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Litter Quality and Soil Microorganisms Mediate Reduced Litter Decomposition Following Understory Vegetation Removal in Forest Ecosystems

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Abstract

Understory vegetation is a critical component of forest ecosystems. Its removal can substantially alter litter decomposition processes, with cascading effects on carbon (C) and nutrient cycling in terrestrial ecosystems. However, the global response patterns of litter decomposition to understory removal and underlying controlling factors remain unclear. We conducted a meta-analysis of 330 observations from 29 peer-reviewed field litterbag studies to assess the effects of understory removal on litter decomposition. We evaluated the changes in decomposition rate, mass loss, and nutrient dynamics to quantify the impacts of understory removal on litter decomposition. We assessed the associated shifts in soil microbial communities, measured using phospholipid fatty acids (PLFAs), to examine how microbial responses mediate decomposition during understory removal. We examined whether canopy type moderated these responses and explored the key predictors of decomposition for understory removal. Understory removal significantly reduced litter decomposition rate and mass loss by an average of 29.6% and 14.8%, respectively, while increasing lignin remaining by 30.1%. Soil microbial biomass also declined, with total, fungal, and actinomycete PLFAs decreasing by 12.0%, 30.8%, and 27.5%, respectively. Across canopy types, understory removal decreased litter mass loss in both broadleaved and coniferous forests. However, the remaining N and P increased significantly in broadleaved forests but changed only marginally in coniferous forests. Random forest analysis showed that initial litter quality and variations in fungal biomass were the primary predictors of decomposition responses. Understory vegetation removal significantly suppresses litter decomposition by reducing fungal biomass, and interacting with litter quality constraints and canopy type strongly moderates these effects. This highlights the essential role of understory vegetation in sustaining nutrient cycling and microbial functioning in forest ecosystems and underscores its critical role in guiding sustainable forest management.

Keywords: meta-analysis; understory removal; litter mass loss; phospholipid fatty acids

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1. Introduction

Although it comprises a relatively small fraction of total forest biomass, understory vegetation is a critical component of forest ecosystems [1,2]. It regulates forest structure

and regeneration and plays a pivotal role in shaping heterogeneous microenvironments and driving nutrient cycling [3,4]. As a widely implemented forest management measure, understory removal is commonly applied in both natural forests and intensively managed plantations. In natural forests, this practice is often used to reduce fuel loads and lower wildfire risk, to facilitate tree regeneration, or to manipulate vegetation composition for conservation or restoration objectives [5]. In commercial plantations, understory removal is primarily conducted to minimize competition for resources between trees and understory vegetation and improve stand productivity [6,7]. However, the lack of understory vegetation is typically associated with negative effects on soil fertility and microbial community structure [8–11]. These are closely linked to plant litter decomposition processes. Therefore, changes caused by understory removal substantially alter litter decomposition, with consequences for carbon cycling and functioning in terrestrial ecosystems [12–14]. Therefore, a better understanding of the underlying drivers and mechanisms that regulate litter decomposition responses to understory removal is essential for sustaining forest ecosystem structure and function.

Litter decomposition is a critical process that regulates soil organic matter formation, nutrient availability, vegetation community composition, and forest productivity [15,16]. The effects of understory removal on litter decomposition have been extensively examined. Understory removal may inhibit litter decomposition by altering the forest microclimate, decreasing nutrient inputs from understory litter and root exudates, and diminishing microbial biomass and diversity [17–19]. However, the findings remain inconsistent across forest ecosystems. Understory removal suppresses litter decomposition, primarily because of shifts in soil microbial community composition [20,21], or alterations in microenvironmental conditions [14,22]. In contrast, understory removal can accelerate litter decomposition, owing to increased nutrient availability and altered soil resource allocation [23,24]. Matsushima and Chang [25] suggested that understory removal has only marginal or negligible effects on the litter decomposition rate. These contrasting results highlight the complex and context-dependent role of understory vegetation in regulating litter decomposition and the associated nutrient cycling processes. Therefore, a synthesis of litter decomposition experiments under understory removal is necessary to determine the effects on decomposition and to elucidate the underlying ecological mechanisms.

Aboveground and belowground communities are tightly interconnected, and these linkages play a critical role in regulating ecosystem functions [26,27]. Therefore, removing understory vegetation from the aboveground communities likely has a substantial impact on the belowground communities. Understory removal can alter the availability and quality of organic carbon inputs to soil microbes, leading to bottom-up regulation of microbial communities [10]. However, the evidence remains inconsistent. Soil microbial biomass can increase [19,28], decrease [29,30], or remain unchanged [31] following understory vegetation removal. Owing to the differences in survival strategies and nutritional preferences between bacterial and fungal communities [32,33], they often have divergent responses to understory removal. Soil microbes are key biotic drivers of litter decomposition [34,35]. However, it remains unclear whether changes in litter decomposition following understory removal are primarily mediated by shifts in microbial communities. Although the effects of understory removal on litter decomposition and soil microbes have been examined, contrasting outcomes have limited general conclusions on the role of microbial dynamics in regulating decomposition at broader spatial scales [36,37]. This knowledge gap highlights the need for large-scale investigations that integrate microbial community responses with decomposition processes to better elucidate the mechanisms by which understory vegetation removal influences forest C cycling.

