RESEARCH ARTICLE

Impacts of different fertilization practices and climatic conditions on soil carbon to nitrogen ratio and a meta-analysis of their effects

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Generally, unlike chemical fertilizers, organic fertilizers remarkably reduce carbon to nitrogen (C/N) ratio in the soil. Additionally, the influence of climate change on the microbial activities of soil and the decomposition speed of organic material should not be overlooked. Humid climates facilitate microbial proliferation and nitrogen mineralization, thereby decreasing C/N ratio. This research performed a meta-analysis using the observational data extracted from 162 publications. The results indicated that the application of organic fertilizers significantly reduced the soil's C/N ratio and increased the build-up of organic material, particularly in humid and hot climatic conditions. In contrast, the application of chemical fertilizer exhibited weaker effects on C/N ratio and might even increase it under arid or extreme climatic conditions due to nitrogen loss. In addition, climate change profoundly affected soil microbial activity and organic matter decomposition rates with humid climates accelerating microbial activity and nitrogen mineralization, thus decreasing C/N ratio. Consequently, the interplay between fertilization methods and weather patterns was identified as crucial in the fluctuating ratios of C/N in soil. These findings provided a theoretical foundation and practical guidance for future soil management and sustainable agricultural practices.

Keywords: meta-analysis; carbon to nitrogen ratio; fertilization practices; climatic conditions; soil properties; chemical fertilizer; organic fertilizer.

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Introduction

Soil, as one of the most complex ecosystems on earth, is the cornerstone of terrestrial ecological balance. It plays irreplaceable roles in supporting plant growth, regulating water cycles, and acting as a crucial reservoir for carbon and nitrogen [1]. These fundamental functions make soil health and sustainability vital for the stability and prosperity of both natural ecosystems and human societies. In the context of global climate change, with rising temperatures, altered precipitation patterns, and extreme weather events becoming more frequent, soil systems are facing unprecedented pressures. Meanwhile, rapid population growth has led to increased demands for food, driving intensified land-use changes such as deforestation for agriculture and urban expansion, all of which further threaten the integrity of soil ecosystems [2]. Within the realm of soil science, the soil carbon-to-nitrogen (C/N) ratio has emerged as a key ecological indicator, drawing growing attention from researchers worldwide [3]. The C/N ratio, defined as the proportion of organic carbon to nitrogen in a soil sample, is a multifaceted parameter that reflects the composition of soil organic matter, indicates soil fertility levels, and mirrors the activity of soil microbial communities [4]. Fluctuations in this ratio have profound impacts on the physical, chemical, and biological properties of the soil [5]. A higher C/N ratio is generally associated with slower decomposition rates of soil organic matter, which can delay the release of essential nutrients and impede plant uptake [6]. Conversely, a lower C/N ratio often leads to faster organic matter decomposition, increasing nutrient availability and thereby promoting plant growth [7]. These dynamics highlight that the C/N ratio is not only a critical marker of soil quality but also a key factor influencing soil ecological functions [8]. Moreover, extensive research has revealed that the soil C/N ratio is intricately linked to a range of environmental factors, landscape features, vegetation types, and human activities [7]. In arid regions, due to the slow decomposition of organic matter, soils typically exhibit higher C/N ratios, while in humid regions, the rapid breakdown of organic material results in lower ratios [9]. Agricultural practices such as fertilization and tillage have also been shown to significantly alter the soil C/N balance, affecting nutrient cycling and the composition of microbial communities [10]. Additionally, given that soils constitute a major component of the global carbon pool, storing vast amounts of carbon, the study of the C/N ratio has become increasingly important for understanding carbon sequestration and release mechanisms, which are central to addressing global climate change [11]. Maintaining an optimal C/N ratio under changing land-use and soil management practices can enhance soil fertility and improve its resilience to climate change with further implications for improving agricultural productivity and the stability of ecosystem services [12, 13].

Despite the growing body of research on the soil C/N ratio, significant gaps remain. To date, most studies examining the dynamics of the soil C/N ratio have been conducted at individual experimental sites with relatively few extensive studies carried out across multiple sites at larger scales. This limited scope hinders the ability to draw general conclusions about the factors influencing the C/N ratio and its responses to various management practices. Furthermore, the effects of different fertilizer types, their application durations, and varying land-use techniques on the soil C/N ratio can vary significantly, and these variations are not yet fully understood [14]. There is an urgent need to synthesize existing data to clarify these inconsistencies and provide a more comprehensive understanding of how fertilization practices affect the soil C/N ratio across different contexts.

To address these knowledge gaps, this research aimed to systematically evaluate the impact of fertilization on the soil C/N ratio through a meta-analysis of long-term fertilization experiments in China with specific objectives of assessing the effects of different fertilization techniques on the soil C/N ratio, analyzing variations in C/N ratio responses across different soil types under various treatment conditions, and evaluating the temporal changes in the soil C/N ratio relative to the duration of fertilization. This study employed a meta-analysis method for systematic compilation and synthesis of previously published data from long-term fertilization experiments in China. By aggregating data from multiple studies, this approach allowed for a more robust assessment of the overall effects of fertilization on the soil C/N ratio, as well as the identification of patterns and variations across different soil types and fertilization durations. The results of this research would provide a comprehensive understanding of how different fertilization practices affected the soil C/N ratio and offer valuable scientific guidance for sustainable agricultural soil management. It could inform the farmers to optimize soil fertilization techniques, helping to enhance soil fertility, improve agricultural productivity, and strengthen the resilience of soil ecosystems to climate change. Furthermore, by clarifying the temporal dynamics of the soil C/N ratio in response to fertilization, this research would advance the knowledge of soil nutrient cycling and contribute to the development of more effective strategies for mitigating the impacts of climate change at the local level. Ultimately, this work would support the transition towards more sustainable and environmentally friendly agricultural practices, benefiting both food security and ecological stability.

