Ecology Letters

WILEY

ECOLOGY LETTERS

SYNTHESIS OPEN ACCESS

Environmental Conditions Modulate Warming Effects on Plant Litter Decomposition Globally

Sarah Schwieger[1,2] | Ellen Dorrepaal[1] | Matteo Petit Bon[3,4,5] | Vigdis Vandvik[6] | Elizabeth le Roux[7,8] | Maria Strack[9] | Yan Yang[10] | Susanna Venn[11] | Johan van den Hoogen[12] | Fernando Valiño[13] | Haydn J. D. Thomas[14] | Mariska te Beest[15,16,17] | Satoshi Suzuki[18] | Alessandro Petraglia[19] | Isla H. Myers-Smith[20,21] | Tariq Muhammad Munir[22] | Anders Michelsen[23] | Jørn Olav Løkken[24] | Qi Li[25] | Takayoshi Koike[26] | Kari Klanderud[27] | Ellen Haakonsen Karr[27] | Ingibjörg Svala Jónsdóttir[28] | Robert D. Hollister[29] | Annika Hofgaard[30] | Ibrahim A. Hassan[31,32] | Wang Genxu[10] | Nina Filippova[33] | Thomas W. Crowther[12] | Karin Clark[34] | Casper T. Christiansen[23] | Angelica Casanova-Katny[35,36] | Michele Carbognani[19] | Stef Bokhorst[37] | Katrín Björnsdóttir[38] | Johan Asplund[27] | Inge Althuizen[39] | Rocío Alonso[13] | Juha Alatalo[40] | Evgenios Agathokleous[26,41,42] | Rien Aerts[37] | Judith M. Sarneel[1,2]

Correspondence: Sarah Schwieger (sarah.schwieger@umu.se)

Received: 31 January 2024 | **Revised:** 25 September 2024 | **Accepted:** 13 October 2024

Editor: Edith Bai

Funding: For S.S. and J.M.S., funding was received from Formas (Grant No: 2021–02449). JMS also acknowledges support from the Swedish Research Council VR (Grant No: 2014–04270). Support for E.D. was provided by the Swedish Research Council VR (Grant No: 2018–04004). The research conducted by M.S. and T.M. was funded by Alberta Innovates Technology Futures. Additionally, M.S. acknowledges support from an NSERC Canada Research Chair (CRC-2019-00299). EA was an International Research Fellow of the Japan Society for the Promotion of Science (JSPS) with ID No: P17102. Funding for I.A. and V.V. was provided by the Research Council of Norway under the KLIMAFORSK program (Grant No: 244525). MPB acknowledges support from the Governor of Svalbard (Svalbard Environmental Protection Fund, Grant Project No: 15/128), the Research Council of Norway (Arctic Field Grant, Project No: 269957), and the National Science Foundation (Grant Project No: ANS-2113641). R. Alonso acknowledges funding from the Framework on atmospheric pollution and persistent organic pollutants between DGCEA and CIEMAT (ACTUA-MITERD). NF was funded by a grant for the organisation of a new laboratory for young researchers at Yugra State University as part of the implementation of the National Project "Science and Universities." R.D.H. acknowledges support from the US National Science Foundation (Grant No: 1836839). I.J.S. was funded by the University of Iceland Research Fund for the years 2016 and 2017. Q.L. acknowledges the C.A.S. International partnership project (Grant No: 131323KYSB20210004). I.M.S. acknowledges funding from the UK Natural Environment Research Council for the ShrubTundra Project (Grant No: NE/M016323/1). Y.Y. was supported by the Sichuan Provincial Science and Technology Plan Project (Grant No: 2022ZHYZ0005).

Keywords: climate change | decomposition | experimental warming | litter bags | litter quality | macro-environment | meta-analysis | precipitation | tea bags | temperature

ABSTRACT

Empirical studies worldwide show that warming has variable effects on plant litter decomposition, leaving the overall impact of climate change on decomposition uncertain. We conducted a meta-analysis of 109 experimental warming studies across seven continents, using natural and standardised plant material, to assess the overarching effect of warming on litter decomposition and identify potential moderating factors. We determined that at least 5.2° of warming is required for a significant increase in decomposition. Overall, warming did not have a significant effect on decomposition at a global scale. However, we found that warming reduced decomposition in warmer, low-moisture areas, while it slightly increased decomposition in colder regions, although this increase was not significant. This is particularly relevant given the past decade's global warming trend at higher latitudes where a large proportion of terrestrial carbon is stored. Future changes in vegetation towards plants with lower litter quality, which we show were likely to be more sensitive to warming, could increase carbon release and reduce the amount of organic matter building up in the soil. Our findings highlight how the interplay between warming, environmental conditions,

For affiliations refer to page 13.

and litter characteristics improves predictions of warming's impact on ecosystem processes, emphasising the importance of considering context-specific factors.

1 | Introduction

Understanding the temperature sensitivity of plant litter decomposition is a key to predicting future nutrient and carbon cycling, as changes in decomposition may alter nutrient availability, plant growth, and carbon storage in terrestrial ecosystems (Gregorich et al. 2017; Bai et al. 2023). Carbon modelling (e.g., Davidson, Trumbore, and Amundson 2000; Knorr et al. 2005), kinetic theory (e.g., Davidson and Janssens 2006), and laboratory incubations (e.g., Conant, Drijber, et al. 2008; Rey, Pegoraro, and Jarvis 2008) show that decomposition rates increase with increasing temperature. However, site-specific empirical field studies reveal that experimental warming can increase (Li et al. 2022; Zhou et al. 2022), have no effect (Bhuiyan et al. 2023; Bélanger and Chaput-Richard 2023), as well as decrease litter decomposition (Romero-Olivares, Allison, and Treseder 2017; Hong et al. 2021). Results from these site-specific studies pose a challenge to generalisations of the effects of climate change on nutrient and carbon cycling across ecosystems. Here, we synthesise the latest available results from in situ experimental warming studies across terrestrial biomes worldwide that measured decomposition by the mass loss of incubated plant litter. We combine these results with the implementation of a globally distributed, standardised decomposition experiment to improve our understanding of how and where climate warming may affect plant litter decomposition, and to identify potential moderating factors. We use a sixfold larger dataset of 637 paired observations of warmed and non-warmed plots, compared to the recent meta-analysis by Wu et al. (2020). This larger dataset allows us to substantially expand the geographical coverage compared to previous studies in high-latitude systems such as Aerts (2006) and to investigate interactions with both climate and litter quality. That is, previous studies have often focused on a limited set of moderators, primarily temperature and precipitation, while often neglecting more complex interactions, such as those involving litter quality. By including literature data on natural litter as well as a complementary dataset on warming effects on standard litter (i.e., tea bags), we further broadened the geographical and environmental scope of the study. The use of both natural litter and standardised litter allows more reliable comparisons of environmental factors across geographically diverse sites, as well as some assessment of home field effects. The inclusion of two contrasting types of litter (i.e., rapidly decomposing green tea and more slowly decomposing rooibos tea) increased the variety of litter types, allowing us to test for interactions between warming and litter type.

Litter decomposition is a complex process involving the biological (i.e., microbial and soil fauna activity), chemical, and physical transformation and breakdown of organic matter (Bardgett, Freeman, and Ostle 2008; Kirchman 2018; Dai et al. 2020), including leaching of solubles into the soil (Lind et al. 2022). Warming can directly stimulate microbial and enzymatic activity (Xue et al. 2016), as well as leaching (Lind et al. 2022), and thus increase decomposition rates. Global in situ experiments show a strong connection between temperature and precipitation gradients and litter decomposition across biomes and elevations. Projected shifts in temperature and precipitation are expected to significantly impact decomposition rates (Zhang et al. 2008; Conant et al. 2011; Wu et al. 2011; Joly, Scherer-Lorenzen, and Hättenschwiler 2023). However, the exact nature of temperature-precipitation interactions and their combined influence on decomposition remains uncertain. Addressing these complexities requires large-scale datasets that cover diverse environmental conditions and litter types.

Because the type and intensity of climate change vary globally (IPCC 2021), its effects on plant litter decomposition may differ based on environmental settings and litter types, leading to spatial variations in decomposition. For example, cold temperatures tend to inhibit decomposition, creating huge carbon stocks in high-latitude soils (Tarnocai et al. 2009). Concurrently, decomposition in cold environments is particularly sensitive to small changes in temperature (Chen et al. 2015). Therefore, climate warming is expected to increase litter decomposition more strongly in colder high-latitude and high-altitude regions, creating a positive carbon-climate feedback loop. This feedback loop occurs when warming releases greenhouse gases from these carbon-rich soils, further amplifying warming, unless plant growth at higher latitudes and altitudes compensates for the additional release of greenhouse gases (Cox et al. 2000; Fenner and Freeman 2011). In other regions, such as temperate grasslands, climate warming is predicted to increase the frequency and intensity of droughts, which could in turn reduce litter decomposition by limiting the biological activity of decomposer organisms (Vogel et al. 2013; Walter et al. 2013). Therefore, in warmer systems and systems with high variability in precipitation (e.g., savannahs), the warming response is thought to depend strongly on concurrent moisture conditions (Aerts 1997; Seres et al. 2022). Our meta-analysis of 109 experimental warming studies assessing the effect of warming on litter decomposition will improve understanding of the interaction between the prevailing environmental conditions and the warming-induced changes in decomposition. This will enhance our ability to better predict the consequences of these changes for carbon and nutrient cycling in terrestrial ecosystems. Therefore, our study aims to identify recognisable patterns in litter decomposition responses to warming under different macro-environmental conditions.

There is increasing evidence that litter quality (i.e., the chemical characteristics of the decomposing material) may control the temperature sensitivity of litter decomposition (Bosatta and Ågren 1999; Fierer et al. 2005; Davidson and Janssens 2006; Conant, Drijber, et al. 2008; Suseela et al. 2013). Litter with low quality is thought to be more temperature-sensitive, implying that warming could disproportionately accelerate its decomposition compared to that of litter with high quality (Biasi et al. 2005; Davidson and Janssens 2006; Conant, Steinweg, et al. 2008). Given the complex and diverse chemical make-up of plant litter, comparisons across species on a global scale often rely on functional traits or classifications such as carbon to nitrogen (C:N) ratios (Aerts 1997; Prescott 2010), plant functional types (e.g., trees, shrubs, mosses, graminoids) (Chapin et al. 1996; Dorrepaal et al. 2005), or plant organs (e.g., shoots, leaves, roots) (Freschet, Aerts, and Cornelissen 2012; Xia, Talhelm, and Pregitzer 2015). In addition to these, we used ambient decomposability, quantified as the rate of litter mass loss under ambient conditions (without manipulation), as a proxy for assessing litter quality (Cornelissen et al. 2004; Freschet, Aerts, and Cornelissen 2012). This metric integrates both the inherent chemical composition of the litter, which provides a proxy for how easily decomposers can break it down, and the environmental conditions that affect decomposition rates. Litter with a high C:N ratio (commonly found in trees, shrubs, and roots) has lower decomposability and is considered lower quality due to the presence of more recalcitrant compounds like lignin, tannin, and complex carbohydrates. Conversely, litter with a lower C:N ratio (such as forbs and leaves) is considered high quality with a higher decomposability because it contains less of these recalcitrant materials (Zhang et al. 2008; Prescott 2010; Kirchman 2018). However, understanding how litter quality interacts with warming across large-scale environmental gradients remains a key knowledge gap, crucial for predicting changes in nutrient and carbon cycling under warming. As warming frequently alters plant community composition and thereby litter quality, it is essential to understand how these changes will influence decomposition responses to climate change (Elmendorf et al. 2012; Pearson et al. 2013; Munir et al. 2017).

In this study, we aim to quantify the effect of experimental warming on plant litter decomposition across a wide range of ecosystems and environmental conditions and to identify the contextual dependence of variable warming effects at a global scale. To this end, we assessed whether the effect of warming on litter decomposition varied across (1) macro-environmental regions (i.e., regions derived from map-based environmental variables), (2) experimentally induced changes in micro-environment (i.e., plot-level temperature and moisture changes with warming), and (3) litter quality (i.e., C:N ratio, decomposability under ambient conditions, and plant functional type) within macro-environmental regions. We hypothesize the following:

i. The macro-environmental region is a key determinant of the effect of warming on litter decomposition. In temperature-limited systems, we expect a higher sensitivity and an increase in litter decomposition with warming, whereas in moisture-limited systems, we expect a lower sensitivity to warming and a decrease in decomposition.

ii. A stronger warming will proportionally increase litter decomposition, provided that warming does not limit moisture availability.

iii. Litter quality modulates the effect of warming on litter decomposition, with lower-quality litter being more sensitive to warming than high-quality litter.

To test these hypotheses, we conducted a global meta-analysis examining 109 datasets with experimental setups comprising 637 paired (i.e., warmed and ambient) observations on litter decomposition of plant litter under ambient conditions vs. experimental warming. These datasets were obtained from in situ warming experiments that either decomposed natural local plant species litter (52 paired studies, sourced from published literature) or two standardised plant litter materials, green tea and rooibos (57 paired experiments each, from unpublished primary research). This comprehensive analysis provides a unique opportunity not only to quantify the global effects of warming on litter decomposition, but also to elucidate the interplay between warming, environmental context, and litter quality. Unravelling these complex interactions will be critical for predicting future changes in litter decomposition rates and their associated feedbacks to the global carbon and nutrient cycle.

2 | Methods

In this meta-analysis, we combined two global datasets. First, we extracted data from the 52 published studies that measured decomposition responses of natural litter to experimentally imposed higher temperatures. Further, we buried green tea and rooibos as standardised plant litter in 57 warming experiments (Keuskamp et al. 2013). Whereas the natural litter data mainly covers the United States, Western Europe, and China, the standardised plant litter decomposition data ranges from higher latitudes to the Mediterranean and a few sites in the southern hemisphere (Figure 1).

3 | Data Collection

3.1 | Literature Data on Natural Plant Litter Decomposition

We conducted an extensive literature survey for peer-reviewed publications in the ISI Web of Science database (http://apps.webofknowledge.com/) on September 1st 2023. We used (*warming OR heat* OR OTC OR open-top chamber**) *AND* (*litter* OR litter bag*) *AND* (*decomposition OR mass loss*) as search criteria, which returned 1184 articles (Figure S1). We considered terrestrial field studies that compared litter decomposition (mass loss and decomposition rate of plant material) under experimentally increased temperatures and ambient conditions. Methods found in our search were open-top chambers, heating cables, infrared heaters, sunlit controlled-environment chambers, UVB filter films, open-topped polythene tents, and closed-top chambers. In total, 60 studies met our criteria. We contacted the corresponding authors to obtain access to the raw data for studies that did not report them and had to exclude eight studies due to insufficient reporting. This resulted in 52 studies used for the meta-analysis (Table S1). From these, we extracted mean values, sample sizes, and measures of variation (i.e., standard errors or standard deviations) for litter decomposition (i.e., decomposition rates, absolute and relative mass loss, remaining mass of plant material). Whenever warming was applied in factorial combination with one or more additional treatments (e.g., warming and plant species removal), we only retained the warming vs. ambient contrasts. Each litter bag incubation conducted at different sites, with different plant species, at various time intervals, or using different mesh sizes, was treated as a separate data point.

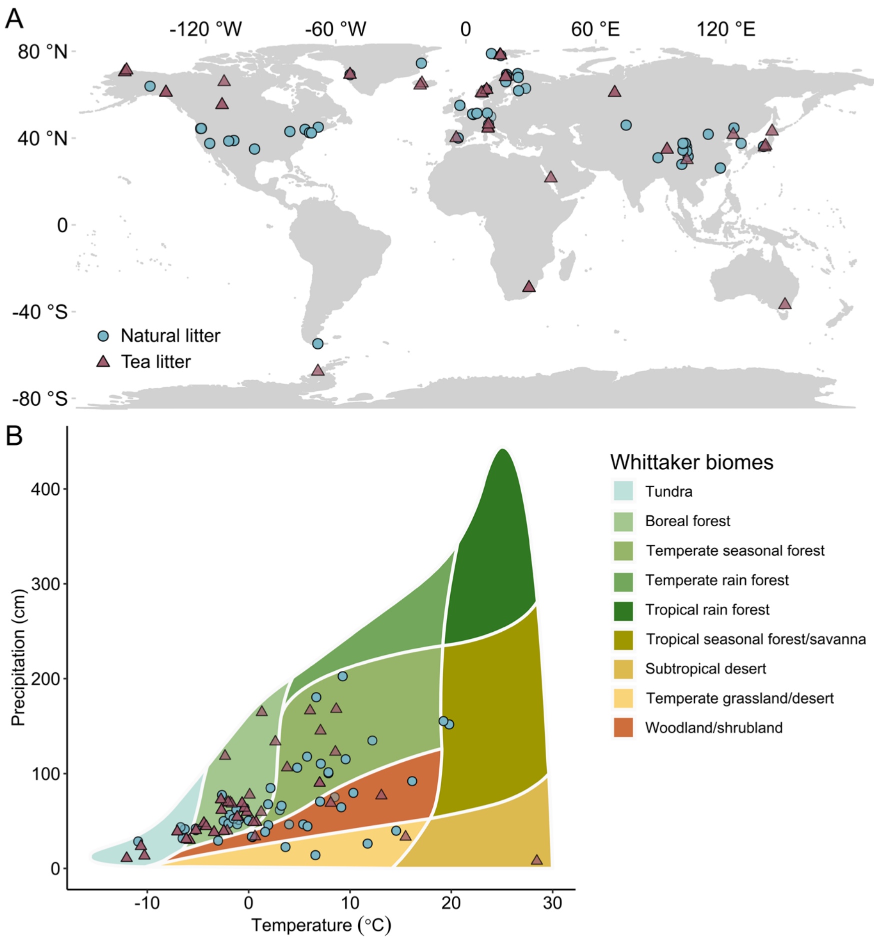

FIGURE 1 | (A) Map and (B) Whittaker biome diagram showing the location of the 52 published studies of natural litter decomposition in warming experiments (blue circles) and the location of the 57 open-top chamber experiments where we deployed tea as a standardised plant litter to assess decomposition response to experimental warming (purple triangles) used in this meta-analysis. Data availability was limited in temperate and tropical rain forests.

We thus extracted a total of 523 paired (warmed vs. ambient) data points from the 52 studies, either directly from the text or tables or from figures using the software WebPlotDigitizer (v. 4.6, Rohatgi 2021). When litter decomposition was reported as the remaining mass of plant material, this was converted to percentage mass loss:

$$\text{Percentage mass loss} = \frac{\text{Initial mass} - \text{Final mass}}{\text{Initial mass}} \times 100 \qquad (1)$$
$$= 100 - \text{percentage mass remaining}$$

We extracted coordinates of each study location (Figure 1A), the incubation duration of the litter (from 14 days to 4.9 years, standardised to days), the mesh size of the litter bags (from 0.02 to 5 mm), the position of incubation (i.e., if litter bags were put on the soil surface or buried below ground), the duration of the warming experiment prior to incubation start (from first year to 23 years), the plant species, the plant functional type (i.e., forb, nonvascular, graminoid, woody species), and the plant organ type (i.e., leaf, shoot, or root). For 32 studies, we also extracted the C:N ratio of the litter reported by the researchers (ranging from 12 to 201). All reported mass losses were from single species incubations, with the only exception being two studies on root decomposition, which included a mixture of grass species. Yet, as all the species in these samples were within the graminoid functional type, we included these studies in the meta-analysis.

The warming method was classified as heating cables (number of studies $n = 11$), infrared heaters ($n = 17$), and open-top chambers ($n = 19$), with 'other methods' including sunlit controlled-environment chambers ($n = 1$), UVB filter films ($n = 1$), open-topped polythene tents ($n = 2$), and closed-top chambers ($n = 1$).

3.1.1 | Standardised Plant Litter Data from Open-Top Chamber Warming Experiments

Following the standard Tea Bag Index protocol (Keuskamp et al. 2013), green (*Camellia sinensis*; EAN no.: 8722700 055525) and rooibos (*Aspalathus linearis*; EAN no.: 8722700 188,438, Lipton, Unilever) tea bags with woven nylon mesh (0.257 mm) were buried at a depth of 8 cm and at a distance of at least 15 cm from each other in open-top chambers (OTCs) and controls under ambient, i.e., non-warmed, conditions at 57 locations (Figure 1 and Table S2). OTCs are commonly used across biomes because they are a cost-effective, robust method of in situ warming, effectively replicating the natural patterns of interannual variability and latitudinal temperature gradients observed across ecosystems (Hollister et al. 2023). Thus, they are well suited to conduct a global, standardised decomposition experiment. The incubations covered one growing season (82 ± 18 days; mean ± SD), that is, from May/June 2016 to August/September 2016 in the northern hemisphere and from January 2017 to March 2017 in the southern hemisphere. For two sites in Japan (i.e., JPN_1 and JPN_3, Table S2), tea bags were incubated from July to October 2012. Retrieved bags were cleaned of adhering soil and roots, usually by gently brushing the litter bags with a soft brush after air drying to ensure minimal loss of material and avoid damage to the bags. The mass of the remaining tea was determined after drying it in an oven at 60°C–70°C for at least 48 h. To align with the literature data, we calculated treatment means of mass loss (Equation 1), sample sizes, and standard deviations for each experiment location. This resulted in 57 locations with paired (warmed vs. ambient) measurements of both green tea and rooibos (114 data points in total; Figure 1).

