amendments alter microbial biomass and community structure over multi-year application periods, often with amendment-specific and soil-specific outcomes [16, 17]. Crop residue and straw management studies demonstrate trade-offs between nutrient release and greenhouse gas emission that vary with local climate and flooding regime [18, 19]. Comparable work on tillage-cropping interactions confirms that microbial and enzymatic responses to residue retention are highly context-dependent [20].

Environmental controls including temperature, moisture, texture, and pH remain the dominant drivers of decomposition rate constants across biomes [21], with subtropical forest manipulations showing that carbon input quantity directly regulates both respiration magnitude and microbial community composition [22]. Incubation-based studies isolating temperature and moisture interactions demonstrate non-additive effects on mineralization that complicate simple extrapolation from laboratory to field [23]. Despite this substantial body of work, few studies integrate respiration, mineralization kinetics, and multiple organic amendments within a single, replicated, season-resolved field trial, which constitutes the central limitation this study addresses.

3. Soil Respiration and Carbon Mineralization under Organic Farming Systems

3.1. Conceptual Framework of Soil Carbon Cycling

Carbon entering the soil system through organic amendments and root exudates is partitioned among three principal fates: rapid mineralization to CO2, transformation into microbial biomass, and progressive humification into more recalcitrant SOC fractions. The relative allocation among these pathways depends on substrate biochemical quality, particularly lignin and polyphenol content, the carbon-to-nitrogen ratio, and the composition of the resident microbial community, as summarized in Table 1 for the amendments evaluated in this study.

Table 1: Substrate Quality Parameters of Organic Amendments Influencing Carbon Partitioning.

Amendment	C:N Ratio	Lignin Content (%)	Mineralization Rate Constant, k (day^{-1})
Farmyard manure	18:1	9.8	0.061
Vermicompost	14:1	6.2	0.074
Green manure	12:1	5.1	0.081
Biochar	112:1	38.6	0.006

3.2. Mechanisms of Microbial Decomposition and Mineralization Kinetics

Decomposition proceeds through extracellular enzymatic depolymerization of complex polymers into soluble monomers, which are subsequently assimilated and respired by heterotrophic microorganisms. Carbon mineralization typically follows first-order kinetics, with an initial rapid phase dominated by labile substrates followed by a slower phase governed by more recalcitrant compounds. Organic amendments differ markedly in this kinetic signature: manures and green manures release carbon rapidly, whereas biochar, owing to its aromatic structure, mineralizes slowly while contributing disproportionately to stable carbon pools.

3.3. Seasonal Variation and Microbe-Root-Residue Interactions

Soil respiration exhibits pronounced seasonal fluctuation, peaking during warm, moist periods coinciding with active root growth and residue decomposition, and declining under cold or waterlogged conditions that constrain microbial and root activity. Rhizosphere priming, whereby root exudates stimulate mineralization of native SOC, interacts with residue decomposition to create spatially heterogeneous hotspots of biological activity, ultimately shaping both short-term nutrient availability and longer-term ecosystem carbon balance, as reflected in the monthly respiration trends in Figure 1.