To address these inconsistencies and improve our understanding of how litter decomposition responds to understory vegetation removal, we conducted a global meta-analysis of 330 observations extracted from 29 peer-reviewed articles across natural terrestrial ecosystems (Figure 1). All of the included articles reported the effects of understory removal on litter decomposition processes. Our objectives were to (1) quantify the response of litter decomposition to understory removal on a global scale, (2) evaluate whether litter decomposition responses vary according to canopy type, and (3) examine the potential relationship between litter decomposition responses and changes in soil microorganisms under understory removal. We hypothesized that (1) the removal of the understory would suppress litter decomposition, (2) the magnitude of these effects is context-dependent, varying with canopy type, and (3) alterations in soil microbial biomass and community composition represent the primary mechanisms driving this reduction.

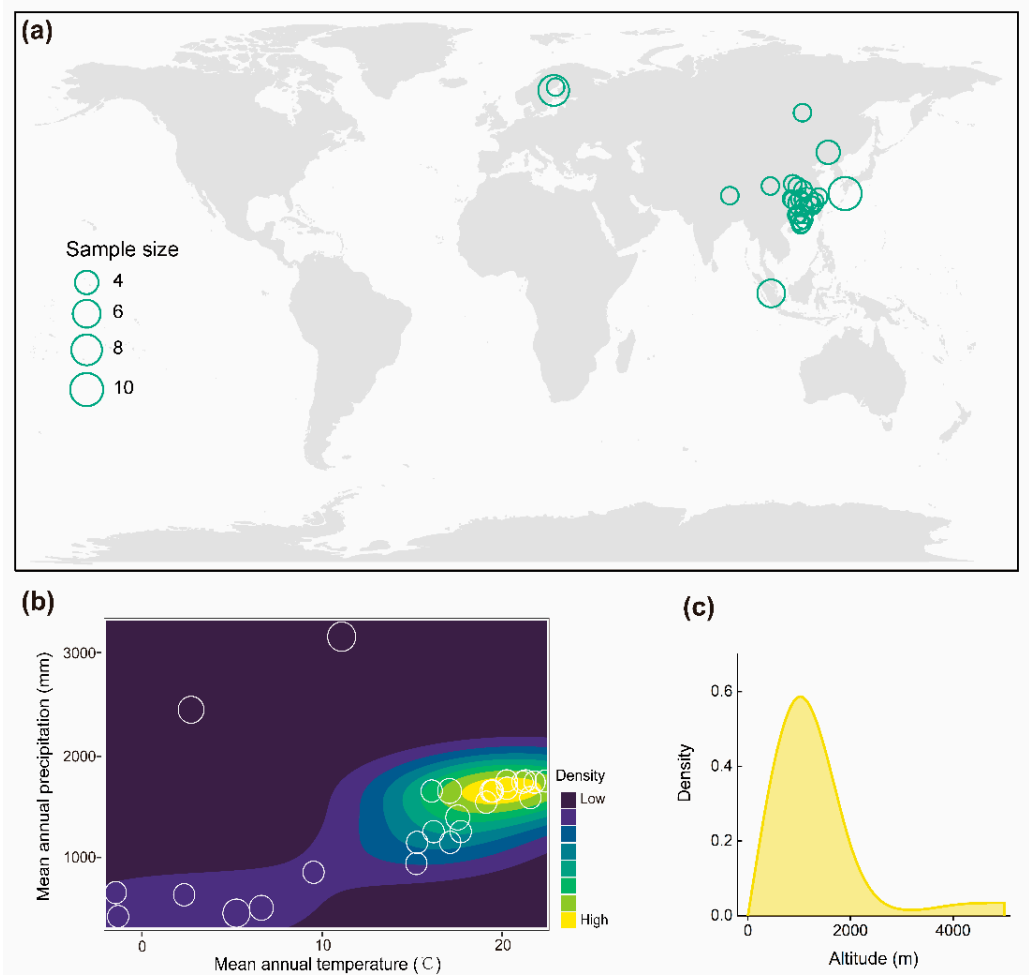

Figure 1. Characteristics of the study sites selected for the meta-analysis. (**a**) Distribution of study sites at the global scale, (**b**) mean annual temperature and precipitation of study sites, and (**c**) density observed by altitude of study sites.

2. Materials and Methods

2.1. Data Compilation

Peer-reviewed articles included in this meta-analysis were retrieved from the Web of Science (http://apps.webofknowledge.com/, accessed on 1 July 2025) and China National Knowledge Infrastructure (https://www.cnki.net/, accessed on 20 July 2025)). We synthesized studies that examined the effects of understory vegetation removal on litter decomposition using the following search string:

("understory vegetation removal" OR "understory vegetation management" OR "vegetation removal" OR "understory thinning") AND (decomposition OR decay OR breakdown OR processing) AND (litter OR leaf OR foliar OR needle)

All the relevant studies included in this meta-analysis were published before July 2025.

