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Review

Meta-Analysis of the Effects of Different Farming Measures on Greenhouse Gas Emissions from Farmland in China

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Abstract: Reducing greenhouse gas (GHG) emissions from agricultural fields is crucial for mitigating climate change and promoting sustainable agriculture. This study conducted a meta-analysis of 82 domestic experimental studies to assess the effects of fertilization, tillage, and straw return on CH_4, CO_2, and N_2O emissions across different regions in China. The key findings include: fertilization measures: split fertilization increased CH_4 and N_2O emissions, whereas a single application had the strongest impact on CO_2 emissions. The application of carbon alone or in combination with NPK reduced GHG emissions, while the combination of nitrogen and farmyard manure significantly increased CH_4 and CO_2 emissions. Tillage measures: tillage generally reduced CH_4 and CO_2 emissions but increased N_2O emissions. No-tillage effectively suppressed CH_4 emissions, while rotary tillage significantly reduced CO_2 emissions. Straw return: straw returning through rotary tillage led to the highest increase in CH_4 and CO_2 emissions, whereas direct straw return most notably enhanced N_2O emissions. This study provides insights into optimizing agricultural practices to mitigate GHG emissions and offers guidance for sustainable and low-carbon agricultural development.

Keywords: greenhouse gas; fertilization; tillage; straw returning; meta-analysis

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Academic Editor: Xin Zhao

Received: 7 January 2025
Revised: 9 February 2025
Accepted: 10 February 2025
Published: 17 February 2025

Citation: Wang, S.; Wei, X.; Luan, X.; Li, J.; Yang, Y.; Pang, J.; Gao, F. Meta-Analysis of the Effects of Different Farming Measures on Greenhouse Gas Emissions from Farmland in China. *Land* **2025**, *14*, 413. https://doi.org/10.3390/land14020413

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1. Introduction

Global warming, driven by greenhouse gas emissions, is a critical global concern, primarily caused by human activities. The Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) highlights agriculture as a substantial source of these emissions. As one of the world's leading agricultural nations [1], China faces the challenge of reducing emissions from agriculture, particularly methane (CH_4), nitrous oxide (N_2O), and carbon dioxide (CO_2), which are the primary greenhouse gases produced by this sector. The agricultural sector in China is responsible for a significant share of national greenhouse gas emissions, with livestock, rice paddies, and fertilization practices contributing heavily to CH_4 and N_2O emissions. Despite efforts to adopt more sustainable farming practices, emissions from this sector have been steadily increasing due to factors such as extensive fertilizer use and the expansion of rice cultivation, which exacerbate GHG emissions. Farmland CO_2 primarily originates from the respiration of soil microorganisms, as well as from organic matter decomposition and microbial processes in the soil, and farmland N_2O comes

from the nitrification and denitrification of nitrifying and denitrifying bacteria during their growth and reproduction [2,3]. Long-term anaerobic conditions provide a suitable growth environment for methanogenic bacteria, resulting in the release of large amounts of CH_4 into the atmosphere [4]. The accumulation of these greenhouse gases contributes to global warming by causing the Earth's surface temperature to increase [5]. Therefore, minimizing GHG emissions from agricultural systems is crucial for mitigating the greenhouse effect, ensuring ecological sustainability, and maintaining food production security.

Greenhouse gas emissions from farmland are closely linked to field management practices, including fertilization, tillage, and straw returning. Among these, fertilization is a critical factor in agroecosystems [6]. China is currently the largest consumer of chemical fertilizers in agricultural production globally [7]. Straw returning, a prevalent method of straw utilization in agricultural measure, can substantially impact the soil carbon and nitrogen balance, thereby increasing greenhouse gas emissions from farmland [8]. Zhang et al. [9] emphasized that the greenhouse gas emissions resulting from straw returning should not be overlooked. Zhou et al. [10] noted that straw returning increases the substrate for microbial activity, thereby promoting N_2O emissions from soil. However, other studies have shown that straw returning can reduce N_2O emissions, depending on soil type, nitrogen fertilizer application, and straw management measures [11]. A global data analysis by Liu et al. [12] highlighted that straw returning increased CH_4 emissions by 110.7%, a value derived from studies conducted under specific conditions, including certain soil types and climate conditions. In contrast, Gao et al. [13] found that applying crop residues reduced CH_4 emissions from paddy fields, likely due to differences in soil moisture management.

Tillage measures also play a crucial role in regulating the environment for organic matter decomposition in the soil, affecting factors such as soil respiration and soil–straw interactions, which in turn influence greenhouse gas emissions [14]. Abdalla et al. [15] found that tillage substantially affects soil carbon emissions and is a key agronomic activity responsible for organic carbon loss from soil. Studies by Pelster et al. [16] and Bordoloi et al. [17] observed that rotary tillage (RT) and no-tillage (NT) treatments increased N_2O emissions in maize and rice cropping systems, respectively. Conversely, Nawaz et al. [18] found that NT treatment reduced CO_2 emissions by improving the soil properties.

While various factors regulate greenhouse gas emissions from farmland, most current research focuses on the impact of a single crop or farming measure, such as fertilization or tillage, with fewer studies providing a comprehensive evaluation of the effects of different farming measures on these emissions.

Meta-analysis was initially applied primarily in the field of medicine but has since been widely adopted across various research disciplines. In agroforestry and ecological research, meta-analysis offers a systematic and statistically rigorous method to integrate data and compare studies [19]. It is particularly useful for determining the effects of changes in various factors on study indicators and understanding how these effects manifest. Since 2010, numerous studies have employed meta-analysis to evaluate the impact of different agricultural measures on greenhouse gas emissions from farmland. For example, Zheng et al. [20] conducted a meta-analysis of global data and found that the application of nitrogen fertilizers substantially increased N_2O emissions. Similarly, Li et al. [21] used meta-analysis to investigate the effects of tillage measures on N_2O emissions, revealing that these emissions increased systematically with higher soil moisture and straw inputs, while decreasing with reduced fertilization under certain tillage regimes.

This study hypothesizes that different agricultural practices, including fertilization, tillage, and straw returning, exert distinct and significant influences on greenhouse gas emissions (CH_4, CO_2, and N_2O) from farmland in China. To test this hypothesis, the study aims to quantitatively and comprehensively evaluate the effects of these agricultural

measures on greenhouse gas emissions, identify key influencing factors, and provide actionable insights for developing region-specific agricultural management strategies to mitigate emissions.

2. Materials and Methods

2.1. Data Collection and Filtering

In this study, meta-analysis was employed to analyze and evaluate the emission characteristics of greenhouse gases (CH_4, CO_2, N_2O) from farmland and to assess the various influencing factors. The data were primarily sourced from published research articles on farmland greenhouse gas emissions in China, including both domestic and international studies. Literature published before 1 June 2024 was retrieved using keywords such as 'greenhouse gas', 'nitrous oxide or N_2O', 'methane or CH_4', and 'carbon dioxide or CO_2'. The sources included various Chinese and English databases, such as CNKI (China National Knowledge Infrastructure), Web of Science, and Google Scholar.

To further exclude unqualified literature, reduce publication bias in the meta-analysis results [22], ensure statistical significance, and improve the accuracy of the conclusions, the following criteria were established for selecting the literature in this study: (i) the study area must be located in mainland China, with clearly defined locations and experiment start and end dates; (ii) the experiment must be consistent in conditions and conducted in the field, excluding monoculture experiments; (iii) the experimental design must include both a control group and an experimental group with consistent treatments; (iv) replicated experiments must be used; (v) the experiment must span at least one full growing season of the crop (from planting to harvest); (vi) cumulative gas emissions must be directly provided or calculable from gas emission fluxes and the number of crop growth periods; (vii) the reported data must include at least one of the cumulative emissions of CH_4, CO_2, or N_2O, provided in numerical or graphical form along with mean values, standard deviation (or error), and sample size (number of replicates). Based on these criteria, this study finally screened 82 valid experimental research articles for inclusion in the meta-analysis. Of these, 34 articles focused on fertilization measures, 22 on tillage measures, and 32 on straw returning in relation to CH_4 emissions; 24 on fertilization measures, 9 on tillage measures, and 17 on straw returning in relation to CO_2 emissions; and 45, 27, and 37 articles on fertilization, tillage, and straw returning in relation to N_2O emissions, respectively. The technical roadmap of this study is shown in Figure 1.