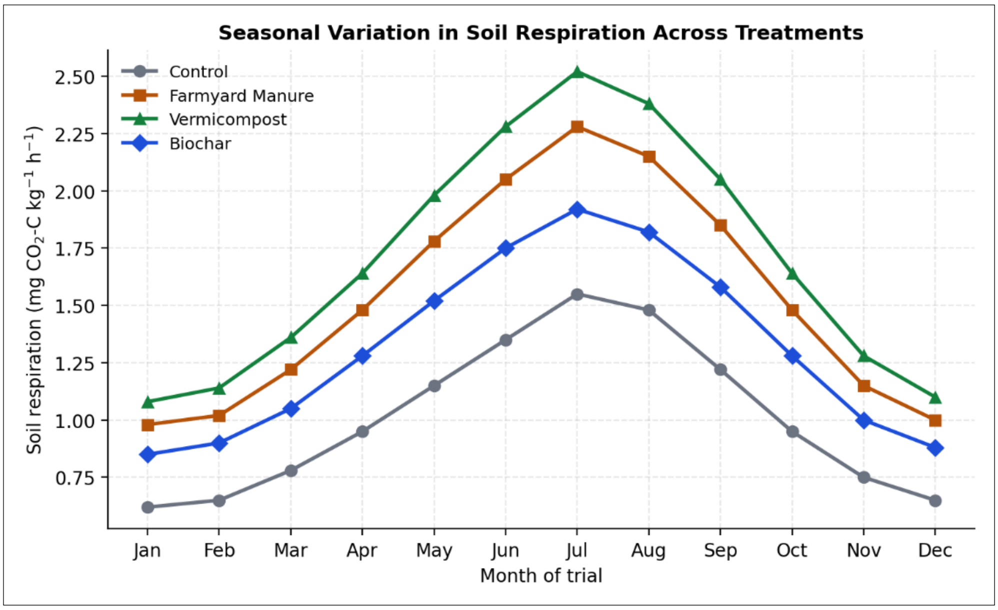

Fig 1: Seasonal Variation in Soil Respiration Across Treatments.

4. Materials and Methods

4.1. Study Area

The field experiment was conducted on an experimental farm situated within a semi-arid, sub-tropical agro-climatic zone characterized by a mean annual temperature range of 18-34°C and average rainfall of approximately 850 mm, concentrated in the monsoon season. The soil was classified as sandy clay loam with near-neutral pH, moderate cation exchange capacity, and a cereal-legume rotation history.

4.2. Experimental Design and Organic Inputs

A randomized complete block design with three replicates compared five treatments: unamended control, conventional inorganic fertilization, farmyard manure, vermicompost, and biochar, applied at agronomically standard rates prior to each cropping season across 5 m x 4 m plots, as detailed in Table 2. Green manure incorporation and crop residue retention were superimposed within respective organic plots to reflect representative organic farming practice.

Table 2: Treatment Composition and Application Details in the Field Trial.

Treatment	Composition	Application Rate	Frequency
Control	Unamended	None	N/A
Conventional	NPK synthetic fertilizer	120:60:40 kg/ha (N:P:K)	Per cropping season
Farmyard manure	Composted cattle manure	10 t/ha	Once per season
Vermicompost	Earthworm-processed organic matter	5 t/ha	Once per season
Biochar	Pyrolyzed crop residue (450°C)	8 t/ha	Single basal application

The randomized complete block layout, comprising three replicate blocks of the five treatments across individual 5 m x 4 m plots, is illustrated schematically in Figure 2.