3.2 | Explanatory Macro-Environmental Drivers

We obtained map-based environmental data based on the geographical locations of the study sites to identify macro-environmental factors that may influence the response of litter decomposition to warming. We used 48 environmental layers reflecting major gradients in climate, soil, vegetation, and topographic variables as covariates in our analysis (Table S3).

Due to the confounding nature of macro-environmental factors, we applied principal component analysis (PCA; Table S3) to scale environmental variables using the R package FactoMineR (v.2.4; Lê, Josse, and Husson 2008). The first principal component (PC 1) was strongly positively correlated with temperature-associated variables and negatively correlated with soil organic carbon (SOC) and explained 26.9% of the total variance (Figure 3A and Table S3). The second component (PC 2) correlated positively with precipitation-associated variables and explained 18.1% of the total variance (Figure 3A, Table S3). The third PC axis was not considered as it described negligible amounts of the variation (4.2%). In our dataset, the range of mean annual temperature was −12°C–28°C, annual precipitation was 78–2100 mm, and soil saturated water content was 42%–81%.

Based on the origin of the PC1 and PC2 axes, we identified four 'macro-environmental' classes, corresponding to the four PCA quadrants. Positive scores on PC1 represent higher values (warmer conditions), while negative scores indicate lower values (colder conditions). Similarly, positive scores on PC2 indicate wetter conditions, and negative scores denote drier conditions. This classification allowed us to identify four contrasting climates across our study sites (Figure S2 and Table S4). These four 'macro-environmental classes' were described as follows: (1) high temperatures and high precipitation (number of effect sizes $k = 156$), (2) high temperatures and low precipitation ($k = 170$), (3) low temperatures and high precipitation ($k = 156$), and (4) low temperatures and low precipitation ($k = 155$).

3.3 | Explanatory Micro-Environmental Drivers Altered by Experimental Warming

For both datasets (i.e., natural and standardised plant litter), we collected available data on the actual degree of warming, that is, the mean absolute temperature difference between warmed and ambient (non-warmed) plots, as well as soil moisture in warmed and ambient plots, when available. We then calculated the degree of warming as the absolute difference between warmed and control plots in air or soil temperature measures, depending on whether the litter was incubated on the soil surface or below ground, respectively. We calculated relative change in soil moisture with warming according to:

$$\text{Relative change in soil moisture} = \left(\frac{\text{Mc}}{\text{MW}} - 1\right) \times 100 \quad (2)$$

where M_C and M_W are soil moisture in ambient (control) and warming treatment, respectively. Positive and negative values indicate respectively drier and wetter conditions under warming than under ambient conditions.

3.3.1 | Litter Quality

We focused on three different, frequently used characterisations of litter qualities: the C:N ratio of the litter before decomposition, which were reported in the original studies and in Keuskamp et al. (2013) for the tea litter; the decomposability measured as decomposition rate under ambient conditions (i.e., standardised to mass loss in % d^{-1}) (Cornelissen et al. 2004; Freschet, Aerts, and Cornelissen 2012); and plant functional type (Dorrepaal et al. 2005). We categorised the plant species into four different plant functional types (*sensu* Chapin et al. 1996), forbs (number of studies $n = 7$), graminoids (i.e., grasses and sedges, $n = 28$), woody species (i.e., shrubs and needle-leaved and broad-leaved trees, $n = 27$), and nonvascular (i.e., mosses, $n = 4$; lichens, $n = 1$). For graminoids and woody species, we were able to further specify litter type as above-ground (i.e., shoots and leaves of graminoids, $n = 25$; broadleaves and needles of woody species, $n = 25$) and below-ground plant organs (i.e., roots of graminoids, $n = 6$; and root of woody species, $n = 2$).

3.4 | Data Analysis

To evaluate the effect of experimental warming on litter decomposition, we used Hedges'g, which is the standardised mean difference (SMD). This was calculated by dividing the difference between the mean mass loss in the warming treatment and the ambient condition by the pooled standard deviation (Hedges 1981; Supporting Information M1). A SMD greater than zero indicates that experimental warming enhanced decomposition, while a SMD lower than zero indicates that warming decreased decomposition. By using the SMD as a measure of effect size, we were able to synthesise data measured on different scales or units (e.g., mass loss vs. decomposition rate) while still accounting for the precision (variance) of the measurement.

We derived SMDs and corresponding 95% confidence intervals (CI) using the *escalc()* function from the R package METAFOR (v.4.0–0; Viechtbauer 2010). Pooled average SMDs across all studies were calculated with multivariate linear mixed-effects models using the *rma.mv()* function, which weights effect sizes based on sample sizes, ensuring larger studies contribute more to the overall estimate. A pooled average effect size was considered significant if its 95% CI did not include zero ($\alpha = 0.05$).

To account for spatial autocorrelation between study locations, we included longitude and latitude as random effects based on great-circle distances (WGS84 ellipsoid method). The Test of Moderators (Q_M test) determined how different factors (moderators) influenced the warming effects on litter decomposition (Koricheva, Gurevitch, and Mengersen 2013).

We first tested for differences between natural and standardised plant litter datasets, using data type (i.e., natural litter or standardised plant litter) as a moderator. As no significant differences were found (Q_M (df = 2) = 2.7, $p = 0.26$), we combined these datasets in subsequent analyses.

We tested the impact of the degree of warming and warming-induced changes in soil moisture, along with their interaction, by incorporating them as moderators in multivariate linear mixed-effects models (METAFOR package). To evaluate whether experimentally induced changes in the micro-environment varied amongst the four macro-environmental classes, we included the 'macro-environmental class' as an interacting moderator in the model (Supporting Information M2).

To determine if experimental warming affected temperature and soil moisture, we conducted independent sample *t*-tests to test whether the absolute difference between the warming treatment and the ambient control differed significantly from zero.

We used linear mixed-effects models to test if different warming methods affected micro-environmental conditions (degree of warming, soil moisture). We employed Tukey HSD post hoc tests (R packages MULTCOMP, v. 1.4–19; Hothorn, Bretz, and Westfall 2008, and EMMEANS, v. 1.7.5; Lenth 2019) for significant differences between methods (Supporting Information M3). We also tested for correlations between warming-induced changes in soil moisture and the degree of warming.

To test for differences in litter quality, measured as the C:N ratio or ambient decomposability, between plant functional types across different macro-environments, we used linear mixed-effects models (R package lmerTest, v. 3.1–3; Kuznetsova, Brockhoff, and Christensen 2017). To identify significant differences in C:N ratio and ambient decomposability between plant functional types (including plant organ types) and across the four macro-environmental classes, we performed Tukey HSD post hoc tests. We also tested the hypothesis that lower-quality litter is associated with a stronger positive warming effect on decomposition. For this, we used multivariate linear mixed-effects models, treating each of the three proxies for litter quality (C:N ratio, ambient decomposability, and plant functional type) as moderators in separate models. In these models, 'macro-environmental class' was included as an interactive factor to assess its influence.

We ensured normality and homogeneity of variance for residuals for all models, applying log (C:N ratio) or rank transformations (warming-induced changes in soil moisture) as needed. All analyses were conducted using R version 4.2.3 (R Core Team 2023), with graphical displays produced using the R packages GGPLOT2 (v. 3.3.6, Wickham, Chang, and Wickham 2016) and ORCHARD (v.2.0, Nakagawa et al. 2021).

We assessed publication bias using Egger's regression test (using the *regtest* function, METAFOR package), which indicated no evidence of publication bias (intercept = 0.01, 95% CI: −0.07, 0.08) (Sterne and Egger 2001).

4 | Results

4.1 | The Effect of Experimental Warming on Natural and Standardised Plant Litter Decomposition

The impact of experimental warming on plant litter decomposition was assessed by comparing treatments with ambient conditions and increased temperatures ranging from −1.6°C–7.5°C. On average, the different warming treatments significantly increased temperatures by 2.1°C ± 0.1°C (mean ± SE, $n = 559$; soil and air combined; *t*-test: $t = 32.30$, $p < 0.001$) and reduced soil moisture by 8.7% ± 0.9% ($n = 317$; *t*-test: $t = -9.23$, $p < 0.001$) compared to ambient conditions. While the effect of experimental warming on decomposition varied amongst studies, overall, experimental warming did not significantly affect plant litter decomposition (SMD = 0.01, $p = 0.84$ [CI95: −0.10, 0.13], $k = 637$, Figure 2). Experimental warming had also no effects on litter decomposition when the natural litter (SMD = −0.04 [CI95: −0.24, 0.10], $p = 0.41$, $k = 523$; Figure 2) and the standardised litter dataset (green tea: SMD = 0.12 [CI95: −0.06, 0.31], $p = 0.17$, $k = 57$; rooibos: SMD = 0.06

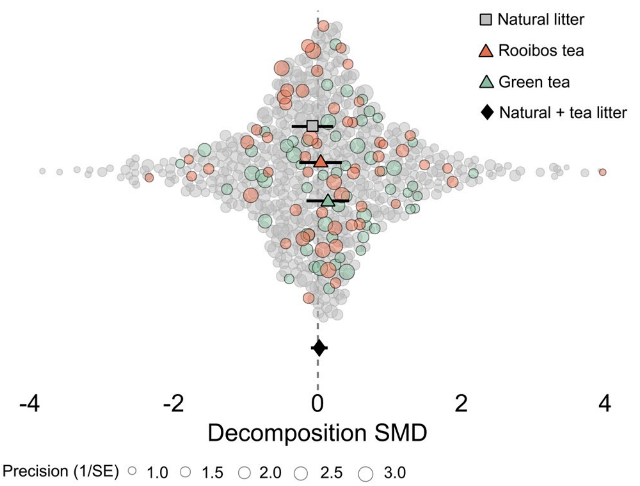

FIGURE 2 | Effects of experimental warming on plant litter decomposition. The pooled average decomposition standardised mean difference (SMD, Hedges' g; triangles) and 95% confidence intervals (black error bars) resulting from warming. Black diamond, represents the overall mean across natural and standardised plant litter; number of effect sizes ($k = 637$), and separately for the natural litter (grey outlined square, $k = 523$), rooibos (red outlined triangle, $k = 57$) and green tea (green outlined triangle, $k = 57$). Each coloured dot is an individual effect size (non-outlined circles) with dot size representing its precision (i.e., the inverse of the standard error, with larger points having greater influence on the model).

[CI95: −0.12, 0.24], $p = 0.52$, $k = 57$, Figure 2) were analysed independently. The effect of experimental warming on decomposition did not significantly differ between natural and standardised plant litter datasets (moderators' test: Q_M (df = 2) = 2.8, $p = 0.25$).

4.2 | The Impact of Macro-Environment on the Warming Effect on Decomposition

Only two of the 48 map-based environmental variables significantly influenced the experimental warming effect on litter decomposition (i.e., precipitation of the coldest month and northness; Table S6). When combined, however, the effect of experimental warming on litter decomposition differed significantly across the four 'macro-environmental classes' identified by the PCA (moderators' test: Q_M (df = 3) = 13.86 $p = 0.003$; Figure 3). In the warm and dry class (high PC1 and low PC2 scores, Figure 3A), we observed a negative warming effect on decomposition (SMD = −0.30 [CI95: −0.52, −0.07], $p = 0.01$, $k = 170$; Figure 3B), driven primarily by a negative effect of experimental warming on natural litter decomposition (SMD = −0.61 [CI 95: −0.94; −0.28], $k = 150$; Figure S3 and Table S7). Despite a trend towards positive effects of experimental warming on litter decomposition in the cold and wet and cold and dry class, which comes with substantial variability, experimental warming did not significantly affect decomposition in any of the other three macro-environmental classes and litter types (Figure 3B, Figure S3 and Table S7).

4.3 | The Impact of Experimentally Induced Changes in Micro-Environment on Decomposition and Its Interaction with Macro-Environment

The degree of experimental warming correlated positively with the overall experimental warming effect on litter decomposition (slope = 0.18 SMD/°C warming [CI95: 0.10, 0.26], $p < 0.001$, $k = 315$; Figure S4A). A significant increase in litter decomposition occurred with a degree of warming of 5.2°C or more. However, the relationship between the degree of warming and the experimental warming effect on litter decomposition varied across macro-environmental classes (moderators' test: Q_M (df = 7) = 54.62, $p < 0.001$), with a significantly positive effect on decomposition in relatively warm and wet areas only (slope = 0.20 SMD/°C warming [CI95: 0.09, 0.31], $p < 0.001$, $k = 315$; Figure 4A).

Changes in soil moisture induced by experimental warming had no impact on litter decomposition for any of the four macro-environmental classes (moderators' test: Q_M (df = 7) = 13.66, $p = 0.0$; Figure 4B–H). There was no significant interaction between degree of warming and changes in soil moisture in their impact of the experimental warming effect on litter decomposition (degree warming × soil moisture: $p = 0.89$).

With increasing mesh size, the experimental warming effect on litter decomposition shifted from no effect to a significant negative effect (moderators' test: $Q_M = 4.41$, $p = 0.036$, Figure S4C).

Warming methods significantly affected the experimental warming effect on litter decomposition (moderators' test: Q_M (df = 4) = 12.14, $p = 0.016$). Warming from heating cables resulted in the largest observed temperature increase (4.18 ± 0.1°C, $n = 121$; Table 1), which also increased soil moisture (4.9 ± 4.1%; $n = 48$; Table 1) and significantly increased litter decomposition (SMD = 0.43 [CI95: 0.10, 0.76], $p = 0.010$, $k = 121$). The experimental warming effect of heating cables on litter decomposition differed significantly from the effect of OTCs on decomposition (Tukey HSD, $p = 0.006$, Table 1), but was similar to the experimental warming effect of infrared heaters or other warming methods on decomposition, none of which had a significant experimental warming effect on decomposition (Table 1 and Figure S5).

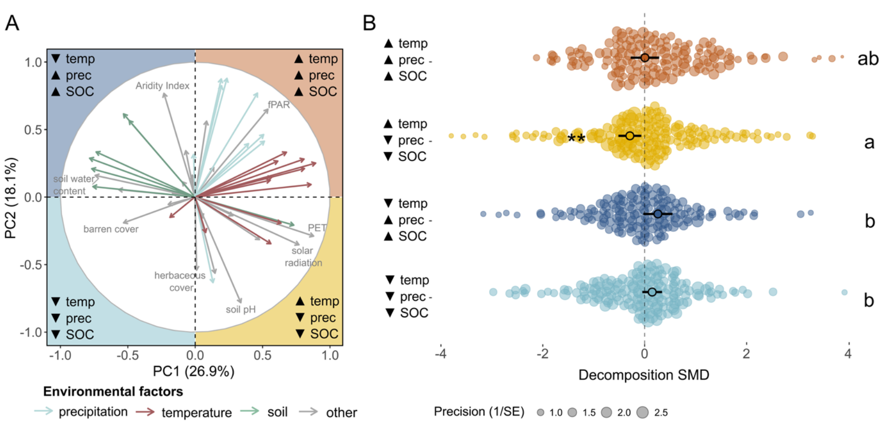

FIGURE 3 | Impacts of macro-environment on litter decomposition responses to experimental warming. (A) Principal component analysis (PCA) of the variation in macro-environmental factors in our dataset. The arrows are coloured according to the components, which are grouped into temperature, precipitation, soil and other factors (Table S3). The first two axes represent temperature and soil organic carbon-related variables (PC1), and precipitation (PC2). Full list of the macro-environmental factors, their scores on PC1 and PC2 and their mean in every class is presented in Tables S3 and S4A. Colours indicate the four macro-environmental classes distinguished by different combinations of high (▲) or low (▼) temperature (temp), precipitation (prec) and soil organic carbon (SOC). (B) Pooled average decomposition SMD per macro-environmental class of natural litter (outlined diamonds), rooibos tea (outlines squares), and green tea (outlined circles) ±95% confidence intervals (error bars). Each coloured dot is an individual effect size (non-outlined circles) with dot size representing its precision (the inverse of the standard error, with larger points having greater influence on the model). Asterisks indicate that the overall pooled average SMD is significantly different from zero (**$p < 0.01$), whereas different letters denote overall significant differences in the pooled average SMD between macro-environmental classes, averaged over data type.

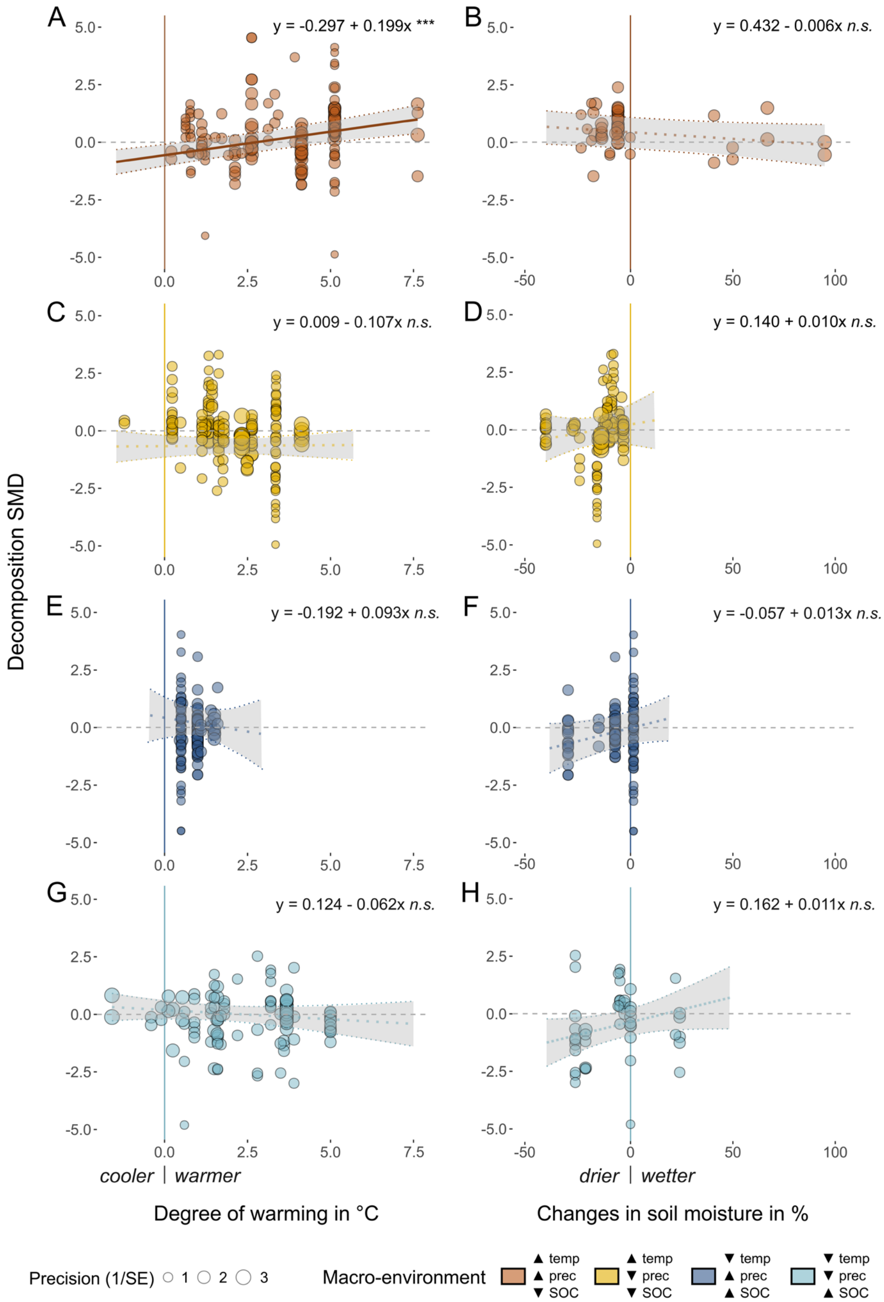

FIGURE 4 | Relationships between the effect of experimental warming on litter decomposition (SMD) and either (A, C, E, G) the degree of warming (i.e., absolute temperature difference between warmed and ambient plots) or (B, D, F, H) warming-induced changes in soil moisture (i.e., difference between warmed and ambient plots) separately for the four macro-environmental classes (different panels). Colours indicate the four macro-environmental classes distinguished by different combinations of high (▲) or low (▼) temperature (temp), precipitation (prec) and soil organic carbon (SOC), consistent with Figure 3. Each coloured dot is an individual effect size (non-outlined circles) with dot size representing its precision (the inverse of the standard error, with larger points having greater influence on the model). Solid lines indicate regression lines with shaded areas representing the 95% confidence intervals (***$p < 0.001$). Dashed lines indicate no significant relationship (n.s. = not significant).

4.4 | The Relationship between Litter Quality Proxies and the Warming Effect on Decomposition

Plant functional types (including green and rooibos tea) and plant organ types differed significantly in their C:N ratio (ANOVA: $F(9, 72) = 417.9$, $p < 0.001$, $n = 72$; Figure S6A).

