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Temperature dependence of the contribution of soil moisture to soil respiration and the soil respiration temperature threshold in a temperate deciduous forest

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Abstract. Soil respiration (Rs) in forest soils is a key flux governing forest carbon balance and the global carbon cycle. Because this flux is expected to respond rapidly to climate warming, understanding the controls on Rs is essential for predicting changes in forest carbon balance induced by warming. In natural field conditions, soil temperature (Ts) and soil moisture content (SMC) often covary seasonally, which tends to limit our ability to isolate and quantify the independent contribution of SMC and to evaluate how its contribution varies with temperature. Although temperature thresholds in Rs have been reported, few studies have quantitatively identified such thresholds from field observations and interpreted potential shifts in the dominant controls based on how moisture responses differ across the threshold. Here, we used two years of continuous automated chamber measurements in a temperate deciduous forest to estimate a Ts threshold for Rs and to assess how the relative contribution of SMC varies with Ts by comparing models across temperature ranges, with particular attention to changes near the threshold. At the annual scale, the explanatory power of SMC alone was limited, but the relationship between SMC and Rs was significant. In contrast, above 15°C, the relationship between SMC and Rs strengthened consistently, indicating that the contribution of SMC is constrained at low Ts but increases markedly at high Ts. Piecewise regression of the relationship between Rs and Ts identified a Ts threshold near 17°C, and models including this threshold improved fit relative to an exponential model. These results show that the relative contribution of SMC can change across a specific temperature range, suggesting that changes in the relative influence of SMC on Rs variability across the threshold may reorganize the dominant controls on Rs. Therefore, projections of forest Rs should jointly consider temperature dependent changes in moisture contribution and the presence of Ts thresholds.

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1 Introduction

Global warming is altering not only air temperature but also precipitation regimes, thereby changing the frequency and intensity of extreme hydrological events such as droughts and heavy rainfall. Forest ecosystems are known to play a central role in the global carbon cycle (IPCC, 2021). Forest soils store approximately 40% of global soil organic carbon (Mayer et al., 2020), and forests have been reported to account for about 40 to 90% of terrestrial soil respiration emissions (Rodtassana et al., 2021). This indicates that forests are important for regulating carbon balance and climate and carbon interactions through their dual function as major carbon reservoirs and sources of CO_2 emissions (Win and Sato, 2024). In particular, soil respiration (Rs) is the CO_2 flux from soil to the atmosphere, and the global annual magnitude is estimated to be about 70 to 100 Pg C per year (Jian et al., 2018; Lei et al., 2021). Consequently, changes in Rs directly affect forest carbon balance and atmospheric CO_2 variability, and variability in Rs strongly influences uncertainty in forest carbon balance estimates.

Under climate change, forest ecosystems are expected to be exposed not only to warming and rising atmospheric CO_2 concentrations but also to shifts in precipitation seasonality and variability, yet substantial uncertainty remains regarding associated plant physiological responses and changes in forest soil microclimate (IPCC, 2021; Liu et al., 2025). Such changes may modify the relative contributions of soil temperature (Ts) and soil moisture content (SMC) and reorganize the control structure governing Rs, thereby increasing uncertainty in predicting Rs responses (Liang et al., 2024). Nevertheless, quantitatively constraining the spatiotemporal variability of forest Rs and its controlling mechanisms remains a core challenge in carbon cycle research (Le Quéré et al., 2018).

Soil respiration is composed of root respiration from plant roots and microbial respiration associated with the decomposition of organic matter by soil microorganisms (Yan et al., 2025), and it responds strongly to seasonal biological activity and changes in meteorological conditions (Wang et al., 2021). Because Rs is observed as the combined flux of these two processes, their relative contributions may vary with phenological transitions and changes in soil moisture status, and the resulting sensitivities to Ts and SMC may therefore differ across seasons and temperature ranges (Yan et al., 2024). In general, increasing Ts enhances enzyme activity and metabolic rates, stimulating microbial decomposition and root physiological activity and thereby increasing Rs (Sáez-Sandino et al., 2023; Kengdo et al., 2023). Soil moisture governs diffusion of oxygen and substrates in soil and can directly constrain or promote root water uptake and microbial physiological activity. Microbial activity is suppressed under dry conditions, whereas respiration can be limited by oxygen deficiency under wet conditions (Huang et al., 2023). Thus, Ts and SMC are key environmental factors controlling both root and microbial respiration.

To quantify these controls, previous studies have often simplified the influences of Ts and SMC using empirical functions. The Ts and Rs relationship has typically been represented using exponential or Q10 models, whereas the SMC and Rs relationship has commonly been described using polynomial functions that allow inhibition under both dry and wet extremes (Lloyd and Taylor, 1994; Davidson et al., 1998). Recent studies have introduced approaches that incorporate interactions between Ts and SMC, yet it remains poorly quantified how the relative influence of SMC varies with temperature conditions and at what temperature range this transition tends to occur (Lai et al., 2012; Cui et al., 2020; Mao et al., 2024). In particular, at relatively low Ts, variations in Rs tend to be more strongly governed by temperature driven biochemical reaction rates, whereas at high Ts, changes in moisture supply and variability, or constraints associated with moisture deficit or excess, may jointly act to increase the sensitivity of Rs to changes in SMC (He et al., 2024). Even so, quantitative evidence from field observations remains limited regarding when the relative contribution of SMC begins to shift systematically with Ts and whether this shift emerges as a breakpoint within a specific temperature range.

