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Impacts of Land-Use Change from Primary Forest to Farmland on the Storage of Soil Organic Carbon

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Abstract: Land-use change (LUC) is a significant contributor to the increase in atmospheric CO₂ concentrations, with previous studies demonstrating its profound impact on soil organic carbon (SOC). The conversion of primary forests to farmland has been recognized as the most significant type of LUC inducing CO₂ release from the soil. Therefore, it is critical to understand the impacts of forest LUC on SOC storage, with a particular focus on primary forest to farmland conversion. In this study, we conducted a meta-analysis of 411 observations from 41 published works and found that SOC storage decreased significantly following the conversion of primary forests to farmland. Factors such as soil depth and climate zone influenced the degree of SOC storage loss, with SOC loss being less severe in deeper soil following a conversion from primary forests to farmland. Moreover, the loss of SOC storage was more severe in temperate regions compared to tropical regions. The input and output of surface SOC, changes in soil structure, and increases in atmospheric CO₂ concentrations were significant reasons for the loss of SOC following primary forest to farmland LUC. However, improving tillage methods and implementing sustainable agricultural management strategies can help reduce SOC loss. These findings highlight the importance of sustainable land-use practices in mitigating the negative impacts of forest LUC on SOC storage and the global carbon cycle.

Keywords: primary forest; farmland; soil organic carbon; land-use change; meta-analysis



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1. Introduction

Global warming induced by soaring atmospheric CO₂ is one of the most pressing environmental concerns we face today. Land-use change (LUC) is the second most significant anthropogenic activity contributing to the rise in atmospheric CO₂ levels after the burning of fossil fuels. LUC has a profound effect on the carbon cycle of the terrestrial ecosystem, causing soil carbon pools to become either a “source” or a “sink” of CO₂ [1]. These pools are composed of inorganic and organic carbon, mainly in the form of carbonates, making them relatively stable [2]. Soil organic carbon (SOC) makes up more than half of the soil carbon storage in forest ecosystems and is the primary source of soil CO₂ emission. The content and composition of SOC reflect the level of soil organic matter content and soil fertility, making it critical to evaluate the impact of LUC on SOC storage.

Forests play a crucial role in the carbon cycle of terrestrial ecosystems, serving as the most significant carbon sink and source. With its rich biodiversity and complex structure, forest soil contains a significant portion of global terrestrial carbon storage [3]. The carbon content in forest soil is approximately 2–3 times that of forest biomass and accounts for 73% of global soil carbon [4]. While forest soil is an essential carbon sink, it can also become a

significant carbon source if not adequately managed. For instance, when primary forests are converted to farmland, a previous meta-analysis showed that soil carbon pools can substantially decrease, leading to significant carbon emissions [5]. However, various factors, such as soil geology and climate conditions, can affect soil organic carbon (SOC), resulting in large regional differences in SOC change [6].

Human activities and economic development have led to the conversion of more forests into agricultural land, resulting in significant differences in soil carbon content between the two types of land [7]. Studies have shown that the average soil carbon density in forest ecosystems is 180 Mg/hm², while that of agricultural land is only 116 Mg/hm² [8]. Furthermore, the conversion of forests to farmland can result in substantial soil carbon losses. According to [9], on average, soil carbon can decrease by 20% following forest conversion to agricultural land. Ferreiro-Domínguez et al. (2022) [10] summarized several studies on agricultural reclamation after forest cutting, revealing that the change in soil carbon was +1% to −69%, with an average decrease of 21%. However, some studies have shown that if forests are only temporarily used for farming, soil carbon content may not change much [11]. These conflicting findings suggest that there is a need to better understand the impact of forest land-use change to farmland on soil organic carbon storage [12]. Such an understanding could inform land management practices and improve our understanding of the terrestrial carbon cycle.

We thereby review and analyze the change of SOC storage after primary forests are changed to farmland using meta-analysis. Meta-analysis is a quantitative method for synthesizing research results, enabling the statistical integration of multiple independent experimental results on the same topic. We collected data from 173 published studies to investigate the change of SOC and its driving factors after conversion from primary forest to farmland. This study underscores the originality and significance of our research, providing reference information and theoretical support for an in-depth understanding of the soil carbon cycle in the forest ecosystem.