While the C:N ratio was not significantly related to the experimental warming effect on litter decomposition (slope = −0.001 SMD/C:N ratio [CI: −0.003, 0.001], $p = 0.33$, $k = 428$), plant functional and organ types differed in their warming effect on decomposition (moderators' test: Q_M (df = 8) = 47.92, $p < 0.001$). Experimental warming increased decomposition of graminoid roots (SMD = 0.55 [CI: 0.27, 0.84], $p < 0.001$, $k = 49$) and decreased decomposition of graminoid shoots and leaves (SMD = −0.25 [CI: −0.43, −0.06], $p = 0.010$, $k = 151$). While experimental warming did not significantly affect the decomposition of broadleaves or roots of woody species, it did significantly

TABLE 1 | The impact of warming methods (i.e., Heating cables, Infrared heaters, Open-top chambers, other methods) on the degree of warming, the relative change in percent soil moisture (mean ± SE), and the effect of warming on litter decomposition (SMD).

Warming method	**Warming degree [°C]**		**Soil moisture changes [%]**		**SMD estimate**	***k***	**SMD *p*-value**	**95% CI**
Heating cables	4.18_a	±0.1	4.88_a	±4.1	0.41_a	121	**0.021**	**[0.06; 0.76]**
Infrared heaters	1.91_a	±0.1	-9.46_{ab}	±0.9	0.06_{ab}	120	0.691	[−0.26; 0.39]
Open-top chambers	1.33_a	±0.1	-11.88_b	±0.9	-0.07_b	366	0.594	[−0.33; 0.19]
Other methods	2.51_a	±0.2	-13.25_{ab}	±5.0	-0.25_{ab}	30	0.353	[−0.77; 0.27]

Note: Different letters indicate significant differences in the degree of warming, the soil moisture changes, and the pooled average SMD across warming methods. Bold values indicate a significant effect of the warming method on SMD ($p \leq 0.05$ or CI ≠ 0). Number of effect sizes (*k*), *p*-values for SMD estimates, and 95%-confidence interval are shown.

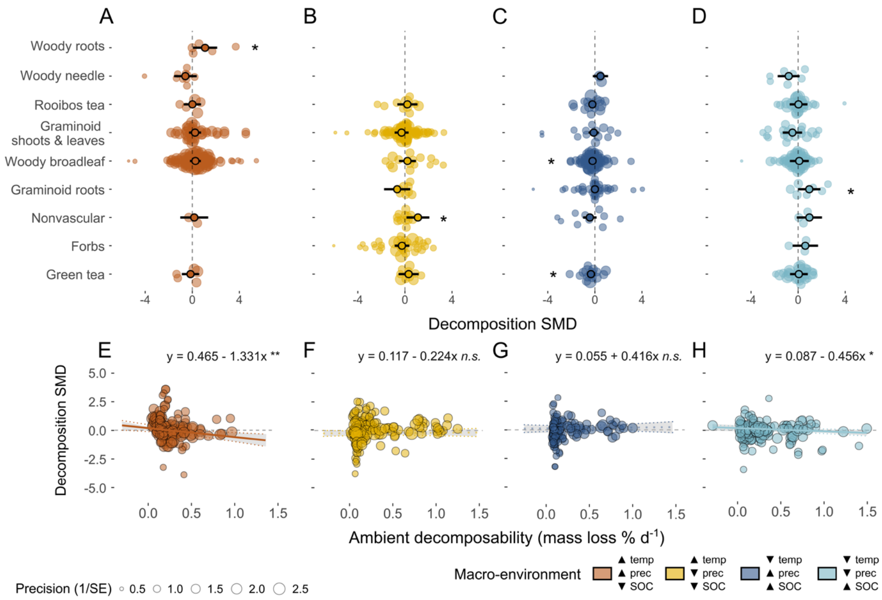

FIGURE 5 | Relationship between plant functional types, ambient decomposability and the experimental warming effect on litter decomposition across the four macro-environmental classes. (A, B, C, D) The pooled average decomposition standardised mean difference (SMD, Hedges' g, black outlined circles) and 95% confidence intervals (black error bars) for different plant functional types (when data was available; see methods) in each of the four macro-environmental classes. (E, F, G, H) Relationship between ambient decomposability (ambient mass loss rate in % d^{-1}) and the warming effect on decomposition for each of the four macro-environmental classes (see also Figure S7). Colours indicate the four macro-environmental classes distinguished by different combinations of high (▲) or low (▼) temperature (temp), precipitation (prec) and soil organic carbon (SOC), consistent with Figure 3. Each coloured dot is an individual effect size (non-outlined circles) with dot size representing its precision (i.e., the inverse of the standard error, with larger points having greater influence on the model). Solid lines indicate regression lines with shaded areas representing the 95% CI. Asterisks, located in association to the direction of the effect, indicate that the overall pooled average SMD is significantly different from zero (*$p<0.05$, **$p<0.01$). Dashed lines indicate no significant relationship (n.s. = not significant).

reduce the decomposition of needle-leaf litter (SMD = −0.44 [CI: −0.82, −0.07], $p = 0.021$, $k = 20$; Figure S6B and Table S8).

Although data were not available for all plant functional types and plant organ types across all four macro-environmental classes, the available data suggest that the macro-environment determined how decomposition of different plant functional types responded to experimental warming (moderators' test: Q_M (df = 28) = 138.82, $p < 0.001$). Data on woody roots were available only for the warm and wet class, where woody roots' decomposition increased with warming (SMD = 1.08 [CI95: 0.05, 2.11], $p = 0.040$, $k = 5$, Figure 5A). In the warm and dry class, only moss and lichen litter decomposition significantly increased with experimental warming (SMD = 1.10 [CI95: 0.13, 2.07], $p = 0.026$, $k = 12$, Figure 5B). In the cold and wet class, experimental warming decreased decomposition of woody broadleaf litter (SMD = −0.20 [CI95: −0.35, −0.05], $p = 0.010$, $k = 66$) and green tea (SMD = 0.34 [CI95: 0.06, 0.61], $p = 0.016$, $k = 15$, Figure 5C). Lastly, in the cold and dry class, only graminoids roots' decomposition significantly increased with experimental warming (SMD = 0.95 [CI95: 0.004, 1.89], $p = 0.049$, $k = 7$, Figure 5D).

Overall, the effect of experimental warming on decomposition was more positive for litter that had lower decomposability under ambient conditions (i.e., mass loss per day in non-warmed conditions) (moderators' test: Q_M (df = 1) = 5.60, $p = 0.018$). Despite similar ambient decomposability across macro-environments (ANOVA: F(3, 124) = 1.21, $p = 0.31$), higher decomposability significantly reduced the effect of experimental warming on litter decomposition in the warm and wet—(slope = −1.33 SMD/ decomposability [CI95: −2-188, −0.48], $p = 0.002$, $k = 154$; Figure 5E), and cold and dry macro-environmental class (slope = −0.46 SMD/ decomposability [CI95: −0.83, −0.08], $p = 0.018$, $k = 151$; Figure 5H). In these macro-environments, litter that is relatively harder to decompose tends to decompose slower under experimental warming compared to ambient conditions.

5 | Discussion

Across 109 datasets and 637 paired observations of plant litter decomposition under experimentally warmed and ambient conditions globally, we found that warming only increased decomposition when it exceeded 5.2°C and moisture was not limited. This estimated threshold is above the global warming predicted for the end of the century (1.4°C–4.4°C; IPCC 2021). The macro-environmental region is a key determinant of the effect of experimental warming on litter decomposition (Figure 6), with our findings showing that warming decreased decomposition in warm and dry macro-environments. Litter quality was an important moderator of the experimental warming effect, and the macro-environmental settings determined which litter characteristics were most important (Figure 6). Overall, the decomposition of litter with low decomposability increased with experimental warming, while the decomposition of litter with high decomposability decreased with warming.

5.1 | Contextual Dependence of the Experimental Warming Effect on Decomposition

We found that the prevailing macro-environmental conditions influence whether experimental warming leads to an increase, a decrease, or no change in litter decomposition. As hypothesised, warming reduced litter decomposition at warm and dry sites with limited moisture availability due to low precipitation and high evapotranspiration (Sierra, Malghani, and Loescher 2017). Macro-environmental conditions in warmer regions, such as temperate and subtropical areas, generally favour decomposition processes (Powers et al. 2009). Thus, additional warming is unlikely to further stimulate litter decomposition in these warm ecosystems (Bradford 2013; Crowther and Bradford 2013). Instead, the role of soil moisture becomes a potentially more important limiting factor (Aerts 2006). Accordingly, our observation that warming led to decreased litter decomposition in warm and dry areas, but not in warm and wet areas aligns with both our expectations and previous studies where warming amplified the effects of drought in dry macro-environments but not in wet ones (Wu et al. 2011; Thakur et al. 2018; Schimel 2018). It is noteworthy that warm and dry systems exhibit the lowest soil organic carbon content (Table S4), indicating limited carbon storage

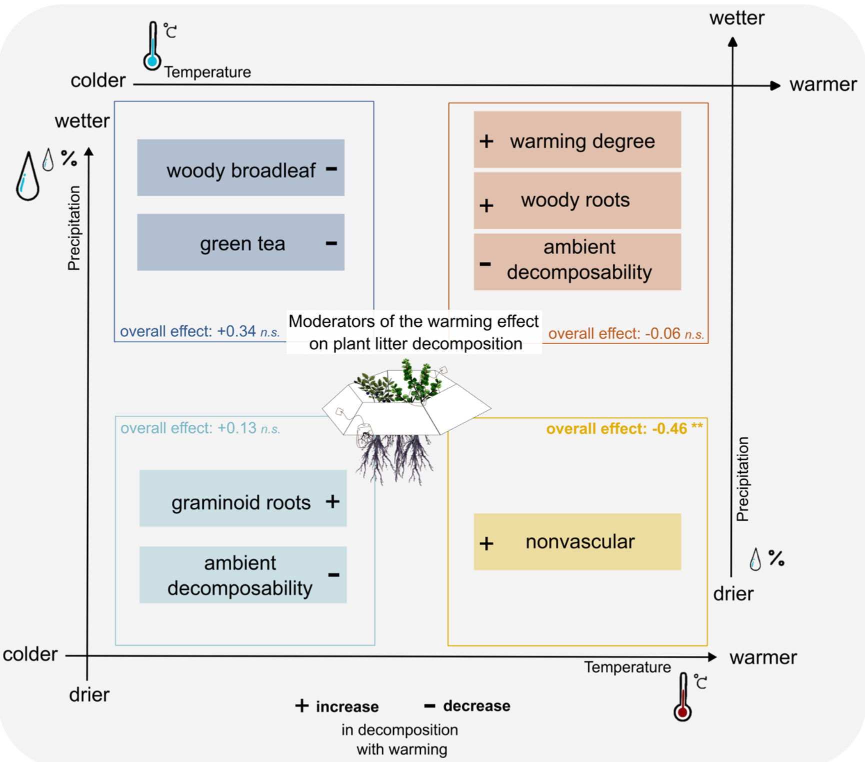

FIGURE 6 | Conceptual summary of significant moderators of the experimental warming effect on plant litter decomposition across four macro-environmental classes. Main effects of macroenvironmental settings is indicated with large squares, Asterisks denote that the overall pooled average SMD is significantly different from zero (**$p < 0.01$; n.s. = not significant). Moderators within classes are indicated as having an increasing (+) or decreasing (−) effect on decomposition compared to ambient conditions for those moderators that were significant. Colours represent the four classes, defined by combinations of high or low temperature and precipitation, consistent with Figure 3.

potential in these warm and dry sites. This implies that while warming decreases litter decomposition in warm and dry systems, the effectiveness of carbon storage is likely compromised due to warmer temperatures and dry conditions (Yi, Wei, and Hendrey 2014; Hartley et al. 2021). While previous studies have reported clear interactions between increasing temperature and moisture (Aerts 2006; Thomas et al. 2023), our research shows that these interactions manifest differently in various macro-environments. Our results highlight that macro-environmental factors can significantly influence how site-specific factors like the degree of warming affect litter decomposition, especially in warm and wet conditions, which in our dataset had the largest range of degree of warming.

A recent meta-analysis by Sagi and Hawlena (2024) highlights the role of macrofauna (e.g., invertebrates) in regulating litter decomposition, particularly in warm and dry environments. While our dataset on standardised litter (mesh size: 0.257 mm) captured primarily microbial-driven decomposition, studies of natural litter using larger meshes (> 1 mm) likely included macrofaunal effects. We found that the warming effect on litter decomposition was negligible for smaller mesh sizes, where only microbes were included. However, experimental warming significantly reduced litter decomposition in larger mesh sizes, where marcofauna was involved. This suggests that macrofauna may be more negatively impacted by warming than microbes. Sagi and Hawlena (2024) proposed that higher temperatures regulate macrofaunal activity, leading to an increased contribution of macrofauna to decomposition in warm and dry environments. However, in our study, we observed a reduction in decomposition rates with warming in conditions that favoured macrofaunal activity, such as larger mesh sizes and warm, dry macro-environments. This suggests that the activity of macrofauna may be down-regulated by warming, reducing their role in decomposition.

Contrary to our expectations, we did not observe significant overall effects of warming on litter decomposition at colder sites, where temperature is typically the main constraint. Cold ecosystems, such as high latitude and alpine regions with tundra and boreal forests (Figure S2B), are dominated by recalcitrant litter that decomposes relatively slowly and has higher temperature sensitivity (Biasi et al. 2005; Davidson and Janssens 2006; Conant, Steinweg, et al. 2008). In addition, these ecosystems contain a greater proportion of below-ground plant material (Mokany, Raison, and Prokushkin 2006; Poorter et al. 2012; Iversen et al. 2015; Wang et al. 2016). Consequently, these ecosystems were expected to show increased litter decomposition upon warming. However, while there was no statistically significant warming effect for the cold and wet macro-environment class, we observed a tendency towards increased decomposition with experimental warming. Our analysis suggests that a minimum warming threshold of 5.2°C is necessary for a positive effect on litter decomposition. However, the passive methods predominantly used in those cold systems do not achieve this degree of warming. Since warming in high latitude and high-altitude systems has outpaced the global average, with the Arctic warming nearly four times faster over the last four decades (Tingley and Huybers 2013; Rantanen et al. 2022), our predicted temperature threshold could become relevant for these systems in the near future. Hence, the ongoing warming trend may potentially accelerate decomposition in these environments with exceptionally high carbon storage.

5.2 | Litter Quality Proxies as Regulators of the Experimental Warming Effect on Decomposition

We found that litter material that decomposes slowly under ambient conditions (i.e., lower decomposability) decomposed faster under warming compared to litter material that decomposes fast under ambient conditions, which was significant under warm and wet as well as cold and dry conditions. As lower decomposability is frequently associated with lower-quality litter (Cornelissen et al. 2004; Freschet, Aerts, and Cornelissen 2012), this supports our hypothesis that lower-quality litter is more sensitive to warming than high-quality litter (Fierer et al. 2005; Conant, Drijber, et al. 2008; Suseela et al. 2013). This finding may have implications for soil organic matter (SOM) formation. That is, warming may accelerate the decomposition of the existing pool of slow-cycling, recalcitrant litter that was previously decomposing very slowly (Davidson and Janssens 2006). This faster decomposition could lead to a short-term carbon release, potentially contributing to a positive feedback loop, accelerating climate change (Cox et al. 2000; Fenner and Freeman 2011). However, it may not necessarily deplete the total SOM pool in the long term, as SOM formation might be primarily driven by the decomposition of fast-cycling, high-quality litter (Cotrufo et al. 2013, 2015), which was less affected by experimental warming in our study.

Surprisingly, the experimental warming effect on decomposition appears to be unrelated to a classic measure of litter quality (C:N ratio). Instead, we observed the strongest correlation of the warming effect on litter decomposition with ambient decomposability, which integrates both litter quality and environmental conditions (Cornelissen et al. 2004; Freschet, Aerts, and Cornelissen 2012). While the quality of the litter material (e.g., C:N ratio) may not strongly drive litter decomposition under experimental warming, our study emphasises the importance of considering the interaction between litter quality and environmental conditions for understanding decomposition dynamics in response to climate change (Joly, Scherer-Lorenzen, and Hättenschwiler 2023). The varying effects of warming on the decomposition of litter from different plant functional types and plant organs suggest that the specific composition of plant species or functional groups within a plant community significantly influences warming responses.

Specifically, we found that warming decreased decomposition for shoots and leaves (including needles), while it increased decomposition for roots (Figure S6B). This contrasting response might be due to inherent traits in roots, such as high lignin, carbon, and dry matter content, making them more resistant to decomposition (Freschet, Aerts, and Cornelissen 2012; Xia, Talhelm, and Pregitzer 2015) and consequently, more temperature-sensitive and responsive to warming (Bosatta and Ågren 1999; Fierer et al. 2005; Conant, Drijber, et al. 2008; Suseela et al. 2013). The distinct responses to warming of shoot/leaves compared to roots might be partly attributed to their incubation position in the soil or on the soil surface (Blok et al. 2018, Table S8). Needle-leaf litter, while also rich in lignin, is exposed directly to surface-level conditions, where it experiences more extreme temperature fluctuations and drying, which may limit microbial activity compared to roots that decompose in the more buffered, moister soil environment (Wang et al. 2009; Fanin et al. 2020). The specific environmental conditions in which above- and below-ground decomposition occurs likely influence the response to warming. Drier soil surface conditions likely contributed to the negative impact of warming on leaf and shoot decomposition (Blok et al. 2018), whereas wetter soil conditions enhanced decomposition under warming, irrespective of the plant organ type (Hicks Pries et al. 2013). The distinct impact of warming on roots and shoots/leaves is unlikely to be caused by differences in litter quality since the C:N ratio did not differ between roots and shoots/leaves (Figure S6A). This opposite response of plant organ types was exclusive to graminoids and not observed in woody species, indicating an undiscovered potential interaction between warming and plant functional type. This urges further investigation, especially for accurate assessments of carbon and nutrient budgets on a global scale in a warming climate, since root production and turnover account for 20%–80% of the global annual net primary productivity (Jackson, Mooney, and Schulze 1997; McCormack et al. 2015). This knowledge gap is currently posing a challenge for carbon cycle modelling especially in ecosystems with a substantial portion of biomass located below ground.

5.3 | Limitations of Specific Warming Methods

Specific warming methods can have limitations, such as their impact on soil moisture and their ability to achieve large temperature changes. Our study found that heating cables, used primarily in the warm and wet macro-environment class, effectively increased temperature with minimal impact on soil moisture, leading to a significant increase in litter decomposition. However, variations in soil moisture effects could be attributed to methodological artefacts or site-specific conditions. The pre-existing moist conditions in the warm and wet environment likely contributed to the effectiveness of the heating cables and allowed them to exceed the 5.2°C warming threshold required for a significant increase in litter decomposition. In other macro-environmental classes where heating cables were not widely used, the temperature increases did not reach the 5.2°C threshold, potentially limiting the impact on decomposition. However, by warming soils rather than air, heating cables may provide less realistic warming conditions. Infrared heaters instead replicate natural warming conditions (Aronson and McNulty 2009), but those had no effect on litter decomposition as their warming capacity was relatively small (1.91 ± 0.1; Table 1). The non-significant effect of passive warming by OTCs on litter decomposition might be explained by confounding factors, such as reduced soil temperatures due to shade or increased radiation absorption in OTCs (Marion et al. 1997). Notably, OTCs were associated with the largest decrease in soil moisture ($-11.88 \pm 0.9\%$) and a modest warming of $+1.33 \pm 0.1$°C (Table 1), in line with the lower end of global warming projections (e.g., SSP1–1.9, IPCC 2021). By combining studies of different warming methods, we were able to demonstrate the contextual dependence of the experimental warming effect with the micro-environment. We found a significant experimental warming effect on litter decomposition only for warming methods (i.e., heating cables) with a high degree of warming, which did not decrease but increased soil moisture (Table 1).

Our dataset covers large parts of the world and most biomes (Figure 1), but notably lacks data from tropical and temperate rain forests, particularly in the Southern Hemisphere. This gap is likely reflecting a global scarcity of experimental in situ warming studies conducted in these biomes rather than their exclusion based on our inclusion criteria. Hence, in our study, the impact of warming on litter decomposition in rain forests remains uncertain, and we suggest it should be a priority for future research (Cavaleri et al. 2015).

5.4 | Global Implications

This global meta-analysis integrates all available data from in situ experimental warming studies on litter decomposition across terrestrial ecosystems worldwide. The global approach enabled us to explore contextual dependence amongst warming, environmental factors (e.g., moisture, degree of warming), and litter quality. This represents an advancement over previous research, which often focused on regional scales or the impacts of experimental warming on litter decomposition within a specific environment (Aerts 2006; Blok et al. 2018; Hong et al. 2021). We show that accurate predictions of climate change impacts on key ecosystem processes, such as decomposition, must account for the complex interactions between macro-environmental conditions and litter quality.

In particular, our findings highlight the need for further investigation into below-ground decomposition under warming. Our results indicate an important interaction between experimental warming and below-ground litter decomposition (i.e., roots) that is distinct from the warming effects of above-ground litter (i.e., shoots). This presents a challenge for accurate carbon cycle modelling, especially in regions like tundra, cold deserts, and temperate grasslands, where up to 80% of the plant biomass is located below ground (Mokany, Raison, and Prokushkin 2006; Poorter et al. 2012; Iversen et al. 2015; Wang et al. 2016). This distinction underscores the importance of incorporating both above- and below-ground decomposition responses in carbon models, which could help improve predictions of future carbon storage (Bai et al. 2023).