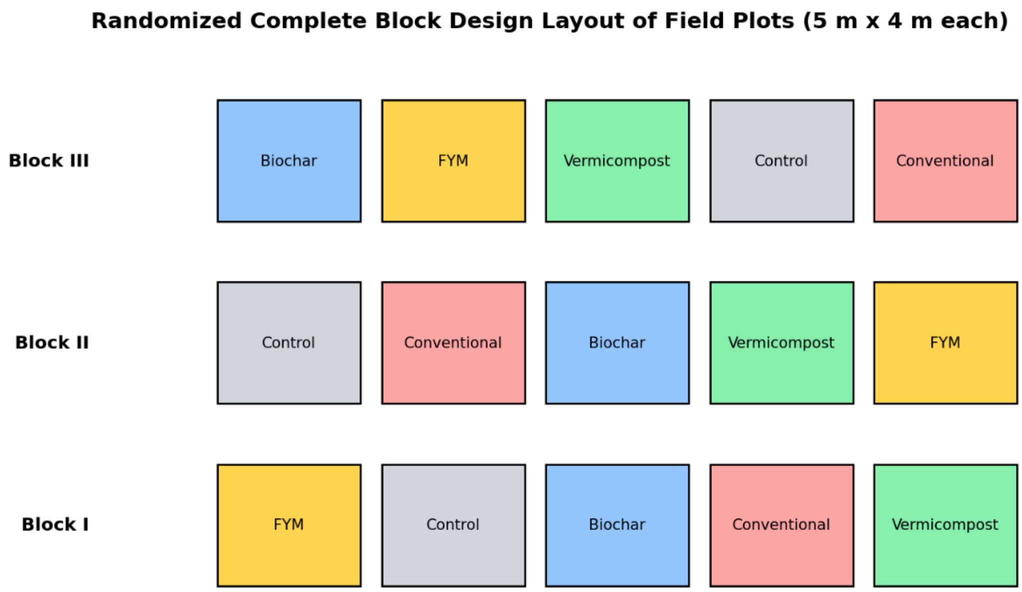

Fig 2: Randomized Complete Block Design Layout of Field Plots.

4.3. Soil Sampling and Laboratory Analysis

Composite soil samples were collected monthly over twelve months from 0-15 cm and 15-30 cm depths, sieved to 2 mm, and subdivided for fresh and air-dried analysis. Soil respiration was quantified using the alkali absorption (sodium hydroxide trap) method under standardized laboratory incubation; carbon mineralization was determined through sequential CO2 evolution measurements over a 28-day incubation; microbial biomass carbon was measured by chloroform fumigation-extraction; SOC was analyzed by the Walkley-Black wet oxidation method; soil moisture and bulk density were determined gravimetrically and by the core method respectively; pH was measured in a 1:2.5 soil-water suspension; and dehydrogenase and urease activities were assayed colorimetrically as indices of enzymatic function.

4.4. Statistical Analysis and Evaluation Parameters

Treatment effects were evaluated using one-way and repeated-measures ANOVA with Duncan's multiple range test for mean separation at $p < 0.05$. Regression and Pearson correlation analyses examined relationships among soil respiration, carbon mineralization, microbial biomass carbon, and environmental covariates, while principal component analysis (PCA) was applied to reduce dimensionality across the full indicator suite, including carbon use efficiency and estimated carbon sequestration potential.

5. Results and Performance Evaluation

Soil respiration displayed clear seasonal variation across all treatments, peaking during the warm, moist monsoon months and declining sharply during the cool dry season, with organic treatments maintaining consistently higher rates than the control throughout the annual cycle. Among amendments, vermicompost produced the highest mean respiration rate, followed closely by farmyard manure, while biochar exhibited a comparatively moderated respiratory response consistent with its lower short-term decomposability, as summarized in Table 3.

Table 3: Soil Respiration, Carbon Mineralization, and Soil Quality Indicators under Different Treatments.

Indicator	Control	FYM	Vermicompost	Biochar
Soil respiration (mg CO2-C/kg/h)	1.02	1.74	1.93	1.58
Carbon mineralization (mg C/kg/28d)	178	298	336	262
Microbial biomass C (mg/kg)	241	402	447	368
Soil organic carbon (g/kg)	9.4	13.8	15.1	16.3
Dehydrogenase activity (ug TPF/g/24h)	18.2	27.6	31.4	25.9

Carbon mineralization rates followed a similar treatment ranking, with vermicompost and farmyard manure releasing carbon more rapidly than biochar, whose slower, sustained mineralization pattern instead translated into markedly greater SOC accumulation over the trial period. Microbial biomass carbon and dehydrogenase activity were strongly and positively correlated with carbon mineralization rate ($r = 0.84$ and $r = 0.79$ respectively, $p < 0.01$), confirming that microbial abundance and enzymatic capacity are principal proximate drivers of observed mineralization differences.

Comparative analysis against the conventionally fertilized system showed that, despite receiving no synthetic nutrient input, organic treatments achieved significantly higher respiration, mineralization, and SOC values ($p < 0.05$), indicating that biologically mediated nutrient cycling can substitute effectively for synthetic inputs while additionally enhancing carbon retention, as illustrated in Figure 3. Principal component analysis explained 78 percent of total variance across the first two components, with the first component, dominated by microbial biomass, respiration, and enzyme activity, clearly separating organic from conventional and control plots.