It has been reported that the extent to which SMC explains variability in Rs depends strongly on time scale, phenological state, and temperature conditions. Accordingly, annual scale analyses can average out these effects and reduce the apparent influence of SMC (Kim et al., 2019; Podzikowski et al., 2025). This averaging may also mask temperature dependent properties of moisture effects, limiting efforts to quantify the dependence of SMC contributions on Ts. Therefore, based on field observations, it remains uncertain how moisture effects transition across temperature ranges, and it is necessary to identify a threshold Ts that may serve as a boundary for shifts in the control structure of Rs (Liu et al., 2023; Bond-Lamberty et al., 2024).

Rather than changing monotonically with increasing Ts, Rs can exhibit nonlinearity when changes in moisture conditions and associated constraints alter the relative importance of dominant controlling factors, leading to changes in response slopes. Breakpoint based interpretation is therefore important for capturing the key temperature range where such changes occur (Carey et al., 2016; Li et al., 2025a).

Here, we used continuous chamber observations of Rs in a temperate deciduous forest to quantitatively assess whether the relative contribution of SMC varies systematically with Ts. By partitioning analyses by temperature conditions to reduce the dilution that can arise from annual scale averaging, we aim to provide field based evidence for the dependence of moisture effects on temperature conditions and to evaluate the potential for shifts in the control structure governing Rs.

This study formulated and tested the following research questions.

1. At the annual scale, the explanatory power of soil moisture effects is often limited. We evaluate whether a statistically significant relationship between SMC and Rs exists despite this limitation.

2. If a relationship between SMC and Rs is observed, we examine whether its magnitude and statistical significance vary with Ts conditions.

3. Considering the seasonal covariation between Ts and SMC, we quantify how the relative contribution of SMC to Rs changes across temperature ranges after accounting for the temperature effect.

4. We assess whether a breakpoint exists as the relative contribution of SMC varies with Ts and, if identified, interpret its implications in terms of shifts in the relative importance of controlling factors or a potential reorganization of the control structure governing Rs.

2 Materials and methods

2.1 Study area

This study was conducted in a temperate deciduous forest in Gongju, Chungcheongnamdo, Republic of Korea (36°34′16″ N, 127°00′34″ E; 218 m above sea level). The site is influenced by the Asian monsoon climate, with mean annual precipitation of 1256.6 mm, of which more than 65% occurs in summer from June to September. This pronounced precipitation seasonality results in warm, humid summers and cold, dry winters. Seasonal vegetation dynamics are distinct. Leaf development typically begins in April, and leaf senescence and abscission occur during October and November. Accordingly, leaf on and leaf off periods can be separated relatively clearly. The dominant tree species is konara oak (*Quercus serrata*), with oriental white oak (*Quercus aliena*), Japanese snowbell (*Styrax japonicus*), and Japanese cherry (*Prunus serrulata*) also present. During the study period, mean air temperature was 13.1°C, and mean Ts measured at the site was 13.3°C.

2.2 Measurement of environmental factors

Precipitation was continuously measured at 1.5 m above the ground surface within the forest using a tipping bucket rain gauge (S-RGB-M002, Onset, MA, USA). Ts was measured at 5 cm depth, and SMC was measured over the 0 to 15 cm depth using moisture sensors (CS616, Campbell Scientific Inc., Logan, UT, USA). Precipitation, Ts, and SMC were recorded at 1 min intervals using a CR1000 datalogger (Campbell Scientific Inc.) and stored as 15 min means. The clocks of all devices were synchronized to a common reference time.

Periods flagged by quality control criteria, including rainfall, condensation, instrument maintenance, and sensor contamination, were excluded. For subsequent analyses, precipitation was aggregated to daily totals, and Ts and SMC were processed as daily means.

2.3 Measurement of soil respiration

Soil respiration (Rs) was continuously measured using automated chambers that alternated between open and closed phases for two years from January 2022 to December 2023. Each chamber operated on a 30 min cycle with 25 min open and 5 min closed. During the closed period, chamber air was circulated through an infrared gas analyzer (IRGA; LI-840, LI-COR, Lincoln, NE, USA) using a pump. CO_2 concentration was recorded at approximately 30 s intervals, and Rs was calculated from the rate of CO_2 increase during the closed period. The IRGA inlet and outlet flow rates were regulated to 1.0 L min^{-}1 using a flow meter. The chamber collars were inserted 10 cm into the soil and fixed in place. Measurements related to Rs were logged at 1 min intervals using a CR1000 datalogger. Aboveground vegetation inside the chambers was periodically removed to prevent CO_2 interference from photosynthesis, while the litter layer was maintained to minimize disturbance to the soil surface. After applying exclusion criteria, Rs data were aggregated to daily means for all subsequent analyses.