Subsequently, we screened titles, abstracts, and conclusions to identify studies that met the following criteria:

(1) Only field experiments were included in this meta-analysis. Laboratory incubations and model-based predictions were excluded to ensure ecological relevance and comparability of the results.
(2) Studies should be designed to incorporate a control retaining understory vegetation and a treatment from which it is removed, with all abiotic and biotic conditions held constant between the groups throughout the experimental period. For experiments involving multiple drivers with shared control, we extracted data only from the understory presence and absence treatments to avoid potential confounding effects.
(3) Only studies that used the litterbag method were included to minimize methodological bias. The initial litter mass and litter type are reported.
(4) At least one decomposition metric, for example, litter mass loss, decomposition rate, residual C, N, P, or lignin, must be reported for a defined period. The decomposition rate coefficient k is generally calculated using the single exponential model [38]:

$$(litter\ mass\ remaining/initial\ mass) = e^{-kt} \quad (1)$$

where t is decomposition time. According to this model, litter mass loss could be used as a proxy for decomposition rate in subsequent analyses.
(5) For each variable, mean values, variability estimates (standard deviation or error), and sample sizes were necessary, and these could be directly reported or extracted from published figures, tables, or supplementary data. When data were presented graphically, Web Plot Digitizer 4.6 (https://automeris.io/WebPlotDigitizer, accessed on 1 August 2025) was used to extract the values.

Given that litter decomposition is strongly associated with soil microbial communities [39], we also extracted data on soil microbial biomass from these included peer-reviewed articles when available using PLFA analysis. We categorized these data into total, fungal, bacterial, and actinomycete PLFAs.

Moderator variables considered included geographic factors (latitude and elevation), climate (mean annual temperature (MAT) and mean annual precipitation (MAP)), stand characteristics (age, density, diameter at breast height, and canopy type (broadleaved, coniferous, or mixed)), ecosystem type (primary forests and plantations), experimental duration, and edaphic characteristics (pH, moisture, C, and N contents). These variables were used to evaluate the impact of moderator variables on the effects of understory vegetation removal on litter decomposition. If MAT or MAP were unavailable, they were extracted from the WorldClim database (https://www.worldclim.org/, accessed on 10 August 2025).

In total, 330 paired observations were compiled from 29 articles, all of which were conducted in forest ecosystems (Table S1). Among these, 24.1%, 72.4%, and 3.4% of the experiments were conducted in broadleaved, coniferous, and mixed forests, respectively. Stand ages ranged from 2 to 160 years. Study sites spanned latitudes from 0.92° N to 63.82° N, with MAT ranging from –2.0 °C to 22.5 °C and MAP ranging from 256 mm to 3278 mm (Figure 1). Altitude ranged from 36 to 4640 m, with 93.1% of study sites located between 36 and 1400 m (Figure 1c). These ranges encompass diverse climatic

and topographic conditions, ensuring a broad representation of forest ecosystems across temperate and tropical regions.

2.2. Statistical Analysis

We quantified the effect of understory removal on litter decomposition using the natural logarithm response ratio (ln *RR*) as the effect size [40]. For each pair of control (with understory) and treatment (without understory), ln *RR* was calculated as follows:

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

where $\overline{X}_t$ and $\overline{X}_c$ are the mean values for the control and treatment groups, respectively.

The variance (v) associated with each ln *RR* was estimated using:

$$v = \frac{S_t^2}{n_t \overline{X}_t^2} + \frac{S_c^2}{n_c \overline{X}_c^2} \quad (3)$$

Here, $\overline{X}_t$, S_t, and n_t denote the mean, standard deviation, and sample size of the treatment group (t), while $\overline{X}_c$, S_c, and n_c refer to the corresponding values for the control group (c).

To assess whether the meta-analytic dataset was representative, publication bias was examined using Egger's regression test [41], with funnel plots constructed from ln *RR* values and their variances. The analysis revealed no significant bias, supporting the reliability and comprehensiveness of the compiled studies (Figure S1).

To evaluate whether understory removal had considerable effects on litter decomposition, we performed linear mixed-effects models using the "lme4" package [42]. The natural logarithm of individual ln *RR* was fitted as the response variable, and the identity of the study and plots nested inside study identity were included as the random effect factors. The reciprocal of the variance (v) was used as a weighting factor to calculate the overall weighted effect size (ln RR_{++}) and its bias-corrected 95% bootstrap-confidence interval (CI).