2.2. Data Classification

Greenhouse gas emissions from farmland are influenced by various factors. This study focuses on analyzing the effects of three specific treatments: fertilization measures, tillage measures, and straw returning on greenhouse gas emissions from farmland. The control group for the fertilization measures is no fertilizer, the control group for the tillage measures is traditional tillage, and the control group for straw return is no straw return. The fertilization subgroup includes factors such as fertilization times, types of fertilizers, and crop types. The tillage subgroup considers different tillage methods and associated crops. The straw returning subgroup examines the methods of straw returning, types of straw, and crops involved. The data classification is presented in Table 1.

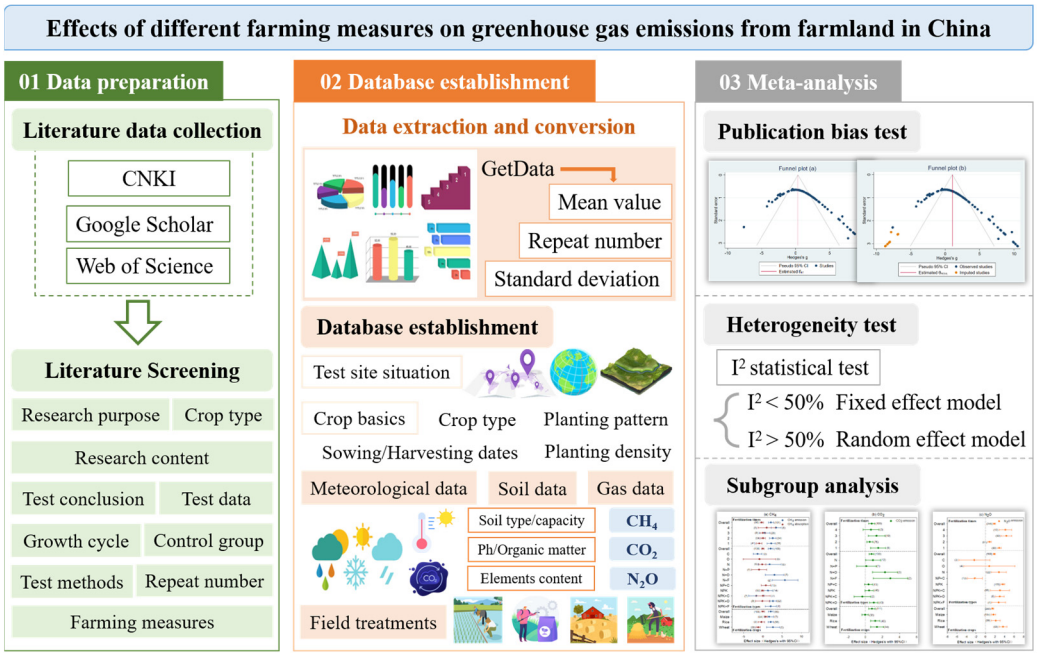

Figure 1. Technical roadmap.

Table 1. Data classification.

Treatment	Subgroup	Subgroup Content
Fertilization	Fertilization times	Once, twice, 3 times, 4 times
	Fertilizer types	C, O, N, N + P, N + O, N + F, NP + C, NPK, NPK + C, NPK + O, NPK + F
	Fertilization crops	Wheat, rice, maize
Tillage measures	Tillage methods	Rotary tillage (RT), no tillage (NT), deep tillage (DT)
	Tillage crops	Wheat, rice, maize
Straw returning	Straw returning methods	Rotary tillage returning to field (SR), plowing and returning to field (SP), straw mulching (SM)
	Straw type	Wheat straw, rice straw, maize straw
	Straw returning crops	Wheat, rice, maize

2.3. Research Area

Grain cultivation in China is widely distributed, with rice primarily grown south of the Qinling Mountains and the Huaihe River, wheat mainly cultivated in the North China Plain and Northeast China Plain, and maize predominantly planted in the northeast, north, and southwest regions. Grain cultivation in China is widely distributed, with rice primarily grown south of the Qinling Mountains and the Huaihe River due to the region's warm, humid climate and abundant water resources. Wheat is mainly cultivated in the North China Plain and Northeast China Plain, where cooler temperatures and moderate rainfall are suitable for its growth. Maize is predominantly planted in the northeast, north, and southwest regions, which provide diverse climatic conditions and sufficient sunlight for maize cultivation. Farming measures differ across regions and crop types, making it necessary to analyze the characteristics of greenhouse gas emissions from farmland and their influencing factors in China's main grain-producing areas through comprehensive meta-analysis. This analysis aims to provide a scientific basis for formulating rational

greenhouse gas emission reduction measures in farmland. Figure 2 presents a map of the distribution of research sites included in this study.

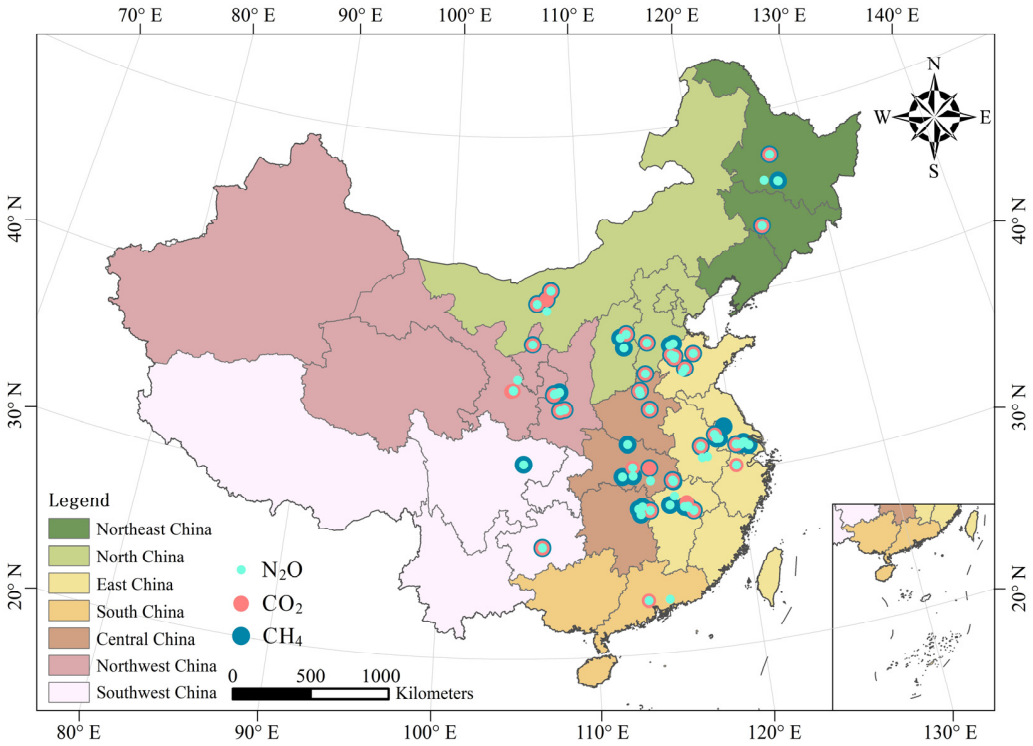

Figure 2. Map of the study area. China is divided into seven regions: North China (Beijing, Tianjin, Hebei, Inner Mongolia, Shanxi); Northeast China (Heilongjiang, Jilin, Liaoning); East China (Shandong, Anhui, Jiangsu, Shanghai, Zhejiang, Jiangxi, Fujian, Taiwan); Central China (Henan, Hubei, Hunan); South China (Guangxi, Guangdong, Hainan, Hong Kong, Macao); Southwest China (Sichuan, Yunnan, Guizhou, Chongqing, Tibet); and Northwest China (Shaanxi, Gansu, Ningxia, Xinjiang, Qinghai). The present study categorized experimental sites based on these regional divisions.

2.4. Data Analysis

Meta-analysis of raw data requires the calculation of individual effect sizes. Common effect size indicators in ecological studies include Hedges' d and the response ratio lnR. In this study, we used Hedges' d as the effect size indicator because it accounts for sample size and variability, making it more suitable for studies with small sample sizes or unequal variance between groups. Additionally, Hedges' d is widely used in ecological and environmental studies to compare continuous variables with greater precision. In this study, we used Hedges' d as the effect size indicator, calculated using the following formula [19]:

$$d = \frac{(X_e - X_c)}{S} J = \sqrt{\frac{(N_e - 1)(S_e)^2 + (N_c - 1)(S_c)^2}{N_e + N_c - 2}} \quad (1)$$

Here, X_e and X_c are the mean values of the test and control groups, respectively; S_e and S_c are t the standard deviations of the test and control groups; N_e, N_c are the sample sizes of the test and control groups [23].

The correction factor J is calculated as follows:

$$J = 1 - \frac{3}{4(N_e + N_c - 2) - 1} \quad (2)$$

J accounts for variance when the sample size is small [19]; it will show an obvious variance.