2. Materials and Methods

2.1. Data

We utilized electronic databases such as CAB Abstracts, Biological Abstract, Web of Science, and Google Scholar to search for relevant documents. Soil texture can influence SOC change by stabilization and protection of organic matter, water holding capacity, aeration, soil temperature, and so on. However, in this study, we focused on the impact of LUC, thus we included literature that reported SOC or soil organic matter (SOM) concentration before and after LUC as well as reserves per unit land area, with specific experimental designs such as paired sites, time series, or retrospective designs. From 173 publications, we collected data on the impact of converting primary forests to farmland on SOC storage across a wide range of regions. For each paper, we compiled information such as the source, first author, year of publication, location information (latitude and longitude), climatic data (mean annual temperature, MAT; precipitation and climatic zones), SOC or SOM concentration, storage per unit land area, soil sample depth, and soil bulk density. We calculated the mean value and standard error of soil organic carbon storage before and after LUC.

As SOC takes years or decades to reach a new equilibrium after LUC, studies of the same land-use type were assumed to have similar soil conditions before LUC. Literature that lacked information on land-use types and soil types were excluded from the analysis. Additionally, studies that did not report time series data for LUC or had observation periods less than 5 years were excluded [7]. We also excluded studies that did not report standard deviations for changes in SOC or SOM before and after LUC. In this study, primary forest refers to natural vegetation that has not been reported or found to have significant human influence, which could be a mixture of trees, understory shrubs, and grasses. Farmland mainly includes annual crops (e.g., corn and beans) and perennial crops (e.g., sugar cane and coffee plantations). According to the above criteria after the filtering,

a total of 411 observations from 41 publications were assembled, and 75% of them report the SOC or SOM storage (see Table S1 in Supplementary Materials). Three reviewers were involved in the screening and inclusion process of the literature, ensuring the reliability of the results.

2.2. Data Processing

For the data reported SOM concentration, it is converted into SOC storage by the equation [13,14] as follows:

$$SOC = SOM \times 0.58 \quad (1)$$

Here, SOC is soil organic carbon storage (Mg/ha), and the unit is SOM (storage of soil organic matter) (Mg/ha).

For studies that reported only SOC concentrations, SOC storage was calculated using the following formula [15]:

$$SOC = SOC_c \times BD \times \Delta H \times 10^{-1} \quad (2)$$

In the formula, SOC is soil organic carbon content (g/kg), BD is soil bulk density (g/cm³), and ΔH is soil sample thickness (cm).

In the collected research data, unless the authors of the original data reported the soil bulk density of each soil sample depth before and after LUC, SOC storage was calculated by using the same soil bulk density at any depth.

According to Equation (2), the soil bulk density BD before and after the LUC needs to be known to calculate SOC storage, but some of the collected data lack BD. In this study, based on the existing data set, the average estimated value of BD was obtained by using the doubly truncated normal distribution random vector Monte Carlo simulation [16] to replace the real value (10,000 iterations). To avoid the distortion of BD value caused by the unboundedness of normal distribution, if the simulation value exceeded the observation range of each land-use type, the simulation value was discarded. Kishchuk et al. (2016) [17] showed that these Monte Carlo simulations had good adaptability for all types of LUC, including the study of converting the estimated volume density into SOC storage, which could greatly reduce the uncertainty of estimation.

2.3. Meta Analysis

In this study, weighted mean difference (MD) and response ratio (RR) were selected as the dependent variables of meta-analysis, and the calculation formula was as follows:

$$MD = \mu_e - \mu_c \quad (3)$$

$$RR = \frac{\mu_e}{\mu_c} \quad (4)$$

In the formula, μ_c and μ_e represent the average SOC storage before and after LUC.

The random effect model (REM) of the single-arm meta-analysis method module of Stata software (version 17.0) was used to achieve a series of operations such as effect size merging, drawing the funnel plot, and linear testing of the symmetry of the funnel plot, and the forest plot was drawn by Origin2022 software. REM was based on the NNHM framework: it was assumed that the meta-analysis included $k = 1, \dots, N$ independent studies, where θ_k is the true value of each independent study, y_k , S_k , and τ^2 are the estimated value, the standard deviation of the estimated value (S_k^2 was the variation of the true effect within the study), and the variation of the true effect between studies, and the total combined effect is μ . The model is divided into two layers. The first layer is the sampling model $y_k \sim N(\theta_k, S_k^2)$, which assumes that y_k obeys the normal distribution of the unknown mean value θ_k and the known standard deviation S_k ; the second layer is the parameter model $\theta_k \sim N(\mu, \tau^2)$, which assumes that θ_k obeys the normal distribution of the mean value μ and the standard deviation τ , where μ is the main parameter of interest and the parameter to be estimated,

and the heterogeneous parameter τ is considered as the annoying parameter. Based on the frequency framework, the parameter μ is estimated by the constrained maximum likelihood estimation parameter estimation method. For this study, MD and RR were the parameters to be estimated. It should be noted that RR should be logarithmized before merging, that is, the logarithm of RR $\ln(RR) = \ln(\mu_e) - \ln(\mu_c)$, in order to make it statistically significant. Assuming that μ_e and μ_c both approximately follow the normal distribution, and both are positive numbers, then the logarithm of the quotient approximately follows the normal distribution, and its mean value is the same as the true mean value of RR .