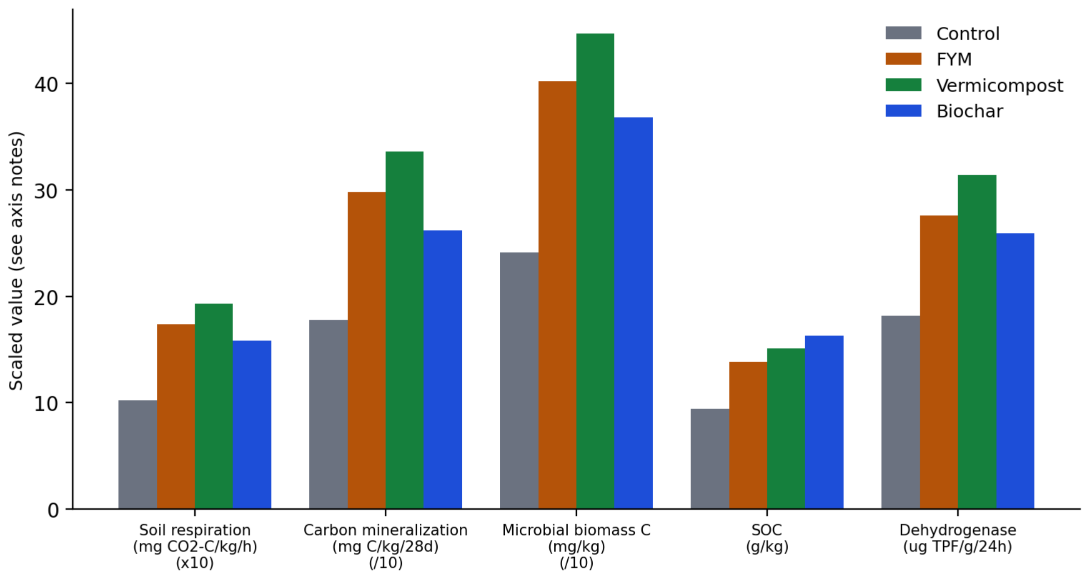

Fig 3: Comparative Performance of Organic and Conventional Farming on Soil Respiration, Carbon Mineralization, and Soil Organic Carbon.

Estimated carbon sequestration potential, derived from the balance between carbon inputs and respiratory losses, was highest under biochar amendment, followed by vermicompost and farmyard manure, while the control and conventional systems showed near-neutral or slightly negative carbon balances. Limitations observed during the trial included seasonal sampling gaps during extreme monsoon events and inherent spatial heterogeneity in manure application, both of which introduced modest variance into within-treatment replicate values.

6. Discussion

The observed elevation in soil respiration and carbon mineralization under organic treatments is consistent with the substrate-driven activation of microbial communities documented in prior meta-analyses [2, 3], and confirms that increased biological activity under organic management need not compromise carbon retention provided that inputs include amendments of contrasting lability. The strong correlation between microbial biomass, enzyme activity, and mineralization rate observed here aligns with mechanistic evidence that microbial carbon-use efficiency, rather than gross decomposition rate alone, governs whether carbon inputs translate into stabilized SOC [4, 5].

The contrasting behavior of vermicompost and biochar illustrates a practically important trade-off: readily decomposable amendments support immediate nutrient mineralization and microbial proliferation, whereas recalcitrant amendments such as biochar favor long-term carbon storage at the expense of short-term nutrient release, a pattern broadly consistent with amendment-specific findings in the biochar literature [16, 17]. These findings suggest that combining fast- and slow-cycling organic inputs within a single management strategy may optimize both immediate soil fertility and long-term sequestration, echoing recommendations from long-term fertilization trials [6, 24].