Materials and methods

Data collection

The literature for this research was obtained from China National Knowledge Infrastructure (CNKI) (https://www.cnki.net/), CONNECTED PAPERS (https://www.connectedpapers.com/), Science Direct (https://www.sciencedirect.com/) using the searching keywords of "soil carbon to nitrogen ratio", "ecological stoichiometry", "soil carbon pool" to identify relevant researches up to 2025 on how various fertilization techniques impacted the soil C/N ratio. To eliminate publication bias during selection process, the initially retrieved literature was filtered according to the following criteria, which included the experiment should be conducted within the territory of China and encompass a baseline treatment (excluding fertilization) along with various other fertilization control methods (like chemical, organic, straw fertilization, *etc*.), while maintaining uniformity in all other experimental scenarios throughout the various treatments; the studies should base on field trials with a minimum duration of 2 years, and soil C/N ratio data should be obtained for surface soil (0 – 20 cm); when data spanning several years were accessible for an identical experimental location, consideration was given solely to the latest data, and, if parameters for multiple soil depths were included in a study, the average value across the entire soil profile was calculated. The research reports that met the above criteria were categorized to establish a database in this study. The mean (AVG), standard deviation (SD), and sample size (n) of soil C/N ratio measurements were systematically organized. For the statistical data demonstrated in figures within some publications, GetData Graph Digitizer (version 2.26) (https://getdata-graph-digitizer.software.informer.com/download/) was applied to digitize the images. In addition to key indicators such as soil carbon pool, soil nitrogen pool, vegetation carbon pool, and soil C/N pool, the background details of the literature such as authors and publication year, sample replication number, experimental methods and durations, nitrogen fertilization details including application rate and form, land use type, sampling site information like climate type, average yearly temperature, yearly rainfall, latitude, and longitude, and physicochemical properties of soil (such as soil carbon and nitrogen contents, soil temperature, pH, and moisture content were extracted. Under these conditions, 22 valid articles and 486 valid observations were collected.

Meta-analysis

Data from included research works contained sample mean ($\overline{X}$), sample size (n), and sample standard deviation (SD). If standard error (SE) was provided in the literature, the following conversion between SD and SE was applied.

$$SD = SE \times \sqrt{n} \quad (1)$$

The response ratio (RR) was selected as the benchmark for assessing effect size to reduce discrepancies in experimental measures among various studies and enable a straightforward comparison of treatment impacts and was calculated below.

$$\ln (RR) = \ln \left(\frac{\overline{X}_t}{\overline{X}_c}\right) \quad (2)$$

where X_t and X_c were the mean figures for the experimental and control cohorts in that order. The variance was calculated as follows.

$$V = \frac{SD_t^2}{n_t \overline{X}_t^2} + \frac{SD_c^2}{n_c \overline{X}_c^2} \quad (3)$$

where n_t and n_c were the sizes of the samples. SD_t and SD_c were the standard deviations corresponding to the treatment and control groups, respectively. To obtain objective results, weighting factor (Wij), overall effect size (RR++), standard error (S(RR++)), and 95% confidence interval (CI) were calculated as follows.

$$W_{ij}=\frac{1}{V} \tag{4}$$

$$RR++=\frac{\sum_{i=1}^{m}\sum_{j=1}^{k}W_{ij}RR_{ij}}{\sum_{i=1}^{m}\sum_{j=1}^{k}W_{ij}} \tag{5}$$

$$S(RR++)=\sqrt{\frac{1}{\sum_{i=1}^{m}\sum_{j=1}^{k}W_{ij}}} \tag{6}$$

$$95\%CI=RR++\pm 1.96\times S(RR++) \tag{7}$$

where i and j were the i^{th} and j^{th} treatments. m and k were the count of comparison groups and their respective intra-group comparisons. A significant effect of *P* less than 0.05 was indicated if 95% CI did not cross zero.

Data retrieved, originating from various independent research efforts, underwent analysis *via* R software (https://www.r-project.org/). Considering the ongoing presence of outcome indicators in academic literature, the standardized mean difference (SMD) was employed to represent the effect's extent with its 95% confidence interval being calculated. Meta-analyses were performed using the meta-cont feature within R's meta package. The diversity across various studies was investigated through the application of Q and I^2 statistics. A fixed-effects model was applied when I^2 fell below 50%, while a random-effects model was used when I^2 surpassed 50%. The assessment of publication bias was conducted through funnel plots, where a *P* value less than 0.05 signified a notable bias. Review Manager 5.4 (https://review-manager.software.informer.com/5.4/) was applied for risk assessment and the screening flowchart was generated (Figure 1).