The specific calculation steps of the effect size in this study are as follows:

- (i) Calculate the absolute change of SOC in each sample of a single study as follows:

$$MD_{mi} = \mu_{e,mi} - \mu_{c,mi} \quad (5)$$

where m represents the i -th sample of the m -th study.

- (ii) Calculate the mean of the absolute change in SOC of a single study as follows:

$$MD_m = \sum_{i=1}^n \frac{MD_{mi}}{n} \quad (6)$$

where n is the sample size of each study.

- (iii) Calculate the variance of the absolute change in SOC of a single study (intra-study variance) as follows:

$$SD_{m,within}^2 = \sum_{i=1}^n \frac{(MD_{mi} - MD_m)^2}{n-1} \quad (7)$$

- (iv) Calculate the standard error of the absolute change in SOC in a single study as follows:

$$SE_{m,within} = \frac{SD_{m,within}}{\sqrt{n_m}} \quad (8)$$

- (v) Estimate the variance between studies as follows:

$$SD_{between}^2 = \left(\frac{1}{k-1} \right) \sum_{m=1}^k (MD_m - \overline{MD})^2 - \frac{1}{k} \sum_{m=1}^k \frac{SD_{m,within}}{n_m} \quad (9)$$

where k is the number of included studies.

- (vi) Thus, the total variance of the absolute change in SOC of a single study is estimated as follows:

$$SD^2 = SD_{between}^2 + SD_{m,within}^2 - 2Cov(SD_{between}^2, SD_{m,within}^2) \quad (10)$$

- (vii) Thus, MD , the absolute change in SOC is estimated as the weighted average as follows:

$$\widehat{MD} = \frac{\sum_{m=1}^k ((1/SD_m^2) \times MD_m)}{\sum_{m=1}^k (1/SD_m^2)} \quad (11)$$

- (viii) Similarly, $\ln(RR)$, the response ratio of the change in SOC after the log is estimated as the weighted average as follows:

$$\widehat{\ln(RR)} = \frac{\sum_{m=1}^k ((1/SD_m^2) \times \ln(RR)_m)}{\sum_{m=1}^k (1/SD_m^2)} \quad (12)$$

- (ix) Accordingly, the change in SOC ratio is calculated as follows:

$$\exp[\ln(RR) - 1] \times 100\% \quad (13)$$

To explore the change characteristics of SOC storage in different soil profile depths and climatic zones after LUC, the data were compiled into sub-datasets of 0–20 cm, 0–30 cm, greater than 30 cm, and full depth (the total sampling depth). Tropical and temperate zones were determined according to the soil sampling depth and the climatic type of the experimental site. Stata and R software (version 4.3.2) were applied to meta-analysis and statistical analysis, and bias analysis was conducted by creating a funnel plot using R software.

2.4. Publication Bias

Egger's publication bias test is one of the commonly used methods for assessing publication bias in meta-analysis. It is based on the principle of regression analysis, examining the relationship between the effect size of studies and their precision (usually standard error) to determine if there is publication bias. If publication bias exists, an asymmetric pattern in the relationship between effect size and precision is typically observed. This study employs Egger's publication bias test to conduct a publication bias assessment (Egger's publication bias test, Figures 1 and 2).