The variance of the effect size is given by the following:

$$V_d = \frac{N_e + N_c}{N_e \times N_c} + \frac{d^2}{2(N_e + N_c)} \quad (3)$$

After calculating the individual effect sizes, the composite effect values of the studies are determined using an effect model. Meta-analysis typically employs two primary models: the fixed-effect model and the random-effects model. The fixed-effect model assumes a single, common true effect size across studies, with observed variability attributed to random sampling errors. In contrast, the random-effects model assumes that true effect sizes vary between studies and accounts for both differences in true effects and random sampling errors [24]. The random-effects model allows for variability between studies and is more appropriate when the studies differ in their populations, interventions, or other characteristics.

The literature data included in this study came from various trial sites, years, crop varieties, farming measures, and management strategies, which led to variability in the effect sizes across studies. To account for this variability, a random-effects model with balanced weights was employed to calculate the overall effect size. Bootstrapping was used to estimate confidence intervals for the effect size. If the 95% confidence interval for the effect size overlaps with zero, the difference between the test and control groups is considered insubstantial; if it does not overlap with zero, a substantial difference is indicated [25]. Additionally, if the 95% confidence intervals for different subgroups do not overlap, this suggests substantial heterogeneity between the subgroups. The effect of farming measures on greenhouse gas emissions was assessed based on the magnitude of the effect size and its 95% confidence interval. In this study, heterogeneity was quantified using the I^2 statistic. The I^2 statistic indicates mild heterogeneity at values from 0% to 40%, moderate heterogeneity from 40% to 60%, and substantial heterogeneity from 60% to 100%.

Publication bias refers to the tendency for statistically substantial findings to be more likely reported and published compared to non-substantial findings [26]. To minimize deviations from true results, this study employed the funnel plot method to test for publication bias. In the absence of bias, the plot should be symmetrical and resemble a funnel shape. Asymmetry in the funnel plot indicates potential publication bias or other types of bias. To address this, the clipping method was used: asymmetric terms in the funnel plot were clipped, and the clipped regions were filled in along both sides of the funnel's center. Subsequently, effect size calculations were re-evaluated based on the adjusted data to correct for potential bias caused by heterogeneity.

2.5. Data Processing

This study utilized Excel 2019 for data recording and organization, StataMP 16 for meta-analysis, SigmaPlot 14.0 and Origin 2021 for data visualization.

3. Results

3.1. Combined Effect Sizes and Publication Bias Tests

As shown in Figure 3, according to the random-effects model, the effect size (Hedges' d) and 95% confidence intervals were 1.665 [0.967, 2.364] before correction and 1.036 [0.262, 1.809] after correction. Although the effect size changed, its statistical significance remained unchanged. Despite the possibility of publication bias, the results of this meta-analysis are considered robust.

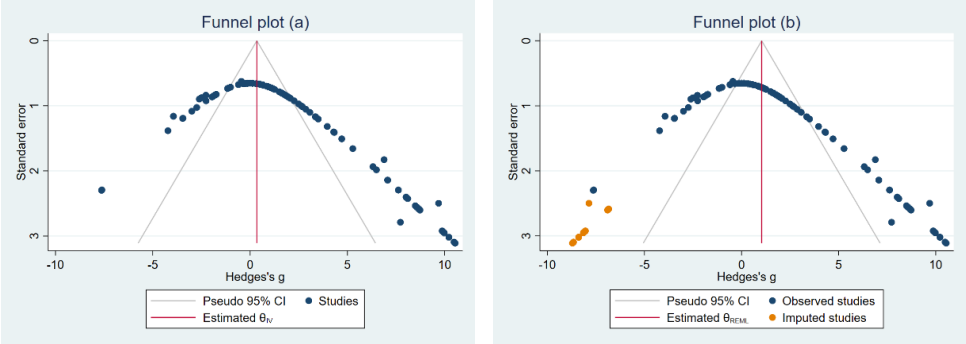

Figure 3. Publication bias test funnel plot. The results of the publication bias test are presented in (**a**). In this figure, the red line represents the combined effect size, the gray diagonal line indicates the 95% confidence interval, and the blue points depict the scatter of each study's effect size against its standard deviation. Asymmetry in the lower left corner of the funnel plot was observed and corrected using the shear-and-patch method. The corrected results are shown in (**b**).

The Hedges' d effect sizes, logarithmic n values, and I^2 test results for the effects of different farming measures on greenhouse gas (CH_4, CO_2, N_2O) emissions from farmland are presented in Table 2, n and I^2 are common statistical measures, representing sample size and heterogeneity.

Table 2. Combined effect sizes and heterogeneity tests.

Parameters	Hedges' d Effect Size	95% Confidence Interval		n	I^2
		Upper Limit	Lower Limit		
CH_4 emissions	0.675	0.239	1.112	284	86.13
CH_4 absorption	−0.008	−0.344	0.328	288	85.42
CO_2 emissions	0.42	0.129	0.711	260	80.47
N_2O emission	0.615	0.499	0.732	719	20.38

Different farming measures demonstrated substantial positive effects on cumulative CH_4, CO_2, and N_2O emissions. However, no substantial difference was observed in cumulative CH_4 uptake compared to the blank control group. Heterogeneity testing revealed that the overall analysis of the effects of different farming measures on greenhouse gas (CH_4, CO_2, N_2O) emissions was highly heterogeneous ($I^2 > 75$), indicating that the impact on greenhouse gas emissions from farmland could not be accurately assessed. To explore the effects of different farming measures on farmland greenhouse gas emissions more precisely, this study performed subgroup analyses based on fertilization measures, tillage measures, and straw returning measures.

Figure 4 presents the results of the meta-analysis. This figure aims to summarize the general patterns in greenhouse gas emissions across different agricultural practices and highlight their variability. They are not intended to combine the results into a single overarching effect. The effects of different farming measures on CH_4 uptake were not significant, as the 95% confidence intervals for these effects overlapped with zero. In contrast, a significant positive effect on CH_4 emissions was observed, with an effect size (ES) of 1.908 (95% CI [1.302, 2.514]), indicating that farming measures generally increased CH_4 emissions. Among the measures, tillage was associated with a reduction in CH_4 emissions (ES = −1.197, 95% CI [−1.786, −0.608]), while fertilization had the largest increase in CH_4 emissions (ES = 1.908, 95% CI [1.302, 2.514]), and straw returning also increased CH_4 emissions (ES = 1.044, 95% CI [0.177, 1.91]).

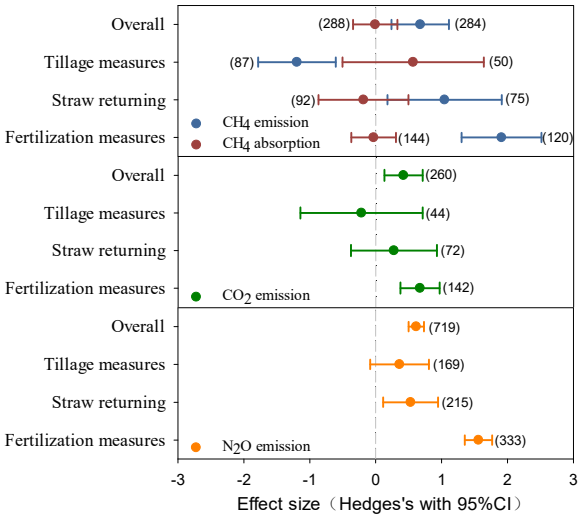

Figure 4. Effects of different farming measures on greenhouse gas emissions from farmland. The vertical gray line represents the effect value Hedges's = 0, the error bar represents the 95% confidence interval (95% CI), and the number in brackets represents the sample size.

For CO_2 emissions, the overall effect size was 0.42 (95% CI [0.129, 0.711]), indicating that farming measures generally promote CO_2 emissions. However, the 95% confidence intervals for straw returning and tillage measures overlapped with zero, indicating no significant effect on CO_2 emissions. Fertilization significantly increased CO_2 emissions (ES = 0.67, 95% CI [0.372, 0.967]).

Regarding N_2O emissions, the overall effect size was 0.615 (95% CI [0.499, 0.732]). All farming measures (fertilization, straw returning, and tillage) positively influenced N_2O emissions, with the strongest effect from fertilization (ES = 1.559, 95% CI [1.352, 1.766]), followed by straw returning (ES = 0.53, 95% CI [0.114, 0.945]), and tillage (ES = 0.362, 95% CI [−0.084, 0.809]).