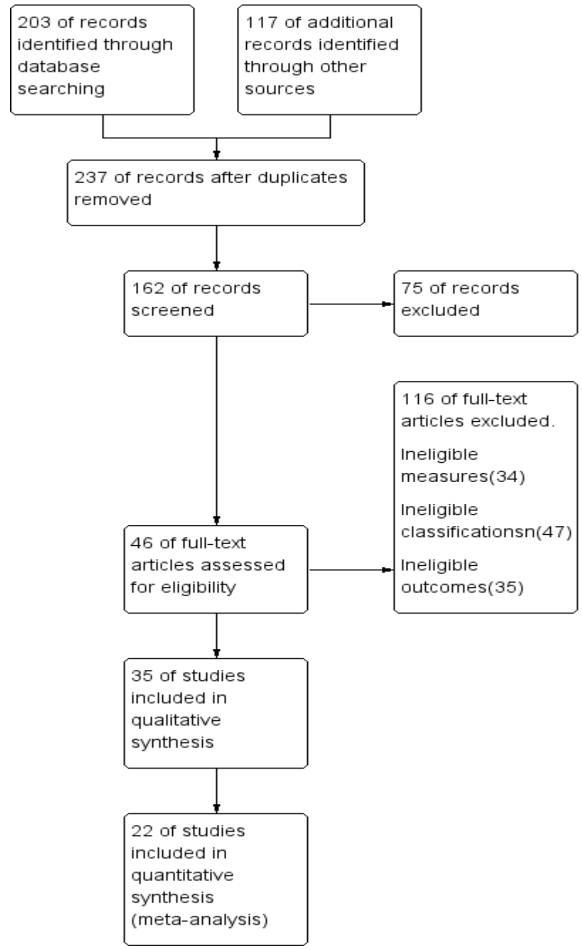

Figure 1. Article screening flowchart.

Results

Risk assessment and the distribution of experimental sites

The results of risk assessment were shown in Figure 2, and the distribution of the experimental sites were shown in Figure 3.

Soil C/N ratio under various fertilization treatments

The impacts of diverse fertilization methods on nitrogen-to-phosphorus (N/P) ratios and soil C/N ratios, as well as nitrogen application rates on both crop yield and soil C/N ratio demonstrated statistically significant difference ($P < 0.05$). For N/P ratios, when considering crop yield, the weighted mean effect sizes for ratios of 21:1, 15:1, 9:1, and 3:1 were 0.289, 0.27, 0.136, and

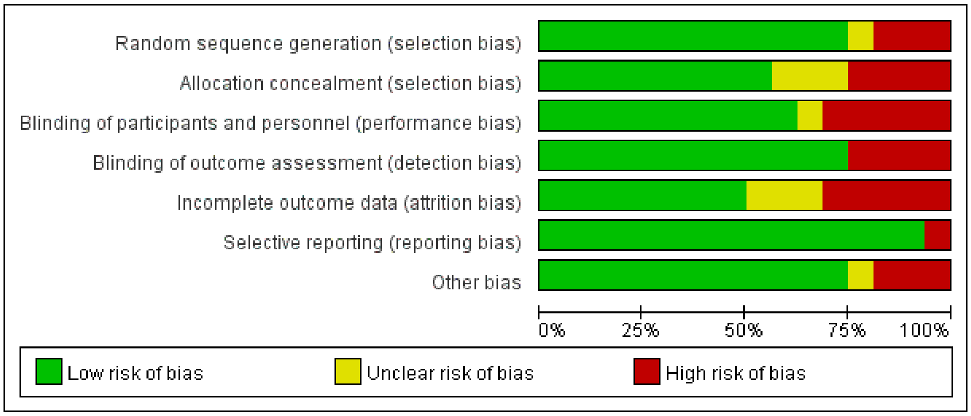

Figure 2. Risk assessment results.