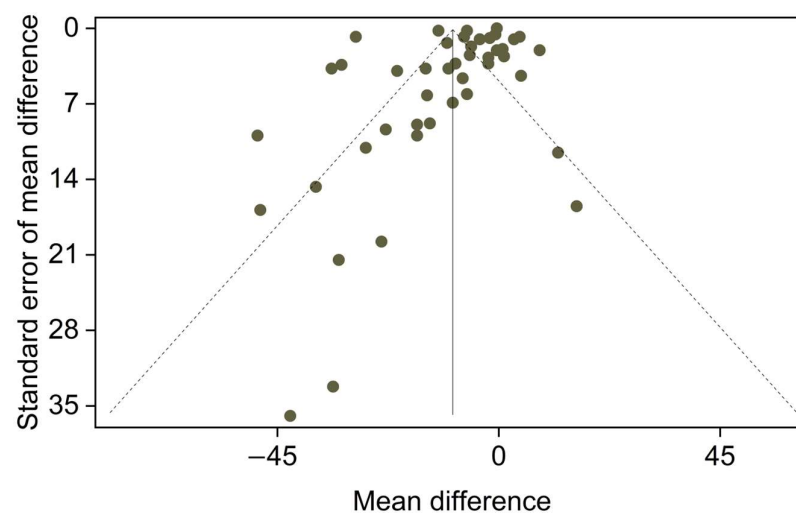


Figure 1. Funnel plot of analysis results with pseudo 95% confidence limits.

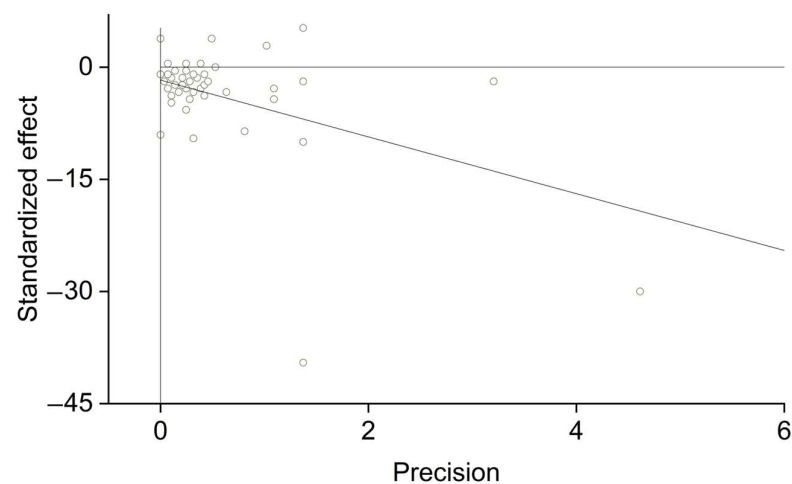


Figure 2. Symmetry test of funnel plot by Egger's publication bias method.

3. Results

3.1. Changes in SOC Storage after Primary Forest Converted to Farmland

The results (Figure 3a,b) showed that the SOC storage decreased by 8.69 Mg/ha, corresponding to a decrease of 26.3% ($p < 0.05$). According to the climate zone, the SOC storage in the tropical region decreased by 6.70 Mg/ha, and the ratio decreased by 23.6% ($p < 0.05$). The SOC storage in temperate regions decreased by 12.09 Mg/ha, and the ratio decreased by 30.6% ($p < 0.05$).

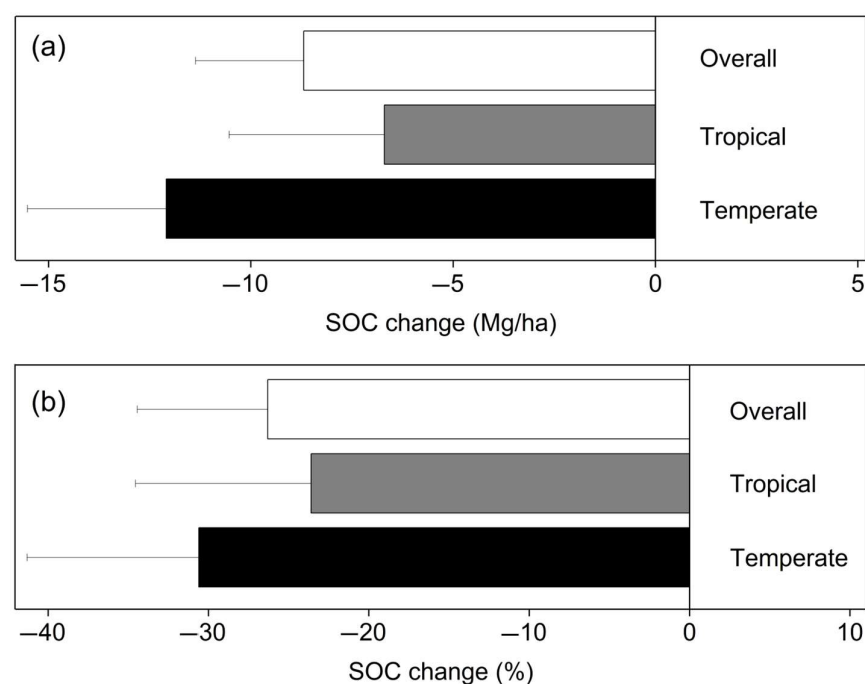


Figure 3. (a) Changes of absolute SOC storage in different climatic zones. (b) Percentage of SOC storage changes in different climate zones.