To facilitate interpretation of the results, the percentage change (%) was calculated using ln RR_{++} and the corresponding 95% CI as follows:

$$\text{Percentage change} = \left(e^{\ln RR_{++}} - 1\right) \times 100 \quad (4)$$

To examine whether the effects of understory removal varied with the context, we applied linear mixed-effects models using ln *RR* as the response variable. Climatic factors (MAT and elevation), litter quality (initial litter mass and litter C and N contents), edaphic conditions (soil initial C/N), and experimental characteristics (duration), were fitted as continuous or categorical fixed effect factors. Meanwhile, study identity was treated as a random effect. We used weighted random forest analysis to assess the relative importance of environmental variables in explaining the significant responses of litter decomposition to understory removal. Predictor importance was evaluated using the percentage increase in the mean square error (%IncMSE). All the statistical analyses were performed using R version 4.5.1 (R Core Team, 2022).

3. Results

3.1. Overall Effects of Understory Removal

Across all the studies, understory vegetation removal significantly reduced the litter decomposition rate and mass loss by an average of 29.6% and 14.8%, respectively. The remaining litter C, N, and P contents, and the C:N, C:P, and N:P ratios, showed no signifi-

cant responses to understory vegetation removal. In contrast, the removal of understory significantly increased lignin content by an average of 30.1% (Figure 2a). Soil total, fungal, and actinomycetes PLFAs significantly decreased by an average of 12.0%, 30.8%, and 27.5%, respectively. Meanwhile, bacteria and the fungi-to-bacteria ratio exhibited marginal changes after understory vegetation removal (Figure 2b).

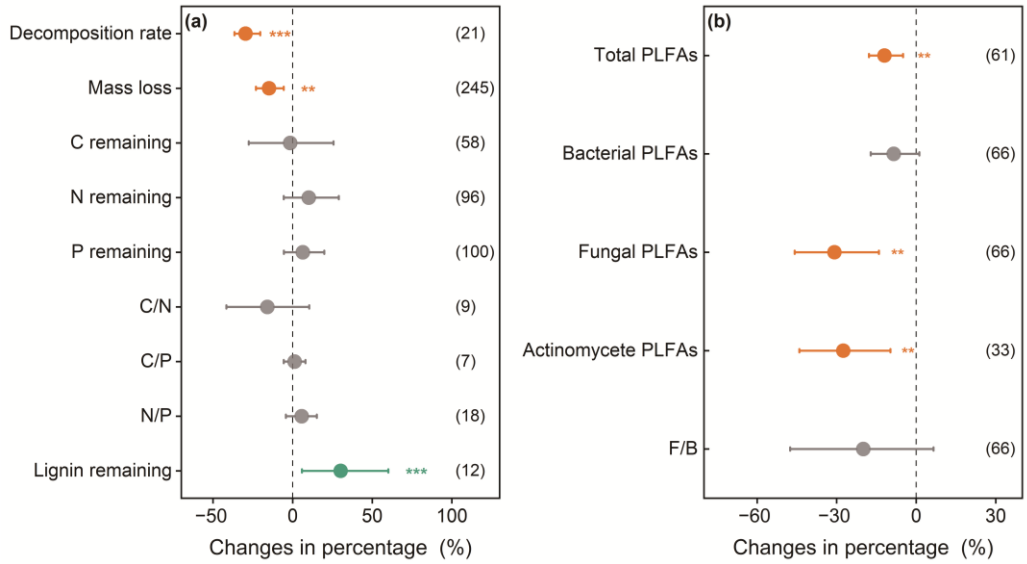

Figure 2. Effects of understory vegetation removal on (**a**) litter decomposition and (**b**) soil microbial communities. Values represent means with 95% confidence intervals (CIs). The number of pairwise observations is shown along the right y-axis. Vertical dashed lines indicate the null expectation (zero effect). Green and orange bars denote significant positive and negative effects, respectively. Levels of statistical significance are indicated as follows: **, $p < 0.01$; ***, $p < 0.001$. C, carbon; N, nitrogen; P, phosphorus; PLFAs: phospholipid fatty acids.

3.2. Variations Among Canopy Types

The effects of understory removal on mass loss and remaining N and P contents during litter decomposition varied significantly among canopy types. Meanwhile, the responses of the litter decomposition rate and C remained largely unaffected (Figure 3a). Understory removal decreased litter mass loss in both broadleaved and coniferous forests but changed marginally in mixed forests. In contrast, the remaining N and P increased significantly in broadleaved forests but changed marginally in coniferous forests. The canopy type also had a strong influence on the response of soil microbes to understory removal (Figure 3b). In coniferous forests, understory removal significantly reduced soil total PLFAs, bacteria, fungi, actinomycetes, and the fungi-to-bacteria ratio by 10.6%–39.2%. In contrast, in broadleaved forests, understory removal significantly increased fungal abundance and the fungi-to-bacteria ratio by an average of 117.4% and 108.2%, respectively, while producing only marginal effects on total, bacterial, and actinomycetes PLFAs.