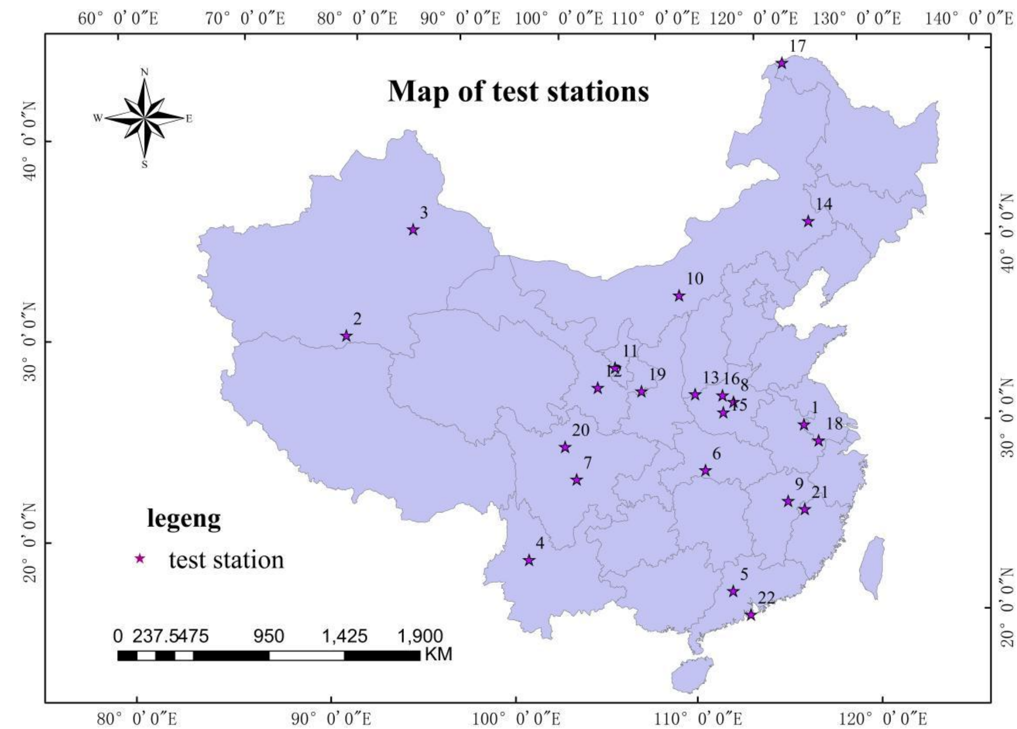

Figure 3. Map of the distribution of experimental sites.

0.112, respectively, and all four ratios exhibited statistically significant beneficial impacts compared to the control group (P < 0.05). In terms of the soil C/N ratio under the same N/P ratios, the weighted mean effect sizes were -0.209, -0.251, -0.052, and -0.175, respectively, and none of them demonstrated statistically significant difference compared to the control group. For soil C/N ratios and their impact on crop yield, the weighted mean effect sizes for ratios of 26:1, 24:1, 16:1, and 8:1 were 0.106, 0.02, 0.036, and 0.048, respectively. Only the 26:1 ratio showed a statistically significant positive effect (P < 0.05), while the others had non-significant impacts. Regarding the effect of these C/N ratios on the soil C/N ratio itself, the

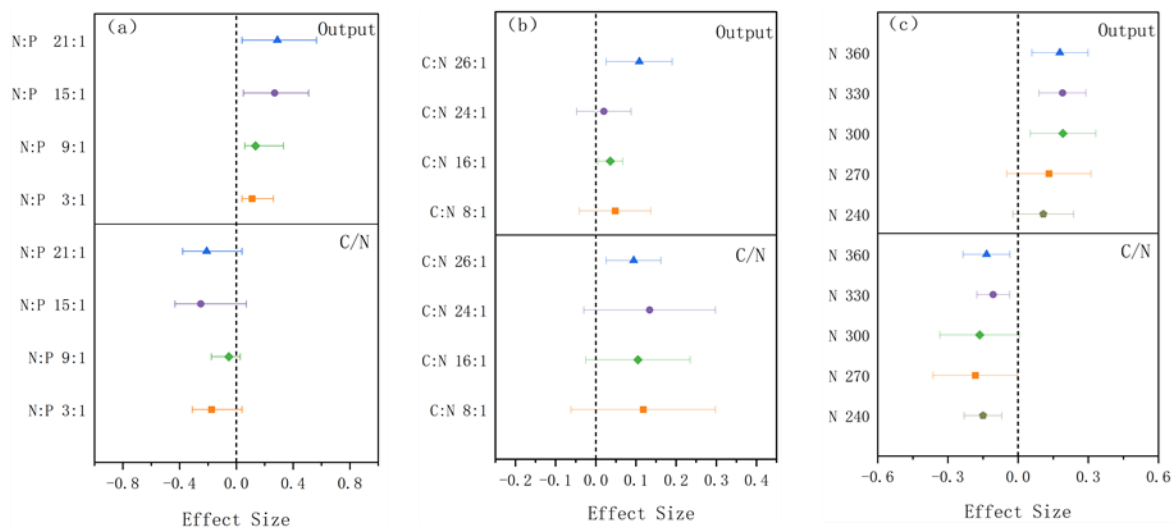

Figure 4. Effects of soil yield and C/N ratio under nitrogen and phosphorus fertilization, carbon fertilizer, and nitrogen fertilizer ($P < 0.05$). (**a**) Effects of different N/P ratios on soil C/N and crop yield. (**b**) Effects of different C/N ratios on soil C/N and crop yield. (**c**) Effects values of different nitrogen application rates on soil C/N and crop yield.

weighted mean effect sizes were 0.094, 0.134, 0.105, and 0.118, respectively, with only the 36:1 ratio exhibiting a statistically significant positive effect ($P < 0.05$). When it came to nitrogen application rates and crop yield, the weighted mean effect sizes for rates of 360, 330, 300, 270, and 240 kg/hm² were 0.179, 0.19, 0.192, 0.132, and 0.108, respectively. Significant beneficial effects were observed at the three highest rates ($P < 0.05$), while the lower rates did not reach statistical significance. For the impact of these nitrogen application rates on the soil C/N ratio, the weighted mean effect sizes were -0.135, -0.106, -0.164, -0.183, and -0.15, respectively, with significant effects at 360, 330, and 240 kg/hm² ($P < 0.05$) (Figure 4). By quantifying the percentage increase in crop yield associated with each fertilization method, for N/P ratios, the yield increased 33.5% (21:1), 31% (15:1), 14.5% (9:1), and 11.8% (3:1) with the 21:1 ratio yielding the largest increase. The percentage increases in yield were 20.7% (26:1), 2.3% (24:1), 3.7% (16:1), and 5% (8:1) with the 26:1 ratio showing the strongest effect. The percentage yield increases were 46.2% (360 kg/hm²), 47.7% (330 kg/hm²), 33.8% (300 kg/hm²), 26.1% (270 kg/hm²), and 23% (240 kg/hm²) with the highest yields observed at 330 kg/hm² (Figure 5).