The depth analysis of different soil profiles (Figure 4a,b) shows that the SOC storage of the 0–20 cm soil profile was the most affected after the primary forest changed to farmland. The absolute amount decreased by 10.45 Mg/ha, and the ratio also decreased by 31.6% ($p < 0.05$). In the 0–30 cm soil profile, SOC storage decreased by 8.97 Mg/ha, and the ratio decreased by 28.2% ($p < 0.05$). For the soil depth above 30 cm, SOC storage changed the

least; the absolute amount decreased by 7.22 Mg/ha, and the ratio decreased by 10.1% ($p < 0.1$).

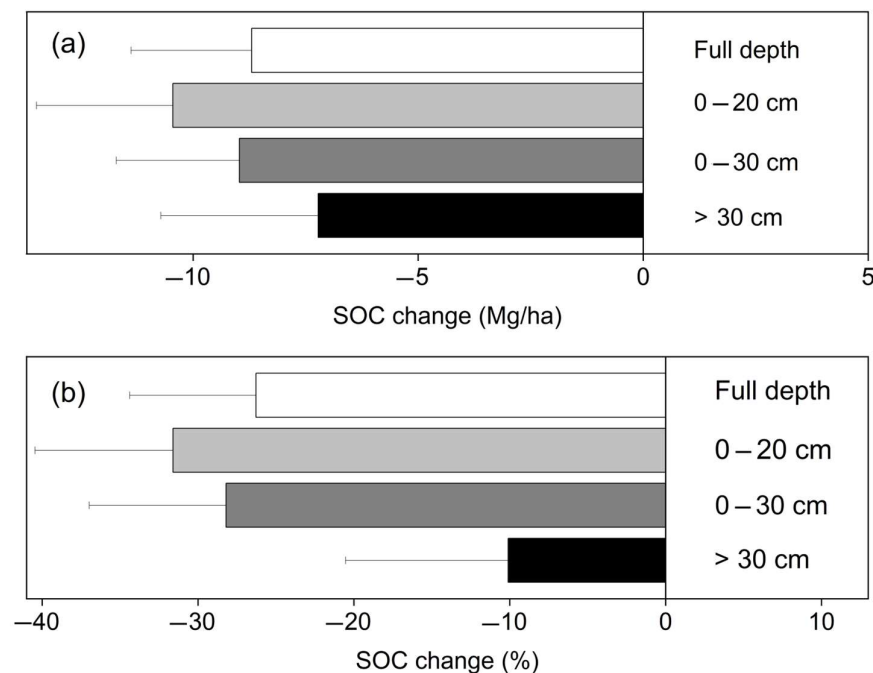


Figure 4. (a) Changes of absolute SOC storage in soil profiles at different sampling depths. (b) Percentage of SOC storage changes in soil profiles at different sampling depths.

3.2. Influencing Factors of SOC Storage Change

When primary forests are converted to farmland, soil organic carbon declines rapidly. Different climatic zones have different degrees of impact on SOC loss. SOC storage in tropical areas decreased by 6.70 Mg/ha, and the ratio decreased by 23.6% ($p < 0.05$). However, SOC storage in temperate regions decreased by 12.09 Mg/ha, and the ratio decreased by 30.6% ($p < 0.05$), that is, the variation of SOC storage in tropical regions was less than that in temperate regions.

The conversion of primary forest to farmland caused significant changes in SOC storage in soils at different depths. The differentiation degree of SOC storage in the surface layer (0–20 cm) was the highest, followed by the middle layer (20–30 cm), and the bottom layer (above 30 cm) was the lowest.