3.3. Factors Driving the Responses of Litter Decomposition to Understory Removal

Weighted random forest analysis showed that variations in litter mass loss under understory removal were primarily explained by the responses of remaining litter C, total PLFAs, fungal PLFAs, and litter quality related to initial litter C content, N content, and C:N ratios (Figure 4). Consistently, we found that the responses of litter mass loss were negatively correlated with the responses of the remaining litter C, fungal PLFAs, and initial litter C and C:N ratios (Figure 5a,b,d,f). In contrast, the effects of understory removal on litter mass loss were positively correlated with ln *RR* of total PLFAs and initial litter N (Figure 5c,e).

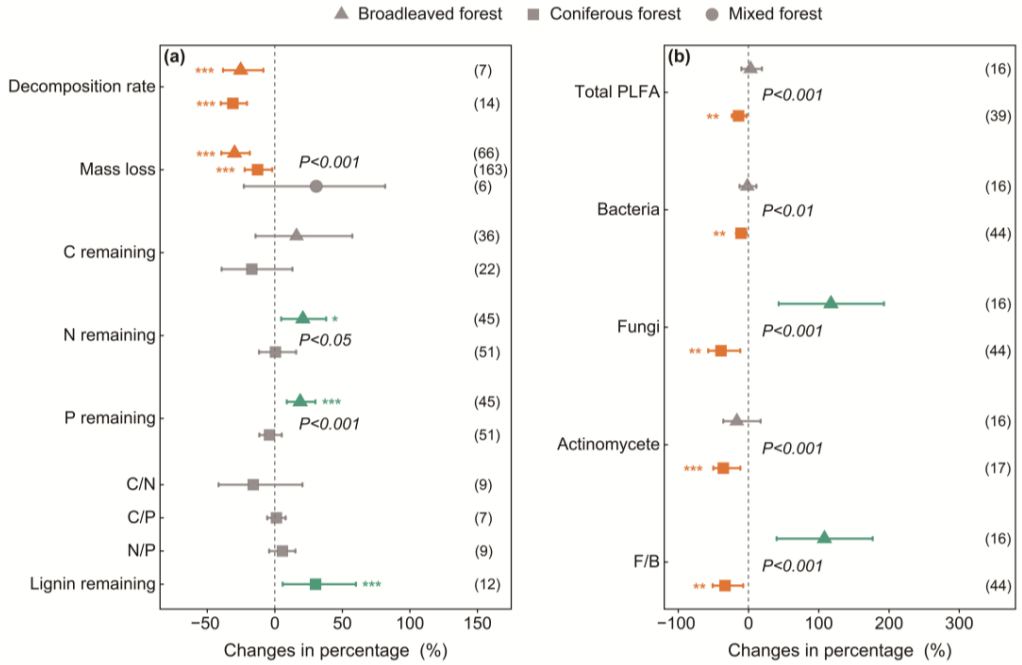

Figure 3. Influences of canopy type on the responses of (**a**) litter decomposition and (**b**) soil microbial communities to understory vegetation removal. Values represent means with 95% CIs, with the number of pairwise observations shown in parentheses. Statistical significances are indicated as follows: *, $p < 0.05$; **, $p < 0.01$; ***, $p < 0.001$. Vertical dashed lines indicate the null expectation (zero effect). Green and orange bars denote significant positive and negative effects, respectively. C, carbon; N, nitrogen; P, phosphorus; PLFAs: phospholipid fatty acids. *p*-values between-group heterogeneity along the right y-axis indicate significant differences in response ratios among canopy types.

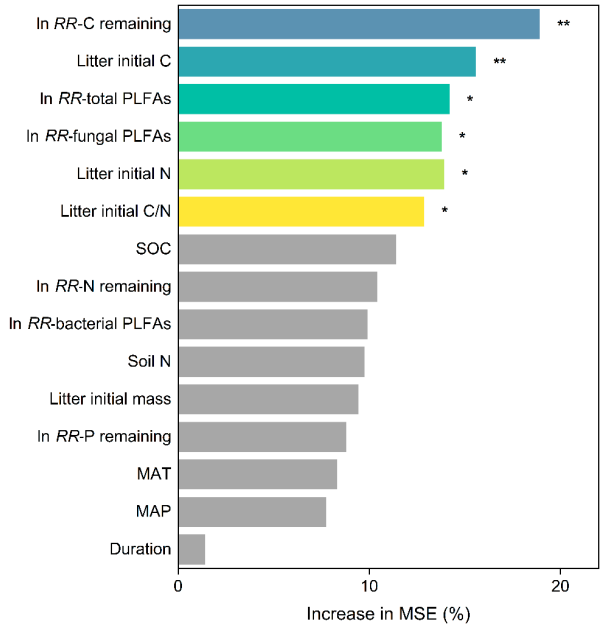

Figure 4. Relative importance of moderator variables influencing the responses of litter mass loss to understory vegetation removal, based on random forest model analysis. Predictor importance was assessed using mean squared error (MSE), with colored bars denoting significant predictors and gray bars denoting non-significant predictors. Statistical significance is indicated as follows: *, $p < 0.05$; **, $p < 0.01$. C, carbon; N, nitrogen; P, phosphorus; MAT: mean annual temperature; MAP: mean annual precipitation; SOC, soil carbon content; PLFAs: phospholipid fatty acids.