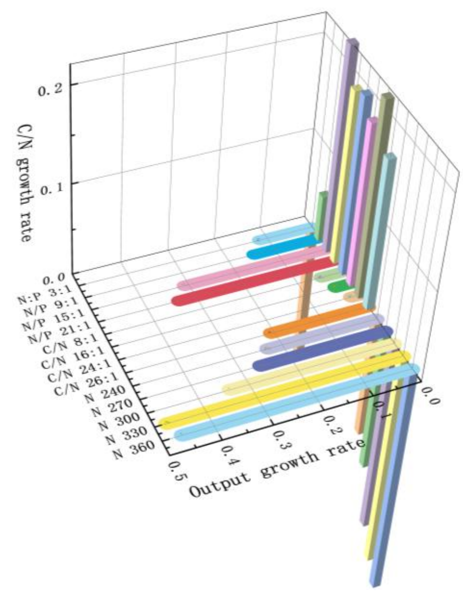

Figure 5. Variations of C/N and yield after the application of different ratios of fertilizers.

The most significant enhancement in crop yield was obtained at 330 kg/hm² nitrogen application rate followed by 360 kg/hm². A significant enhancement in the soil C/N ratio was noted with a 15:1 N/P ratio followed closely by a 24:1 C/N ratio. Despite fertilization boosting crop production, its impact on the soil C/N ratio was somewhat restricted, possibly owing to the soil's intrinsic characteristics and the prolonged consequences of fertilization [15]. Increasing nitrogen application rates effectively boosted crop yield, but yield-enhancing effect gradually diminished once nitrogen input exceeded a critical threshold. Noticeable variances were observed in how various fertilization methods impacted crop production and the C/N ratio in the soil. Appropriate N/P ratios and nitrogen application rates were found to be able to substantially improve crop production, while their influences on soil C/N ratio remained comparatively minor [16].

Soil C/N ratio under different climatic conditions
Meta-analysis results revealed distinct soil C/N ratios across different climatic zones. Weighted mean effect sizes for different climates showed -0.297 for mid-subtropical monsoon climate, -0.067 for plateau mountain climate, 0.136 for cold-temperate continental monsoon climate, -0.373 for north-subtropical continental monsoon climate, and 0.089 for warm-temperate climate. Compared to national average soil C/N ratio, mid-subtropical monsoon, plateau mountain, and north-subtropical continental monsoon climates presented non-significant effects, whereas cold-temperate continental monsoon and warm-temperate climates showed significant positive effects ($P < 0.05$) (Figure 6). The soil C/N ratios in mid-subtropical monsoon, plateau mountain, and north-subtropical continental monsoon climates were reduced by 25.7%, 13%, and 29.4%, respectively, relative to the national average. However, soil C/N ratios in cold-temperate continental monsoon and warm-temperate climates increased by 14.7% and 9.5%, respectively. Analysis of the obtained data suggested that, in warm and humid climates, high biodiversity and vigorous plant growth promoted rapid decomposition of organic matter, which accelerated soil organic matter accumulation, typically resulting in lower C/N ratios [17], indicating relatively higher nitrogen availability that favored plant growth [18]. As latitude increased into temperate zones with distinct seasonal variations, soil C/N ratios generally increased. Prolonged plant growth cycles in these regions combined with slower decomposition of leaf litter and plant residues decreased soil organic matter accumulation rate and nitrogen availability [19]. In the frigid regions of high latitudes, the rapid breakdown of organic material caused by cooler temperatures led to markedly increased C/N ratios [20], which could be attributed to limited plant growth and organic matter accumulation under cold weather conditions and short growing seasons, which were further exacerbated by decreased soil nitrogen availability. Similar findings were reported by Yin *et al*. in 2025 [21]. Soil C/N ratios exhibited relatively stable altitudinal trends and maintained strong stoichiometric homeostasis. Warming in low-latitude regions reduced carbon storage, whereas colder high-latitude regions showed enhanced carbon retention [22, 23].

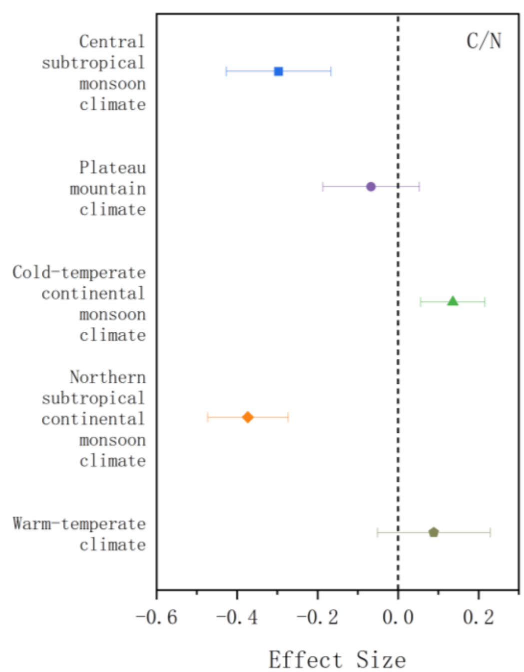

Figure 6. Effect values of soil C/N ratio in different climate types.