4. Discussion

4.1. The Relationship between SOC Storage and Climate

Conversion of primary forests to farmlands typically leads to rapid depletion of soil organic carbon. The extent of SOC loss varies depending on factors such as soil sampling depth and climate zone, with tropical areas experiencing less loss than temperate areas. However, the mechanisms underlying SOC stability under different climatic conditions remain unclear and are thought to involve complex interactions among carbon sources, soil structure, environmental factors (e.g., temperature, precipitation, topography), and microbial activity [18]. Higher temperatures and humidity usually accelerate the decomposition of organic matter and the activity of microorganisms, which may lead to a decrease in SOC. However, in certain circumstances, extreme drought or cold conditions can also limit microbial activity and the rate of organic matter degradation, thereby promoting the accumulation of SOC. Climate is one of the key factors influencing the storage capacity of soil organic carbon, primarily achieved through modulation of the soil microbial community. Climate conditions also directly impact the growth status of vegetation, thus affecting the amount of external organic carbon entering the soil. Additionally, temperature and

humidity conditions influence the rate of decomposition of organic matter and the migration process of organic compounds within the soil [19]. Gaining a deeper understanding of the interactions and mechanisms between climate and SOC is of great significance for understanding soil carbon cycling and addressing climate change. Further research can reveal patterns of SOC dynamics under different climate conditions, providing scientific foundations for the development of effective soil management and conservation strategies.

4.2. The Correlation of Soil Sample Depth and SOC Storage

The loss of SOC storage is relatively less in deeper soil. The conversion of primary forests to farmland not only directly affects the content and distribution of SOC at different soil depths but also indirectly affects them through factors that influence the formation and transformation of SOC. This conversion can also change the decomposition rate of SOC, with the decomposition of SOM accelerated in the surface soil due to the strong disturbance of mechanical tillage by humans, leading to a low SOC content in the surface soil [20]. Additionally, the application of fertilizers after conversion can also have a certain impact on the topsoil. According to relevant studies, fertilization has an effect on SOC with soil depth [21]. In contrast, microorganisms play a crucial role in determining SOC content in deeper soil layers. The amount of soil microorganisms reflects the soil's assimilation and mineralization ability and constitutes a vital source of SOC in deep soil [22]. Microbial activity is also responsible for the decomposition of plant residues, contributing to the replenishment of SOC stocks.

4.3. Effect of Carbon Input and Output on SOC Storage

SOC storage is the result of a dynamic balance between the amount of plant residues entering the soil and decomposition. Tilling, which involves periodic stirring and mixing of soil, mechanically removes organic carbon from the surface soil, reducing its input. Additionally, farmland soil, which contains a low proportion of insoluble substances in easily degradable crop residues, can enhance SOC mineralization through planting. Under suitable soil moisture conditions, microorganisms in farmland soil will fully contact organic residues in the soil, exposing wrapped carbon to degrading enzymes and accelerating soil mineralization. Incineration of crop residues is also a major cause of reduced SOC storage, particularly in tropical areas. Incineration is a common farmland management measure that emits greenhouse gases into the atmosphere and leaves inert carbon components in the soil.

4.4. Effect of Soil Structure on SOC Storage

Soil aggregates are the basic building blocks of soil structure and play a crucial role in protecting SOC, which is a key factor in SOC fixation. Tillage, however, can be detrimental to soil structure, disrupting aggregates and altering soil temperature and moisture levels, leading to accelerated oxidation and mineralization and resulting in a decrease in organic matter content [23]. Several studies [24,25] have shown that, compared to intensive tillage, conservation tillage or no-tillage practices can provide better physical protection for carbon components, resulting in greater accumulation of soil organic carbon. For instance, Elliott (1986) [26] proposed that macro-scale polymers (particle size > 250 µm) contain more unstable SOC and are easily lost under high disturbance. Zheng et al. (2022) [27] estimated that conversion to conservation tillage could sequester about 43 tons of carbon annually in farmland soil across Europe, suggesting that a transition to no-till practices could offset all fossil fuel carbon emissions in European agriculture. Additionally, residue and mulch cover can reduce soil erosion and evaporation and improve soil aggregate stability [28]. Consequently, soil aggregates, soil organic matter content, and soil physical properties all influence soil structure, thus affecting SOC.

4.5. Dynamic Effects of the Growth Environment on SOC

Land tillage can rapidly impact SOC, highlighting the need for appropriate agricultural management to enhance soil carbon sequestration capacity. Tillage affects not only the total carbon pool but also the microbial carbon pool, which can alter soil fauna and metabolic rates [29]. To increase SOC storage and SOM accumulation, management measures such as returning farmland to forests, nutrition management, irrigation management, grazing management, rational use of cover crops and grasses, and introducing beneficial soil organisms such as earthworms can be employed. Secondly, nutrient management and irrigation management can adjust the soil nutrient status and water supply, which is beneficial for crop growth and the accumulation of organic matter. At the same time, grazing management can improve the ecosystem function of grasslands and promote the accumulation of soil organic matter through appropriate grazing intensity and rotational grazing system. Additionally, proper utilization of cover crops and grasslands can increase the input of organic matter to the soil surface and protect the soil from erosion. Finally, introducing beneficial soil organisms such as earthworms and other soil microbes can improve soil structure and aeration, promoting the decomposition and transformation process of soil organic matter.