3.2. Effects of Different Fertilization Measures on Greenhouse Gas Emissions from Farmland

To address the scientific questions and research objectives of this study, we conducted subgroup analyses to explore the effects of different fertilization measures on greenhouse gas (GHG) emissions, specifically CH_4, CO_2, and N_2O, from agricultural soils. Fertilization is a key agricultural management practice that influences soil microbial activity and nutrient cycling, which in turn impact GHG emissions. The analysis was conducted based on various fertilization parameters, including fertilization frequency, fertilization types, and fertilized crops, as they are critical factors in shaping soil emissions.

The fertilization types analyzed included: biochar (C), organic fertilizer (O), nitrogen fertilizer (N), nitrogen plus phosphorus fertilizer (N + P), nitrogen plus organic fertilizer (N + O), nitrogen plus compound fertilizer (N + F), nitrogen and phosphorus plus biochar (NP + C), nitrogen, phosphorus, and potash (NPK), nitrogen, phosphorus, and potash plus biochar (NPK + C), nitrogen, phosphorus, and potash plus organic fertilizer (NPK + O), and nitrogen, phosphorus, and potash plus compound fertilizer (NPK + F). Additionally, we examined the effects of different crops, namely wheat, rice, and maize, under these fertilization regimes.

By incorporating these fertilization parameters, this analysis directly links the key elements of fertilization practices with their effects on GHG emissions, thus addressing the research objectives of understanding how different management practices impact emissions from agricultural soils. The results from these subgroup analyses are presented in Figure 5, highlighting the importance of fertilization type and crop selection in GHG emission patterns.

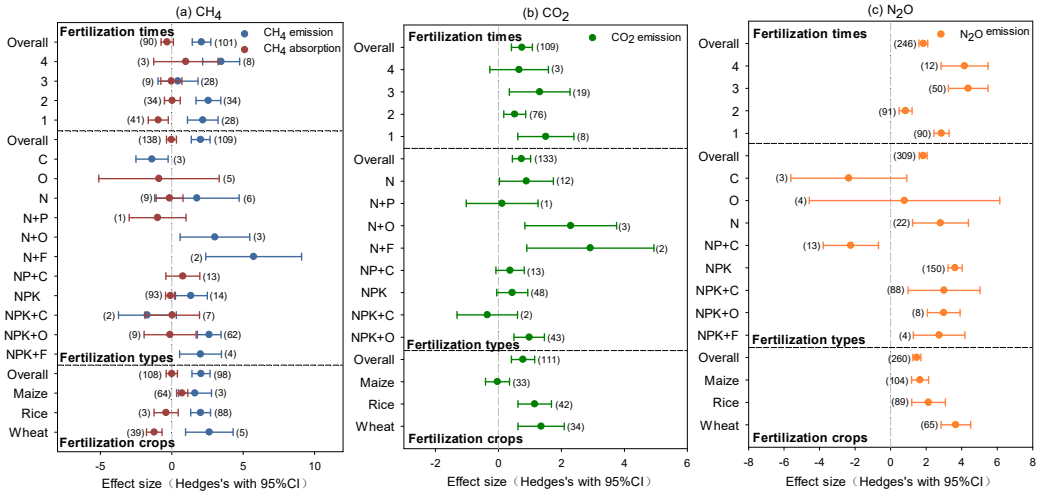

Figure 5. Effects of different fertilization measures on greenhouse gas emissions from farmland. The vertical gray line represents the effect value Hedges's = 0, the error bar represents the 95% confidence interval (95% CI), and the number in brackets represents the sample size.

Different fertilization frequencies had significant effects on CH_4, CO_2, and N_2O emissions from farmland, but did not significantly affect CH_4 uptake (ES = −0.319, 95% CI [−0.747, 0.109]). Fertilization applied four times had the largest effect on CH_4 emissions (ES = 3.46), followed by fertilization applied twice (ES = 2.562), once (ES = 2.174), and three times, which showed a weak positive effect (ES = 0.435, 95% CI [−0.968, 1.838]). The effect sizes for CO_2 emissions were largest for one-time applications (ES = 1.506, 95% CI [0.616, 2.397]), followed by three-time applications (ES = 1.311, 95% CI [0.347, 2.275]), and two-time applications (ES = 0.516, 95% CI [0.168, 0.863]). The effect size for four-time applications (ES = 0.657, 95% CI [−0.272, 1.586]) was not significantly different from zero. All frequencies of fertilization significantly increased N_2O emissions, with effect sizes and 95% confidence intervals for once (ES = 2.865, 95% CI [2.438, 3.292]), twice (ES = 0.842, 95% CI [0.482, 1.203]), three-time (ES = 4.37, 95% CI [3.247, 5.493]), and four-time applications (ES = 4.162, 95% CI [2.838, 5.486]).

Different types of fertilizers exhibited varying effects on CH_4, CO_2, and N_2O emissions from farmland, generally showing positive effects overall. Fertilizers had a non-significant effect on CH_4 uptake (ES = −0.021, 95% CI [−0.371, 0.329]). Specifically, biochar (C) significantly suppressed CH_4 emissions (ES = −1.38), while NPK + C showed a weak negative effect (ES = −1.712, 95% CI [−3.736, 0.312]), and nitrogen (N) application alone had a non-significant effect. Fertilizer combinations including N + O (ES = 3.024), N + F (ES = 5.734), NPK (ES = 1.34), NPK + O (ES = 2.622), and NPK + F (ES = 2.016) all promoted CH_4 emissions. For CO_2 emissions, positive effect sizes increased in the following order: N (ES = 0.888, 95% CI [0.029, 1.746]), NPK + O (ES = 0.978, 95% CI [0.841, 3.754]), N + O (ES = 2.298, 95% CI [0.901, 4.938]), and N + F (ES = 2.92, 95% CI [0.496, 1.46]). The effect sizes for N + P and NPK + C on CO_2 emissions were not significant, with NP + C (ES = 0.369, 95% CI [−0.079, 0.817]) and NPK (ES = 0.44, 95% CI [−0.053, 0.933]) showing weak positive effects. Effects of C and O on N_2O emissions were not significant, with 95% CIs overlapping with 0. NP + C showed a significant negative effect on N_2O emissions (ES = −2.243, 95% CI [−3.798, −0.688]). Other fertilizers exhibited positive effects on N_2O emissions in descending order: NPK + F (ES = 2.734, 95% CI [1.282, 4.187]), N (ES = 2.808, 95% CI [1.235, 4.38]), NPK + O (ES = 2.992, 95% CI [2.075, 3.91]), NPK + C (ES = 3.006, 95% CI [0.978, 5.033]), and NPK (ES = 3.631, 95% CI [3.234, 4.027]).

Different crops exhibited varying contributions to greenhouse gas (CH_4, CO_2, N_2O) emissions from farmland. Overall, the effect of fertilization on crop CH_4 uptake was not

significant (ES = 0.005, 95% CI [−0.387, 0.397]), so this aspect is not discussed further. Fertilization significantly increased CH_4 emissions across different crops, with effect sizes of 1.625 (95% CI [0.475, 2.775]) for maize, 2.026 (95% CI [1.331, 2.721]) for rice, and 2.63 (95% CI [0.965, 4.295]) for wheat. Fertilization had a non-significant effect on CO_2 emissions from maize (ES = −0.03, 95% CI [−0.409, 0.35]), but significantly increased CO_2 emissions for rice (ES = 1.152, 95% CI [0.619, 1.686]) and wheat (ES = 1.357, 95% CI [0.622, 2.092]). Additionally, fertilization had a significant positive effect on N_2O emissions for all crops, with effect sizes of 3.668 (95% CI [2.834, 4.502]) for wheat, 2.134 (95% CI [1.189, 3.08]) for rice, and 1.656 (95% CI [1.179, 2.132]) for maize, respectively.

3.3. Effects of Different Tillage Measures on Greenhouse Gas Emissions from Farmland

This study investigates the influence of tillage measures on greenhouse gas (GHG) emissions, specifically CH_4, CO_2, and N_2O, from farmland. The effects of different tillage crops and tillage methods were analyzed to explore their roles in shaping GHG emissions.

Tillage crops were categorized into three subgroups: maize, rice, and wheat, while tillage methods were divided into rotary tillage (RT), no-tillage (NT), and deep tillage (DT). These tillage measures are crucial as they influence soil structure, microbial activity, and nutrient cycling, which in turn affect GHG emissions from agricultural soils. The findings of this subgroup analysis directly address the research objective of understanding how tillage practices influence the emission characteristics of CH_4, CO_2, and N_2O in different cropping systems. The results are illustrated in Figure 6, which highlights the key elements of how tillage practices and crop types interact to influence GHG emissions.