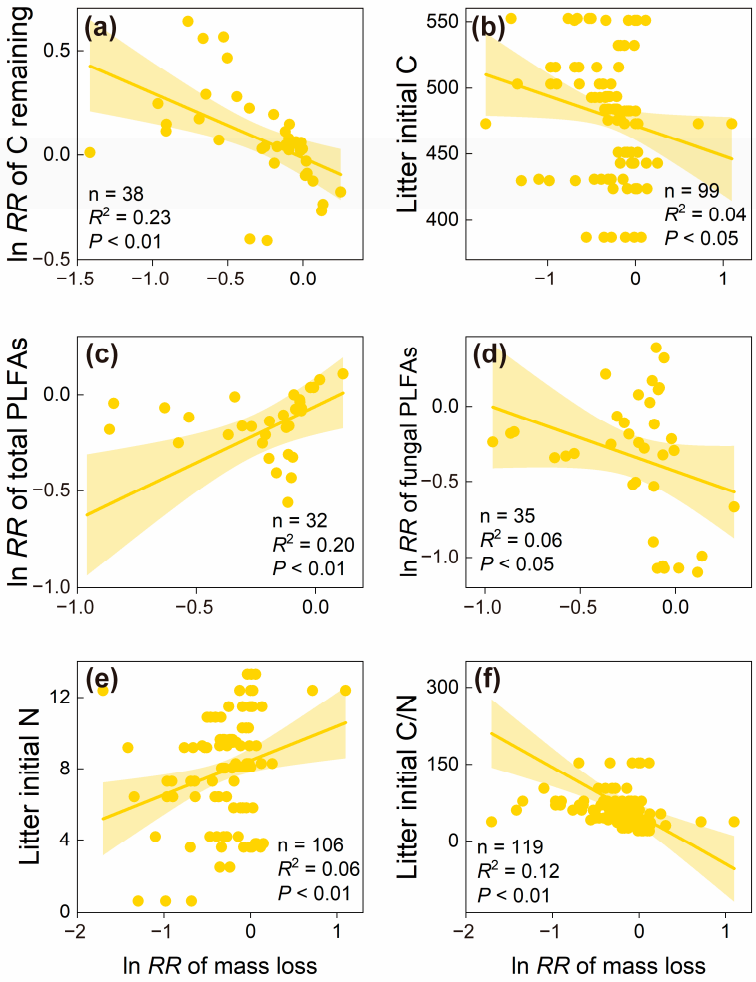

Figure 5. Meta-regression analyses examining the relationships between response ratios (ln *RR*) of litter mass loss and (**a**) ln *RR* of C remaining, (**b**) litter initial C content, (**c**) ln *RR* of total PLFAs, (**d**) ln *RR* of fungal PLFAs, (**e**) litter initial N content, and (**f**) litter initial C:N ratio. Fitted lines represent slopes derived from linear mixed effects, with 95% CI (shaded) shown in each panel. Sample sizes, adjusted R^2 values, and *p*-values are reported with each panel.

4. Discussion

4.1. Effects of Understory Removal on Litter Decomposition and Soil Microorganisms

The results of the meta-analysis demonstrated that understory removal has a strong negative effect on litter decomposition, as shown by a 29.6% reduction in decomposition rate and a 14.8% reduction in mass loss across global forest ecosystems (Figure 2a). The first hypothesis was well supported by this finding. The reduction in decomposition was primarily associated with the increase in lignin remaining. Meanwhile, the remaining nutrients (C, N, and P) remained largely unchanged. This pattern suggests that understory removal constrains the degradation of recalcitrant substrates rather than altering nutrient mineralization processes. The suppression of decomposition during understory removal can be attributed to multiple mechanisms. Understory vegetation contributes fresh and labile organic inputs such as root exudates and litter [43]. This stimulates microbial activity and accelerates the decomposition of more recalcitrant compounds through a priming effect [44]. Removing understory vegetation reduces these inputs, weakening the microbial activity and slowing the degradation of lignin-rich litter. Understory vegetation shapes forest microclimates by buffering soil temperature and conserving soil moisture [18,25]. Its removal likely creates harsher soil conditions that are less favorable for decomposer organisms, further constraining litter decomposition. Although the concentrations of

remaining nutrients in litter were largely unaffected, the reduction in mass loss indicated a slower flux of nutrients from litter to the mineral soil [45]. Consequently, nutrients remain immobilized in undecomposed organic material for extended periods, reducing the rate at which they become available for tree uptake. Over time, this can exacerbate nutrient limitation, particularly in nutrient-poor soils or in fast-growing, high-demand stands. Such delays in nutrient cycling may constrain tree growth and forest productivity, counteracting the intended benefits of understory removal.

