Temperature ~~dependence of~~ dependent changes in the contribution of soil ~~moisture~~water content to soil respiration ~~and the soil respiration temperature threshold in a~~in a monsoon influenced 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~~water content (~~SMC~~SWC) often covary seasonally, which tends to limit our ability to isolate and quantify the independent contribution of ~~SMC~~SWC and to evaluate how its contribution varies with temperature. Although changes in the Rs response to temperature ~~thresholds in Rs~~ have been reported, few studies have quantitatively identified such ~~thresholds~~patterns from field observations and ~~interpreted potential shifts in the dominant controls based on how moisture responses differ~~examined whether the relative contribution of SWC becomes more evident across ~~the threshold~~temperature conditions. 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~~SWC varies with Ts by comparing models across temperature ranges, ~~with particular attention~~and to evaluate whether a breakpoint occurs in the Rs response to ~~changes~~Ts and whether that breakpoint is observed near the ~~threshold.~~temperature range where the contribution of SWC increases. At the annual scale, the explanatory power of ~~SMC~~SWC alone was limited, but the relationship between ~~SMC~~SWC and Rs was significant. In contrast, above 15°C, the relationship between ~~SMC~~SWC and Rs strengthened consistently, indicating that the relative contribution of ~~SMC is constrained at low Ts but increases markedly at high Ts~~SWC became more evident under warm soil conditions. Piecewise regression of the relationship between Rs and Ts identified a ~~Ts threshold~~breakpoint near 17°C, and models including this ~~threshold~~breakpoint improved fit relative to an exponential model. These results ~~show that the relative contribution of SMC can change across~~ suggest a ~~specific temperature range, suggesting that changes~~possible difference in the relative ~~influence~~importance of ~~SMC on Rs variability across the threshold may reorganize the dominant~~ controls on Rs~~.~~ across temperature conditions. Therefore, projections of forest Rs ~~should jointly consider~~may benefit from considering temperature dependent changes in ~~moisture~~the contribution ~~and~~of SWC and a possible breakpoint in the ~~presence of~~Rs response to Ts~~ thresholds~~.

1 Introduction

Global warming is altering ~~not only~~both air temperature ~~but also~~and precipitation regimes, thereby ~~changing the frequency and intensity of extreme hydrological events such as droughts and heavy rainfall~~affecting soil moisture conditions that influence carbon cycling in forest ecosystems. 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~~These findings indicate that forests are important ~~for regulating~~components of the carbon ~~balance and climate and carbon interactions through their dual~~cycle because they function both as major carbon reservoirs and as 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~~water content ~~(SMC) and reorganize the control structure governing Rs,~~SWC), 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~~water conditions, and the resulting sensitivities to Ts and ~~SMC~~SWC 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~~water content 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~~SWC 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~~SWC using empirical functions. The Ts and Rs relationship has typically been represented using exponential or Q_{10} models, whereas the ~~SMC~~SWC 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~~SWC, yet it remains poorly quantified how the relative influence of ~~SMC~~SWC 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~~SWC (He et al., 2024). Even so, quantitative evidence from field observations remains limited regarding when the relative contribution of ~~SMC~~SWC begins to ~~shift~~change systematically with Ts and whether ~~this shift emerges as~~ a breakpoint ~~within a specific~~in the Rs response to Ts occurs near the temperature range where this contribution becomes more evident.

It has been reported that the extent to which ~~SMC~~SWC 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). Accordingly, analyses based on annual aggregation can mask short term and condition dependent effects of SWC by averaging across heterogeneous seasonal conditions. This averaging may also mask temperature dependent properties of ~~moisture~~SWC effects, limiting efforts to quantify the dependence of ~~SMC~~SWC contributions on Ts. Therefore, based on field observations, it remains uncertain how ~~moisture~~the effects ~~transition~~of SWC change 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). It is also important to evaluate whether a breakpoint in the Rs response to Ts occurs near the temperature range where the relative contribution of SWC becomes more evident, because this can help identify whether the two patterns occur over a similar temperature range and support interpretation of possible differences in the relative importance of controls on Rs.

Rather than changing monotonically with increasing Ts, Rs can exhibit nonlinearity when changes in moisture conditions and associated constraints ~~alter~~modify the relative importance of ~~dominant~~ controlling factors, leading to changes in response slopes. Breakpoint based interpretation ~~is~~may therefore ~~important for capturing~~help identify the ~~key~~ temperature range where such changes ~~occur~~in response become more evident (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~~SWC varies systematically with Ts. By partitioning the analyses by temperature conditions to reduce the dilution that can arise from annual scale averaging, we ~~aim~~aimed to provide field based evidence for the temperature dependence of ~~moisture~~SWC effects and to examine possible differences in the relative importance of controls on Rs across 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~~SWC is often limited. We evaluate whether a statistically significant relationship between ~~SMC~~SWC and Rs exists despite this limitation.