Soil respiration measurements were conducted using five automated chambers operated in repeated open and closed cycles. Consistent with the processing of Ts and SMC, outliers and erroneous records were removed, and Rs was calculated for each 30 min chamber cycle from the rate of change in CO_2 concentration per unit time and then aggregated to daily means for all subsequent analyses, following Eq. (1):

$$Rs = \left(\frac{\Delta CO_2}{\Delta t}\right)\left(\frac{V}{A}\right) \tag{1}$$

Where Rs is Soil respiration (mg CO_2 m^{-2} h^{-1}), $\Delta CO_2/\Delta t$ is the rate of change in CO_2 mass concentration in the chamber headspace (mg CO_2 m^{-3} h^{-1}), V is chamber volume (m^3), and A is chamber base area (m^2).

2.4 Model fitting and evaluation

To quantify the combined effects of Ts and SMC on Rs, we applied nonlinear regression models. First, an exponential model describing the baseline temperature response was used as the Ts-only model (Eq. 2).

Ts-only model (Eq. 2):

$$Rs = aexp(bTs) \tag{2}$$

To incorporate the effect of SMC and its temperature dependent influence, we defined an extended model in which the exponential temperature term was multiplied by a quadratic function of SMC, referred to as the Ts plus SMC model (Eq. 3).

Ts + SMC model (Eq. 3):

$$Rs = a\exp\left(bTs\right)\left(cSMC^2 + dSMC + e\right) \tag{3}$$

Model parameters *a*, *b*, *c*, *d*, and *e* were optimized and fitted using the observations. To report parameter estimates and associated uncertainty, we calculated standard errors and p values or 95% confidence intervals. Model fit was compared between the two models using R^2 and AIC. To assess model robustness and potential overfitting, we applied block cross validation that preserved the temporal order, and predictive performance in each iteration was evaluated using CV R^2 and RMSE.

2.5 Statistical analysis

All analyses were conducted using SAS software version 9.4 (SAS Institute Inc., Cary, NC, USA). To evaluate whether the additional contribution of SMC varied with temperature conditions, Ts was binned into 5°C intervals and, for each year, the Ts-only model and the Ts + SMC model were fitted within each Ts bin. Within each bin, model explanatory power was assessed using Adj. R^2 and model fit was evaluated using AIC. The contribution of SMC was quantified as the difference in Adj. R^2 between the two models (ΔAdj. R^2), and the degree of model improvement was quantified as the difference in AIC (ΔAIC). We also calculated p values for the SMC term within each bin to assess the significance of the SMC effect on Rs.

2.6 Threshold analysis of soil respiration

To identify a breakpoint in the temperature response of Rs, we applied segmented regression (Muggeo, 2003). Segmented regression estimates a breakpoint by fitting two or more linear segments with different slopes along a continuous predictor, here Ts. We first fitted an initial linear regression with Ts and then used iterative fitting to estimate the breakpoint and segment specific slopes. Analyses were performed in R (version 4.1.1) using the segmented package. The number of breakpoints was determined by comparing AIC among a model with no breakpoint and candidate models with one or more breakpoints (Table S1). Fit between the segmented regression model and the exponential model was compared using ΔAIC, and the significance of the fit difference between models was evaluated using a bootstrap based test. The estimated breakpoint was interpreted as a reference temperature indicating a structural change in the Rs response to Ts. We further evaluated temperature dependent changes in the relative contribution of SMC using ΔAdj. R^2 and ΔAIC from the Ts bin model comparisons.

3 Results

3.1 Environmental conditions and temporal variation in soil respiration

Mean annual Ts was 12.5°C in 2022 and 13.5°C in 2023, a difference of approximately 1°C, and the difference between years was not statistically significant ($p = 0.08$; Fig. 1a). Ts reached its maximum in July and August and its minimum in January and February, showing a typical seasonal pattern.

Annual precipitation increased from 1018.0 mm in 2022 to 1495.2 mm in 2023, an increase of 46.9%, and the number of precipitation days increased from 90 to 100. Monthly precipitation peaked in August 2022 (362.3 mm) and July 2023 (504.0 mm), and precipitation was also high in September 2023 (204.3 mm).

SMC ranged from 6.2% to 25.3% in 2022 and from 7.7% to 25.5% in 2023, with mean annual values of 14.1% in 2022 and 15.6% in 2023 (Fig. 1b). In 2022, monthly mean SMC was 9.6% in May and 9.2% in June, remaining below 10%, and then increased after July to 20.1% in August. In 2023, monthly mean SMC exceeded 12% throughout the year and reached 20.3% in July and 17.2% in September.