Consistent with these interpretations, understory removal significantly altered soil microbial biomass and community composition, a pattern also reported by Zhang et al. [10]. The decline in soil C inputs and nutrient availability following understory removal likely represents the primary driver of reduced total soil microbial biomass [6,46]. Fungi and actinomycetes showed strong declines, whereas bacterial biomass and fungi-to-bacteria ratio exhibited marginal changes (Figure 2b). These findings indicated that soil fungi, which are widely recognized as the primary decomposers of lignocellulose and other recalcitrant substrates [47,48], are disproportionately sensitive to understory removal. This likely accounted for the suppression of lignin degradation observed in our study. Fungal communities are central to long-term soil C turnover and humus formation; their declines may impair soil structural stability, reduce long-term soil fertility, and limit the accumulation of stable soil organic matter. The decline in actinomycetes, another key group of lignocellulose degraders, further supported this conclusion [49,50]. In contrast, bacterial biomass remained largely unaffected, likely reflecting the greater metabolic flexibility and rapid growth strategies, which enabled them to use alternative C sources and adapt more readily to shifting soil conditions [51,52]. The loss of fungi and actinomycetes following understory removal suggested that the functional capacity of soil microbial communities to decompose complex organic matter was substantially reduced, providing a mechanistic explanation for the observed reduction in litter decomposition. These findings highlighted the critical role of understory vegetation in sustaining the soil microbial biomass and community composition in forest ecosystems. Slower decomposition and microbial depletion threaten the long-term sustainability of forest productivity, soil health, and ecosystem resilience. Therefore, foresters should carefully consider the potential trade-offs associated with understory removal, balancing short-term reductions in plant competition against the long-term consequences for soil nutrient cycling and forest functioning.

4.2. Canopy Types Regulate the Effects of Understory Removal

Canopy type was identified as a significant moderator of the responses of litter decomposition and soil microbial communities to understory removal. Although understory removal substantially reduced the litter decomposition rate and mass loss in broadleaved and coniferous forests, the associated nutrient dynamics and microbial responses differed substantially by canopy type (Figure 3). In broadleaved forests, understory removal led to significant increases in litter N and P remaining. Meanwhile, its effects were negligible in coniferous forests. The results of the univariate linear mixed-effects models indicated that the responses of N and P remaining during decomposition were positively correlated with the initial litter N content (Table S2). The initial litter N content was significantly higher in broadleaved forests than in coniferous forests in our dataset (Figure S2). This likely explains the greater nutrient retention observed in broadleaved forests. These findings underscore the role of canopy-specific litter traits in mediating the decomposition responses to understory removal. Coniferous forests, producing nutrient-poor and lignin-rich litter, tend to be less dependent on soil nutrient cycling and more resilient to resource fluctuations. Meanwhile, broadleaved forests generate nutrient-rich litter that promotes faster decomposition and more efficient nutrient return [9,53–55].

Understory removal in broadleaved forests significantly increased fungal abundance and the fungi-to-bacteria ratio, indicating a potential shift toward a fungal-dominated community (Figure 3b). Fungi are generally more efficient at degrading complex organic matter and compete under low-nutrient conditions [56,57]. Therefore, the enrichment of fungal communities under broadleaved canopies may represent a compensatory mechanism that partially offsets the negative impacts of understory removal on decomposition processes. In contrast, the coniferous forests exhibited different patterns. Understory removal significantly reduced the soil total, bacterial, fungal, and actinomycetes PLFAs, and fungi-to-bacteria ratio (Figure 3b). This reflects a decline in microbial biomass and functional potential [11,58]. Coniferous litter typically has higher recalcitrance, lower nutrient content, and higher concentrations of secondary metabolites [55], which make decomposition more reliant on specialized microbial decomposers. The decline in both fungi and actinomycetes likely explains the stronger suppression of the decomposition processes observed in these systems. These findings align with research showing that coniferous forests are particularly vulnerable to management disturbances because of their nutrient-poor and microbially constrained decomposition environments [59,60]. In contrast, in mixed forests, understory removal had marginal effects on decomposition and microbial communities. This resilience may reflect complementary litter traits and resource heterogeneity in mixed stands, which buffer microbial processes against disturbances [61,62]. These results highlight the canopy type dependence of understory removal effects, suggesting that broadleaved and coniferous forests exhibit contrasting microbial and nutrient-mediated response pathways. Management practices that involve understory removal should account for forest canopy composition, as ecological consequences may vary substantially across forest types.