2. If a relationship between ~~SMC~~SWC 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~~SWC, we quantify how the relative contribution of ~~SMC~~SWC to Rs changes across temperature ranges after accounting for the temperature effect.

4. We assess whether a breakpoint exists ~~as~~in the Rs response to Ts and, if identified, examine whether it occurs near the temperature range where the relative contribution of ~~SMC varies~~SWC becomes more evident, and discuss whether this pattern is associated with ~~Ts and, if identified, interpret its implications in terms of shifts~~possible differences 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~~SWC was measured over the 0 to 15 cm depth using ~~moisture~~soil water content sensors (CS616, Campbell Scientific Inc., Logan, UT, USA). Precipitation, Ts, and ~~SMC~~SWC 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~~SWC were processed as daily means. Because rainfall can induce very brief increases in soil respiration immediately after rewetting, including Birch type pulses (Xu et al., 2004), daily aggregation was used to reduce the influence of these transient responses and to better evaluate the broader effect of SWC on Rs across temperature conditions.

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.~~Soil respiration (Rs) was continuously measured from January 2022 to December 2023 using five automated chambers operated in repeated open and closed cycles. The chambers were installed at least 1 m apart and were arranged to reflect the spatial heterogeneity of soil and surface environmental conditions within the plot, which included slope gradients ranging from 16° to 34°. To avoid spatial bias in chamber placement, the characteristics of each location were carefully assessed, and the five chambers were arranged in a roughly pentagonal configuration. In addition, the chambers were installed at least 50 cm away from tree stems to minimize the potential overestimation of root respiration associated with dense root distribution near tree stems. Locations with substantial surface disturbance or conditions likely to reduce measurement stability were excluded.

For each chamber, Ts and SWC sensors were installed together within 5 cm of the chamber so that both variables represented the same local environmental conditions. The Ts sensor was positioned adjacent to the SWC sensor, while avoiding any direct physical contact or interference that could affect SWC measurements. Each chamber operated on a 30 min cycle consisting of 25 min open and 5 min closed phases. 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 in CO_2 concentration during the closed period. The IRGA inlet and outlet flow rates were regulated to 1.0 L min^{-}~~1~~^{1} using a flow meter. ~~The chamber~~Chamber collars were inserted 10 cm into the soil and fixed in place~~. Measurements~~, and 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.~~As with the Ts and SWC data, outliers and erroneous records were removed, and 30 min mean values were calculated. These were then used to derive daily mean soil respiration values (Eq. 1):

~~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~~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~~SWC 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):

$$Rs = a\exp(bTs) \tag{2}$$

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

Ts + ~~SMC~~SWC model (Eq. 3):

$$Rs = a\exp(bTs)(c\cancel{SMC^2}SWC^2 + \cancel{dSMC}dSWC + e) \tag{3}$$

~~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.~~

Model parameters *a, b, c, d*, and *e* were estimated by fitting the model to the observations. For the full daily dataset, the Ts-only model yielded an R^2 of 0.782, an RMSE of 274.94, and an AIC of 183,047, whereas the Ts + SWC model yielded an R^2 of 0.846, an RMSE of 230.77, and an AIC of 177,346.

2.5 Statistical analysis

All analyses were conducted using SAS software version 9.4 (SAS Institute Inc., Cary, NC, USA). ~~To evaluate whether~~(Eq. 2) and (Eq. 3) were fitted to the full daily dataset. The daily data were then grouped into 5°C Ts intervals for each year to further examine how the additional contribution of ~~SMC varied with~~SWC changed across temperature conditions~~, Ts was binned into 5°C intervals and, for each year~~. Within each temperature range, the Ts-only model and the Ts + ~~SMC~~SWC model were ~~fitted within each Ts bin. Within each bin, model explanatory power was assessed~~compared using Adj. R^2 and ~~model fit was evaluated using~~ AIC. The contribution of ~~SMC~~SWC 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~~ evaluated the significance of the ~~SMC effect on Rs~~SWC term within each temperature range.

2.6 ~~Threshold~~Breakpoint analysis of the soil respiration response to soil temperature

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~~ , rather than as a direct threshold in SWC sensitivity. Temperature dependent changes in the relative contribution of ~~SMC~~SWC were evaluated separately using ΔAdj. R^2 and ΔAIC from the Ts bin model comparisons. In addition, to visually examine whether unexplained variation in Rs became more dispersed across temperature conditions after removing the Ts effect, residuals were calculated as observed Rs minus Rs predicted by the Ts-only model and plotted against Ts with SWC indicated by color (Fig. S2).