Mean annual Rs was 351.4 mg CO2 m^{-2} h^{-1} in 2022 and 701.9 mg CO2 m^{-2} h^{-1} in 2023 (Fig. 1c). Rs showed clear seasonality consistent with the seasonal variation in Ts, and cumulative Rs during July to September accounted for 68% of annual cumulative Rs in 2022 and 64% in 2023.

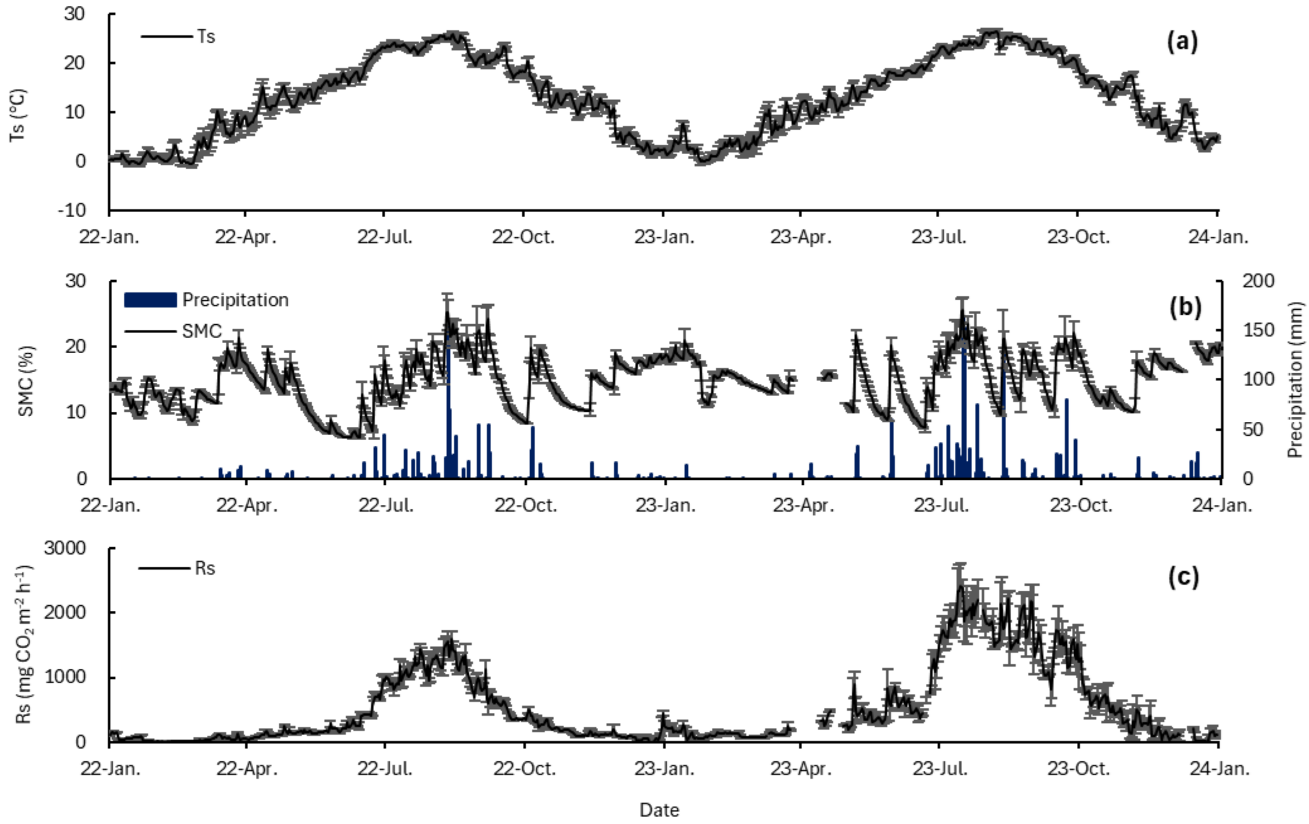

Figure 1: Temporal variation in (a) Ts, (b) SMC and precipitation, and (c) Rs during the 2022–2023 observation period. Data gaps in SMC and Rs occurred from 26 March to 13 April 2023 and from 21 April to 29 April 2023 due to instrument malfunction. Error bars represent ±1 standard error (SE).

3.2 Variability in soil respiration in relation to soil moisture content as a single factor

To examine the relationship between SMC and Rs, we first fitted a single variable regression with SMC as the sole predictor. In both years, Rs showed a consistent tendency to increase when SMC increased above a certain level. Based on the fitted trend, the SMC level at which the increase in Rs became more apparent was estimated at approximately 10.8% in 2022 and 13.1% in 2023 (Fig. 2). However, Rs was widely distributed even within the same SMC range, indicating substantial variability. When considering SMC alone, the coefficient of determination for explaining variability in Rs was low, with $R^2 = 0.29$ in 2022 and $R^2 = 0.21$ in 2023, but the relationship between SMC and Rs was statistically significant in both years ($p < 0.0001$).