4.3. Mechanisms Related to the Effects of Soil Microorganisms on Litter Decomposition

Weighted random forest analysis identified initial litter quality and shifts in soil microorganisms, particularly fungi, as the strongest predictors of variation in litter decomposition following understory removal (Figure 4). These findings suggest a dual mechanism in which both microbial community alterations and substrate quality constraints interact to shape decomposition outcomes. This is consistent with previous research highlighting the interplay between litter traits and microbial activity [63,64]. The strong negative correlation between the responses of litter mass loss and fungal PLFAs underscores the critical role of fungal decomposers in driving litter decomposition (Figure 5d) [65,66]. Understory removal suppressed the fungal biomass, reducing the capacity of the community to degrade complex carbon compounds, as reflected by the accumulation of litter C remaining. This suggests that the decline in fungal decomposers represents a key bottleneck in decomposition during the removal of understory vegetation. Litter quality had an equally important effect on litter decomposition. High initial litter C and C:N ratios are generally associated with lower decomposition because of nutrient limitation and substrate recalcitrance [45,67]. In contrast, a higher initial litter N content enhances decomposition under understory removal, likely by alleviating microbial nutrient constraints and promoting the enzymatic degradation of lignin-rich substrates [68,69]. The suppression of litter decomposition by understory removal operates through two interlinked mechanisms: (1) reduced fungal biomass diminishes the functional capacity of microbial communities to degrade recalcitrant C, and (2) litter quality modulates the magnitude of this suppression. Therefore, the microbial community composition and substrate quality act as interactive drivers that determine the sensitivity of litter decomposition to understory vegetation removal across ecosystems.

4.4. Study Limitations and Future Perspectives

Litter decomposition was significantly suppressed by the removal of understory vegetation, primarily through changes in litter quality and shifts in soil microbial community structure. Our study provides a synthesis of the litter decomposition responses to understory removal across terrestrial ecosystems, advancing our understanding of the mechanisms linking vegetation management, microbial dynamics, and nutrient cycling. Nevertheless, several limitations should be acknowledged. First, the compiled dataset was strongly weighted toward forests in the Northern Hemisphere, particularly subtropical regions of China (Figure 1a). This geographic concentration introduced a clear sampling bias and may limit the broader applicability of our findings. Temperate and tropical ecosystems, which were largely underrepresented in our dataset, may exhibit distinct responses to understory removal. For instance, temperate forests typically experience lower soil temperatures and slower baseline decomposition rates [70]. Therefore, the effects of understory removal may have stronger impacts than those suggested by our synthesis. In contrast, tropical forests, characterized by warm climates and rapid nutrient turnover, may either buffer the impacts of understory removal due to their high metabolic activity or show amplified responses because they rely on continuous organic inputs and tightly coupled nutrient cycles [71]. These potential differences highlight the need for targeted studies across diverse climatic regions. Second, the presence of multiple forest subtypes within the main ecosystem categories could not be resolved owing to insufficient data. This limitation restricted our ability to evaluate how specific forest types modulate the effects of understory removal on litter decomposition. Third, overall fungal biomass changed significantly under understory removal. However, the responses of specific functional groups, such as saprotrophic versus symbiotic mycorrhizal fungi, were not directly assessed in the compiled dataset. This restricted further mechanistic insights into their roles in litter decomposition and nutrient cycling. Fourth, understory removal may disrupt internal soil interactions, such as those among soil moisture, nutrient availability, and soil fauna, thereby affecting litter decomposition [17,18]. However, these mechanisms are rarely examined directly in primary research, limiting our capacity to evaluate how such internal feedback mediates the decomposition response. To improve our understanding of how litter decomposition responds to understory removal, future experimental studies should focus on underrepresented regions. Studies incorporating a wider range of soil measurements can provide more detailed context for understanding the mechanisms underlying understory removal effects.

5. Conclusions

This study advanced our understanding of how litter decomposition responds to understory vegetation removal across global forest ecosystems. Although understory removal is commonly conducted to reduce competition for resources and to enhance stand productivity, our study demonstrated that this practice has substantial unintended consequences for belowground processes. Specifically, understory removal markedly reduced litter decomposition rates and mass loss while increasing the amount of lignin remaining in litter. Concurrently, it also decreased soil microbial biomass, particularly total, fungal, and actinomycete PLFAs, at a global scale. These findings demonstrated that understory removal strongly suppressed litter decomposition and altered soil microbial communities, thereby reducing nutrient availability for trees. The magnitude of these effects varied across canopy types, with coniferous forests exhibiting greater sensitivity to understory removal than broadleaved forests, underscoring the moderating role of canopy composition. Management strategies involving understory removal should therefore consider overarching forest structural characteristics, particularly canopy types. To avoid impairing nutrient cycling, understory removal should be avoided or minimized in conifer-dominated forests

and systems where decomposition-driven nutrient supply is essential for regeneration or productivity. Suppression of decomposition is jointly regulated by reductions in fungal biomass and constraints imposed by litter quality, highlighting the interactive roles of microbial community composition and substrate traits in mediating ecosystem responses to vegetation management. Collectively, these results indicated that understory removal may fail to achieve its intended objectives. This study provides mechanistic insights into the biogeochemical consequences of understory removal and offers a scientific basis for refining forest management practices involving understory modification.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/f16121783/s1.

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Data Availability Statement: All data needed to evaluate the conclusions in the paper are present in the paper and Supplementary Materials.

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

Abbreviations

The following abbreviations are used in this manuscript:

C	Carbon
N	Nitrogen
P	Phosphorus
SOC	Soil carbon content
PLFAs	Phospholipid fatty acids
MAT	Mean annual temperature
MAP	Mean annual precipitation

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