Discussion

Soil C/N ratio and its effects under different fertilization treatments
Utilizing nitrogen and phosphorus fertilizers in a 21:1 proportion led to a soil C/N ratio of 8.94 and

a notable rise in crop production, demonstrating the effectiveness of this fertilization approach in boosting plant development. Nitrogen fertilization provided abundant nitrogen sources for plants, promoting the synthesis of protein and chlorophyll, thereby improving photosynthetic efficiency and growth rate [24, 25]. Meanwhile, phosphorus fertilization supported root development and energy transfer, further boosting nutrient uptake capacity [26]. Lower soil C/N ratios indicated nitrogen enrichment, which stimulated microbial activity. The rapid multiplication of microbes and metabolic activities hastened the breakdown of organic substances, leading to an increased release of nutrients available to plants [27, 28]. Furthermore, achieving the ideal N/P ratio enhanced fertilizer use efficiency, reduced nutrient leakage, and maintained a balanced nutrient distribution throughout plant development. The N/P ratio of 21:1 not only optimized soil nutrient conditions but also enhanced microbial activity, maximizing crop productivity. For the treatment with a C/N ratio of 26:1, soil C/N ratio was reduced to 11.75 accompanied by a significant improvement in yield, indicating the critical role of this fertilization approach in crop growth promotion. Soil organic carbon was enriched by carbon fertilization, stimulating microbial proliferation and activity. Microbial metabolism accelerated the decomposition of organic matter, increasing nutrient availability for plants [29]. Nitrogen fertilization supplied essential nitrogen for the growth and development of plants, particularly protein synthesis and chlorophyll formation [30]. Decrease of soil C/N ratio to 11.75 reflected nitrogen sufficiency, which further enhanced microbial growth and nutrient cycling efficiency. In addition, balanced C/N ratio optimized soil nutrient structure and decreased nutrient loss [31]. This research represented the first systematic integration of multi-source observational data among different climatic zones and soil types in China. Using meta-analysis, the combined effects of fertilization practices and climatic conditions on soil C/N ratios were measured. Compared to previous single-site or regional research works, this large-scale data synthesis strengthened the universality and reliability of the conclusions, addressing a critical research gap in cross-regional, multi-factor comprehensive analysis.

Soil C/N ratio for different climate types

The research revealed significant variations in soil C/N ratios across various climatic zones and their ecosystem impacts. Compared to the national average, mid-subtropical monsoon, plateau mountain, and north-subtropical continental monsoon climates presented significantly lower soil C/N ratios, while cold-temperate continental monsoon and warm-temperate climates demonstrated significant positive effects. These findings were in line with previously established relationships between climate and soil characteristics [32, 33]. In warm, humid climates characterized by high biodiversity and vigorous plant growth, rapid organic matter accumulation resulted in relatively low C/N ratios [34], which reflected higher nitrogen availability, supporting plant growth and ecosystem health. As latitude increased into temperate zones with pronounced seasonal variations, soil C/N ratios typically increased [35], which could be attributed to longer plant growth cycles and slower decomposition of leaf litter and residues, decreasing organic matter accumulation and nitrogen availability [36]. In high-latitude cold climates, extremely slow decomposition of organic matter under low temperatures resulted in elevated C/N ratios. Limited plant growth and organic input due to short growing seasons combined with lower nitrogen availability further amplified this trend. The research further underscored the possible effects of climate change on soil C/N ratios. Rising worldwide temperatures could diminish carbon sequestration in low-latitude zones but amplifying it in high-latitude zones [37-39]. Such shifts could profoundly alter the chemistry and ecosystem functionality of soil, underscoring the need for long-term research on climate-driven C/N ratio changes to inform ecological conservation and sustainable management. This research elucidated why organic fertilization was more effective in humid climates. Moisture-enhanced microbial activity and nitrogen mineralization accelerated organic matter decomposition, significantly decreasing C/N ratios. In contrast, application of synthetic fertilizer in arid conditions might exacerbate nitrogen loss and elevate C/N ratios. This breakthrough transcended previous research results that focused solely on single factors either fertilization or climate, establishing for the first time the regulatory role of climate in shaping fertilization outcomes. These insights provided a theoretical foundation for region-specific fertilization strategies. In cold-temperate and warm-temperate zones, soil C/N ratios significantly increased in high-latitude cold regions but decreased in low-latitude humid areas [40]. Future research should prioritize exploring the intricate relationship between soil C/N ratios and climate change, particularly among diverse climatic zones and ecosystems. As global temperature increases, carbon storage in low-latitude regions may decrease, while high-latitude regions may experience an increase. Such shifts could profoundly change the chemical properties and ecosystem functionality of soil. As a result, comprehensive field research and monitoring efforts play a vital role in evaluating the impact of fertilization practices and management strategies on the C/N ratios in soil.