Furthermore, rapid vegetation shifts in biomes such as tundra, alpine systems, and savannahs, characterised by increasing shrub cover, are likely to introduce harder-to-decompose litter (Harte et al. 1995; Myers-Smith et al. 2011; Elmendorf et al. 2012; Pearson et al. 2013; García Criado et al. 2020). Our results suggest two key changes that could affect carbon storage: (1) the increase in lower-quality plant litter will lead to faster decomposition under warming conditions, and (2) the higher sensitivity of below-ground decomposition to warming, often overlooked, may lead to an underestimation of warming's overall impact on decomposition. Together, these processes could contribute to increased carbon release and reduce carbon storage potential.

Our findings indicate that litter decomposition is likely to increase significantly under more extreme warming scenarios in the range of 3.3°C–5.7°C (SSP5-8.5, IPCC 2021). This is particularly concerning in light of recent record-breaking global temperatures. High-latitude ecosystems, which are warming rapidly, could see substantial shifts in decomposition rates, with an average temperature increase of 0.65°C ± 0.09°C per decade (1979–2022) according to ERA5 (ECMWF Reanalysis v5, European Centre for Medium-Range Weather Forecasts).

In addition, rising drought intensity in Europe, the Mediterranean, and large parts of Asia suggests that additional warming leading to drier soils might increasingly become a limiting factor for litter decomposition (NOAA National Centers for Environmental Information). Our findings suggest that ecosystems in warm and dry regions may experience reduced decomposition rates in the future, which could lead to reduced soil carbon emissions from the soil depending on how drought will affect primary productivity. However, our findings suggest further that this effect is more prominent in ecosystems with inherently lower initial carbon storage potential, which might indicate that warming effects on litter decomposition in these warm and dry systems may play a minor role for worldwide carbon budgets.

Certainly, the net carbon balance of a system is as well determined by carbon uptake, yet decomposition plays a pivotal role in the carbon budget. This study improves our understanding of the contextual dependence of warming sensitivity, contributing to more accurate predictions of climate change impacts on decomposition as a key ecosystem process.

Author Contributions

J.M.S. conceived the idea and S.S., J.M.S., and E.D. designed the study. J.M.S., E.D., M.P.B., V.V., E.l.R., and M.S. gave extensive feedback on the analyses and manuscript. R.A., E.A., J.A., I.A., K.B., S.B., M.P.B., M.C., A.C., C.T.C., K.C., R. Alonso, N.F., W.G., I.A.H., A.H., R.D.H., I.S.J., E.H.K., K.K., Q.L., J.O.L., A.M., T.M., I.M.S., A.P., M.S., S. Suzuki, T.K., M.t.B., H.T., F.V, V.V., S.V., Y.Y., J. Asplund, and E.l.R. collected the data on standardised plant litter decomposition from open-top-chamber warming experiments. J.v.d.H. and T.W.C. provided the map-based environmental data. All authors excluding S.S., E.D., and J.M.S. contributed data. S.S. and J.M.S. assembled the data for meta-analysis and meta-regression. S.S. analysed the data with feedback from J.M.S. and E.D. S.S. designed the figures and tables and wrote the manuscript.

Affiliations

[1]Climate Impacts Research Centre, Department of Ecology and Environmental Sciences, Umeå University, Umeå, Sweden | [2]Department of Ecology and Environmental Sciences, Umeå University, Umeå, Sweden | [3]Department of Arctic Biology, The University Centre in Svalbard, Longyearbyen, Norway | [4]Department of Arctic and Marine Biology, Faculty of Biosciences Fisheries and Economics, The Arctic University of Norway, Tromsø, Norway | [5]Department of Wildland Resources, Quinney College of Natural Resources and Ecology Center, Utah State University, Logan, Utah, USA | [6]Department of Biological Sciences and Bjerknes Centre for Climate Research, University of Bergen, Bergen, Norway | [7]Center for Ecological Dynamics in a Novel Biosphere (ECONOVO) & Center for Biodiversity Dynamics in a Changing World (BIOCHANGE), Department of Biology, Aarhus University, Aarhus, Denmark | [8]Mammal Research Institute, University of Pretoria, Hatfield, South Africa | [9]Department of Geography and Environmental Management, University of Waterloo, Waterloo, Ontario, Canada | [10]Chinese Academy of Sciences, Institute of Mountain Hazards and Environment, Chengdu, People's Republic of China | [11]Centre for Integrative Ecology, School of Life and Environmental Sciences, Deakin University, Burwood, Victoria, Australia | [12]Department of Environmental Systems Science, Institut für Integrative Biologie, Zürich, Switzerland | [13]Ecotoxicology of Air Pollution, Environmental Department, CIEMAT, Madrid, Spain | [14]Department of Geosciences, University of Edinburgh, Edinburgh, Scotland | [15]Centre for African Conservation Ecology, Nelson Mandela University, Gqeberha, South Africa | [16]Copernicus Institute for Sustainable Development, Utrecht University, Utrecht, The Netherlands | [17]South African Environmental Observation Network (SAEON), Grasslands, Forests and Wetlands Node, Montrose, South Africa | [18]The University of Tokyo Hokkaido Forest, Graduate School of Agricultural and Life Sciences, The University of Tokyo, Tokyo, Japan | [19]Department of Chemistry, Life Sciences and Environmental Sustainability, University of Parma, Parma, Italy | [20]Department of Forest & Conservation Sciences, Faculty of Forestry, University of British Columbia, Vancouver, British Columbia, Canada | [21]School of GeoSciences, Kings Buildings, University of Edinburgh, Edinburgh, Scotland | [22]Department of Geography, University of Calgary, Calgary, Alberta, Canada | [23]Terrestrial Ecology Section, Department of Biology, University of Copenhagen, Copenhagen, Denmark | [24]Naturrestaurering AS, Oslo, Norway | [25]Chinese Academy of Sciences, Institute of Applied Ecology, Shenyang, China | [26]Research Faculty of Agriculture, Hokkaido University, Sapporo, Hokkaido, Japan | [27]Faculty of Environmental Sciences and Natural Resource Management, Norwegian University of Life Sciences, Ås, Norway | [28]Institute of Life and Environmental Sciences, University of Iceland, Reykjavík, Iceland | [29]Biology Department, Grand Valley State University, Allendale, Michigan, USA | [30]Norwegian Institute for Nature Research, Trondheim, Norway | [31]Centre of Excellence in Environmental Studies (CEES), King Abdulaziz University, Jeddah, Saudi Arabia | [32]Department of Botany & Microbiology, Faculty of Science, Alexandria University, Alexandria, Egypt | [33]Yugra State University, Hanty-Mansijsk, Russia | [34]Cumulative Effects at Government of the Northwest Territories, Yellowknife, Northwest Territories, Canada | [35]Department of Environmental Sciences, Natural Resources Faculty, Catholic University of Temuco, Temuco, Chile | [36]Núcleo de Estudios Ambientales, NEA, Natural Resources Faculty, Catholic University of Temuco, Temuco, Chile | [37]Amsterdam Institute for Life and Environment (A-LIFE), Section Systems Ecology, Vrije Universiteit Amsterdam, Amsterdam, The Netherlands | [38]Department of Biological and Environmental Sciences, University of Gothenburg, Gothenburg, Sweden | [39]NORCE Norwegian Research Centre, Bjerknes Centre for Climate Research, Bergen, Norway | [40]Environmental Science Center, Qatar University, Doha, Qatar | [41]Collaborative Innovation Center on Forecast and Evaluation of Meteorological Disasters (CIC-FEMD), Nanjing University of Information Science & Technology, Nanjing, Jiangsu, People's Republic of China | [42]Research Center for Global Changes and Ecosystem Carbon Sequestration & Mitigation, School of Ecology and Applied Meteorology, Nanjing University of Information Science and Technology, Nanjing, Jiangsu, People's Republic of China

Acknowledgements

We would like to acknowledge the numerous students and field assistants, including Eleanor Walker, Bin Xu, Courtney Campbell, Sasha van Stavel, Jordanna Branham, and Golnoush Fard, involved in the collection of tea measurements and like to thank station managers for their help and access to field sites. We thank Melanie Bird for her assistance in the laboratory and Albin Bjärhall for his support in extracting raw data from the published literature. Recognising the importance of Indigenous lands, we acknowledge that parts of our fieldwork were conducted on territories historically and presently belonging to Indigenous

peoples. We express our respect and gratitude to these communities. Special thanks are extended to the residents of Utqiagvik and Atqasuk, Alaska, for their cooperation and understanding during our research activities in the Arctic region. This research would not have been possible without the collective efforts and support of these individuals and communities.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data supporting the results of this study have been published on Dryad and can be accessed here: https://doi.org/10.5061/dryad.p5hqbzkw5

Peer Review

The peer review history for this article is available at https://www.webofscience.com/api/gateway/wos/peer-review/10.1111/ele.70026.

References

Aerts, R. 1997. "Climate, Leaf Litter Chemistry and Leaf Litter Decomposition in Terrestrial Ecosystems: A Triangular Relationship." *Oikos* 79: 439.

Aerts, R. 2006. "The Freezer Defrosting: Global Warming and Litter Decomposition Rates in Cold Biomes: *Global Warming and Litter Decomposition*." *Journal of Ecology* 94: 713–724.

Aronson, E. L., and S. G. McNulty. 2009. "Appropriate Experimental Ecosystem Warming Methods by Ecosystem, Objective, and Practicality." *Agricultural and Forest Meteorology* 149: 1791–1799.

Bai, T., P. Wang, Y. Qiu, Y. Zhang, and S. Hu. 2023. "Nitrogen Availability Mediates Soil Carbon Cycling Response to Climate Warming: A Meta-Analysis." *Global Change Biology* 29: 2608–2626.

Bardgett, R. D., C. Freeman, and N. J. Ostle. 2008. "Microbial Contributions to Climate Change Through Carbon Cycle Feedbacks." *ISME Journal* 2: 805–814.

Bélanger, N., and C. Chaput-Richard. 2023. "Experimental Warming of Typically Acidic and Nutrient-Poor Boreal Soils Does Not Affect Leaf-Litter Decomposition of Temperate Deciduous Tree Species." *Soil Systems* 7: 14.

Bhuiyan, R., P. Makiranta, P. Strakova, et al. 2023. "Fine-Root Biomass Production and Its Contribution to Organic Matter Accumulation in Sedge Fens Under Changing Climate." *Science of the Total Environment* 858: 159683.

Biasi, C., O. Rusalimova, H. Meyer, et al. 2005. "Temperature-Dependent Shift From Labile to Recalcitrant Carbon Sources of Arctic Heterotrophs." *Rapid Communications in Mass Spectrometry* 19: 1401–1408.

Blok, D., S. Faucherre, I. Banyasz, R. Rinnan, A. Michelsen, and B. Elberling. 2018. "Contrasting Above- and Belowground Organic Matter Decomposition and Carbon and Nitrogen Dynamics in Response to Warming in High Arctic Tundra." *Global Change Biology* 24: 2660–2672.

Bosatta, E., and G. I. Ågren. 1999. "Soil Organic Matter Quality Interpreted Thermodynamically." *Soil Biology and Biochemistry* 31: 1889–1891.

Bradford, M. 2013. "Thermal Adaptation of Decomposer Communities in Warming Soils." *Frontiers in Microbiology* 4: 1–16.

Cavaleri, M. A., S. C. Reed, W. K. Smith, and T. E. Wood. 2015. "Urgent Need for Warming Experiments in Tropical Forests." *Global Change Biology* 21: 2111–2121.

Chapin, F. S., M. Bret-Harte, S. Hobbie, and H. Zhong. 1996. "Plant Functional Types as Predictors of Transient Responses of Arctic Vegetation to Global Change." *Journal of Vegetation Science* 7: 347–358.

Chen, J., Y. Luo, J. Xia, et al. 2015. "Stronger Warming Effects on Microbial Abundances in Colder Regions." *Scientific Reports* 5: 18032.

Conant, R. T., R. A. Drijber, M. L. Haddix, et al. 2008. "Sensitivity of Organic Matter Decomposition to Warming Varies With Its Quality." *Global Change Biology* 14: 868–877.

Conant, R. T., M. G. Ryan, G. I. Ågren, et al. 2011. "Temperature and Soil Organic Matter Decomposition Rates–Synthesis of Current Knowledge and a Way Forward." *Global Change Biology* 17: 3392–3404.

Conant, R. T., J. M. Steinweg, M. L. Haddix, E. A. Paul, A. F. Plante, and J. Six. 2008. "Experimental Warming Shows That Decomposition Temperature Sensitivity Increases With Soil Organic Matter Recalcitrance." *Ecology* 89: 2384–2391.

Cornelissen, J. H. C., H. M. Quested, D. Gwynn-Jones, et al. 2004. "Leaf Digestibility and Litter Decomposability Are Related in a Wide Range of Subarctic Plant Species and Types." *Functional Ecology* 18: 779–786.

Cotrufo, M. F., J. L. Soong, A. J. Horton, et al. 2015. "Formation of Soil Organic Matter via Biochemical and Physical Pathways of Litter Mass Loss." *Nature Geoscience* 8: 776–779.

Cotrufo, M. F., M. D. Wallenstein, C. M. Boot, K. Denef, and E. Paul. 2013. "The Microbial Efficiency-Matrix Stabilization (MEMS) Framework Integrates Plant Litter Decomposition With Soil Organic Matter Stabilization: Do Labile Plant Inputs Form Stable Soil Organic Matter?" *Global Change Biology* 19: 988–995.

Cox, P. M., R. A. Betts, C. D. Jones, S. A. Spall, and I. J. Totterdell. 2000. "Acceleration of Global Warming due to Carbon-Cycle Feedbacks in a Coupled Climate Model." *Nature* 408: 184–187.

Crowther, T. W., and M. A. Bradford. 2013. "Thermal Acclimation in Widespread Heterotrophic Soil Microbes." *Ecology Letters* 16: 469–477.

Dai, Z., M. Yu, H. Chen, et al. 2020. "Elevated Temperature Shifts Soil N Cycling From Microbial Immobilization to Enhanced Mineralization, Nitrification and Denitrification Across Global Terrestrial Ecosystems." *Global Change Biology* 26: 5267–5276.

Davidson, E. A., and I. A. Janssens. 2006. "Temperature Sensitivity of Soil Carbon Decomposition and Feedbacks to Climate Change." *Nature* 440: 165–173.

Davidson, E. A., S. E. Trumbore, and R. Amundson. 2000. "Soil Warming and Organic Carbon Content." *Nature* 408: 789–790.

Dorrepaal, E., J. H. C. Cornelissen, R. Aerts, B. Wallén, and R. S. P. Van Logtestijn. 2005. "Are Growth Forms Consistent Predictors of Leaf Litter Quality and Decomposability Across Peatlands Along a Latitudinal Gradient?: *Plant Growth Forms and Litter Quality*." *Journal of Ecology* 93: 817–828.

Elmendorf, S. C., G. H. R. Henry, R. D. Hollister, et al. 2012. "Global Assessment of Experimental Climate Warming on Tundra Vegetation: Heterogeneity Over Space and Time: Warming Effects on Tundra Vegetation." *Ecology Letters* 15: 164–175.

Fanin, N., S. Bezaud, J. M. Sarneel, S. Cecchini, M. Nicolas, and L. Augusto. 2020. "Relative Importance of Climate, Soil and Plant Functional Traits During the Early Decomposition Stage of Standardized Litter." *Ecosystems* 23: 1004–1018.

Fenner, N., and C. Freeman. 2011. "Drought-Induced Carbon Loss in Peatlands." *Nature Geoscience* 4: 895–900.

Fierer, N., J. M. Craine, K. K. McLauchlan, and J. P. Schimel. 2005. "Litter Quality And the Temperature Sensitivity of Decomposition." *Ecology* 86: 320–326.

Freschet, G. T., R. Aerts, and J. H. C. Cornelissen. 2012. "A Plant Economics Spectrum of Litter Decomposability." *Functional Ecology* 26: 56–65.

García Criado, M., I. H. Myers-Smith, A. D. Bjorkman, C. E. R. Lehmann, and N. Stevens. 2020. "Woody Plant Encroachment Intensifies Under Climate Change Across Tundra and Savanna Biomes." *Global Ecology and Biogeography* 29: 925–943.

Gregorich, E. G., H. Janzen, B. H. Ellert, et al. 2017. "Litter Decay Controlled by Temperature, Not Soil Properties, Affecting Future Soil Carbon." *Global Change Biology* 23: 1725–1734.

Harte, J., M. S. Torn, F.-R. C. Chang, et al. 1995. "Global Warming and Soil Microclimate: Results From a Meadow-Warming Experiment." *Ecological Applications* 5: 132–150.

Hartley, I. P., T. C. Hill, S. E. Chadburn, and G. Hugelius. 2021. "Temperature Effects on Carbon Storage Are Controlled by Soil Stabilisation Capacities." *Nature Communications* 12: 6713.

Hedges, L. V. 1981. "Distribution Theory for Glass's Estimator of Effect Size and Related Estimators." *Journal of Educational Statistics* 6: 107–128.

Hicks Pries, C. E., E. A. G. Schuur, J. G. Vogel, and S. M. Natali. 2013. "Moisture Drives Surface Decomposition in Thawing Tundra." *Journal of Geophysical Research: Biogeosciences* 118: 1133–1143.

Hollister, R. D., C. Elphinstone, G. H. R. Henry, et al. 2023. "A Review of Open Top Chamber (OTC) Performance Across the ITEX Network." *Arctic Science* 9: 331–344.

Hong, J., X. Lu, X. Ma, and X. Wang. 2021. "Five-Year Study on the Effects of Warming and Plant Litter Quality on Litter Decomposition Rate in a Tibetan Alpine Grassland." *Science of the Total Environment* 750.

Hothorn, T., F. Bretz, and P. Westfall. 2008. "Simultaneous Inference in General Parametric Models." *Biometrical Journal* 50: 346–363.

IPCC. 2021. "Climate Change 2021: The Physical Science Basis." https://www.cambridge.org/core/books/climate-change-2021-the-physical-science-basis/415F29233B8BD19FB55F65E3DC67272B. 9Aug.2024.

Iversen, C. M., V. L. Sloan, P. F. Sullivan, et al. 2015. "The Unseen Iceberg: Plant Roots in Arctic Tundra." *New Phytologist* 205: 34–58.

Jackson, R. B., H. A. Mooney, and E.-D. Schulze. 1997. "A Global Budget for Fine Root Biomass, Surface Area, and Nutrient Contents." *Proceedings of the National Academy of Sciences* 94: 7362–7366.

Joly, F.-X., M. Scherer-Lorenzen, and S. Hättenschwiler. 2023. "Resolving the Intricate Role of Climate in Litter Decomposition." *Nature Ecology & Evolution* 7: 214–223.

Keuskamp, J. A., B. J. J. Dingemans, T. Lehtinen, J. M. Sarneel, and M. M. Hefting. 2013. "Tea Bag Index: a Novel Approach to Collect Uniform Decomposition Data Across Ecosystems (H Muller-Landau, ed.)." *Methods in Ecology and Evolution* 4: 1070–1075.

Kirchman, D. L. 2018. *Degradation of Organic Matter*. Oxford, UK: Oxford University Press.

Knorr, W., I. C. Prentice, J. I. House, and E. A. Holland. 2005. "Long-Term Sensitivity of Soil Carbon Turnover to Warming." *Nature* 433: 298–301.

Koricheva, J., J. Gurevitch, and K. Mengersen, eds. 2013. *Handbook of Meta-Analysis in Ecology and Evolution*. Princeton, New Jersey: Princeton University Press.

Kuznetsova, A., P. B. Brockhoff, and R. H. B. Christensen. 2017. "lmerTest Package: Tests in Linear Mixed Effects Models."

Lê, S., J. Josse, and F. Husson. 2008. "FactoMineR: An *R* Package for Multivariate Analysis." *Journal of Statistical Software* 25: 1–18.

Lenth, R. 2019. "Emmeans: Estimated Marginal Means, Aka Least-Squares Means."

Li, B., W. Lv, J. Sun, et al. 2022. "Warming and Grazing Enhance Litter Decomposition and Nutrient Release Independent of Litter Quality in an Alpine Meadow." *Journal of Plant Ecology* 15: 977–990.

Lind, L., A. Harbicht, E. Bergman, J. Edwartz, and R. L. Eckstein. 2022. "Effects of Initial Leaching for Estimates of Mass Loss and Microbial Decomposition—Call for an Increased Nuance." *Ecology and Evolution* 12: e9118.

Marion, G. M., G. H. R. Henry, D. W. Freckman, et al. 1997. "Open-Top Designs for Manipulating Field Temperature in High-Latitude Ecosystems." *Global Change Biology* 3: 20–32.

McCormack, M. L., I. A. Dickie, D. M. Eissenstat, et al. 2015. "Redefining Fine Roots Improves Understanding of Below-Ground Contributions to Terrestrial Biosphere Processes." *New Phytologist* 207: 505–518.