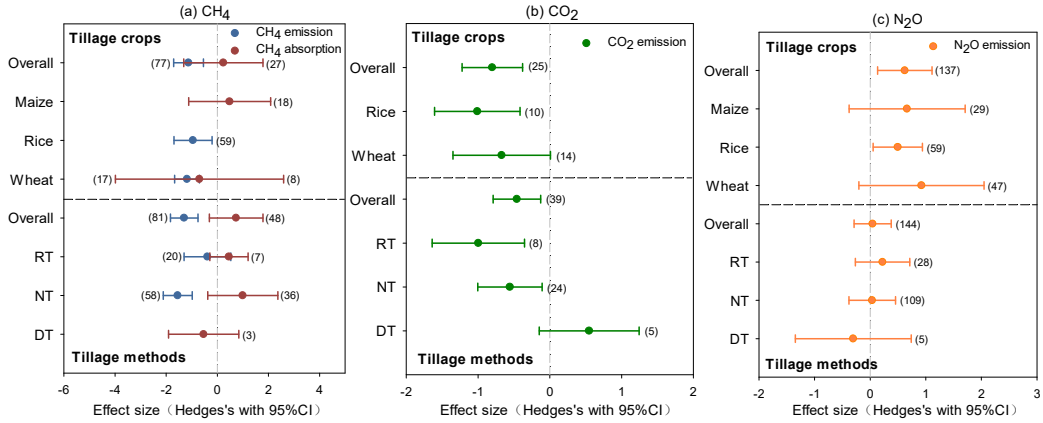

Figure 6. Effects of different tillage measures on greenhouse gas emissions from farmland. The vertical gray line represents the effect value Hedges's = 0, the error bar represents the 95% confidence interval (95% CI), and the number in brackets represents the sample size.

Different tillage measures did not significantly affect CH_4 uptake in various crops (ES = 0.236, 95% CI [−1.314, 1.786]). However, all tillage methods significantly inhibited CH_4 emissions (ES = −1.126, 95% CI [−1.709, −0.544]), with a stronger inhibitory effect observed for wheat (ES = −1.183, 95% CI [−1.668, −0.698]) compared to rice (ES = −0.948, 95% CI [−1.693, −0.204]). Tillage measures also reduced CO_2 emissions from crops, with effect sizes and 95% confidence intervals of −1.011 (95% CI [−1.606, −0.416]) for rice and −0.671 (95% CI [−1.350, 0.008]) for wheat. For N_2O emissions, tillage measures had a significant positive effect on rice (ES = 0.497) and weak positive effects on maize (ES = 0.664, 95% CI [−0.380, 1.709]) and wheat (ES = 0.923, 95% CI [−0.202, 2.048]).

Different tillage methods impacted greenhouse gas (CH_4, CO_2, N_2O) emissions from farmland in varying degrees. No-tillage (NT) had a significant negative effect on CH_4 emissions (ES = −1.548, 95% CI [−2.115, −0.981]), effectively reducing CH_4 emissions. In contrast, deep tillage (DT) showed a non-significant positive effect on CH_4 emissions

(ES = 0.548, 95% CI [−0.148, 1.243]). Both rotary tillage (RT) and NT significantly suppressed CO_2 emissions, with effect sizes of −0.996 (95% CI [−1.640, −0.352]) and −0.556 (95% CI [−1.005, −0.108]), respectively. Different tillage methods did not significantly affect N_2O emissions, as indicated by 95% confidence intervals overlapping with 0.

3.4. Effects of Different Returning Measures on Greenhouse Gas Emissions from Farmland

To further investigate the influence of straw returning on greenhouse gas (CH_4, CO_2, N_2O) emissions from farmland, the study conducted subgroup analyses based on various factors, including straw returning methods, straw types, and the crops being planted. These measures are critical as they significantly affect soil properties, such as carbon sequestration and microbial activity, which, in turn, influence the emission of greenhouse gases from agricultural soils.

The subgroup analyses focused on three straw returning methods: rotary tillage (SR), plowing (SP), and mulching (SM), while the straw types included maize, rice, and wheat straw. Additionally, the study examined the effects of straw returning on maize, rice, and wheat crops. These analyses directly address the research objectives, as they explore how different straw management practices, in combination with crop types, impact the emission of CH_4, CO_2, and N_2O.

The results of these subgroup analyses are illustrated in Figure 7, providing a clear understanding of how straw returning methods and crop types contribute to the changes in greenhouse gas emissions from farmland. This visual summary is crucial in identifying effective mitigation strategies for reducing emissions.

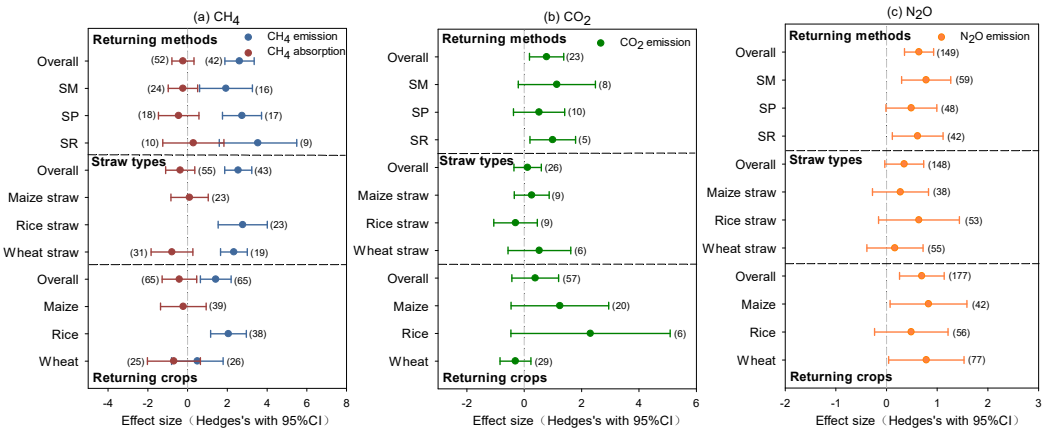

Figure 7. Effects of different returning measures on greenhouse gas emissions from farmland. The vertical gray line represents the effect value Hedges's = 0, the error bar represents the 95% confidence interval (95% CI), and the number in brackets represents the sample size.

Rotary tillage (SR) involves mixing straw with 5 to 10 cm of soil, plowing (SP) buries the straw in a 20 to 30 cm soil layer, and mulching (SM) places the straw directly on the soil surface. The effects of these straw returning methods on CH_4 uptake were minimal, with 95% confidence intervals overlapping with 0. All three methods significantly increased CH_4 emissions, with effect sizes in the order of SR (ES = 3.541) > SP (ES = 2.738) > SM (ES = 1.933). Compared to no straw returning, SR (ES = 0.997, 95% CI [0.202, 1.792]), SP (ES = 0.518, 95% CI [−0.376, 1.412]), and SM (ES = 1.138, 95% CI [−0.206, 2.481]) all increased CO_2 emissions, with SR showing the largest effect. All three methods also increased N_2O emissions, though the differences between methods were not significant, with effect sizes of 0.616 (95% CI [0.115, 1.117]) for SR, 0.490 (95% CI [−0.012, 0.993]) for SP, and 0.783 (95% CI [0.297, 1.268]) for SM.

The results of the subgroup analysis presented in Figure 7a indicate that different types of straw returning increased CH_4 emissions. Rice straw (ES = 2.777, 95% CI [1.541, 4.013])

had a greater effect on CH_4 emissions compared to wheat straw (ES = 2.328, 95% CI [1.656, 2.999]), but neither type significantly affected CH_4 uptake. The effects of straw types on CO_2 emissions were not significant, as evidenced by 95% confidence intervals overlapping with 0. For N_2O emissions, different straw types showed weak positive effects, with effect sizes ordered as follows: wheat straw < maize straw < rice straw. Specifically, the effect sizes were 0.166 (95% CI [−0.388, 0.72]) for wheat straw, 0.275 (95% CI [−0.277, 0.827]) for maize straw, and 0.64 (95% CI [−0.158, 1.439]) for rice straw.

The effect of straw returning on CH_4 emissions varied by planting crop. The effect was more pronounced for rice, with an effect size of 2.055 (95% CI [1.157, 2.953]), compared to a weaker effect for wheat, with an effect size of 0.493 (95% CI [−0.803, 1.79]). There were no significant effects from straw return on CH_4 uptake across the different crops, as indicated by confidence intervals overlapping with 0. The impact of straw return on CO_2 emissions was also not significant, with a weak positive overall effect size of 0.386 (95% CI [−0.429, 1.201]). For N_2O emissions, straw return had a promotive effect, with the most significant increase observed for maize (ES = 0.829, 95% CI [0.072, 1.586]), followed by wheat (ES = 0.786, 95% CI [0.043, 1.53]), and rice (ES = 0.489, 95% CI [−0.235, 1.213]).