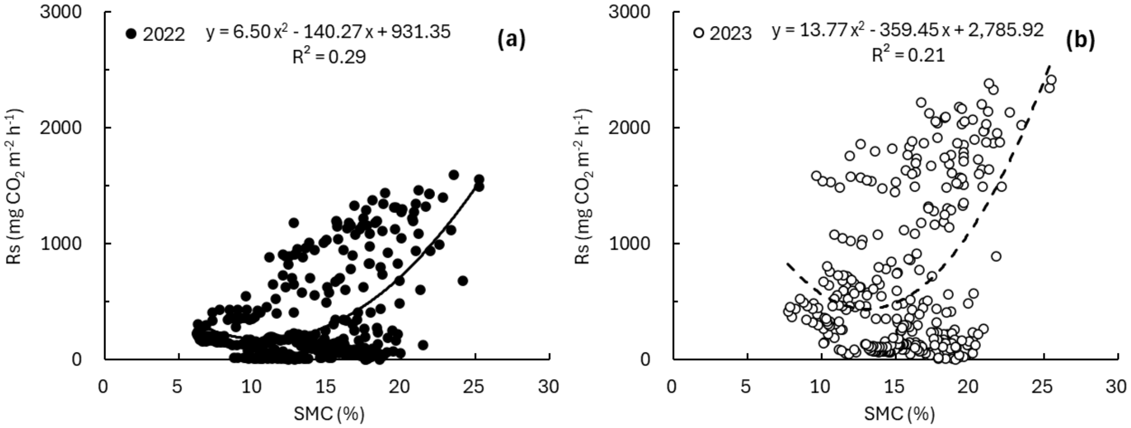

Figure 2: Relationship between soil moisture content and soil respiration in 2022 (a) and 2023 (b).

3.3 Soil respiration responses to soil moisture content across soil temperature ranges

Rs varied widely even within the same SMC range, and the single factor analysis did not show a consistent pattern between Rs and SMC. We therefore binned Ts and examined Rs responses to SMC under comparable temperature conditions (Fig. 3). For Ts bins above 15°C, R^2 ranged from 0.39-0.76 in 2022 and from 0.48-0.61 in 2023, and R^2 generally increased with higher temperature bins. In both years, the relationship between SMC and Rs was statistically significant for Ts bins above 15°C ($p < 0.0001$). In 2022, within the 20-25°C Ts bin, Rs increased with increasing SMC, but the rate of increase declined at higher SMC, indicating a reduced slope at high SMC (Fig. 3). In contrast, for Ts bins below 15°C, R^2 was low, ranging from 0.07-0.13 in 2022 and from 0.00 to 0.06 in 2023, and the relationship between SMC and Rs was not statistically significant in some bins.

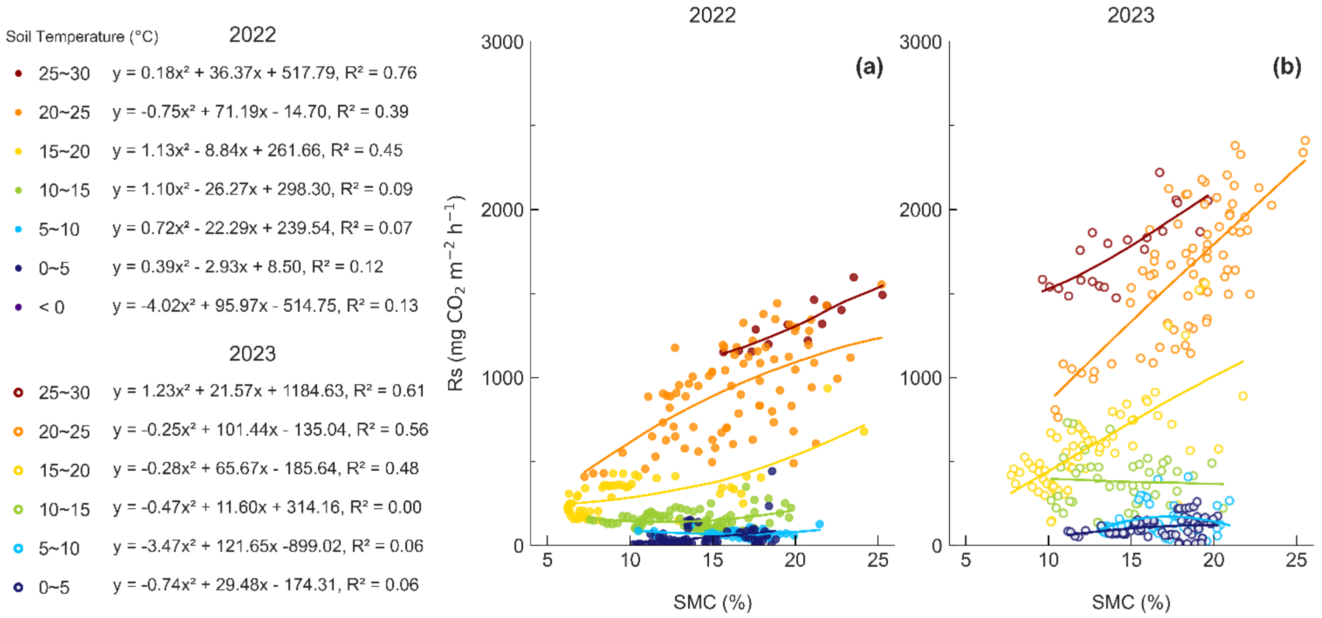

Figure 3: Relationship between SMC and Rs across Ts bins in (a) 2022 and (b) 2023. In 2023, no days had Ts below 0°C, so the Ts bins below 0°C were excluded from the analysis.