Mokany, K., R. J. Raison, and A. S. Prokushkin. 2006. "Critical Analysis of Root : Shoot Ratios in Terrestrial Biomes." *Global Change Biology* 12: 84–96.

Munir, T. M., B. Khadka, B. Xu, and M. Strack. 2017. "Mineral Nitrogen and Phosphorus Pools Affected by Water Table Lowering and Warming in a Boreal Forested Peatland." *Ecohydrology* 10: e1893.

Myers-Smith, I. H., B. C. Forbes, M. Wilmking, et al. 2011. "Shrub Expansion in Tundra Ecosystems: Dynamics, Impacts and Research Priorities." *Environmental Research Letters* 6: 045509.

Nakagawa, S., M. Lagisz, R. E. O'Dea, et al. 2021. "The Orchard Plot: Cultivating a Forest Plot for Use in Ecology, Evolution, and Beyond." *Research Synthesis Methods* 12: 4–12.

Pearson, R. G., S. J. Phillips, M. M. Loranty, et al. 2013. "Shifts in Arctic Vegetation and Associated Feedbacks Under Climate Change." *Nature Climate Change* 3: 673–677.

Poorter, H., K. J. Niklas, P. B. Reich, J. Oleksyn, P. Poot, and L. Mommer. 2012. "Biomass Allocation to Leaves, Stems and Roots: Meta-Analyses of Interspecific Variation and Environmental Control." *New Phytologist* 193: 30–50.

Powers, J. S., R. A. Montgomery, E. C. Adair, et al. 2009. "Decomposition in Tropical Forests: a Pan-Tropical Study of the Effects of Litter Type, Litter Placement and Mesofaunal Exclusion Across a Precipitation Gradient." *Journal of Ecology* 97: 801–811.

Prescott, C. E. 2010. "Litter Decomposition: What Controls It and How Can We Alter It to Sequester More Carbon in Forest Soils?" *Biogeochemistry* 101: 133–149.

R Core Team. 2023. *R: A Language and Environment for Statistical Computing*. Vienna, Austria: R Foundation for Statistical Computing.

Rantanen, M., A. Y. Karpechko, A. Lipponen, et al. 2022. "The Arctic Has Warmed Nearly Four Times Faster Than the Globe Since 1979." *Communications Earth & Environment* 3: 1–10.

Rey, A., E. Pegoraro, and P. G. Jarvis. 2008. "Carbon Mineralization Rates at Different Soil Depths Across a Network of European Forest Sites (FORCAST)." *European Journal of Soil Science* 59: 1049–1062.

Rohatgi, A. 2021. "Webplotdigitizer: Version 4.5."

Romero-Olivares, A., S. Allison, and K. Treseder. 2017. "Decomposition of Recalcitrant Carbon Under Experimental Warming in Boreal Forest." *PLoS One* 12: e0179674.

Sagi, N., and D. Hawlena. 2024. "Climate Dependence of the Macrofaunal Effect on Litter Decomposition—A Global Meta-Regression Analysis." *Ecology Letters* 27: e14333.

Schimel, J. P. 2018. "Life in Dry Soils: Effects of Drought on Soil Microbial Communities and Processes." *Annual Review of Ecology, Evolution, and Systematics* 49: 409–432.

Seres, A., G. Kröel-Dulay, J. Szakálas, et al. 2022. "The Response of Litter Decomposition to Extreme Drought Modified by Plant Species, Plant Part, and Soil Depth in a Temperate Grassland." *Ecology and Evolution* 12: e9652.

Sierra, C. A., S. Malghani, and H. W. Loescher. 2017. "Interactions Among Temperature, Moisture, and Oxygen Concentrations in

Controlling Decomposition Rates in a Boreal Forest Soil." *Biogeosciences* 14: 703–710.

Sterne, J. A. C., and M. Egger. 2001. "Funnel Plots for Detecting Bias in Meta-Analysis." *Journal of Clinical Epidemiology* 54: 1046–1055.

Suseela, V., N. Tharayil, B. Xing, and J. S. Dukes. 2013. "Labile Compounds in Plant Litter Reduce the Sensitivity of Decomposition to Warming and Altered Precipitation." *New Phytologist* 200: 122–133.

Tarnocai, C., J. G. Canadell, E. A. G. Schuur, P. Kuhry, G. Mazhitova, and S. Zimov. 2009. "Soil Organic Carbon Pools in the Northern Circumpolar Permafrost Region." *Global Biogeochemical Cycles* 23: GB2023. https://doi.org/10.1029/2008GB003327.

Thakur, M. P., P. B. Reich, S. E. Hobbie, et al. 2018. "Reduced Feeding Activity of Soil Detritivores Under Warmer and Drier Conditions." *Nature Climate Change* 8: 75–78.

Thomas, H., I. Myers-Smith, T. Høye, et al. 2023. "Litter Quality Outweighs Climate as a Driver of Decomposition Across the Tundra Biome." *Life Sciences*. https://doi.org/10.32942/X28W2T.

Tingley, M. P., and P. Huybers. 2013. "Recent Temperature Extremes at High Northern Latitudes Unprecedented in the Past 600 Years." *Nature* 496: 201–205.

Viechtbauer, W. 2010. "Conducting Meta-Analyses in *R* With the Metafor Package." *Journal of Statistical Software* 36: 1–48.

Vogel, A., N. Eisenhauer, A. Weigelt, and M. Scherer-Lorenzen. 2013. "Plant Diversity Does Not Buffer Drought Effects on Early-Stage Litter Mass Loss Rates and Microbial Properties." *Global Change Biology* 19: 2795–2803.

Walter, J., R. Hein, C. Beierkuhnlein, et al. 2013. "Combined Effects of Multifactor Climate Change and Land-Use on Decomposition in Temperate Grassland." *Soil Biology & Biochemistry* 60: 10–18.

Wang, E., H. Cresswell, J. Xu, and Q. Jiang. 2009. "Capacity of Soils to Buffer Impact of Climate Variability and Value of Seasonal Forecasts." *Agricultural and Forest Meteorology* 149: 38–50.

Wang, P., L. Mommer, J. van Ruijven, F. Berendse, T. C. Maximov, and M. M. P. D. Heijmans. 2016. "Seasonal Changes and Vertical Distribution of Root Standing Biomass of Graminoids and Shrubs at a Siberian Tundra Site." *Plant and Soil* 407: 55–65.

Wickham, H., W. Chang, and M. H. Wickham. 2016. "Package 'ggplot2.' *Create Elegant Data Visualisations Using the Grammar of Graphics. Version* 2: 1–189."

Wu, Q., K. Yue, X. Wang, Y. Ma, and Y. Li. 2020. "Differential Responses of Litter Decomposition to Warming, Elevated CO_2, and Changed Precipitation Regime." *Plant and Soil* 455: 155–169.

Wu, Z., P. Dijkstra, G. W. Koch, J. Peñuelas, and B. A. Hungate. 2011. "Responses of Terrestrial Ecosystems to Temperature and Precipitation Change: a Meta-Analysis of Experimental Manipulation." *Global Change Biology* 17: 927–942.

Xia, M., A. F. Talhelm, and K. S. Pregitzer. 2015. "Fine Roots Are the Dominant Source of Recalcitrant Plant Litter in Sugar Maple-Dominated Northern Hardwood Forests." *New Phytologist* 208: 715–726.

Xue, K. M., M. J. Yuan, Z. Shi, et al. 2016. "Tundra Soil Carbon Is Vulnerable to Rapid Microbial Decomposition Under Climate Warming." *Nature Climate Change* 6: 595–600.

Yi, C., S. Wei, and G. Hendrey. 2014. "Warming Climate Extends Dryness-Controlled Areas of Terrestrial Carbon Sequestration." *Scientific Reports* 4: 5472.

Zhang, D., D. Hui, Y. Luo, and G. Zhou. 2008. "Rates of Litter Decomposition in Terrestrial Ecosystems: Global Patterns and Controlling Factors." *Journal of Plant Ecology* 1: 85–93.

Zhou, Y., W.-W. Lv, S.-P. Wang, et al. 2022. "Additive Effects of Warming and Grazing on Fine-Root Decomposition and Loss of Nutrients in an Alpine Meadow." *Journal of Plant Ecology* 15: 1273–1284.

Websites

European Centre for Medium-Range Weather Forecasts. 2022. "European State of the Climate." Last Accessed 29 January 2024. https://climate.copernicus.eu/esotc/2022.

National Centers for Environmental Information. 2023. "Global Drought Information System." Last Accessed 29 January 2024. https://www.ncei.noaa.gov/access/monitoring/monthly-report/global-drought/202309.

Supporting Information

Additional supporting information can be found online in the Supporting Information section.

Supporting Information

List of Figures 2

List of Tables 3

Literature screening process 4

Peer-reviewed literature included in the meta-analysis 5

Locations of open-top chamber warming experiments measuring standardised plant litter (tea) decomposition 10

Detailed Methodological Information 12

M1 - Calculation of Hedges' g 12
M2 - Handling of macro-environmental factors 12
M3 - Warming methods and micro-environmental effects 12

Macro-environmental factors 14

The effect of experimental-induced warming on decomposition 23

Plant functional types and plant organ types interacting with the position of incubation (on soil surface, buried in the soil) 24

Supporting Information

List of Figures

Figure S1 *The literature screening process visualized as a preferred reporting items for systematic reviews and meta-analyses (PRISMA) flow diagram describing the number of screened studies (n) and exclusion rules in this meta-analysis.* 4

Figure S2 *(A) Global distribution of study sites coloured according to the four main macro-environmental classes derived from the principal component analysis. (B) Study sites plotted in a Whittaker Biome Diagram with dots for study sites coloured according to the four main macro-environmental classes.* 16

Figure S3 *Impacts of experimentally induced changes in micro-environment on decomposition. Effect of (A) degree of warming (i.e., absolute temperature difference between warmed and control plots, k=315); (B) warming-induced changes in soil moisture with warming (i.e., difference between warmed and control plots in soil moisture, k=315) on decomposition SMD; and (C) mesh size of the litter bags in mm with 1 mm as the minimal threshold for macrofauna exclusion (Sagi and Hawlena 2024). Each grey outlined circle is an individual effect size with circle size representing its precision (the inverse of the standard error, larger points having greater influence on the model). Asterisks indicate that the overall pooled average SMD is significantly different from zero. Solid lines indicate regression lines with shaded areas representing the 95%CI (***p < 0.001, **p < 0.01). Dashed lines indicate no significant relationship (n.s. = not significant).* 22

Figure S4 *Impacts of experimentally induced changes in micro-environment on decomposition and its interaction with macro-environment. Effect of (A) degree of warming (i.e., absolute temperature difference between warmed and control plots, k=315); and (B) warming-induced changes in soil moisture with warming (i.e., difference between warmed and control plots in soil moisture, k=315) on decomposition SMD. Each coloured dot is an individual effect size (non-outlined circles) with dot size representing its precision (the inverse of the standard error, larger points having greater influence on the model). Asterisks indicate that the overall pooled average SMD is significantly different from zero. Solid lines indicate regression lines with shaded areas representing the 95%CI (***p < 0.001). Dashed lines indicate no significant relationship (n.s. = not significant).* 23

Figure S5 *Impact of warming methods on decomposition SMD. The pooled average decomposition standardised mean difference (SMD, Hedges' g; outlined circles) and 95% confidence intervals (black error bars) resulting from warming for the different experimental warming methods (see Table S1). Each coloured dot is an individual effect size (non-outlined circles) with dot size representing its precision (the inverse of the standard error, larger points having greater influence on the model). Letters indicate significant differences between the pooled average SMD of warming methods. Asterisks indicate a significant deviation of decomposition SMD from zero (*p ≤ 0.05).* 23

Figure S6 *Differences in C:N ratio and warming effect on decomposition across plant functional types. (A) Plant functional types ranked based on carbon to nitrogen ratios (C:N ratios). Large, coloured points represent mean C:N ratios and small transparent dots individual plant species. (B) The pooled average decomposition standardized mean difference (SMD, Hedges' g, black outlined circles) and 95% confidence intervals (95%CI, black error bars) per plant functional type of natural litter and standardised plant litter combining data from above and below ground incubations. Different letters indicate differences in (A) mean C:N ratio and (B) decomposition SMD between the different plant functional litter types, as well as the standard material green and rooibos tea. Asterisks indicate that the overall pooled average SMD is significantly different from zero (*p < 0.05, **p < 0.01, ***p < 0.001).* 24

Figure S7 *Differences in ambient decomposability, measured as ambient mass loss rate per day (% d^{-1}), for the plant functional types and plant organs of natural plant litter and the standardised tea material (i.e., rooibos and green tea) for each of the four macro-environmental classes. Colours indicate the four macro-environmental classes of temperature (temp), precipitation (prec) and soil organic carbon (SOC) that are either high (▲) or low (▼), consistent with Figure 3 in the main text. Different letters indicate significant differences in decomposition SMD between plant functional types.* 25

Supporting Information

List of Tables

Table S1 *Scientific research articles included in the meta-analysis, sorted by first author. The country of the study and used warming method (detailed information on the methods can be found in the original articles) of the reported/included study. Number of effect sizes per study (k), and sum of observations per study for the paired warming treatment and control.* 5

Table S2 *Study sites in which standardised litter decomposition was measured in open-top chamber experiments. Observations per study are treatment replications in space and resulted in one effect size per site.* 10

Table S3 *Correlation off the map-based macro-environmental climatic factors to the Principal component axes (PC1, PC2) together with the units and sources, including WorldClim2 = database of high spatial resolution global weather and climate data, SoilGrids = system for global digital soil mapping, CGIAR=Consortium of International Agricultural Research Centers, EarthEnv = Global, remote-sensing supported environmental layers for assessing status and trends in biodiversity, ecosystems, and climate, MODIS=Moderate Resolution Imaging Spectroradiometer.* 14

Table S4 *Means and standard error (SE) of the map-based macro-environmental factors per macro-environmental class that are defined by the scores on the PCA axis and the correlation of these axis to climatic variables of temperature (temp), precipitation (prec), and soil organic carbon (SOC) that are either high (upward arrow) or low (downward arrow).* 17

Table S5 *Results of single effects multivariate linear mixed-effects models for reported and measured macro-environmental factors with the standardised mean difference of decomposition (SMD) as dependent and measured or reported site-specific environmental factors as predictor. Values in bold indicate significant effect of the predictor on decomposition SMD ($p \leq 0.05$). The number of effect sizes (k) used in the models, lower and upper bounds of the 95% confidence intervals, and heterogeneity explained by the model structure (Q_M) are reported.* 20

Table S6 *Map-based macro-environmental results of single multivariate linear mixed-effects models with the standardised mean difference of decomposition (SMD) as dependent variable and the map-derived macro-environmental factors as predictor. Values in bold indicate significant effect of the predictor on decomposition SMD ($p \leq 0.05$). The number of effect sizes (k) used in the models, lower and upper bounds of the 95% confidence intervals, and heterogeneity explained by the model structure (Q_M) are reported.* 20

Table S7 *The impact of the four macro-environmental classes four macro-environmental classes distinguished by different combinations of high (▲) or low (▼) of temperature (temp), precipitation (prec) and soil organic carbon (SOC) and the natural and the standardised plant litter (i.e., green and rooibos tea) on the effect of warming on decomposition (SMD). Bold values indicate a significant effect of the macro-environmental class and litter type on SMD ($p \leq 0.05$ or $CI \neq 0$). Number of effect sizes (k), p-values, and 95%-confidence interval are shown.* 22

Table S8 *The pooled average decomposition standardised mean difference (SMD) of different plant functional types of the natural litter and natural and the standardised plant litter (i.e., green and rooibos tea) with respect to the position of incubation (i.e., on soil surface, buried in the soil) as well as the number of effect sizes (k) for each category, the p-value and 95%-confidence interval describing whether the pooled average SMD significantly differs from zero (in bold, $p \leq 0.05$). For forbs and nonvascular plants no reports of buried or root litter were available.* 25

Supporting Information

Literature screening process

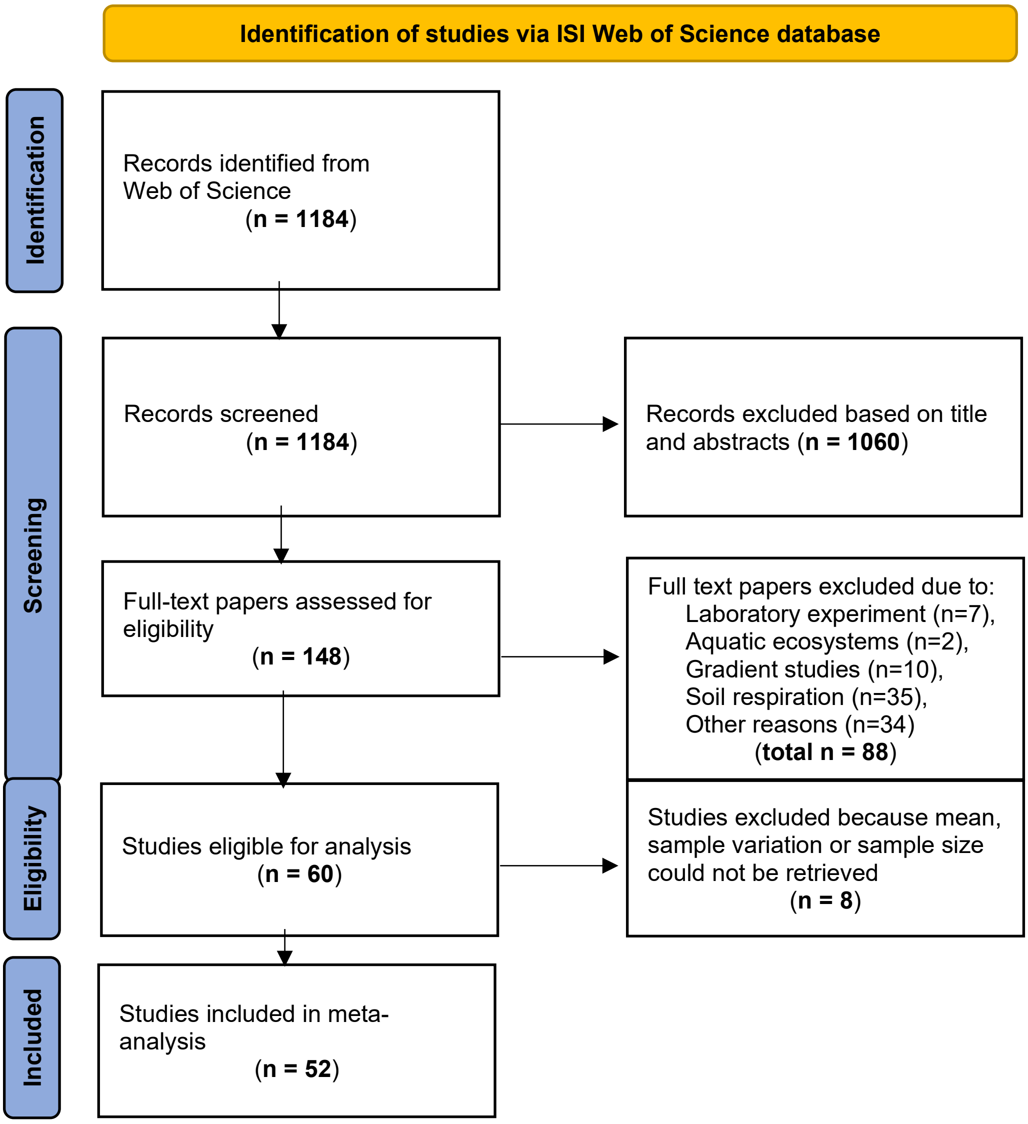

Figure S1 The literature screening process visualized as a preferred reporting items for systematic reviews and meta-analyses (PRISMA) flow diagram describing the number of screened studies (n) and exclusion rules in this meta-analysis.

Supporting Information

Peer-reviewed literature included in the meta-analysis

Table S1 Scientific research articles included in the meta-analysis, sorted by first author. The country of the study and used warming method (detailed information on the methods can be found in the original articles) of the reported study. Number of effect sizes per study (k), and sum of observations from ambient vs warmed treatments per study for the paired warming treatment and control.