3.5. Characteristics of Greenhouse Gas Emissions from Farmland in Different Regions

To better address the scientific questions and research objectives, this study investigates the regional effects of different farming measures on greenhouse gas (GHG) emissions (CH_4, CO_2, N_2O), including fertilization, tillage, and straw returning. Figure 8 illustrates the effects of these farming measures on GHG emissions, with detailed analyses of fertilization measures, tillage practices, and straw returning presented in Figure 8a–c, respectively. These analyses effectively integrate the emission characteristics of different farming practices with the research questions and objectives, aiming to provide scientific insights for sustainable agricultural development and GHG mitigation strategies.

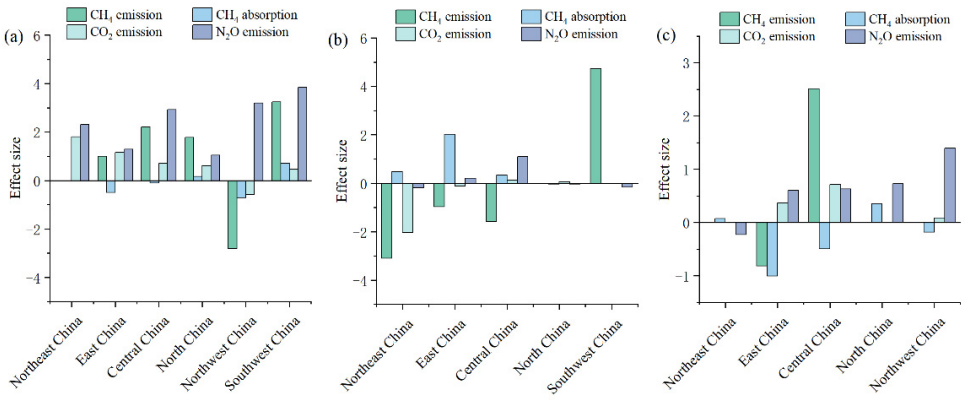

Figure 8. Effects of different farming measures on greenhouse gas emissions from farmland in different regions. (**a**) Effects of fertilization measures on greenhouse gas emissions. (**b**) Effects of tillage practices on greenhouse gas emissions. (**c**) Effects of straw returning on greenhouse gas emissions.

Fertilization did not significantly affect CH_4 uptake across the different regions (ES = −0.036, 95% CI [−0.346, 0.274]), as the 95% confidence interval overlapped with 0; therefore, no regional analysis for CH_4 uptake will be discussed further. The analysis shown in Figure 8a indicates that fertilization significantly increased CO_2 (ES = 1.812) and N_2O (ES = 2.304) emissions in Northeast China. In East China and Central China, fertilization positively impacted greenhouse gas emissions (CH_4, CO_2, N_2O), but with varying magnitudes: East China had effect sizes of 0.993 for CH_4, 1.164 for CO_2, and 1.282 for N_2O, while Central China had effect sizes of 2.202 for CH_4, 0.718 for CO_2, and 2.93 for N_2O. In North China, fertilization similarly increased CH_4 (ES = 1.782), CO_2 (ES = 0.614), and N_2O

(ES = 1.036) emissions. In Northwest China, fertilization suppressed CH_4 (ES = −2.804) and CO_2 (ES = −0.575) emissions but increased N_2O (ES = 3.197) emissions. Fertilization also positively affected CH_4 (ES = 3.246), CO_2 (ES = 0.468), and N_2O (ES = 3.841) emissions in Southwest China.

The effects of tillage measures on greenhouse gas (GHG) emissions from farmland in the different regions are illustrated in Figure 8b. Similar to the effects of fertilization measures, tillage measures did not significantly affect CH_4 uptake, as indicated by a 95% confidence interval overlapping with 0 (ES = 0.601, 95% CI [−0.462, 1.663]). This suggests that, while the statistical results were comparable, the mechanisms underlying the effects of fertilization and tillage may differ, and therefore this aspect will not be discussed further. Tillage measures reduced emissions of CH_4 (ES = −3.098), CO_2 (ES = −2.037), and N_2O (ES = −0.196) in Northeast China. In East China, tillage measures suppressed CH_4 emissions (ES = −0.977) but had a minor positive effect on CO_2 (ES = 0.118) and N_2O (ES = 0.215) emissions. In Central China, tillage measures had similar effects to those in East China, with varying magnitudes: −1.583 for CH_4, 0.122 for CO_2, and 1.099 for N_2O. In North China, tillage measures suppressed CH_4 (ES = −0.006) and N_2O (ES = −0.392) emissions, and had a minor positive effect on CO_2 emissions (ES = 0.066). In Southwest China, tillage measures significantly increased CH_4 emissions (ES = 4.739) while suppressing N_2O emissions (ES = −0.161), showing a generally weak negative effect.

The effects of straw returning measures on greenhouse gas (GHG) emissions from farmland are illustrated in Figure 8c. The results indicate that straw returning measures do not have a significant effect on CH_4 uptake (ES = −0.203, 95% CI [−0.87, 0.463]), and thus this aspect will not be discussed further. Straw returning measures exhibited an inhibitory effect on N_2O emissions in Northeast China (ES = −0.224), while significantly promoting CO_2 and N_2O emissions in East China and Central China. In East China, the effect sizes were 0.367 for CO_2 and 0.601 for N_2O, whereas in Central China, the effect sizes were 0.715 for CO_2 and 0.631 for N_2O. Additionally, straw returning measures inhibited CH_4 emissions in East China (ES = −0.817) but promoted CH_4 emissions in Central China (ES = 2.513). In North China, straw returning measures promoted N_2O emissions (ES = 0.724), and in Northwest China, they increased CO_2 (ES = 0.089) and N_2O (ES = 1.397) emissions.

4. Discussion

4.1. Analysis of Greenhouse Gas Emission Characteristics of Farmland

Key factors influencing greenhouse gas (GHG) emissions from agriculture include agricultural management measures such as crop types, tillage methods, fertilizer types, straw returning, organic biochar, irrigation, and the use of agricultural films [27]. Jiang et al. [28] found that the average N_2O emission intensity in soils treated with nitrogen was significantly higher compared to untreated soils. Additionally, CO_2 and CH_4 emissions are closely linked to the application of chemical fertilizers. These fertilizers significantly enhance soil fertility, promote plant root growth, and increase respiration, leading to higher CO_2 emissions [29]. Furthermore, chemical fertilizers create anaerobic conditions in the soil, which provide abundant nutrients for methanogenic bacteria, thereby facilitating substantial CH_4 emissions [30]. We have directly analyzed the emission characteristics of CH_4, CO_2, and N_2O from agricultural fields under different management practices, emphasizing the impact of fertilization, tillage, and straw returning. The findings of increased N_2O emissions due to fertilization and tillage, as observed in this study, are consistent with previous research.

Several studies indicate that tillage measures can negatively impact CH_4 emissions [31] by altering soil structure, which affects the physical and chemical properties of the soil, and consequently influences the population and habitat of CH_4-oxidizing bacteria [32].

Conversely, tillage measures affect soil CO_2 emissions through changes in soil temperature, compaction, and nutrient status [33]. Zhang's study found that no-tillage measures reduced CO_2 emissions by minimizing soil organic carbon exposure [34], a finding consistent with the results of this study. Further discussion is warranted to explore the effects of other tillage measures on CO_2 emissions. Additionally, Xu's use of the DNDC model demonstrated that tillage facilitates the transition of soil from anaerobic to aerobic conditions, thereby promoting N_2O production through nitrification, which aligns with the conclusions of the present study [35].

Straw returning significantly increased CH_4 emissions from rice, as well as soil CO_2 and N_2O emissions. This is primarily due to the increased content of soluble organic carbon and nitrogen in the soil, which provides additional substrates and energy sources for microorganisms, thereby enhancing microbial activity and subsequently increasing greenhouse gas emissions [36–38]. These findings, referring to the transition of soil conditions from anaerobic to aerobic and the resulting promotion of N_2O production through nitrification, are consistent with the results of this study.