3.4 Changes in soil moisture contribution by soil temperature range

To evaluate the additional contribution of SMC after accounting for the effect of Ts, we compared the Ts only model and the Ts + SMC model within each temperature bin and quantified the difference as the SMC contribution (ΔAdj. R^2) (Fig. 4). Over the full period, the SMC contribution was 0.03 in 2022 and 0.09 in 2023. However, the SMC contribution varied substantially among temperature bins. Below 15°C, the SMC contribution was generally close to zero, ranging from 0.00–0.07 in 2022 and from −0.04–0.05 in 2023, whereas above 15°C it increased markedly, ranging from 0.21–0.43 in 2022 and from 0.44–0.62 in 2023. Consistent with this pattern, AIC(Ts-only) − AIC(Ts+SMC) indicated improved fit of the Ts + SMC model above 15°C, while the improvement was relatively small below 15°C (Fig. S1).

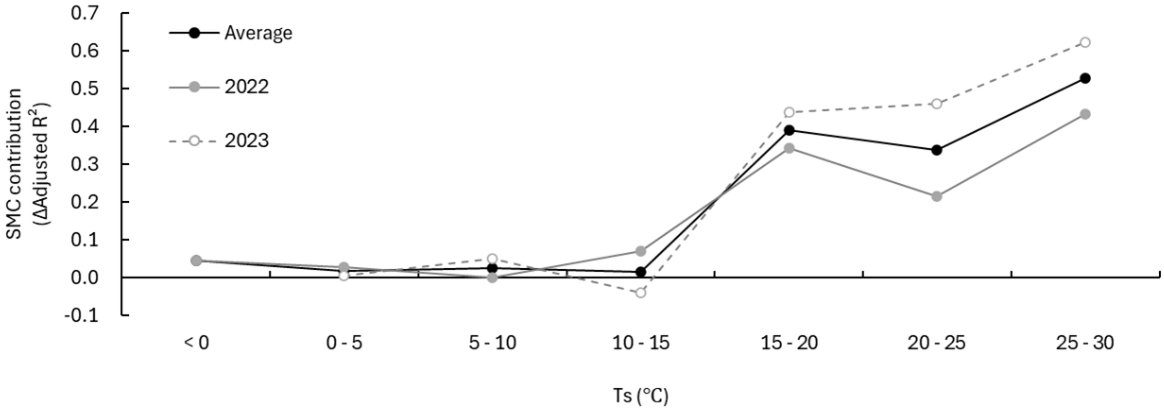

Figure 4: SMC contribution (ΔAdj. R²) by Ts bin. The SMC contribution was calculated as the difference in adjusted R² between the Ts only model and the Ts + SMC model (ΔAdj. R²). The gray solid line indicates 2022, the gray dashed line indicates 2023, and the black solid line indicates the mean across both years.

3.5 Soil temperature breakpoint for changes in the moisture contribution to soil respiration

The contribution of SMC differed across temperature conditions and increased markedly at higher Ts. To estimate the boundary temperature at which this change emerges, we applied segmented regression to the relationship between Rs and Ts to identify a breakpoint (Fig. 5). In both years, a breakpoint was detected near 17°C, with breakpoint estimates of 16.94 ± 0.44°C in 2022 and 16.77 ± 0.75°C in 2023, where ± indicates the 95% confidence interval. The number of breakpoints was optimized by comparing AIC among candidate models, and the segmented regression model with one breakpoint was selected as the best model (Table S1). The segmented regression model also showed improved fit relative to the exponential model, with lower AIC, and this improvement was significant based on a bootstrap test (2022 ΔAIC=20.4, $p < 0.0001$; 2023 ΔAIC=112.4, $p < 0.0001$).