4.6. Effects of Tillage and No-Tillage on SOC Reserves in Cultivated Land

When the virgin forest was converted to cultivated land system, soil organic carbon decreased rapidly, partly due to the low proportion of insoluble substances in the easily decomposed crop residues. Cultivated soil enhances the mineralization of SOC through cultivation and releases CO₂ into the atmosphere. Tillage requires periodic mixing of the soil, which destroys soil aggregates and produces carbon compounds that cannot be decomposed by microorganisms. Incineration of crop residues is also a major cause of the reduction of SOC storage, especially in tropical regions. Incineration of crop residues is a common management measure of cultivated land systems. This process emits various greenhouse gases into the atmosphere, leaving inert components such as charcoal as residual substances in the soil. Skjemstad et al. (2002) [30] reported that, in fire-prone ecosystems, charcoal produced by incomplete biomass combustion may account for about 35% of the total organic carbon. The study of Zech et al. (2001) [31] also showed that an important reason for the reduction of SOC storage caused by crop cultivation in cultivated soil is that incineration measures separate a large number of soil organic carbon components from the organic carbon pool into intractable carbon, which accounts for a very large proportion of the total organic carbon pool in the soil. Tillage is a major soil management practice that alters soil structure, leading to the destruction of soil aggregates, increasing soil compaction, and disrupting soil plant and animal communities. Soil structure is defined as the size, shape, and arrangement of solids and voids. Void and pore spaces in turn regulate the flow of fluids in the soil and the growth and development of plant roots. Intensive tillage alters soil structure and affects soil organic carbon. Tillage promotes the mineralization of organic carbon, and the optimal soil moisture conditions for mineralization allow organic residues to be fully exposed to microorganisms, exposing the encapsulated carbon to degrading enzymes. There is also a strong interaction between tillage and drainage, both of which reduce soil moisture and increase soil temperature, thereby reducing SOC mineralization rates. Echeverria et al. (2000) [32] found that the timing and intensity of tillage determined the extent of its impact on SOC. Compared with intensive tillage, no-till crop management systems have relatively more macropores, biological pathways, stable soil aggregates, and more SOC sequestration. The positive effects of no-till or disturbance-reduced tillage on soil sequestration depend on the specific soil and location, for example, in poorly drained soils and fine-textured soils, which are inconsistent with the general increase in SOC. In contrast, studies in North America, Brazil, Argentina, and Europe have reported high levels of carbon sequestration in soils under conservation tillage. Tillage systems with low disturbance usually result in the release of easily degraded organic matter substrates. Six et al. (2004) [33] reported that conservation or no-till soils provided more

physical protection of carbon components than intensively tilled soils, thereby promoting carbon accumulation. Elliott (1986) [26] proposed that macroscale polymers (particle size > 250 µm) contain more unstable SOC, which his research found was easily lost under high disturbance. Smith et al. (1998) [34] estimated that conservation tillage could sequester about 43 tons of carbon per year in the soils of cultivated systems in the EU, and they proposed a shift to no-till for all tillage practices to offset all fossil fuel carbon emissions from European agriculture. Similar to tillage, crop residue management and mulching change soil structure through a variety of processes and methods. Adding residues and mulch can reduce erosion and evaporation, protect soil from rainwater, and improve the stability of soil aggregates. Other studies have shown that mulch can improve SOC pools, change humidity and temperature conditions, and affect soil fauna and flora. With the addition of plant residues, the increase in SOC pools is mainly determined by the quality and quantity of residues and mulch added to the soil.