Ecologically, the enhanced enzymatic and microbial indicators under organic treatments reflect improved soil ecosystem functioning, with likely co-benefits for aggregate stability, water-holding capacity, and resilience to environmental stress, consistent with soil quality frameworks emphasizing biological indicators as sensitive, integrative measures of soil condition [8]. From a climate mitigation perspective, the positive carbon balance observed under amended plots supports the broader argument that soil carbon management constitutes a viable, scalable component of climate-smart agriculture [28].

Several limitations warrant acknowledgment. The trial spanned a single annual cycle, which may not capture multi-year equilibration of SOC pools, and the alkali absorption method, while robust, offers coarser temporal resolution than continuous infrared gas analysis. Future research should incorporate high-frequency automated respiration monitoring, microbial genomic profiling to resolve functional community shifts, and process-based carbon models capable of simulating long-term trajectories under varying amendment combinations and climate scenarios.

7. Conclusion

This study demonstrates that organic farming practices meaningfully enhance soil respiration and carbon mineralization relative to conventional management, driven primarily by increased microbial biomass and enzymatic activity following organic amendment. Importantly, this heightened biological activity does not come at the expense of carbon storage: amendments such as biochar promote substantial SOC accumulation even as more labile inputs like vermicompost and farmyard manure sustain rapid nutrient cycling. Collectively, these results indicate that organic farming can reconcile the frequently perceived tension between active nutrient mineralization and long-term carbon sequestration, offering a practical pathway toward improved soil health and climate-resilient agricultural production. Wider adoption of combined fast- and slow-cycling organic inputs is recommended, alongside long-term, multi-site field validation and continuous soil monitoring to confirm the durability of these benefits across diverse agro-climatic conditions.

References

1. Bhattacharyya SS, Ros GH, Furtak K, Iqbal HMN, Parra-Saldivar R. Soil carbon sequestration: An interplay between soil microbial community and soil organic matter dynamics. Sci Total Environ. 2022;815:152928.
2. Lori M, Symnaczik S, Mäder P, De Deyn G, Gattinger A. Organic farming enhances soil microbial abundance and activity: A meta-analysis and meta-regression. *PLoS One*. 2017;12(7):e0180442.
3. Gattinger A, Müller A, Haeni M, Skinner C, Fliessbach A, Buchmann N, *et al*. Enhanced top soil carbon stocks under organic farming. Proc Natl Acad Sci U S A. 2012;109(44):18226-18231.
4. Six J, Frey SD, Thiet RK, Batten KM. Bacterial and fungal contributions to carbon sequestration in agroecosystems. Soil Sci Soc Am J. 2006;70(2):555-569.
5. Kallenbach CM, Frey SD, Grandy AS. Direct evidence for microbial-derived soil organic matter formation and its ecophysiological controls. Nat Commun. 2016;7:13630.
6. Ghosh A, Bhattacharyya R, Meena MC, Dwivedi BS, Singh G, Agnihotri R, *et al*. Long-term fertilization effects on soil organic carbon sequestration in a rice-wheat cropping system. Soil Tillage Res. 2018;177:134-144.
7. Mondal S, Chakraborty D, Bandyopadhyay K, Aggarwal P, Rana DS. A global analysis of the impact of zero-tillage on soil physical condition, organic carbon content, and plant root response. Land Degrad Dev. 2020;31(5):557-567.
8. Bunemann EK, Bongiorno G, Bai Z, Creamer RE, De Deyn G, de Goede R, *et al*. Soil quality: A critical review. Soil Biol Biochem. 2018;120:105-125.
9. Chen Y, Yu Z, Li Y, Yao Q, Li Y, Zhang W, *et al*. Land use conversion affects soil respiration by altering microbial metabolic quotient in a karst region. Agric Ecosyst Environ. 2020;303:107117.
10. Jian S, Li J, Chen J, Wang G, Mayes MA, Dzantor KE, *et al*. Soil extracellular enzyme activities, soil carbon and nitrogen storage under nitrogen fertilization: A meta-analysis. Soil Biol Biochem. 2016;101:32-43.
11. Wang J, Song Y, Ma T, Raza W, Li J, Howland JG, *et al*. Impacts of inorganic and organic fertilization treatments on bacterial and fungal communities in a paddy soil. Appl Soil Ecol. 2017;112:42-50.
12. Zhang X, Zhu A, Xin X, Yang W, Zhang J, Ding S. Tillage and residue management for long-term wheat-maize cropping in the North China Plain. I. Crop yield and integrated soil fertility index. Field Crops Res. 2018;221:157-165.
13. Luo Z, Wang E, Sun OJ. Can no-tillage stimulate carbon sequestration in agricultural soils? A meta-analysis of paired experiments. Agric Ecosyst Environ. 2010;139(1-2):224-231.
14. Chen Z, Wang H, Liu X, Zhao X, Lu D, Zhou J, *et al*. Changes in soil microbial community and organic carbon fractions under short-term straw return in a rice-wheat cropping system. Soil Tillage Res. 2017;165:121-127.
15. Verma S, Marschner P. Compost effects on microbial biomass and soil P pools as affected by particle size and soil properties. J Soil Sci Plant Nutr. 2013;13(2):313-318.
16. Lehmann J, Rillig MC, Thies J, Masiello CA, Hockaday WC, Crowley D. Biochar effects on soil biota: A review. Soil Biol Biochem. 2011;43(9):1812-1836.
17. Zhang QZ, Dijkstra FA, Liu XR, Wang YD, Huang J, Lu N. Effects of biochar on soil microbial biomass after four years of consecutive application in the North China Plain. *PLoS One*. 2014;9(7):e102062.