Nr	Study	DOI	Country	Warming method	Effect sizes (*k*)	Obser-vations
1	Aerts et al., 2012	10.1007/s00442-012-2330-z	USA	Open-top chamber	6	30
2	Bélanger et al., 2023	10.3390/soilsystems7010014	Kazakhstan	Heating cable	24	480
3	Berbeco et al., 2012	10.1007/s11104-012-1130-x	USA	Heating cable	16	144
4	Berdugo et al., 2021	10.1007/s10021-020-00599-0	Spain	Open-top chamber	12	57
5	Bhuiyan et al., 2023	10.1016/j.scitotenv.2022.159683	Finland	Open-top chamber	50	300
6	Blok et al., 2016	10.1007/s10021-015-9924-3	Greenland	Open-top chamber	6	36
7	Blok et al., 2018	10.1111/gcb.14017	Greenland	Open-top chamber	4	20
8	Bokhorst et al., 2010	10.1016/j.soilbio.2009.12.011	Sweden	Infrared heater	12	72
9	Brigham et al., 2018	10.1080/15230430.2018.1494941	Belgium	Open-top chamber	4	16
10	Carbognani et al., 2014	10.1007/s11104-013-1982-8	Italy	Open-top chamber	4	20
11	Chen et al., 2008	10.2134/jeq2007.0266	USA	Sunlit controlled-environment chamber	2	78
12	Cheng et al., 2010	10.1016/j.agee.2010.04.019	Sweden	Infrared heater	14	70
13	Christiansen et al., 2017	10.1111/gcb.13362	Greenland	Open-top chamber	2	24
14	Chuckran et al., 2020	10.1016/j.soilbio.2020.107799	USA	Infrared heater	6	120
15	Cui et al., 2021	10.1007/s13157-021-01445-2	China	Open-top chamber	20	60
16	De Long et al., 2016	10.1016/j.soilbio.2016.04.009	Sweden	Open-top chamber	6	60
17	Gewirtzman et al., 2019	10.3389/fpls.2019.01097	USA	Heating cable	23	77
18	Gong et al., 2015	10.1371/journal.pone.0116013	China	Infrared heater	6	36
19	Han et al., 2019	10.3906/tar-1807-162	South Korea	Infrared heater	3	9
20	Henry et al., 2015	10.1007/s11104-014-2346-8	Canada	Infrared heater	8	80
21	Hong et al., 2021	10.1016/j.scitotenv.2020.142306	China	Open-top chamber	20	60
22	Kasurinen et al., 2017	10.1007/s11104-016-3122-8	Finland	Infrared heater	2	28
23	Li et al., 2022a	10.1016/j.soilbio.2022.108716	China	Heating cable	14	140

24	Li et al., 2022b	10.1093/jpe/rtac009	China	Infrared heater	1	8
25	Liu et al., 2021	10.1007/s11104-020-04551-y	China	Infrared heater	6	30
26	Liu et al., 2022	10.1016/j.geoderma.2022.116139	China	Heating cable	8	160
27	Lukas et al., 2018	10.1016/j.apsoil.2017.10.018	Germany	Heating cable	4	16
28	Luo et al., 2010	10.1111/j.1365-2486.2009.02026.x	China	Infrared heater	2	8
29	Luo et al., 2023	10.1098/rspb.2023.0613	China	Open-top chamber	8	160
30	McHale et al., 1998	10.1139/cjfr-28-9-1365	USA	Heating cable	12	108
31	Moise et al., 2014	10.1007/s00442-014-3068-6	Canada	Infrared heater	4	40
32	Morrison et al., 2019	10.1016/j.soilbio.2019.02.005	USA	Heating cable	1	10
33	Prieto et al., 2019	10.1111/1365-2745.13168	Spain	Open-top chamber	2	20
34	Remy et al., 2018	10.1007/s10021-017-0182-4	Netherlands	Open-top chamber	24	48
35	Ren et al., 2018	10.15302/J-FASE-2017194	China	Infrared heater	5	30
36	Robinson et al., 1995	10.2307/3545996	Sweden; Norway:Svalbard	Open-topped polythene tents	5	30
37	Robinson et al., 1997	10.1046/j.1365-2486.1997.d01-133.x	Sweden; Norway:Svalbard	Open-topped polythene tents	11	72
38	Romero-Olivares et al., 2017	10.1371/journal.pone.0179674	USA:Alaska	Open-top chamber	4	20
39	Rustad et al., 1998	10.2136/sssaj1998.03615995006200040031x	USA	Heating cable	6	40
40	Shaw et al., 2001	10.2307/3061022	USA	Infrared heater	34	176
41	Shu et al., 2019	10.1038/s41598-019-53450-5	China	Open-top chamber	2	8
42	Sjögersten et al., 2004	10.1023/B:PLSO.0000037044.63113.fe	Norway; Greenland	Open-top chamber	60	300
43	Sjögersten et al., 2012	10.1007/s10021-011-9514-y	Norway:Svalbard	Open-top chamber	4	20
44	Suseela et al., 2014	10.1016/j.soilbio.2014.03.022	USA	Infrared heater	6	36
45	Walter et al., 2013	10.1016/j.soilbio.2013.01.018	Germany	Infrared heater	1	15
46	Ward et al., 2015	10.1890/14-0292.1	UK	Open-top chamber	6	24
47	Xu et al., 2012	10.1111/j.1365-2389.2012.01449.x	China	Heating cable	9	36
48	Ye et al., 2022	10.1016\j.soilbio.2022.108588	China	Open-top chamber	12	576
49	Yin et al., 2022	10.1007/s00374-022-01639-8	China	Heating cable	4	32
50	Yoshitake et al., 2021	10.1111/grs.12319	Japan:Honshu	Infrared heater	8	48
51	Zaller et al., 2009	10.1111/j.1365-2486.2009.01970.x	Argentina:Tierra del Fuego	UVB filter film	8	40
52	Zhou et al., 2022	10.1093/jpe/rtac027	China	Infrared heater	2	16

Supporting Information

1. Aerts R, Callaghan TV, Dorrepaal E, Van Logtestijn RSP, Cornelissen JHC. 2012. Seasonal climate manipulations have only minor effects on litter decomposition rates and N dynamics but strong effects on litter P dynamics of sub-arctic bog species. *Oecologia* 170: 809–819.
2. Bélanger N, Chaput-Richard C. 2023. Experimental warming of typically acidic and nutrient-poor boreal soils does not affect leaf-litter decomposition of temperate deciduous tree species. *SOIL SYSTEMS* 7.
3. Berbeco MR, Melillo JM, Orians CM. 2012. Soil warming accelerates decomposition of fine woody debris. *Plant and Soil* 356: 405–417.
4. Berdugo M, Mendoza-Aguilar DO, Rey A, *et al.* 2021. Litter Decomposition Rates of Biocrust-Forming Lichens Are Similar to Those of Vascular Plants and Are Affected by Warming. *Ecosystems* 24: 1531–1544.
5. Bhuiyan R, Makiranta P, Strakova P, *et al.* 2023. Fine-root biomass production and its contribution to organic matter accumulation in sedge fens under changing climate. *SCIENCE OF THE TOTAL ENVIRONMENT* 858.
6. Blok D, Elberling B, Michelsen A. 2016. Initial Stages of Tundra Shrub Litter Decomposition May Be Accelerated by Deeper Winter Snow But Slowed Down by Spring Warming. *Ecosystems* 19: 155–169.
7. Blok D, Faucherre S, Banyasz I, Rinnan R, Michelsen A, Elberling B. 2018. Contrasting above- and belowground organic matter decomposition and carbon and nitrogen dynamics in response to warming in High Arctic tundra. *Global Change Biology* 24: 2660–2672.
8. Bokhorst S, Bjerke JW, Melillo J, Callaghan TV, Phoenix GK. 2010. Impacts of extreme winter warming events on litter decomposition in a sub-Arctic heathland. *Soil Biology and Biochemistry* 42: 611–617.
9. Brigham LM, Esch EH, Kopp CW, Cleland EE. 2018. Warming and shrub encroachment decrease decomposition in arid alpine and subalpine ecosystems. *Arctic, Antarctic, and Alpine Research* 50: e1494941.
10. Carbognani M, Petraglia A, Tomaselli M. 2014. Warming effects and plant trait control on the early-decomposition in alpine snowbeds. *Plant and Soil* 376: 277–290.
11. Chen H, Rygiewicz PT, Johnson MG, Harmon ME, Tian H, Tang JW. 2008. Chemistry and Long-Term Decomposition of Roots of Douglas-Fir Grown under Elevated Atmospheric Carbon Dioxide and Warming Conditions. *Journal of Environmental Quality* 37: 1327–1336.
12. Cheng X, Luo Y, Su B, *et al.* 2010. Experimental warming and clipping altered litter carbon and nitrogen dynamics in a tallgrass prairie. *Agriculture, Ecosystems & Environment* 138: 206–213.
13. Christiansen CT, Haugwitz MS, Priemé A, *et al.* 2017. Enhanced summer warming reduces fungal decomposer diversity and litter mass loss more strongly in dry than in wet tundra. *Global Change Biology* 23: 406–420.
14. Chuckran PF, Reibold R, Throop HL, Reed SC. 2020. Multiple mechanisms determine the effect of warming on plant litter decomposition in a dryland. *Soil Biology and Biochemistry* 145: 107799.
15. Cui W, Mao Y, Tian K, Wang H. 2021. A Comparative Study of Manipulative and Natural Temperature Increases in Controlling Wetland Plant Litter Decomposition. *Wetlands* 41: 48.
16. De Long JR, Dorrepaal E, Kardol P, Nilsson M-C, Teuber LM, Wardle DA. 2016. Understory plant functional groups and litter species identity are stronger drivers of litter decomposition than warming along a boreal forest post-fire successional gradient. *Soil Biology and Biochemistry* 98: 159–170.
17. Gewirtzman J, Tang J, Melillo JM, *et al.* 2019. Soil Warming Accelerates Biogeochemical Silica Cycling in a Temperate Forest. *Frontiers in Plant Science* 10: 1097.
18. Gong S, Guo R, Zhang T, Guo J. 2015. Warming and Nitrogen Addition Increase Litter Decomposition in a Temperate Meadow Ecosystem (M Schädler, Ed.). *PLOS ONE* 10: e0116013.
19. Han SH, Kim S, Chang H, Li G. 2019. Increased soil temperature stimulates changes in carbon, nitrogen, and mass loss in the fine roots of Pinus koraiensis under experimental warming and drought. *TURKISH JOURNAL OF AGRICULTURE AND FORESTRY* 43: 80–87.
20. Henry HAL, Moise ERD. 2015. Grass litter responses to warming and N addition: temporal variation in the contributions of litter quality and environmental effects to decomposition. *Plant and Soil* 389: 35–43.

21. Hong J, Lu X, Ma X, Wang X. 2021. Five-year study on the effects of warming and plant litter quality on litter decomposition rate in a Tibetan alpine grassland. *Science of The Total Environment* 750: 142306.
22. Kasurinen A, Silfver T, Rousi M, Mikola J. 2017. Warming and ozone exposure effects on silver birch (Betula pendula Roth) leaf litter quality, microbial growth and decomposition. *Plant and Soil* 414: 127–142.
23. Li A, Fan Y, Chen S, Song H, Lin C, Yang Y. 2022. Soil warming did not enhance leaf litter decomposition in two subtropical forests. *SOIL BIOLOGY & BIOCHEMISTRY* 170.
24. Li B, Lv W, Sun J, *et al.* 2022. Warming and grazing enhance litter decomposition and nutrient release independent of litter quality in an alpine meadow. *JOURNAL OF PLANT ECOLOGY* 15: 977–990.
25. Liu X, Chen S, Li X, *et al.* 2022. Soil warming delays leaf litter decomposition but exerts no effect on litter nutrient release in a subtropical natural forest over 450 days. *GEODERMA* 427.
26. Liu H, Lin L, Wang H, *et al.* 2021. Simulating warmer and drier climate increases root production but decreases root decomposition in an alpine grassland on the Tibetan plateau. *Plant and Soil* 458: 59–73.
27. Lukas S, Abbas SJ, Kössler P, Karlovsky P, Potthoff M, Joergensen RG. 2018. Fungal plant pathogens on inoculated maize leaves in a simulated soil warming experiment. *Applied Soil Ecology* 124: 75–82.
28. Luo B, Huang M, Wang W, *et al.* 2023. Ant nests increase litter decomposition to mitigate the negative effect of warming in an alpine grassland ecosystem. *PROCEEDINGS OF THE ROYAL SOCIETY B-BIOLOGICAL SCIENCES* 290.
29. Luo C, Xu G, Chao Z, *et al.* 2010. Effect of warming and grazing on litter mass loss and temperature sensitivity of litter and dung mass loss on the Tibetan plateau. *Global Change Biology* 16: 1606–1617.
30. McHale PJ, Mitchell MJ, Bowles FP. 1998. Soil warming in a northern hardwood forest: trace gas fluxes and leaf litter decomposition. *Canadian Journal of Forest Research* 28: 1365–1372.
31. Moise ERD, Henry HAL. 2014. Interactive responses of grass litter decomposition to warming, nitrogen addition and detritivore access in a temperate old field. *Oecologia* 176: 1151–1160.
32. Morrison EW, Pringle A, Van Diepen LTA, Grandy AS, Melillo JM, Frey SD. 2019. Warming alters fungal communities and litter chemistry with implications for soil carbon stocks. *Soil Biology and Biochemistry* 132: 120–130.
33. Prieto I, Almagro M, Bastida F, Querejeta JI. 2019. Altered leaf litter quality exacerbates the negative impact of climate change on decomposition (P Kardol, Ed.). *Journal of Ecology* 107: 2364–2382.
34. Remy E, Wuyts K, Van Nevel L, De Smedt P, Boeckx P, Verheyen K. 2018. Driving Factors Behind Litter Decomposition and Nutrient Release at Temperate Forest Edges. *Ecosystems* 21: 755–771.
35. Ren H, Qin J, Yan B, Alata, Baoyinhexige, Han G. 2018. Mass loss and nutrient dynamics during litter decomposition in response to warming and nitrogen addition in a desert steppe. *Frontiers of Agricultural Science and Engineering* 5: 64.
36. Robinson CH, Michelsen A, Lee JA, *et al.* 1997. Elevated atmospheric CO_2 affects decomposition of *Festuca vivipara* (L.) Sm. litter and roots in experiments simulating environmental change in two contrasting arctic ecosystems. *Global Change Biology* 3: 37–49.
37. Robinson CH, Wookey PA, Parsons AN, *et al.* 1995. Responses of Plant Litter Decomposition and Nitrogen Mineralisation to Simulated Environmental Change in a High Arctic Polar Semi-Desert and a Subarctic Dwarf Shrub Heath. *Oikos* 74: 503.
38. Romero-Olivares AL, Allison SD, Treseder KK. 2017. Decomposition of recalcitrant carbon under experimental warming in boreal forest (D Hui, Ed.). *PLOS ONE* 12: e0179674.
39. Rustad LE, Fernandez IJ. 1998. Soil Warming: Consequences for Foliar Litter Decay in a Spruce-Fir Forest in Maine, USA. *Soil Science Society of America Journal* 62: 1072–1080.
40. Shaw MR, Harte J. 2001. Control of Litter Decomposition in a Subalpine Meadow-Sagebrush Steppe Ecotone under Climate Change. *Ecological Applications* 11: 1206.
41. Shu M, Zhao Q, Li Z, Zhang L, Wang P, Hu S. 2019. Effects of global change factors and living roots on root litter decomposition in a Qinghai-Tibet alpine meadow. *Scientific Reports* 9: 16924.

42. Sjögersten S, Van Der Wal R, Woodin SJ. 2012. Impacts of Grazing and Climate Warming on C Pools and Decomposition Rates in Arctic Environments. *Ecosystems* 15: 349–362.
43. Sjögersten S, Wookey PA. 2004. Decomposition of mountain birch leaf litter at the forest-tundra ecotone in the Fennoscandian mountains in relation to climate and soil conditions. *Plant and Soil* 262: 215–227.
44. Suseela V, Tharayil N, Xing B, Dukes JS. 2014. Warming alters potential enzyme activity but precipitation regulates chemical transformations in grass litter exposed to simulated climatic changes. *Soil Biology and Biochemistry* 75: 102–112.
45. Walter J, Hein R, Beierkuhnlein C, *et al.* 2013. Combined effects of multifactor climate change and land-use on decomposition in temperate grassland. *Soil Biology and Biochemistry* 60: 10–18.
46. Ward SE, Orwin KH, Ostle NJ, *et al.* 2015. Vegetation exerts a greater control on litter decomposition than climate warming in peatlands. *Ecology* 96: 113–123.
47. Xu ZF, Pu XZ, Yin HJ, Zhao CZ, Liu Q, Wu FZ. 2012. Warming effects on the early decomposition of three litter types, Eastern Tibetan Plateau, China. *European Journal of Soil Science* 63: 360–367.
48. Ye C, Wang Y, Yan X, Guo H. 2022. Predominant role of air warming in regulating litter decomposition in a Tibetan alpine meadow: A multi-factor global change experiment. *SOIL BIOLOGY & BIOCHEMISTRY* 167.
49. Yin R, Qin W, Zhao H, Wang X, Cao G, Zhu B. 2022. Climate warming in an alpine meadow: differential responses of soil faunal vs. microbial effects on litter decomposition. *BIOLOGY AND FERTILITY OF SOILS* 58: 509–514.
50. Yoshitake S, Suminokura N, Ohtsuka T, Koizumi H. 2021. Composite effects of temperature increase and snow cover change on litter decomposition and microbial community in cool-temperate grassland. *Grassland Science* 67: 315–327.
51. Zaller JG, Caldwell MM, Flint SD, Ballaré CL, Scopel AL, Sala OE. 2009. Solar UVB and warming affect decomposition and earthworms in a fen ecosystem in Tierra del Fuego, Argentina. *Global Change Biology* 15: 2493–2502.
52. Zhou Y, Lv W-W, Wang S-P, *et al.* 2022. Additive effects of warming and grazing on fine-root decomposition and loss of nutrients in an alpine meadow. *JOURNAL OF PLANT ECOLOGY* 15: 1273–1284

Supporting Information

Locations of open-top chamber warming experiments measuring standardised plant litter (tea) decomposition

Table S2 Study sites in which standardised litter decomposition was measured in open-top chamber experiments. Observations per study are treatment replications in space and resulted in one effect size per site.

Nr	Site_ID	Site name	Country	Observations
1	ATA_1	Anchorage Island	Greenland	5
2	AUS_1	Australia	Australia	4
3	CAN_1	Common garden	Canada	12
4	CAN_2	Drained peatland	Canada	6
5	CAN_3	Kluane Elevation Transect 1	Canada	4
6	CAN_4	Kluane Elevation Transect 10	Canada	4
7	CAN_5	Kluane Elevation Transect 4	Canada	4
8	CAN_6	Kluane Elevation Transect 7	Canada	3
9	CAN_7	Plot B_dry	Canada	4
10	CAN_9	Pristine peatland	Canada	6
11	CHN_1	China meadow	China	18
12	CHN_2	China mountain	China	19
13	CHN_3	China swamp	China	18
14	CHN_4	National Field Observation and Research Station of Agro-ecosystems	China	9
15	ESP_1	Santa Olla	Spain	6
16	GRL_1	High_altitude - mesic mixed shrub tundra	Greenland	6
17	GRL_2	Low_altitude - mesic mixed shrub tundra	Greenland	6
18	ISL_1	Audkuluheidi	Iceland	20
19	ISL_2	Thingvellir	Iceland	19
20	ITA_1	Moss-snowbed	Italy	5
21	ITA_2	Shrub-snowbed	Italy	5
22	ITA_3	Po Valley	Italy	5
23	ITA_4	Northern Apennine	Italy	5
24	JPN_1	NKM2601	Japan:Honshu	10
25	JPN_2	Sapporo	Japan:Hokkaido	8
26	JPN_3	SGDG	Japan:Honshu	8
27	NOR_1	ITEX site Finse	Norway	17
28	NOR_2	Gudmedalen - low elevation	Norway	7
29	NOR_3	Kongsvoll Lower dry tundra	Norway	5
30	NOR_4	Kongsvoll Lower mesic tundra	Norway	4
31	NOR_5	Kongsvoll Upper mesic tundra	Norway	5
32	RUS_1	OTC experimental site, Eriophorum-Sphagnum bog	Russia	8
33	RUS_2	OTC experimental site, Sphagnum bog	Russia	8
34	SAU_1	Saudi Arabia	Saudi Arabia	10
35	SJM_1	Endalen - Cassiope heath	Norway:Svalbard	19
36	SJM_2	Endalen - Dryas heath	Norway:Svalbard	18
37	SJM_3	Endalen - Moss tundra	Norway:Svalbard	19
38	SJM_4	Endalen - Snowbed community	Norway:Svalbard	10
39	SJM_5	Svalbard_mesic	Norway:Svalbard	12

40	SJM_6	Svalbard_moist	Norway:Svalbard	14
41	SJM_7	Svalbard_wet	Norway:Svalbard	14
42	SWE_1	Abisko	Sweden	5
43	SWE_2	Latnajaure – Mesic meadow	Sweden	9
44	SWE_3	Latnajaure – Dry heath	Sweden	3
45	SWE_4	Latnajaure – Dry meadow	Sweden	5
46	SWE_5	Latnajaure – Wet meadow	Sweden	4
47	SWE_6	Latnajaure – Tussock tundra	Sweden	5
48	SWE_7	Latnajaure – Wet meadow	Sweden	5
49	USA_1	Atqasuk ITEX Dry Site	USA:Alaska	6
50	USA_2	Atqasuk ITEX Wet Site	USA:Alaska	6
51	USA_3	Barrow ITEX Dry Site	USA:Alaska	6
52	USA_4	Barrow ITEX Wet Site	USA:Alaska	6
53	ZAF_1	Cathedral Peak - grassland052rburn	South Africa	4
54	ZAF_2	Cathedral Peak - grassland0annual	South Africa	4
55	ZAF_3	Cathedral Peak - grassland0biennual	South Africa	4
56	ZAF_4	Cathedral Peak - grassland0noburn	South Africa	3
57	ZAF_5	Cathedral Peak - grassland0slope	South Africa	4

Supporting Information

Detailed Methodological Information

M1 - Calculation of Hedges' g

Hedges' g was calculated by dividing the difference between the mean mass loss in the warming treatment ($\bar{x}_1$) and ambient ($\bar{x}_2$) by the pooled standard deviation:

$$\text{Hedges' g} = \frac{(\bar{x}_1 - \bar{x}_2)}{\sqrt{((n_1 - 1) * s_1^2 \ + \ (n_2 - 1) * s_2^2) \ / \ (n_1 + n_2 - 2)}}$$

Eq. 3

where n_1 and n_2 are sample size, and s_1^2 and s_2^2 are the sample variance of the warming treatment and ambient conditions, respectively.