In addition, integrating remote sensing technologies and geographic information systems (GIS) could enable comprehensive analyses of soil nutrient dynamics and their interactions with climatic factors. Adopting this method would aid in crafting precise agricultural management tactics to enhance soil vitality and crop yield. Concurrently, studies ought to concentrate on changes in soil microbial populations and their functions in nutrient recycling, clarifying the links between microbial actions and soil C/N ratios. Considering the complexity of global climate change, interdisciplinary collaboration will be essential to advance this field. Merging insights from ecology, soil science, climate science, and agricultural science would enhance the comprehension of soil nutrient dynamics, laying a solid scientific groundwork for sustainable farming and ecological preservation.

Acknowledgements

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References

1. Luo L, Wang JX, Lv JT, Liu ZG, Sun TR, Yang Y, *et al*. 2023. Carbon sequestration strategies in soil using biochar: Advances, challenges, and opportunities. Environ Sci Technol. 57(31):11357-11372.
2. Jin J, Ye LX, Wang Z, Fu WJ, Lin HP, Wu JS. 2023. Abandonment of Moso Bamboo (*Phyllostachys pubescens*) plantations could lead to stand structural complications and changes in soil properties and microbial community. J Soil Sci Plant Nutr. 23(4):6670-6680.
3. Hao ZG, Zhao YF, Wang X, Wu JH, Jiang SL, Xiao JJ, *et al*. 2021. Thresholds in aridity and soil carbon-to-nitrogen ratio govern the accumulation of soil microbial residues. Commun Earth Environ. 2(1):236.
4. Larson J, Kuglerová L, Högberg P, Laudon H. 2024. Variability in soil carbon-to-nitrogen ratios explained by environmental conditions in a boreal catchment. For Ecol Manag. 568:122108.
5. He Y, Zhang Y, Lin S, Du FF, Dong JQ, Zhi YY, *et al*. 2024. Spatial heterogeneity of SOC, STN and C:N and their key influencing factors in main *Torreya grandis* production areas. Environ Sci. 45(9):5441-5450.
6. Getino-Álvarez M, San-Martin R, Pretzsch H, Pach M, Bravo F, Turrión MB. 2023. Assessing soil C stock and C to N ratio of soil organic matter under mixed pine-beech forests at different scales. Eur J For Res. 142(5):1081-1098.
7. Jia XD, Wu LM, Ren JM, Peng XY, Lv HY. 2024. Response of carbon, nitrogen, and phosphorus in leaves of different life forms to altitude and soil factors in Tianshan wild fruit forest. Front Ecol Evol. 12:1368185.
8. Yang X, Bao YW, Li BW, Wang RX, Sun C, Ma DH, *et al*. 2024. Effects of fertilization applications on soil aggregate organic carbon content and assessment of their influencing factors: A meta-analysis. Catena. 242:108135.
9. Chagas JKM, de Figueiredo CC, Ramos MLG. 2022. Biochar increases soil carbon pools: Evidence from a global meta-analysis. J Environ Manage. 305:114403.