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~~SWC 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~~SWC 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~~SWC exceeded 12% throughout the year and reached 20.3% in July and 17.2% in September. Additionally, short term increases in Rs were observed following increases in SWC after rainfall during the study period. Specifically, Rs tended to increase on the day of rainfall and on the following day, and a similar increasing pattern was also observed at 0, 1, and 2 h after rainfall at the hourly scale.

Mean annual Rs was 351.4 mg CO_2 m^{-2} h^{-1} in 2022 and 701.9 mg CO_2 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.

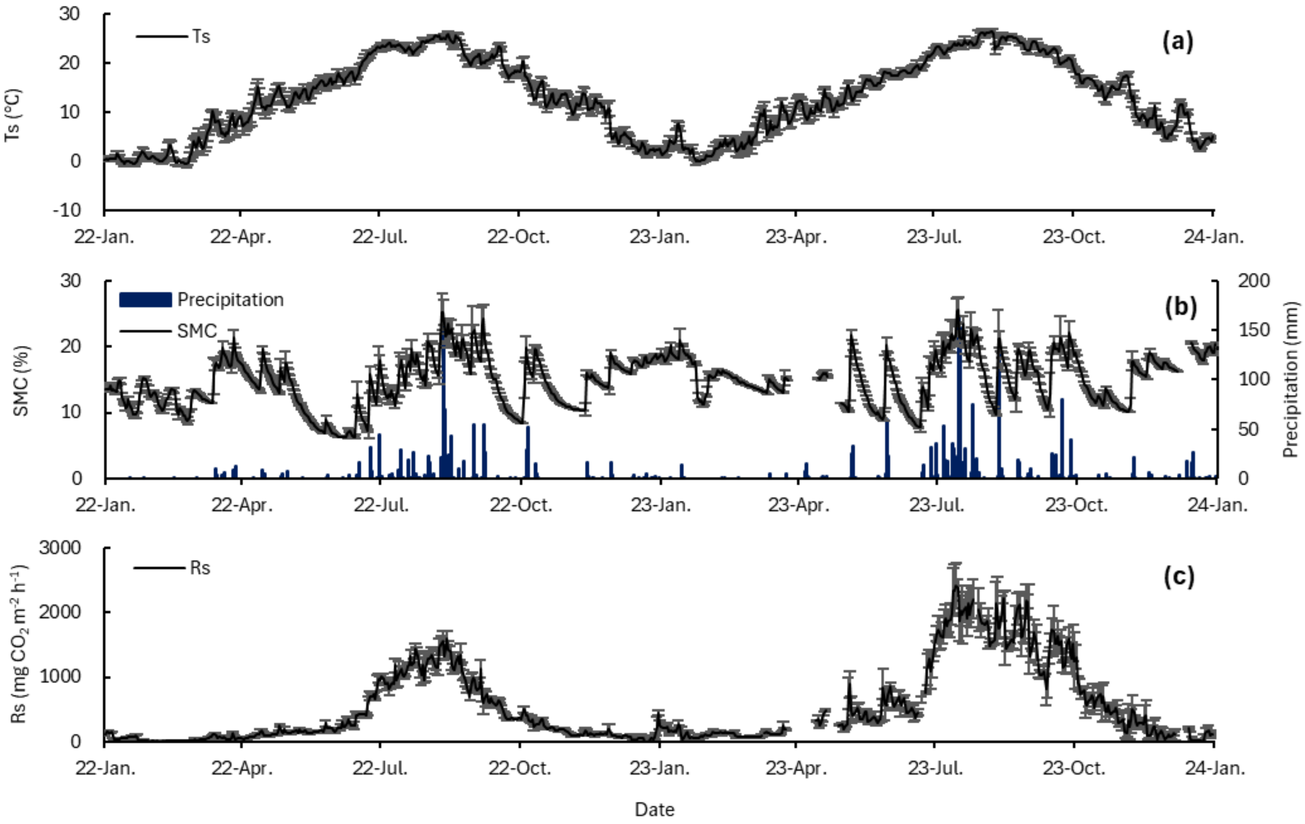
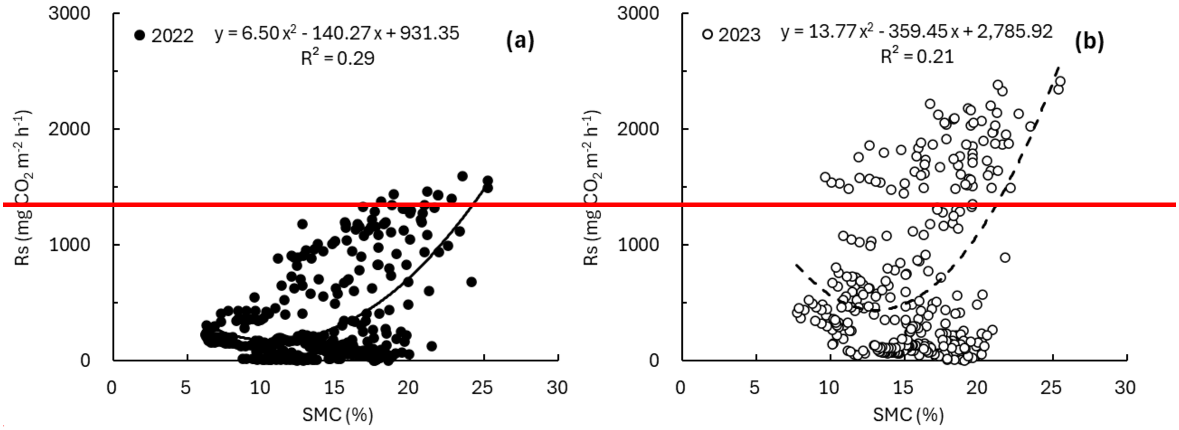