M2 - Handling of macro-environmental factors

To test the impact of macro-environment on the warming effect on decomposition, we first used multivariate linear mixed effects models (n=48; R package METAFOR, v.4.0-0; Viechtbauer 2010) to explore whether the macro-environmental factors individually had a significant effect on the decomposition SMD (Table S6). However, as most environmental factors were confounded, we combined the macro-environmental factors to the underlying gradients using a Principal Component Analysis (PCA) on the scaled environmental variables using the R package FACTOMINER (v.2.4; Lê *et al.* 2008). We then used the four 'macro-environmental classes' created based on the origin of the PC1 and PC2 variables as a separation line, as moderator in the following multivariate linear mixed effects models to test whether the four environmental classes differed in their warming effect on decomposition. We used this factor 'class' as interacting moderator in the model to test for interactions in the macro-environment and the natural and standardised plant litter dataset.

M3 - Warming Methods and Micro-Environmental Effects

To test for differences in the warming effect between the different warming methods used in the different studies and experiments (Table S1, 2), we used 'warming method' as moderator in another multivariate linear mixed effects model. In this model, the macro-environmental class was not integrated because the warming methods were not evenly distributed across the four macro-environmental classes (e.g., more OTC studies in higher latitudes). To test for differences in the warming methods in their effect on micro-environment, we used linear mixed-effects models (R package LMERTEST, v. 3.1-3) to test the overall effect of the categorical independent variable 'warming method' on the continuous dependent variables 'degree of warming' and 'warming-induced changes in soil moisture', respectively. We used Tukey HSD post-hoc tests (R packages MULTCOMP, v. 1.4-19 and EMMEANS, v. 1.7.5) to check for significant differences between the warming methods in degree of warming and warming-induced changes in soil moisture, respectively. We further tested with a linear regression for correlations between warming-induced changes in soil moisture and the degree of warming.

In addition, we tested the site-specific drivers related to environmental conditions (absolute latitude and altitude), experimental setup (duration of warming before the experiment and mesh size) as individual moderators fitting separate multivariate linear mixed-effects models (Table S5).

Supporting Information

Macro-environmental factors

Table S3 Correlation off the map-based macro-environmental climatic factors to the Principal component axes (PC1, PC2) together with the units and sources, including WorldClim2 = database of high spatial resolution global weather and climate data, SoilGrids = system for global digital soil mapping, CGIAR=Consortium of International Agricultural Research Centers, EarthEnv = Global, remote-sensing supported environmental layers for assessing status and trends in biodiversity, ecosystems, and climate, MODIS=Moderate Resolution Imaging Spectroradiometer.

Variables	**Correlation coefficients**		**Unit**	**Global climate layer**	**Source**
	PCA1	**PCA2**			
Temperature					
Annual Mean Temperature	0.89	0.25	°C	WorldClim2	
Max Temperature of Warmest Month	0.86	0.09	°C	WorldClim2	
Air temperature isothermality	0.64	-0.19	unitless	WorldClim2	
Mean Diurnal Range	0.56	-0.35	°C	WorldClim2	
Mean Temperature of Coldest Quarter	0.81	0.28	°C	WorldClim2	
Mean Temperature of Driest Quarter	0.56	0.12	°C	WorldClim2	
Mean Temperature of Warmest Quarter	0.81	0.21	°C	WorldClim2	
Mean Temperature of Wettest Quarter	0.57	0.15	°C	WorldClim2	
Min Temperature of Coldest Month	0.68	0.33	°C	WorldClim2	
Annual Temperature Range	0.08	-0.26	°C	WorldClim2	
Temperature Seasonality	-0.19	-0.15	°C	WorldClim2	
Mean Temperature During Incubation Period	0.61	0.27	°C	WorldClim2	
Precipitation					
Annual Precipitation	0.46	0.77	mm	WorldClim2	
Precipitation of Coldest Quarter	0.20	0.82	mm	WorldClim2	
Precipitation of Driest Month	0.19	0.87	mm	WorldClim2	
Precipitation of Driest Quarter	0.24	0.88	mm	WorldClim2	
Precipitation of Warmest Quarter	0.40	0.39	mm	WorldClim2	
Precipitation of Wettest Month	0.51	0.41	mm	WorldClim2	

Precipitation of Wettest Quarter	0.51	0.46	mm	WorldClim2	
Precipitation Seasonality	0.13	-0.63	unitless	WorldClim2	
Sum Precipitation During Incubation Period	-0.01	0.32	mm	WorldClim2	
Soil					
Bulk density at 5 cm depth	0.73	-0.21	cg cm-3	SoilGrids	https://www.soilgrids.org
SOC Content at 5 cm depth	-0.78	0.29	dg kg-1	SoilGrids	https://www.soilgrids.org
SOC Density at 5 cm depth	-0.73	0.33	dg kg-1	SoilGrids	https://www.soilgrids.org
SOC Stock 0-5 cm depth	-0.49	0.57	kg m²	SoilGrids	https://www.soilgrids.org
Sum of Total Nitrogen at 5 cm depth	-0.53	0.62	cg kg-1	SoilGrids 2.0	https://www.soilgrids.org
Sum of Total Nitrogen at 15 cm depth	-0.76	0.21	cg kg-1	SoilGrids 2.0	https://www.soilgrids.org
Sum of Total Nitrogen at 30 cm depth	-0.76	0.08	cg kg-1	SoilGrids 2.0	https://www.soilgrids.org
Other					
Annal Mean Solar Radiation	0.77	-0.35	kJ/(m² day)	WorldClim2	
Aridity Index	-0.23	0.77	AI Value	CGIAR	http://www.cgiar-csi.org/data/global-aridity-and-pet-database
Aspect Cosine	0.06	-0.15	degree	TopoMed	https://www.earthenv.org/topography
Aspect Sine	-0.07	0.34	degree	TopoMed	https://www.earthenv.org/topography
Cover Barren	-0.53	-0.19	% (0-100)	Concensus	https://www.earthenv.org/landcover
Cover Cultivated	0.48	-0.31	% (0-100)	Concensus	https://www.earthenv.org/landcover
Cover Deciduous Broadleaf Trees	0.09	0.56	% (0-100)	Concensus	https://www.earthenv.org/landcover
Cover Evergreen Broadleaf Trees	0.14	0.22	% (0-100)	Concensus	https://www.earthenv.org/landcover
Cover Evergreen Needleleaf Trees	-0.02	0.16	% (0-100)	Concensus	https://www.earthenv.org/landcover
Cover Herbaceous	0.01	-0.54	% (0-100)	Concensus	https://www.earthenv.org/landcover
Cover Regularly Flooded	-0.17	0.03	% (0-100)	Concensus	https://www.earthenv.org/landcover
Cover Shrubs	-0.20	-0.06	% (0-100)	Concensus	https://www.earthenv.org/landcover
Eastness	-0.09	0.11	index (-1 to 1)	TopoMed	https://www.earthenv.org/topography
Elevation	0.15	-0.56	meters	TopoMed	https://www.earthenv.org/topography
Fraction Photosynthetically Active Radiation (fPAR)	0.54	0.65	Fpar fraction	MODIS	https://explorer.earthengine.google.com/#detail/MODIS%2F006%2FMCD15A3H
Soil water capacity at 5 cm depth	-0.56	0.05	%	SoilGrids	https://www.soilgrids.org

Northness	0.28	-0.14	index (-1 to 1)	TopoMed	https://www.earthenv.org/topography
Potential Evapotranspiration (PET)	0.88	-0.29	PET Value (mm)	CGIAR	http://www.cgiar-csi.org/data/global-aridity-and-pet-database
Saturated Water Content 5 cm depth	-0.74	0.16	%	SoilGrids	https://www.soilgrids.org
Soil pH (water) at 5 cm depth	0.34	-0.78	pH x 10	SoilGrids	https://www.soilgrids.org

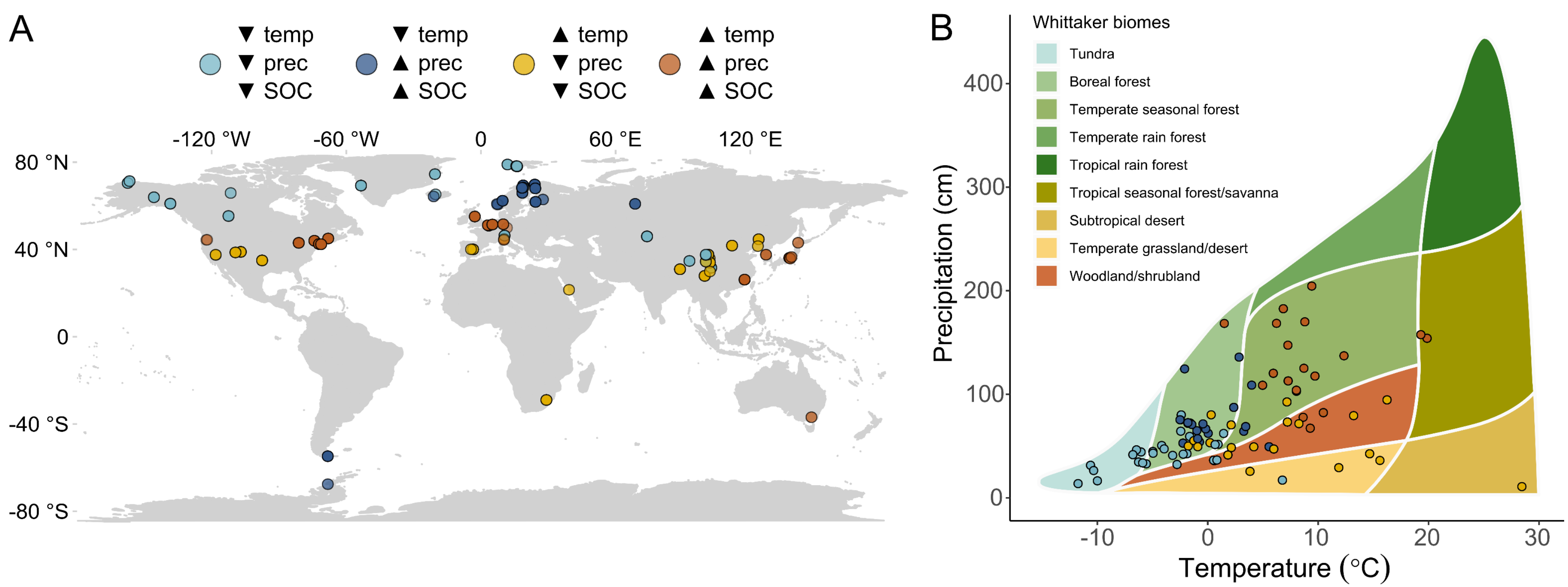

Figure S2 (**A**) Global distribution of study sites coloured according to the four main macro-environmental classes derived from the principal component analysis. (**B**) Study sites plotted in a Whittaker Biome Diagram with dots for study sites coloured according to the four main macro-environmental classes.

Table S4 Means and standard error (SE) of the map-based macro-environmental factors per macro-environmental class that are defined by the scores on the PCA axis and the correlation of these axis to climatic variables of temperature (temp), precipitation (prec), and soil organic carbon (SOC) that are either high (upward arrow) or low (downward arrow).

Variables	**Unit**	**▲ temp ▲ prec ▼ SOC**			**▲ temp ▼ prec ▼ SOC**			**▼ temp ▲ prec ▲ SOC**			**▼ temp ▼ prec ▲ SOC**		
		mean		SE	mean		SE	mean		SE	mean		SE
Temperature													
Annual Mean Temperature	°C	9.3	±	0.3	5.6	±	0.5	0.3	±	0.2	-2.2	±	0.4
Max Temperature of Warmest Month	°C	24.6	±	0.3	22.8	±	0.5	15.5	±	0.2	14.7	±	0.5
Isothermality	unitless	31.1	±	0.3	37.8	±	0.4	25.4	±	0.3	23.7	±	0.5
Mean Diurnal Range	°C	9.8	±	0.1	12.9	±	0.1	7.4	±	0.1	8.0	±	0.2
Mean Temperature of Coldest Quarter	°C	-0.9	±	0.5	-4.4	±	0.6	-9.1	±	0.3	-13.5	±	0.4
Mean Temperature of Driest Quarter	°C	3.0	±	0.7	1.0	±	0.8	-3.9	±	0.4	-4.4	±	1.0
Mean Temperature of Warmest Quarter	°C	19.2	±	0.3	15.2	±	0.5	10.8	±	0.2	9.5	±	0.5
Mean Temperature of Wettest Quarter	°C	13.2	±	0.5	12.5	±	0.4	8.0	±	0.4	3.7	±	0.6
Min Temperature of Coldest Month	°C	-7.5	±	0.6	-12.2	±	0.6	-14.2	±	0.3	-19.1	±	0.4
Annual Temperature Range	°C	32.1	±	0.5	35.0	±	0.5	29.7	±	0.5	33.8	±	0.6
Temperature Seasonality	°C	819.1	±	15.0	799.5	±	17.5	807.1	±	15.0	945.5	±	19.8
Mean Temperature during Incubation Period	°C	11.1	±	0.5	6.7	±	0.6	1.4	±	0.4	2.4	±	0.5
Precipitation													
Annual Precipitation	mm	1172.4	±	24.4	554.2	±	15.3	642.1	±	13.7	357.5	±	13.1
Precipitation of Coldest Quarter	mm	241.6	±	7.1	67.1	±	4.2	141.6	±	5.5	58.5	±	2.7
Precipitation of Driest Month	mm	61.0	±	1.3	13.4	±	1.0	31.5	±	0.7	11.0	±	0.7
Precipitation of Driest Quarter	mm	204.4	±	3.7	49.9	±	3.2	103.4	±	2.2	42.6	±	2.2
Precipitation of Warmest Quarter	mm	337.4	±	12.4	224.4	±	8.6	208.9	±	2.6	140.9	±	7.2
Precipitation of Wettest Month	mm	142.5	±	5.8	95.7	±	2.9	85.1	±	1.4	57.0	±	2.6

Precipitation of Wettest Quarter	mm	399.8 ± 15.7	250.3 ± 7.4	228.1 ± 3.9	148.1 ± 6.9
Precipitation Seasonality	unitless	23.9 ± 1.7	63.5 ± 2.7	32.9 ± 0.6	47.4 ± 2.2
Sum Precipitation during Incubation Period	mm	820069.8 ± 56210.0	490908.5 ± 34505.2	912969.4 ± 47987.0	367516.6 ± 35516.5
Soil					
Bulk density at 5 cm depth	cg cm^{-3}	905.0 ± 17.6	1070.4 ± 20.9	504.9 ± 12.4	736.7 ± 11.1
SOC Content at 5 cm depth	dg kg^{-1}	78.9 ± 3.8	48.1 ± 2.1	142.8 ± 4.3	132.3 ± 3.8
SOC Density at 5 cm depth	dg kg^{-1}	620.9 ± 19.3	447.4 ± 15.4	783.2 ± 8.8	748.9 ± 10.3
SOC Stock 0-5 cm depth	kg m^2	41.2 ± 1.3	25.2 ± 0.8	38.1 ± 0.5	42.7 ± 0.7
Sum of Total Nitrogen at 5 cm depth	cg kg^{-1}	8776.1 ± 321.6	4561.7 ± 175.2	9632.6 ± 103.5	7817.3 ± 200.2
Sum of Total Nitrogen at 15 cm depth	cg kg^{-1}	3023.5 ± 78.2	2220.4 ± 61.1	5676.7 ± 163.6	5483.2 ± 191.8
Sum of Total Nitrogen at 30 cm depth	cg kg^{-1}	2007.3 ± 44.4	1639.6 ± 39.6	3506.9 ± 112.3	4508.9 ± 165.8
Other					
Annual Mean Solar Radiation	kJ/(m^2 day)	12532.0 ± 124.6	15999.4 ± 107.2	8170.1 ± 44.4	10200.2 ± 272.5
Aridity Index	AI Value	12066.2 ± 305.5	4484.7 ± 137.5	12164.9 ± 285.0	6978.2 ± 310.7
Aspect Cosine	degree	0.1 ± 0.0	0.0 ± 0.1	0.0 ± 0.1	0.3 ± 0.1
Aspect Sine	degree	0.2 ± 0.0	-0.2 ± 0.0	-0.1 ± 0.0	-0.1 ± 0.0
Cover Barren	% (0-100)	1.8 ± 0.4	5.3 ± 1.0	12.7 ± 1.3	26.2 ± 1.9
Cover Cultivated	% (0-100)	12.1 ± 1.5	26.1 ± 2.1	0.2 ± 0.1	3.7 ± 0.9
Cover Deciduous Broadleaf Trees	% (0-100)	23.8 ± 2.1	1.5 ± 0.2	5.9 ± 0.9	1.4 ± 0.3
Cover Evergreen Broadleaf Trees	% (0-100)	2.3 ± 0.5	0.0 ± 0.0	1.9 ± 0.7	0.0 ± 0.0
Cover Evergreen Needleleaf Trees	% (0-100)	6.5 ± 1.0	12.0 ± 1.8	17.2 ± 2.0	2.0 ± 0.3
Cover Herbaceous	% (0-100)	4.0 ± 1.4	40.8 ± 2.0	8.3 ± 0.9	24.1 ± 2.3
Cover Regularly Flooded	% (0-100)	0.0 ± 0.0	0.0 ± 0.0	4.1 ± 1.3	0.5 ± 0.2
Cover Shrubs	% (0-100)	0.1 ± 0.1	6.1 ± 1.1	19.7 ± 1.1	5.2 ± 1.2
Eastness	index (-1 to 1)	0.0 ± 0.0	0.0 ± 0.0	0.1 ± 0.0	0.0 ± 0.0
Elevation	meters	348.8 ± 31.2	2585.0 ± 111.3	436.8 ± 30.9	1034.8 ± 114.5
Fraction Photosynthetically Active Radiation (fPAR)	Fpar fraction	49.2 ± 0.8	28.4 ± 0.6	26.0 ± 0.5	17.6 ± 0.6
Soil water capacity at 5 cm depth	%	22.6 ± 0.4	22.9 ± 0.3	27.0 ± 0.5	28.2 ± 0.2

Northness	index (-1 to 1)	0.1 ± 0.0	0.3 ± 0.0	0.0 ± 0.0	-0.1 ± 0.0
Potential Evapotranspiration (PET)	PET value (mm)	987.5 ± 14.0	1305.1 ± 22.5	534.4 ± 5.7	655.6 ± 27.5
Saturated Water Content 5 cm depth	%	57.2 ± 0.5	53.0 ± 0.6	69.2 ± 0.4	63.1 ± 0.3
Soil pH (water) at 5 cm depth	pH x 10	52.9 ± 0.5	68.3 ± 0.7	49.7 ± 0.3	61.0 ± 0.6

Supporting Information

Table S5 Results of single effects multivariate linear mixed-effects models for reported and measured site-specific environmental factors with the standardised mean difference of decomposition (SMD) as dependent and reported or measured site-specific environmental factors as predictor. Values in bold indicate significant effect of the predictor on decomposition SMD ($p \leq 0.05$). The number of effect sizes (*k*) used in the models, lower and upper bounds of the 95% confidence intervals, and heterogeneity explained by the model structure (Q_M) are reported.

Predictor	*k*	slope	95%CI	Test of Moderators (Qm, p-value)
Absolute Latitude	637	-0.002	-0.01, 0.01	0.25, p = 0.620
Duration of warming before experiment	637	0.06	-0.01, 0.12	3.23, p = 0.072
Mesh size	637	-0.045	-0.09, -0.003	**4.41, p = 0.036**
Carbon to Nitrogen ratio	428	0.001	-0.00, 0.00	0.94, p = 0.33
Ambient decomposability (mass loss % d^{-1})	613	-0.243	-0.45, -0.04	**5.60, p = 0.018**

Table S6 Map-based macro-environmental results of single multivariate linear mixed-effects models with the standardised mean difference of decomposition (SMD) as dependent variable and the map-derived macro-environmental factors as predictor. Values in bold indicate significant effect of the predictor on decomposition SMD ($p \leq 0.05$). The number of effect sizes (*k*) used in the models, lower and upper bounds of the 95% confidence intervals, and heterogeneity explained by the model structure (Q_M) are reported.