10. Bai XX, Tang J, Wang W, Ma JM, Shi J, Ren W. 2023. Organic amendment effects on cropland soil organic carbon and its implications: A global synthesis. Catena. 231:107343.
11. He C, Chen Z, Qiu KY, Chen JS, Bohoussou YN, Dang YP, *et al*. 2023. Effects of conservation agriculture on carbon mineralization: A global meta-analysis. Soil Tillage Res. 229:105685.
12. Lu ZX, Yang M, Li B. 2023. Altitudinal gradient distribution patterns of seed plants in the Himalayas and their influencing factors. J Appl Ecol. 34(7):1787-1796.
13. Chen SX, Huang J, Guo RJ, Ma HL, Guo JJ, Ling N, *et al*. 2025. Soil net carbon balance depends on soil C:N:P stoichiometry. Soil Tillage Res. 245:106298.
14. Liao CJ, Wang Y, Wang MH, Li Y, Wu JS. 2025. Soil microbial biomass P status affecting P runoff loss from paddy fields under different agricultural practices. Sci Total Environ. 967:178828.
15. Fan X, Gao YH, Wang YF, Wen ZD, Wang RJ, Wu B, *et al*. 2025. Mechanisms of carbon and nitrogen distribution in soil aggregates in response to soil conditioners. Sci Rep. 15(1):4962.
16. Spohn M, Stendahl J. 2021. Carbon, nitrogen, and phosphorus stoichiometry of organic matter in Swedish forest soils and its relationship with climate, tree species, and soil texture. Biogeosci Discuss. 2021:1-23.
17. Hazarika S, Thakuria D, Sakthivel T. 2023. Combined effect of land use change, long-term soil management and orchard age on variability of soil quality of fruit orchards under monsoon climate. Environ Prog Sustain Energy. 42(2):e14003.
18. Spohn M, Stendahl J. 2024. Soil carbon and nitrogen contents in forest soils are related to soil texture in interaction with pH and metal cations. Geoderma. 441:116746.
19. Dang K, Liang HF, Guo SQ, Fan ZH, Li HB, Ma MS, *et al*. 2025. Adaptive regulation of microbial community characteristics in response to nutrient limitations under mulching practices across distinct climate zones. Soil Tillage Res. 248:106465.
20. Wu WA, Feng JG, Wang XD, Xiao JT, Qin WK, Zhu B. 2025. The response of soil microbial necromass carbon to global change: A global meta-analysis. Catena. 249:108693.
21. Yin S, Chen XL, Piton G, Terrer C, Zhou ZH, De Deyn GB, *et al*. 2025. The complementarity hypothesis reversed: Root trait similarity in species mixtures promotes soil organic carbon in agroecosystems. Soil Biol Biochem. 203:109736.
22. Zhang JH, Zhao N, Liu CC, Yang H, Li ML, Yu GR, *et al*. 2018. C:N:P stoichiometry in China's forests: From organs to ecosystems. Funct Ecol. 32(1):50-60.
23. Lu JN, Feng S, Wang SK, Zhang BL, Ning ZY, Wang RX, *et al*. 2023. Patterns and driving mechanism of soil organic carbon, nitrogen, and phosphorus stoichiometry across northern China's desert-grassland transition zone. Catena. 220:106695.
24. Cao HB, Xie JY, Hong J, Wang X, Hu W, Hong JP. 2021. Organic matter fractions within macroaggregates in response to long-term fertilization in calcareous soil after reclamation. J Integr Agric. 20(6):1636-1648.
25. Li JH, Han YW, Ye LF, Deng HD, Gao, XT, Soromotin AV, *et al*. 2023. Effects of nitrogen and phosphorus fertilization on soil organic matter priming and net carbon balance in alpine meadows. Land Degrad Dev. 34(9):2681-2692.
26. Rezakhani L, Motesharezadeh B, Tehrani MM, Etesami H, Hosseini HM. 2022. The effect of silicon fertilization and phosphate-solubilizing bacteria on chemical forms of silicon and phosphorus uptake by wheat plant in a calcareous soil. Plant Soil. 477(1):259-280.
27. Bhattacharyya R, Rabbi SMF, Zhang Y, Young IM, Jones AR, Dennies PG, *et al*. 2021. Soil organic carbon is significantly associated with the pore geometry, microbial diversity and enzyme activity of the macro-aggregates under different land uses. Sci Total Environ. 778:146286.
28. Yang JY, Wang ZT, Chang Q, Liu ZP, Jiang Q, Fan XL, *et al*. 2025. Temperature effects on microbial carbon use efficiency and priming effects in soils under vegetation restoration. Catena. 249:108632.
29. Lazcano C, Zhu-Barker X, Decock C. 2021. Effects of organic fertilizers on the soil microorganisms responsible for N_2O emissions: A review. Microorganisms. 9(5):983.
30. Yang Y, Chen XL, Liu LX, Li T, Dou YX, Qiao JB, *et al*. 2022. Nitrogen fertilization weakens the linkage between soil carbon and microbial diversity: A global meta-analysis. Glob Change Biol. 28(21):6446-6461.
31. Ye CL, Li N, Gui J, Zhu MY, Zhou Y, Li DM, *et al*. 2024. Long-term organic amendments increase the vulnerability of microbial respiration to environmental changes: Evidence from field and laboratory studies. Sci Total Environ. 920:170979.
32. Lu JN, Feng S, Wang SK, Zhang BL, Ning ZY, Wang RX, *et al*. 2023. Patterns and driving mechanism of soil organic carbon, nitrogen, and phosphorus stoichiometry across northern China's desert-grassland transition zone. Catena. 220:106695.
33. Wang XH, Li SY, Zhu B, Homyak PM, Chen GS, Yao XD, *et al*. 2023. Long-term nitrogen deposition inhibits soil priming effects by enhancing phosphorus limitation in a subtropical forest. Glob Change Biol. 29(14):4081-4093.
34. Hein CJ, Usman M, Eglinton TI, Haghipour N, Galy VV. 2020. Millennial-scale hydroclimate control of tropical soil carbon storage. Nature. 581(7806):63-66.
35. Li XJ, Feng JG, Zhang QF, Zhu B. 2023. Warming inhibits the priming effect of soil organic carbon mineralization: A meta-analysis. Sci Total Environ. 904:166170.
36. Clark P, D'Amato A, Evans KS, Schaberg PG. 2022. Ecological memory and regional context influence performance of adaptation plantings in northeastern US temperate forests. J Appl Ecol. 59(1):314-329.
37. Gelybó G, Barcza Z, Dencső M, Potyó I, Kása I, Horel Á. *et al*. 2022. Effect of tillage and crop type on soil respiration in a long-term field experiment on chernozem soil under temperate climate. Soil Tillage Res. 216:105239.
38. Sünnemann M, Siebert J, Reitz T, Schädler M, Yin R, Eisenhauer N. 2021. Combined effects of land-use type and climate change on soil microbial activity and invertebrate decomposer activity. Agric Ecosyst Environ. 318:107490.
39. Horel Á, Zsigmond T, Farkas C, Gelybó G, Tóth E, Kern A, *et al*. 2022. Climate change alters soil water dynamics under different land use types. Sustainability. 14(7):3908.
40. Rocci KS, Lavallee JM, Stewart CE, Cotrufo MF. 2021. Soil organic carbon response to global environmental change depends on its distribution between mineral-associated and

particulate organic matter: A meta-analysis. Sci Total Environ. 793:148569.