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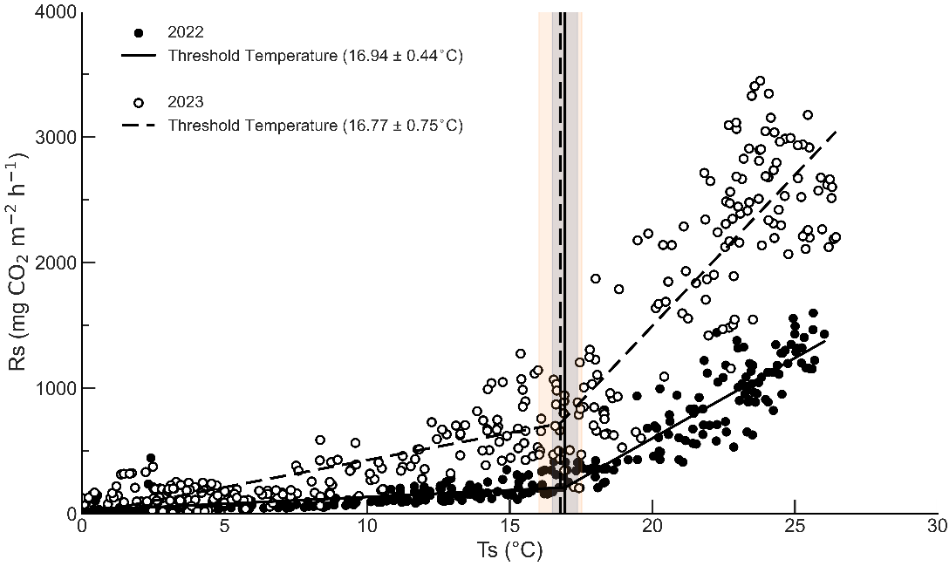

230 **Figure 5: Soil temperature breakpoint estimated by applying segmented regression to the relationship between Rs and Ts. Vertical lines indicate the estimated breakpoint temperatures (16.94°C in 2022 and 16.77°C in 2023), and shaded areas indicate the 95% confidence intervals for each breakpoint.**

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4 Discussion

This study shows that the effect of SMC on Rs is temperature dependent. In particular, the presence of a temperature range in which the relative contribution of SMC changes supports the possibility that the control structure governing Rs variability may shift. Therefore, to identify temperature dependent patterns in the contribution of SMC and the key temperature range at which a transition occurs, we quantified moisture effects within discrete temperature conditions and evaluated the presence of a breakpoint.

4.1 Relationship between soil moisture content as a single factor and soil respiration

In this study, the single factor analysis showed a statistically significant relationship between SMC and Rs ($p < 0.0001$). However, Rs exhibited large scatter even within the same SMC range, and the coefficient of determination for the SMC only regression was low, with values of 0.29 in 2022 and 0.21 in 2023 (Fig. 2). These results support previous findings that variability in Rs is difficult to explain using soil moisture alone (Liang et al., 2010; Yu et al., 2021). Soil respiration is influenced by environmental drivers beyond SMC, and key factors such as Ts can change concurrently with seasonal environmental conditions (Rodtassana et al., 2021). Accordingly, Rs responses can differ across environmental conditions. Consistent with previous studies, Rs in our study showed a seasonal pattern similar to that of Ts (Matsumoto et al., 2023), suggesting that Rs levels can differ with temperature conditions even at the same SMC.

4.2 Changes in the effect of soil moisture content under different temperature conditions

These results suggest that the effect of SMC is not expressed uniformly across the full Ts range but may differ depending on Ts conditions (Fig. 3). For Ts above 15°C, the relationship between SMC and Rs was consistently significant in both years ($p < 0.0001$), and Rs generally increased with increasing SMC. In contrast, for Ts below 15°C, some bins showed less consistent relationships between SMC and Rs.

Under sufficiently warm conditions, microbial and root activity becomes more active (Birgander et al., 2013; González-García et al., 2023), and Rs may respond more sensitively to changes in moisture status. In forests such as our site, rainfall events during warm periods can produce large short term changes in SMC (Fig. 1), and these moisture fluctuations can act as an important regulator of Rs. For example, under dry conditions, solute transport and substrate movement decline, and under extreme drought microbial and root activity can decrease or shift toward dormancy (Huang et al., 2005; Wang et al., 2014). Under wet conditions, Rs can be suppressed as oxygen diffusion is limited and gas diffusion resistance increases (Yan et al., 2018).

We also observed that in some warm Ts bins, the Rs response weakened at higher SMC (Fig. 3), which is consistent with reports that increasing moisture does not always increase Rs linearly and that physical constraints at high SMC, such as limited oxygen diffusion, can constrain the response (Zhu et al., 2020). Thus, the moisture effect observed at high Ts can be interpreted as a nonlinear control that includes both relaxation of moisture limitation and physical constraints under high SMC.

In contrast, under low Ts conditions, metabolic activity of microbial and root respiration generally declines (Chen et al., 2021; Schnecker et al., 2023), and the magnitude of the Rs response to moisture change can be constrained even for similar changes in SMC. Consistent with this interpretation, the SMC and Rs relationship was weak and not consistently evident for Ts below 15°C. In addition, during cold periods, lower rainfall frequency and weaker evapotranspiration effects can reduce the amplitude of SMC variability. This low variability can reduce the precision of slope estimates for SMC effects in regression analyses.

4.3 Soil moisture contribution after accounting for the temperature effect

Under field conditions, Ts and SMC often change together with seasonal variability (Li et al., 2022), and Rs is generally higher during warmer periods (Zhang et al., 2023). Therefore, it is necessary to distinguish whether the SMC and Rs relationship observed during warm periods reflects a direct moisture effect or an apparent strengthening driven by concurrent increases in Ts and shared seasonal patterns.