Predictor	*k*	slope	95%CI	Test of Moderators (Qm, p-value)
Temperature				
Annual Mean Temperature	635	0.010	-0.00, 0.02	2.07, p = 0.150
Max Temperature of Warmest Month	635	0.008	-0.01, 0.02	1.21, p = 0.270
Air temperature isothermality	635	0.001	-0.01, 0.01	0.02, p = 0.894
Mean Diurnal Range	635	-0.016	-0.05, 0.02	0.89, p = 0.375
Mean Temperature of Coldest Quarter	635	0.007	-0.00, 0.02	1.42, p = 0.233
Mean Temperature of Driest Quarter	635	0.003	-0.00, 0.01	0.68, p = 0.411
Mean Temperature of Warmest Quarter	635	0.012	-0.00, 0.03	2.37, p = 0.124
Mean Temperature of Wettest Quarter	635	0.006	- 0.01, 0.02	0.83, p = 0.361
Min Temperature of Coldest Month	635	0.008	-0.00, 0.02	1.88, p = 0.171
Annual Temperature Range	635	-0.003	-0.02, 0.01	0.22, p = 0.639
Temperature Seasonality	635	-0.000	-0.00, 0.00	0.00, p = 0.981
Mean Temperature during Incubation Period	625	-0.007	-0.02, -0.00	2.08, p = 0.149
Precipitation				
Annual Precipitation	635	0.000	-0.00, 0.00	0.00, p = 0.974
Precipitation of Coldest Quarter	635	0.000	-0.00, 0.00	1.13, p = 0.288
Precipitation of Driest Month	635	0.004	0.00, 0.01	**3.97, p = 0.046**
Precipitation of Driest Quarter	635	0.001	-0.00, 0.00	3.33, p = 0.068
Precipitation of Warmest Quarter	635	-0.000	-0.00, 0.00	0.36, p = 0.550

Precipitation of Wettest Month	635	0.000	-0.00, 0.00	0.00, p = 0.973
Precipitation of Wettest Quarter	635	-0.000	-0.00, 0.00	0.01, p = 0.906
Precipitation Seasonality	635	0.001	-0.00, 0.00	0.39, p = 0.535
Sum Precipitation during Incubation Period	625	0.000	-0.00, 0.00	1.27, p = 0.259
Soil				
Bulk density at 5 cm depth	635	0.000	-0.00, 0.00	0.04, p = 0.844
SOC Content at 5 cm depth	635	0.000	-0.02, 0.01	0.03, p = 0.855
SOC Density at 5 cm depth	635	0.000	-0.00, 0.00	0.20, p = 0.656
SOC Stock 0-5 cm depth	635	0.000	-0.01, 0.01	0.01, p = 0.904
Sum of Total Nitrogen at 5 cm depth	604	0.000	-0.00, 0.00	0.01, p = 0.904
Sum of Total Nitrogen at 15 cm depth	604	0.000	-0.00, 0.00	0.00, p = 0.997
Sum of Total Nitrogen at 30 cm depth	604	0.000	-0.00, 0.00	0.03, p = 0.861
Other				
Annal Mean Solar Radiation	635	0.000	-0.00, 0.00	0.36, p = 0.547
Aridity Index	635	0.000	-0.00, 0.00	0.30, p = 0.583
Aspect Cosine	635	-0.031	-0.13, 0.07	0.39, p = 0.532
Aspect Sine	635	-0.103	-0.25, 0.05	1.81, p = 0.179
Cover Barren	635	0.003	-0.01, 0.003	0.90, p = 0.342
Cover Cultivated	635	-0.002	-0.01, 0.003	0.49, p = 0.483
Cover Deciduous Broadleaf Trees	635	0.004	0.002, 0.01	1.49, p = 0.222
Cover Evergreen Broadleaf Trees	635	-0.009	-0.01, 0.03	0.78, p = 0.372
Cover Evergreen Needleleaf Trees	635	-0.002	-0.01, 0.00	0.23, p = 0.634
Cover Herbaceous	635	0.002	-0.00, 0.00	0.01, p = 0.912
Cover Regularly Flooded	635	0.004	-0.00, 0.01	1.14, p = 0.285
Cover Shrubs	635	0.000	-0.01, -0.01	0.02, p = 0.884
Eastness	635	-0.006	-0.35, 0.34	0.00, p = 0.974
Elevation	635	-0.000	-0.00, 0.00	1.96, p = 0.162
Fraction Photosynthetically Active Radiation (fPAR)	635	0.000	-0.01, 0.01	0.01, p = 0.911
Soil water capacity at 5 cm depth	635	-0.001	-0.02, 0.02	0.01, p = 0.923
Northness	635	-0.240	-0.44, -0.04	**5.44, p = 0.020**
Potential Evapotranspiration (PET)	635	0.000	-0.00, 0.00	1.97, p = 0.161
Saturated Water Content 5 cm depth	635	-0.002	-0.01, 0.01	0.12, p = 0.732
Soil pH (water) at 5 cm depth	635	-0.003	-0.01, 0.01	0.24, p = 0.625

Supporting Information

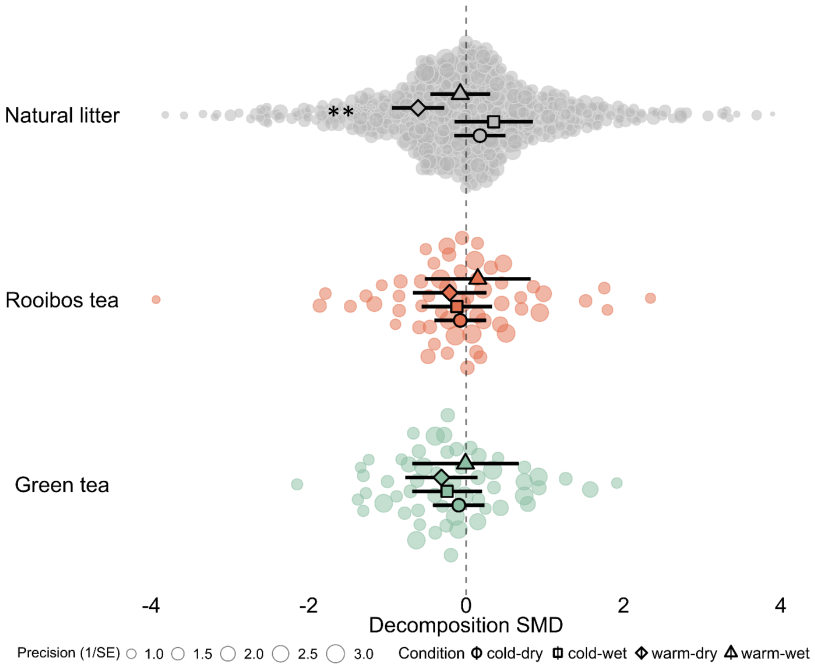

Figure S3 Effects of experimental warming on plant litter decomposition. The pooled average decomposition standardised mean difference (SMD, Hedges' g; outlined circles) and 95% confidence intervals (black error bars) resulting from warming for the macro-environmental classes cold and dry (outlined circles), cold and wet (outlined squares), warm and dry (outlined diamonds), and warm and wet (outlined triangles) for the natural litter (blue, number of effect sizes k=523) and the standardised plant litter, separated into rooibos (red, k=57) and green tea (green, k=57). Each coloured dot is an individual effect size (non-outlined circles) with dot size representing its precision (the inverse of the standard error, larger points having greater influence on the model). Asterisks indicate that the overall pooled average SMD is significantly different from zero (**p < 0.01).

Table S7 The impact of the four macro-environmental classes four macro-environmental classes distinguished by different combinations of high (▲) or low (▼) of temperature (temp), precipitation (prec) and soil organic carbon (SOC) and the natural and the standardised plant litter (i.e., green and rooibos tea) on the effect of warming on decomposition (SMD). Bold values indicate a significant effect of the macro-environmental class and litter type on SMD (p ≤ 0.05 or CI ≠ 0). Number of effect sizes (k), p-values, and 95%-confidence interval are shown.

Macro-environment	**litter type**	**SMD estimate**	***k***	**p-value**	**95%CI**
▲ temp ▲ prec ▼ SOC	Natural litter	-0.07	155	0.703	[-0.45; 0.30]
	Rooibos	-0.15	5	0.666	[-0.82; 0.52]
	Green	0.01	5	0.981	[-0.67; 0.68]
▲ temp ▼ prec ▼ SOC	Natural litter	**-0.61**	150	**<0.001**	[-0.94; -0.28]
	Rooibos	0.21	10	0.382	[-0.26; 0.68]
	Green	0.31	10	0.180	[-0.15; 0.77]
▼ temp ▲ prec ▲ SOC	Natural litter	0.35	126	0.167	[-0.15; 0.85]
	Rooibos	0.12	15	0.607	[-0.33; 0.56]
	Green	0.24	15	0.285	[-0.20; 0.69]
▼ temp ▼ prec ▲ SOC	Natural litter	0.18	101	0.290	[-0.15; 0.50]
	Rooibos	0.07	27	0.659	[-0.25; 0.40]
	Green	0.09	15	0.575	[-0.23; 0.42]

Supporting Information

The effect of experimental-induced warming on decomposition

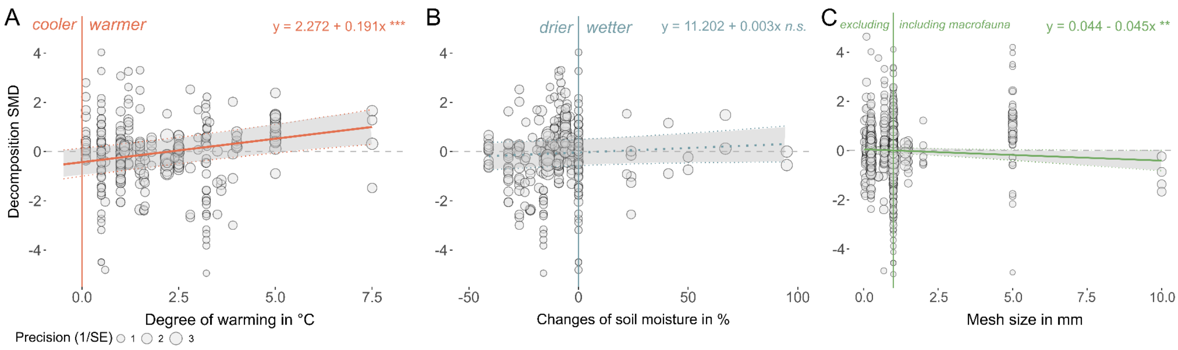

Figure S4 Impacts of experimentally induced changes in micro-environment on decomposition. Effect of **(A)** degree of warming (i.e., absolute temperature difference between warmed and control plots, k=315); **(B)** warming-induced changes in soil moisture with warming (i.e., difference between warmed and control plots in soil moisture, k=315) on decomposition SMD; and **(C)** mesh size of the litter bags in mm with 1 mm as the minimal threshold for macrofauna exclusion (Sagi and Hawlena 2024). Each grey outlined circle is an individual effect size with circle size representing its precision (the inverse of the standard error, larger points having greater influence on the model). Asterisks indicate that the overall pooled average SMD is significantly different from zero. Solid lines indicate regression lines with shaded areas representing the 95%CI (***p < 0.001, **p < 0.01). Dashed lines indicate no significant relationship (n.s. = not significant).

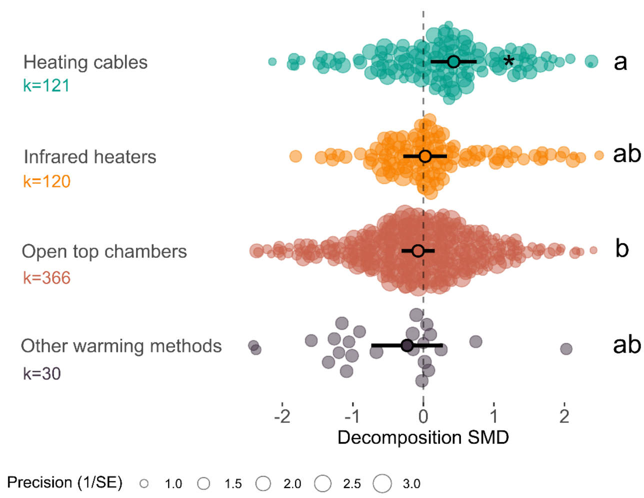

Figure S5 Impact of warming methods on decomposition SMD. The pooled average decomposition standardised mean difference (SMD, Hedges' g; outlined circles) and 95% confidence intervals (black error bars) resulting from warming for the different experimental warming methods (see Table S1). Each coloured dot is an individual effect size (non-outlined circles) with dot size representing its precision (the inverse of the standard error, larger points having greater influence on the model). Letters indicate significant differences between the pooled average SMD of warming methods. Asterisks indicate a significant deviation of decomposition SMD from zero (*p ≤ 0.05).

Supporting Information

Plant functional types and plant organ types interacting with the position of incubation (on soil surface, buried in the soil)

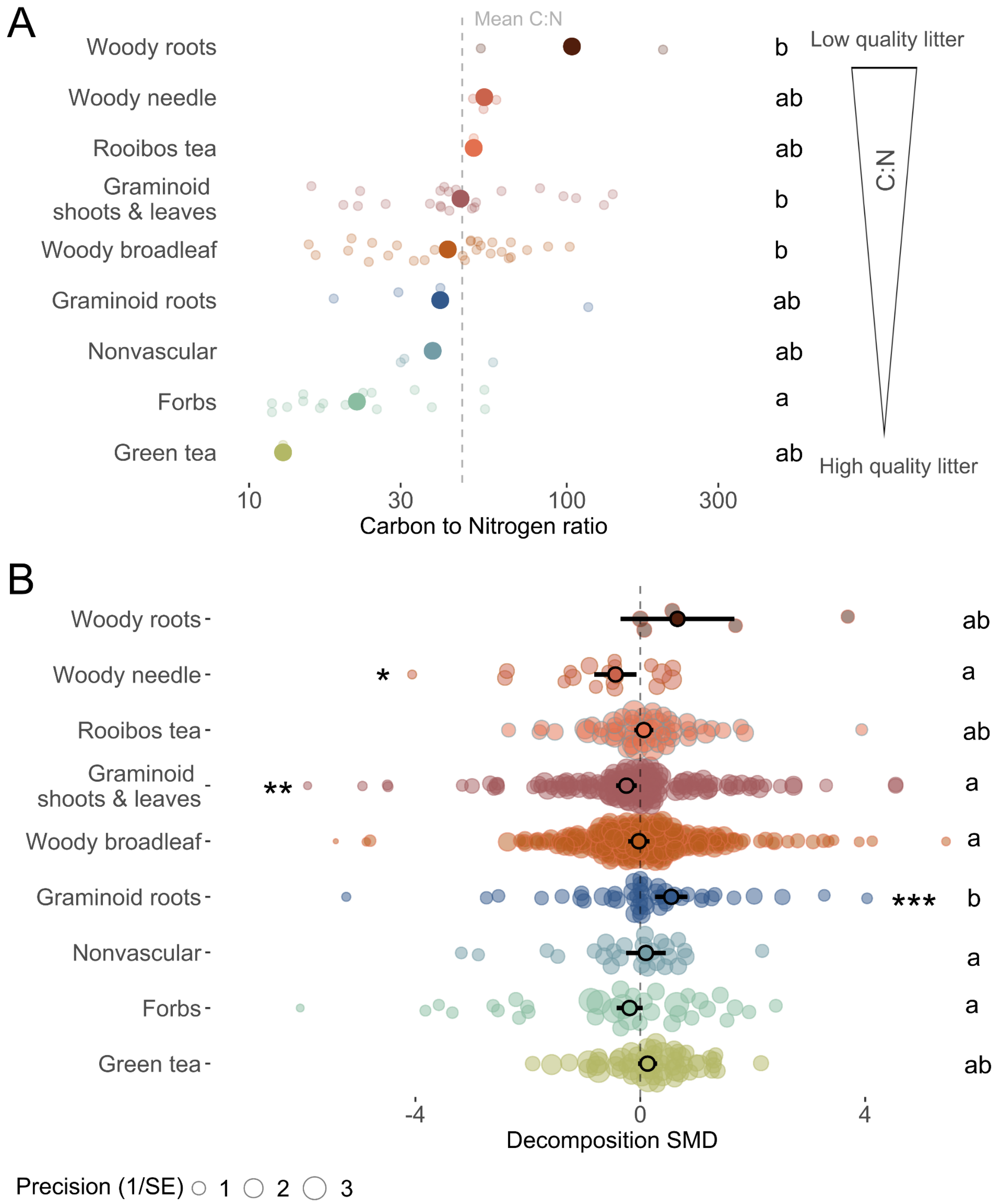

Figure S6 Differences in C:N ratio and warming effect on decomposition across plant functional types**.** **(A)** Plant functional types ranked based on carbon to nitrogen ratios (C:N ratios). Large, coloured points represent mean C:N ratios and small transparent dots individual plant species. **(B)** The pooled average decomposition standardized mean difference (SMD, Hedges' g, black outlined circles) and 95% confidence intervals (95%CI, black error bars) per plant functional type of natural litter and standardised plant litter combining data from above and below ground incubations. Different letters indicate differences in **(A)** mean C:N ratio and **(B)** decomposition SMD between the different plant functional litter types, as well as the standard material green and rooibos tea. Asterisks indicate that the overall pooled average SMD is significantly different from zero (*p < 0.05, **p < 0.01, ***p < 0.001).

Supporting Information

Table S8 The pooled average decomposition standardised mean difference (SMD) of different plant functional types of the natural litter and natural and the standardised plant litter (i.e., green and rooibos tea) with respect to the position of incubation (i.e., on soil surface, buried in the soil) as well as the number of effect sizes (*k*) for each category, the p-value and 95%-confidence interval describing whether the pooled average SMD significantly differs from zero (in bold, p ≤ 0.05). For forbs and nonvascular plants no reports of buried or root litter were available.

Plant functional type	Position incubated	*k*	SMD estimate	p-value	95%CI
Forb	surface	36	-0.19	0.114	[-0.42; 0.05]
Graminoid root	buried	49	**0.55**	**<0.001**	[0.27; 0.84]
Graminoid shoot/leaf	surface	151	**-0.25**	**0.010**	[-0.43; -0.06]
Green tea	buried	57	0.13	0.133	[-0.04; 0.30]
Nonvascular	surface	27	0.10	0.589	[-0.26; 0.45]
Rooibos tea	buried	57	0.06	0.469	[-0.11; 0.23]
Woody broadleaf	buried	48	-0.05	0.799	[-0.44; 0.34]
Woody broadleaf	surface	192	-0.02	0.874	[-0.21; 0.18]
Woody needle	surface	21	**-0.44**	**0.021**	[-0.82; -0.07]
Woody root	buried	5	0.35	0.337	[-0.37; 1.08]

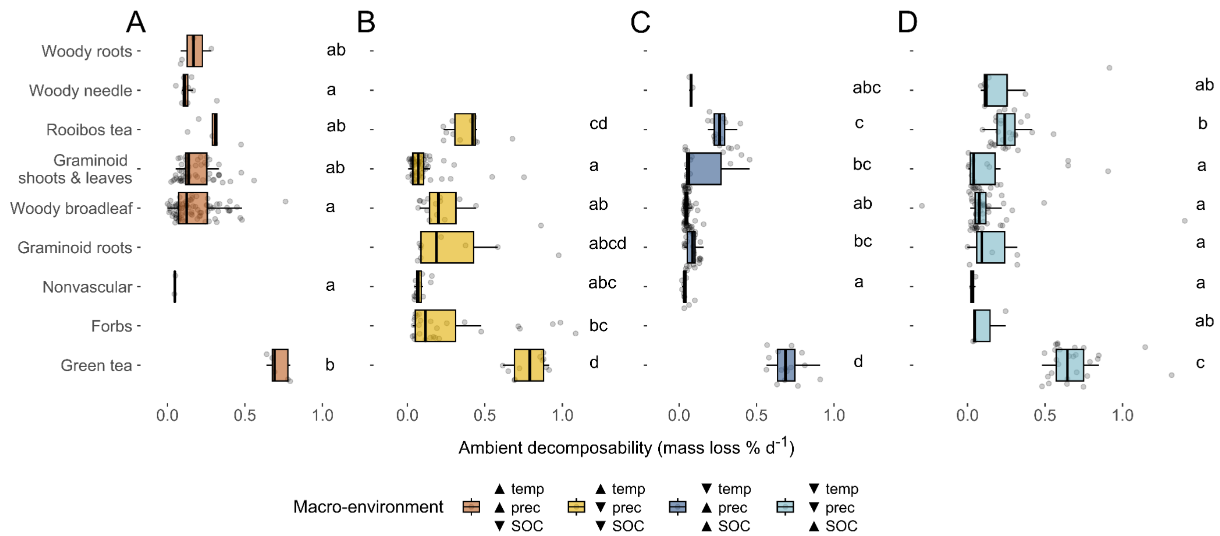

Figure S7 Differences in ambient decomposability, measured as ambient mass loss rate per day (% d^{-1}), for the plant functional types and plant organs of natural plant litter and the standardised tea material (i.e., rooibos and green tea) for each of the four macro-environmental classes. Colours indicate the four macro-environmental classes of temperature (temp), precipitation (prec) and soil organic carbon (SOC) that are either high (▲) or low (▼), consistent with Figure 3 in the main text. Different letters indicate significant differences in decomposition SMD between plant functional types.