4.2. Effects of Fertilization Measures on Greenhouse Gas Emissions from Farmland

Fertilization frequency and its impact on greenhouse gas emissions. Fertilization frequency is a key management measure influencing crop nitrogen use efficiency, with split applications of nitrogen fertilizer serving to reduce nitrogen losses and enhance fertilizer utilization [39]. The results of this study indicate that the effect of fertilization frequency on CH_4 emissions increased with the number of applications, with the order being four times > twice > once. This pattern may be attributed to the occurrence of CH_4 emission peaks at different stages of crop growth, where multiple applications can promote a secondary peak in CH_4 emissions [40]. Additionally, multiple fertilizer applications significantly reduced CO_2 emissions compared to a single application. This reduction is likely due to improved soil structure and the maintenance of soil organic matter balance, which decreases the decomposition of organic matter and lowers carbon emissions. The effect of fertilization frequency on N_2O emissions was observed in the following order: three times > four times > once > twice. Zheng [41] noted that fertilizer applications provide materials and energy for nitrification and denitrification processes, thereby promoting these processes.

Effect of fertilizer types on greenhouse gas emissions. The use of different types of fertilizers significantly impacts greenhouse gas (GHG) emissions from agricultural systems [42]. The application of biochar (C) or biochar mixed with NPK fertilizers effectively inhibited CH_4 emissions. Biochar's influence on microbial activity and nutrient dynamics plays a crucial role in reducing soil GHG emissions [43]. Other fertilizers varied in their contributions to CH_4 emissions, with the following order of effect: C < NPK < NPK + F < NPK + O < N + O < N + F. Fertilizer application creates an anaerobic environment in the soil, providing substrates for CH_4 bacteria and fostering conditions that enhance bacterial growth, thus increasing soil CH_4 emissions [44]. The results of this study found that the positive effect of N, NPK + O, N + O, and N + F on CO_2 emissions increased in that order, while NPK + C had a non-significant negative effect on CO_2. Organic fertilizers, particularly those with NPK, promote crop root growth, enhancing root respiration and accelerating soil CO_2 emissions [45], which aligns with the results of this study. The application of compound fertilizers (F) increased soil organic matter and microbial activity, significantly affecting CO_2 emissions [46]. Organic fertilizers (O) elevated soil carbon sources and effective nitrogen, providing an optimal soil C/N ratio for microbes and plants, thereby increasing soil respiration and CO_2 emissions [47]. NP + C suppressed N_2O emissions, while other fertilizers had positive effects on N_2O emissions in the following

order: NPK + F < N < NPK + O < NPK + C < NPK. Biochar reduced nitrate availability to microbes, limited the release of reactive carbon and nitrogen, and improved soil aeration, thus lowering CO_2 and N_2O emissions [48–50]. Organic fertilizers, by supplying additional organic carbon, enhancing soil nutrient effectiveness, and stimulating microbial activity, can increase N_2O emissions, a finding consistent with the results reported by [32,51], and also observed in the present study.

Impact of fertilization on greenhouse gas emissions across different crops. Ladha et al. [52] reported that 50% of the global population depends on nitrogen fertilizers for food production, with about 60% of these fertilizers used for the major cereals: rice, wheat, and maize. Each crop has distinct mechanisms and impacts on greenhouse gas (GHG) emissions, leading to varying effects from fertilization. However, all three crops—rice, wheat, and maize—stimulate emissions of CH_4, CO_2, and N_2O. Rice fields, typically flooded, create an anoxic environment conducive to CH_4 bacteria growth. Organic matter decomposition in these fields releases CO_2, while nitrification and denitrification processes produce N_2O [53]. Maize, which grows in conditions similar to wheat but with fewer anaerobic conditions, produces minimal CH_4 due to limited anaerobic zones. Decomposition of organic matter generates CO_2, and nitrification of NH_4^+ under aerobic conditions converts NO_3^- to N_2O under hypoxic or anaerobic conditions through microbial denitrification [54]. The common effect of nitrogen fertilization across these crops is the increased availability of soil nitrogen, which enhances nitrification and denitrification processes, thereby elevating N_2O emissions. Organic fertilization boosts soil organic matter and microbial activity, resulting in increased soil respiration and CO_2 release. Notably, rice paddies, due to prolonged flooding, emit significant amounts of CH_4, whereas maize and wheat, which are typically not waterlogged, exhibit lower CH_4 emissions [55,56].

4.3. Effects of Tillage Measures on Greenhouse Gas Emissions from Farmland

As shown in Figure 6, tillage significantly affects carbon emissions from soil [15]. This study found that tillage measures suppressed CH_4 and CO_2 emissions from rice and wheat but increased N_2O emissions from rice, maize, and wheat. Bayer et al. [57] noted that tillage disrupts the soil surface structure, increases soil aeration, and alters the microbial habitat, which reduces the decomposition of organic matter and the intensity of soil respiration. This, in turn, lowers CH_4 production and bacterial activity. Additionally, tillage mineralizes organic nitrogen from the crop root system, leading to increased nitrogen inputs. Increased soil porosity and aeration from tillage enhance nitrification processes, thereby promoting N_2O production and emissions [58,59].

Impact of different tillage practices. In this study, no-tillage (NT) and rotary tillage (RT) measures inhibited CH_4 and CO_2 emissions while promoting N_2O emissions. Conversely, deep tillage (DT) increased CO_2 emissions and suppressed N_2O emissions. Bista et al. [60] observed from a two-year trial that NT reduced CO_2 emissions by 35% compared to conventional tillage, likely due to reduced soil disturbance and slower degradation of soil organic carbon, leading to decreased CO_2 emissions [61]. Pascal et al. [62] reported significantly higher CO_2 emissions from conventional tillage compared to RT or NT, and conventional tillage resulted in a 20% increase in cumulative seasonal CH_4 emissions compared to NT [63], which aligns with our findings. Additionally, Kushal et al. [64] found that RT increased N_2O emissions by 9.77% compared to conventional tillage. The higher soil density and moisture content associated with NT created a more anaerobic environment, enhancing biological denitrification in the topsoil and contributing to increased N_2O emissions [65], consistent with our results.

4.4. Effects of Straw Returning on Greenhouse Gas Emissions from Farmland

Straw returning and greenhouse gas emissions. As shown in Figure 7, various straw returning methods increased greenhouse gas emissions from farmland, with effect values for CH_4 emissions ranked as SM < SP < SR, for CO_2 emissions as SP < SR < SM, and for N_2O emissions as SP < SR < SM. Hu et al. [66] found that SP and SR treatments increased CH_4 emissions compared to the CK treatment. Straw returning resulted in higher NH_4^+-N content during crop growth, which inhibited CH_4-oxidizing bacteria activity, leading to a lower CH_4 oxidation rate and increased CH_4 emissions. Hu et al. also observed that the SR treatment significantly increased cumulative N_2O emissions, while the SP treatment had a weaker effect. The SR treatment also significantly increased cumulative CO_2 emissions, more than the SP treatment, which aligns with our findings. Additional studies have shown that straw returning promotes the accumulation of organic matter in soil, enhancing the carbon source in the soil. Straw mulching (SM) improves temperature stabilization and moisture retention, which together enhance microbial activity in nitrification and denitrification processes, leading to increased N_2O emissions [67]. Furthermore, SM can indirectly affect CH_4 emissions by altering soil anaerobic conditions, physical properties, and nutrient conditions [68].

Impact of different straw types on greenhouse gas emissions. The effect of straw returning on greenhouse gas (GHG) emissions depends on the specific crop type, soil conditions, and management measures. Rice straw had a weak negative effect on CO_2 emissions, while maize straw and wheat straw both had a weak positive effect. Wheat, maize, and rice straw exhibited similar effects on N_2O emissions, all promoting N_2O emissions. Huang et al. [69] found that rice straw (RS), wheat straw (WS), and maize straw (MS) significantly increased CH_4 emissions, with the order of emissions being MS > RS > WS > CK. This study observed similar trends (see Figure 7), where different straw types positively affected CH_4 emissions, with rice straw having a greater promoting effect than wheat straw. Xie et al. [70] noted that straw returning significantly promoted N_2O emissions due to the easily decomposable organic matter in straw, which enhances nitrifying and denitrifying microbial activities, thus increasing N_2O production. Additionally, the varying C/N ratios between the different straw types affect soil organic carbon content, microbial activity, and microbial respiration, leading to higher CO_2 emissions, as shown with wheat and maize straw [71,72].

Overall effects of straw returning in different crops. Straw returning increased CH_4, CO_2, and N_2O emissions in rice fields, promoted CH_4 and N_2O emissions in wheat while suppressing CO_2 emissions, and enhanced CO_2 and N_2O emissions in maize. As indicated in Figure 7, straw returning is a key measure for increasing soil carbon content in rice fields and promoting CH_4 production [73]. Liu et al. [12] found that straw returning raised CH_4 emissions by 110.7% based on global data. Additionally, straw returning significantly increased cumulative CO_2 emissions by providing ample carbon and nitrogen sources for microorganisms, thereby boosting microbial activity and respiration [37,74]. Cumulative N_2O emissions also rose substantially with straw returning, as it supplied carbon and nitrogen for nitrification and denitrification processes, creating a favorable environment for microbial growth and enhancing N_2O emissions [75,76].