18. Blanco-Canqui H, Lal R. Crop residue removal impacts on soil productivity and environmental quality. Crit Rev Plant Sci. 2009;28(3):139-163.
19. Bhattacharyya P, Roy KS, Neogi S, Adhya TK, Rao KS, Manna MC. Effects of rice straw and nitrogen fertilization on greenhouse gas emissions and carbon storage in tropical flooded soil planted with rice. Plant Soil. 2012;357(1-2):143-156.
20. Raiesi F, Salek-Gilani S. The response of soil microbial biomass and enzyme activities to tillage and cropping systems in Iran. Pedosphere. 2018;28(3):422-433.
21. Xu X, Shi Z, Li D, Rey A, Ruan H, Craine JM, *et al*. Soil properties control decomposition of soil organic carbon: Results from data-assimilation analysis. Geoderma. 2016;262:235-242.
22. Wang Q, He T, Wang S, Liu L. Carbon input manipulation affects soil respiration and microbial community composition in a subtropical forest. Agric For Meteorol. 2013;178-179:152-160.
23. Curtin D, Beare MH, Hernandez-Ramirez G. Temperature and moisture effects on microbial biomass and soil organic matter mineralization. Soil Sci Soc Am J. 2012;76(6):2055-2067.
24. Fuentes M, Govaerts B, Gonzalez-Martin I, Hidalgo C, Etchevers J, Sayre KD, *et al*. Fourteen years of applying zero and conventional tillage, crop rotation and residue management systems and its effect on soil quality. Eur J Agron. 2009;30(3):228-237.
25. Poeplau C, Don A. Carbon sequestration in agricultural soils via cultivation of cover crops: A meta-analysis. Agric Ecosyst Environ. 2015;200:33-41.
26. Kong AY, Six J, Bryant DC, Denison RF, van Kessel C. The relationship between carbon input, aggregation, and soil organic carbon stabilization in sustainable cropping systems. Soil Sci Soc Am J. 2005;69(4):1078-1085.
27. Diacono M, Montemurro F. Long-term effects of organic amendments on soil fertility: A review. Agron Sustain Dev. 2010;30(2):401-422.
28. Paustian K, Lehmann J, Ogle S, Reay D, Robertson GP, Smith P. Climate-smart soils. Nature. 2016;532(7597):49-57.