To address this issue, we evaluated the relationship between SMC and Rs within the same Ts bins (Fig. 3). We also compared the Ts only model and the Ts + SMC model and reported SMC contribution (ΔAdj. R^2) and model fit improvement (ΔAIC) to test whether moisture explains additional variability in Rs after accounting for the Ts effect (Fig. 4; Fig. S1).

The increase in SMC contribution and improved fit of the Ts + SMC model for Ts above 15°C indicate that SMC can explain additional variability in Rs under warm conditions even after accounting for the Ts effect. In contrast, for Ts below 15°C, SMC contribution and model improvement were limited. This pattern is consistent with reduced biological activity under low Ts, which can reduce moisture sensitivity of Rs (Huang et al., 2005). In addition, reduced SMC variability during cold periods can limit the extent to which moisture changes are expressed in Rs variability. Overall, these results show that the contribution of SMC can differ across Ts conditions and suggest a potential transition in moisture contribution around 15°C.

4.4 Effect of soil moisture content on soil respiration before and after the breakpoint

Previous studies that quantified temperature breakpoints in Rs have reported breakpoints near 18°C in forests, and our estimates fall within a similar range (Almagro et al., 2025). In our study, the breakpoint in the Ts and Rs relationship was 16.94 ± 0.44°C in 2022 and 16.77 ± 0.75°C in 2023 (Fig. 5). Across the breakpoint near 17°C, the relative contribution of SMC to Rs variability changed, supporting the possibility that the dominant controls on Rs shift from primarily temperature driven regulation to a combined control structure involving both Ts and SMC (Johnston et al., 2021). This breakpoint can be interpreted as emerging from the combined effects of increasing plant and microbial activity with warming and changes in moisture supply and variability during warm periods, which together strengthen the relative influence of SMC (Kaisermann et al., 2017; Wang et

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al., 2022; Li et al., 2025b). The location of such a breakpoint may vary with regional climate, vegetation characteristics, and soil environmental conditions, including moisture status (Lellei-Kovács et al., 2016; Almagro et al., 2025).

4.5 Implications and considerations

This study suggests that Rs variability is not governed consistently by a single factor but that the relative importance of key controls may be reorganized depending on Ts conditions. In particular, the change in the relative contribution of SMC near 17°C indicates that understanding and predicting Rs variability during warm periods requires consideration of not only Ts but also the moisture regime, including moisture supply, variability, and seasonality. This implies that under conditions expected to involve longer warm periods or increased precipitation variability, Rs responses may not be adequately described by a temperature sensitivity metric such as Q10 alone. Accordingly, carbon cycle modeling and predictions based on field observations should explicitly represent the role of moisture terms under warm conditions or adopt a structure that allows moisture sensitivity to differ with Ts, such as interaction terms or models fitted within temperature bins.

At the same time, because breakpoint location can shift with regional climate, vegetation, and soil environmental conditions, caution is required when generalizing our results as a universal temperature threshold. In addition, because Ts and SMC can covary seasonally under field conditions, the breakpoint may reflect combined seasonal drivers rather than a purely physiological boundary. Therefore, interpretation should emphasize the pattern of a change in control structure across the breakpoint rather than the specific temperature value itself. Finally, because Rs consists of root respiration and microbial respiration, separating these components is necessary to clarify the processes underlying breakpoint formation and control structure reorganization. This can be approached by incorporating indicators of vegetation activity, such as phenological classification, together with microbial activity indices, and where possible by additional component partitioning analyses to test how the relative contributions of respiration components change across the breakpoint.

5 Conclusions

This study suggests that the control structure of Rs may be reorganized across a temperature boundary. Although the explanatory power of the SMC only regression was limited, we found a consistent pattern in which the relationship between SMC and Rs strengthened and the relative contribution of SMC increased above a certain Ts. In addition, the Ts breakpoint in the Rs response was estimated near 17°C in both years, and the relative contribution of SMC differed across this breakpoint. Together, these results indicate that the dominant controls on Rs variability may shift from primarily Ts driven regulation below the breakpoint to a combined control structure in which Ts and SMC jointly influence Rs above the breakpoint.

Code availability

The analyses (segmented regression) were performed in R using standard packages, and no custom code beyond basic scripts was developed. The scripts used for data processing and analysis are available from the corresponding author upon reasonable request.

Data availability

Data supporting the findings of this study are available from the corresponding author upon reasonable request.

Author contributions

Dongmin Seo designed the study, carried out field measurements, performed data curation and formal analysis, and wrote the first draft of the manuscript. Minyoung Lee contributed to material preparation and field measurements. Jaeho Lee was responsible for instrument setup and installation. Jaeseok Lee supervised the study and contributed to data interpretation and manuscript revision. All authors commented on previous versions of the manuscript and approved the final version.

Competing interests

The authors declare that they have no conflict of interest.

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