4.5. Characterization of Greenhouse Gas Emissions in Different Regions

Regional variations in farming measures and GHG emissions in China. The varying effects of farming measures on greenhouse gas (GHG) emissions from farmland across different regions of China are primarily attributed to differences in climatic conditions, soil types, crop types, and field management practices. In Northeast China, fertilization increased CH_4, CO_2, and N_2O emissions, while straw returning reduced N_2O emissions,

and tillage measures decreased CH_4, CO_2, and N_2O emissions. Northeast China features a temperate monsoon climate with cold, dry winters and warm, humid summers, and is one of the world's major black soil regions, characterized by high fertility, a thick layer of soil humus (70–100 cm), and a loose, porous soil structure [77]. The carbon sequestration capacity of black soil varies with different tillage measures. No-till enhances organic carbon content and soil capacity, whereas conventional tillage is negatively correlated with soil soluble organic carbon content [78]. Under long-term fertilization, black soil carbon emissions during the maize reproductive period were 37.36% higher compared to no-fertilization treatments [79]. Straw returning also alters the relative abundance of carbon-sequestering microorganisms, resulting in a higher rate of new carbon formation compared to old carbon decomposition, thereby increasing soil organic carbon content [80], which influences greenhouse gas emissions.

Impact of farming measures in East China. East China, which features a subtropical monsoon climate with four distinct seasons, abundant precipitation, and rainy summers, is characterized by rice soil, yellow soil, and red soil types. These soils are known for their wetness and fertility, supporting a variety of cash crops such as rice, tea, and paddy. Fertilization increases CH_4, CO_2, and N_2O emissions, while straw returning and tillage measures both reduce CH_4 emissions but increase CO_2 and N_2O emissions. The primary rice-producing regions in East and Central China account for over 50% of CH_4 emissions in crop production. The higher methane emissions in these regions and the more pronounced impact of farming measures on CH_4 emissions are largely due to the extensive rice cultivation areas.

GHG emissions in Central China. Central China has a subtropical monsoon climate characterized by warm, humid conditions, with relatively uniform precipitation throughout the year and rainy summers. The dominant soil types in this region are purple soil and yellow soil, both of which exhibit high fertility. In this region, both fertilization and straw returning increase CH_4, CO_2, and N_2O emissions, whereas tillage measures reduce CH_4 emissions while increasing CO_2 and N_2O emissions. Xu's experiments indicated that straw returning enhances soil CO_2 and N_2O production in Central China [81].

Farming measures and GHG emissions in North China. North China features a predominantly temperate monsoon climate, characterized by hot and rainy summers and cold, dry winters. The primary soil types in this region are black calcareous soil, wind-sand soil, and saline soil, which are known for their high fertility, dryness, and salinity. Winter wheat and summer maize are the principal crops. In this area, the main farmland management measures include tillage, straw returning, and nitrogen fertilization [82]. Fertilization increases CH_4, CO_2, and N_2O emissions, while straw returning promotes N_2O emissions. Tillage measures reduce CH_4 and N_2O emissions but increase CO_2 emissions. Hu reviewed the response mechanisms of on-farm carbon cycling to nitrogen fertilization, straw returning, and tillage methods in wheat–maize rotation systems in North China over the past 25 years and found that CO_2 emissions were significantly higher under straw returning and tillage compared to other treatments [83].

GHG emissions in Northwest China. The Northwest Region of China has a continental climate characterized by arid conditions, low rainfall, and high evaporation rates throughout the year. The region is dominated by saline and desert soils, making it suitable for saline-tolerant and drought-resistant crops. In Northwest China, fertilization tends to inhibit CH_4 and CO_2 emissions while promoting N_2O emissions. Straw returning, on the other hand, promotes CO_2 and N_2O emissions. Due to the low soil moisture in this region, it is challenging to form anaerobic conditions after fertilization, which reduces the activity of anaerobic microorganisms and subsequently lowers CH_4 production. Fertilization enhances the stability of organic carbon in the soil, making it less likely to decompose

into CO_2. The well-aerated soils in Northwest China facilitate nitrification, resulting in increased nitrate nitrogen, some of which is converted into N_2O during denitrification. Additionally, the significant diurnal temperature variation enhances microbial activity at higher temperatures, leading to increased CO_2 emissions from straw decomposition. While the soil is typically dry, increased moisture from irrigation or rainfall can create temporary anaerobic conditions, promoting N_2O emissions.

Greenhouse gas emissions in Southwest China. Southwest China features a range of climate types, from subtropical monsoon to highland mountainous climates, with abundant precipitation largely concentrated in the summer. This region is one of the most significantly affected by climate change in China [84]. The predominant soil types in Southwest China are red and yellow loam, characterized by iron-rich and humid conditions. Fertilization in this region promotes emissions of CH_4, CO_2, and N_2O, while tillage measures increase CH_4 emissions and reduce N_2O emissions. Wang examined the greenhouse gas emission mechanisms in Southwest China's farmland ecosystems and noted that soil respiration is influenced by crops, seasons, environmental conditions, and management measures. This is distinct from regions like North China and Northeast China. In Southwest China, the tillage layer in the dry slopes is generally shallow, with poor water- and fertilizer-retaining capacity. Additionally, thermal conditions differ due to variations in altitude and latitude, leading to distinct patterns of greenhouse gas emissions compared to other regions [85].

While this study provides important insights into greenhouse gas emissions from farmland, it is important to note that data gaps exist, particularly in regions such as Xinjiang and Qinghai in Northeast China. As such, the findings may not be fully representative of the entire Northwest region. Future studies should aim to include more comprehensive data from these regions to enhance the robustness and generalizability of the conclusions.

This study provides important insights into the effects of various agricultural measures on greenhouse gas emissions from farmland. However, it is important to acknowledge its limitations. First, the data sources were primarily derived from publicly published studies, which may introduce publication bias and limit the generalizability of the findings. Second, the experimental conditions across studies, such as variations in soil types, climate, and management practices, may affect the comparability of the results. Future research should aim to address these limitations by incorporating more diverse data sources, standardized experimental protocols, and advanced statistical methods.

Overall, adopting integrated nutrient management, conservation tillage, and optimized straw management can reduce emissions while maintaining agricultural productivity and improving environmental sustainability.

5. Conclusions

This study provides valuable insights into the effects of various farming practices on greenhouse gas emissions from farmland. Through meta-analysis, we examined the characteristics of these emissions under different farming measures. The key findings of this research are as follows:

(1) Fertilization, particularly through multiple applications, was found to have the most significant influence on increasing emissions of methane (CH_4) and nitrous oxide (N_2O), while a single application had the most pronounced effect on carbon dioxide (CO_2) emissions. The findings underscore the importance of tailored fertilization strategies in managing agricultural greenhouse gas emissions.

(2) Tillage practices demonstrated a clear effect of inhibiting CH_4 and CO_2 emissions while promoting N_2O emissions. This highlights the need to consider the overall impact of tillage methods on different greenhouse gases when developing sustainable farming practices.

(3) Straw management practices, such as straw returning and mulching, were effective in influencing emissions, with straw returning particularly enhancing CH_4 emissions and straw mulching increasing N_2O emissions. The results indicate that the impact of straw management may vary depending on the crop type, emphasizing the need for crop-specific strategies.

These findings suggest several implications for future research, policy development, and agricultural practices. This study contributes to the broader understanding of how agricultural measures can be aligned with efforts to mitigate climate change.

Author Contributions: S.W., writing—review and editing, writing—original draft, visualization, validation, supervision, software, resources, methodology, investigation, formal analysis, data curation, conceptualization. X.W., writing—review and editing, writing—original draft, supervision, resources, investigation. X.L., writing—review and editing, supervision, project administration, funding acquisition, conceptualization. J.L., writing—review and editing, writing—original draft, supervision, resources, investigation. Y.Y., writing—review and editing. J.P., writing—review and editing. F.G., writing—review and editing. All authors have read and agreed to the published version of the manuscript.

Funding: This study was supported by the National Natural Science Foundation of China (W2412160, 52342906), Research Project of Shaanxi Laboratory for Arid Region Agriculture (2024ZY-JCYJ-02-40), China National Postdoctoral Program for Innovative Talents (BX20220255) and Chinese Universities Scientific Fund 2452022007.

Conflicts of Interest: The authors declare no conflicts of interest.

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