4.7. Effects of Continuous Cropping and Fallow on SOC Stocks in Cultivated Land

In order to evaluate the impact of increasing CO₂ concentration in the growing environment of crops due to continuous cropping on SOC dynamics, Srinivasarao et al. (2016) [35] conducted an experiment in Hyderabad, India. Using an open top chamber (OTC) experimental design, they measured the unstable carbon, stable carbon, total carbon, instability index (LI), carbon pool index (CPI), and carbon management index (cmI) of sorghum, pearl millet, sunflower, peanut, cowpea, black bean, and castor bean in three environmental conditions (CO₂ levels were 380 ppm, 550 ppm, and 700 ppm, respectively) after five years (2005–2010) and after planting these crops in open land and in a fallow plot at the depths of 0–0.2 m, 0.2–0.4 m, and 0.4–0.6 m. The results showed that, compared with the fallow condition, the highly unstable carbon, the unstable carbon, and the stable organic carbon components in the depth range of 0–0.4 m increased with the increase in CO₂ level. However, the increases in unstable carbon, stable carbon, and total carbon components at the same depth peaked at the CO₂ level of 550 ppm and decreased until 700 ppm. LI, CPI, and cmI are sensitive indicators of SOC changes due to land use change and management practices. According to Bona et al. (2008) [36], cmI values greater than 100 and less than 100 indicate positive and negative impacts of land use and management practices on SOC changes, respectively, while low CPI values indicate SOC loss. Such experimental results mean that excessive environmental CO₂ levels have a negative impact on soil quality and soil carbon sequestration capacity. After 30 to 50 years of cultivation, SOC loss in the surface soil (0–0.20 m) is as high as 50%, and SOC loss in the upper 1 m soil is about 30%. Such large and relatively rapid changes in soil organic carbon caused by land cultivation indicate that appropriate agricultural management can improve soil carbon sequestration capacity, thereby reversing the negative impact of crop cultivation on soil organic carbon pool. Crop cultivation reduces the size of total carbon pool and microbial carbon pool and affects soil fauna but increases metabolic CO₂. Management measures to improve SOC reserves and organic matter accumulation include returning farmland to forest, nutrition management, irrigation management, grazing management, rational use of cover crops and grasses, and the introduction of beneficial organisms to soil such as earthworms.

4.8. Differences in SOC Storage among Different Cultivating Systems

Srinivasarao et al. (2009) [37] investigated the effects of crop production systems on different SOC components in India, where crops were grown in different climates and soil types. They studied eight production systems: cultivation systems based on lowland rice, sorghum, maize, pearl millet, teosinte, soybean, peanut, and cotton. They found that SOC storage was highest under soybean-based production systems (62.3 Mg/ha), while the lowest SOC storage was found under pearl millet and teosinte-based production systems. The inorganic carbon storage (SIC) was highest under cotton production systems (275.3 Mg/ha), followed by sorghum production systems (243.7 Mg/ha), while the lowest SIC storage was found under lowland rice production systems (18.15 Mg/ha). Differences

in carbon component changes under different crop production systems can be attributed to climate, aboveground and belowground biomass, root–stem ratio, quality of root and stem biomass (e.g., cellulose, protein, polyphenols, and lignin), decomposition rate, and soil characteristics.

5. Conclusions

Through the comprehensive analysis of SOC storage changes after the conversion of primary forest to farmland, the main conclusions are as follows:

1. After the conversion of primary forests into farmland, there is a significant decrease in the storage of soil organic carbon (SOC). This indicates that land use change has a significant impact on SOC content. Primary forests are complex and stable ecosystems that contain a large amount of organic carbon in the soil. However, once the primary forests are cleared for agriculture, the soil is exposed to the atmosphere and human activities, resulting in an accelerated decomposition rate of SOC and a sharp decline in SOC storage.
2. When primary forests are converted into farmland, temperate forests experience greater loss of SOC compared to tropical forests, while the loss of SOC in deeper soil layers is relatively smaller. This suggests that the extent of SOC loss after land use change depends on the type of forest and the soil depth. Temperate forests and tropical forests differ in soil characteristics, climate conditions, and vegetation composition. Therefore, after temperate forests are converted into farmland, the influence of climate change and soil characteristics leads to a more significant loss of SOC. Additionally, SOC decomposition rates are relatively slower in deeper soil layers, resulting in less severe SOC loss compared to shallow soil layers.

The findings of these conclusions help us understand the dynamics of SOC changes after the conversion of primary forests into farmland and provide scientific guidance for agricultural management and land conservation. During the process of land conversion into farmland, implementing soil conservation measures, adopting appropriate fertilization and nutrient management strategies, selecting suitable cultivation methods, and promoting ecosystem restoration can help reduce the rate of SOC loss, promote soil health, and achieve sustainable agricultural development.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/app14114736/s1>, Table S1: List of studies included in this meta-analysis.

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Abbreviations

LUC	Land-Use Change
SOC	Soil Organic Carbon
SOM	Soil Organic Matter
BD	Soil Bulk Density
MD	Weighted Mean Difference
RR	Response Ratio
REM	Random Effect Model

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