Figure 1~~1~~: Temporal variation in (a) Ts, (b) ~~SMC~~SWC and precipitation, and (c) Rs during the 2022–2023 observation period. Data gaps in ~~SMC~~SWC and Rs occurred from 26 March to 13 April 2023 and from 21 April to 29 April 2023 due to instrument malfunction. Error bars represent ±1 standard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

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

To examine the relationship between ~~SMC~~SWC and Rs, we first fitted a single variable regression with ~~SMC~~SWC as the sole predictor. In both years, Rs showed a consistent tendency to increase when ~~SMC~~SWC increased above a certain level. Based on the ~~fitted trend~~quadratic regression, the ~~SMC level at which~~SWC value corresponding to the ~~increase in Rs became more apparent~~minimum of the quadratic function 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~~SWC range, indicating substantial variability. When considering ~~SMC~~SWC 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~~SWC and Rs was statistically significant in both years ($p < 0.0001$).



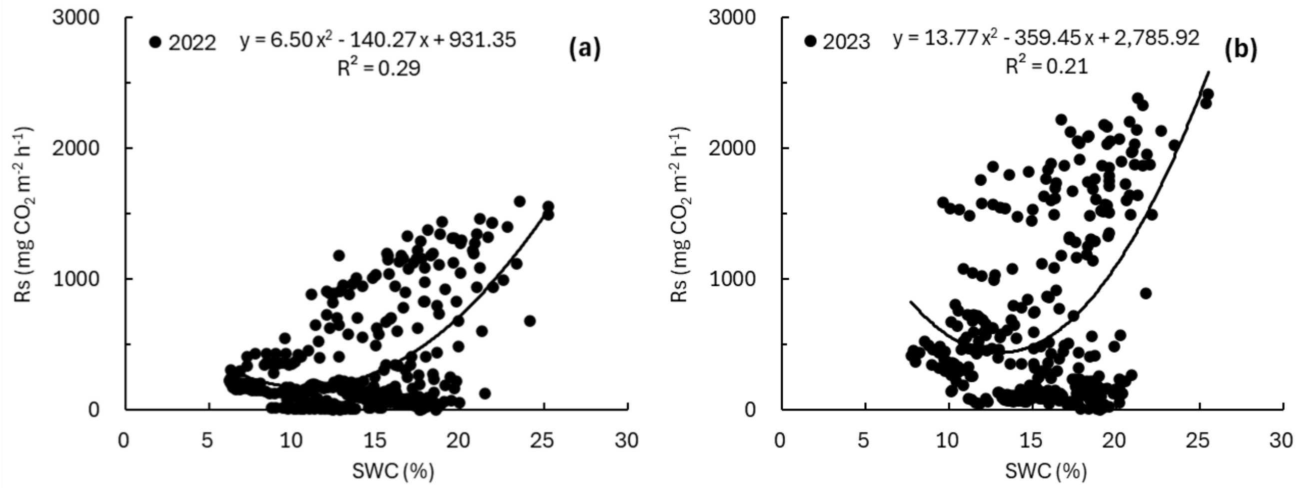


Figure 2: Relationship between ~~soil moisture content~~SWC and ~~soil respiration~~ Rs in 2022 (a) and 2023 (b).

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

Rs varied widely even within the same ~~SMC~~SWC range, and the single factor analysis did not show a consistent pattern between Rs and ~~SMC~~SWC. We therefore binned Ts and examined Rs responses to ~~SMC~~SWC 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~~SWC 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~~SWC, but the rate of increase declined at higher ~~SMC~~SWC, indicating a reduced slope at high ~~SMC~~SWC (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~~SWC and Rs was not statistically significant in some bins.

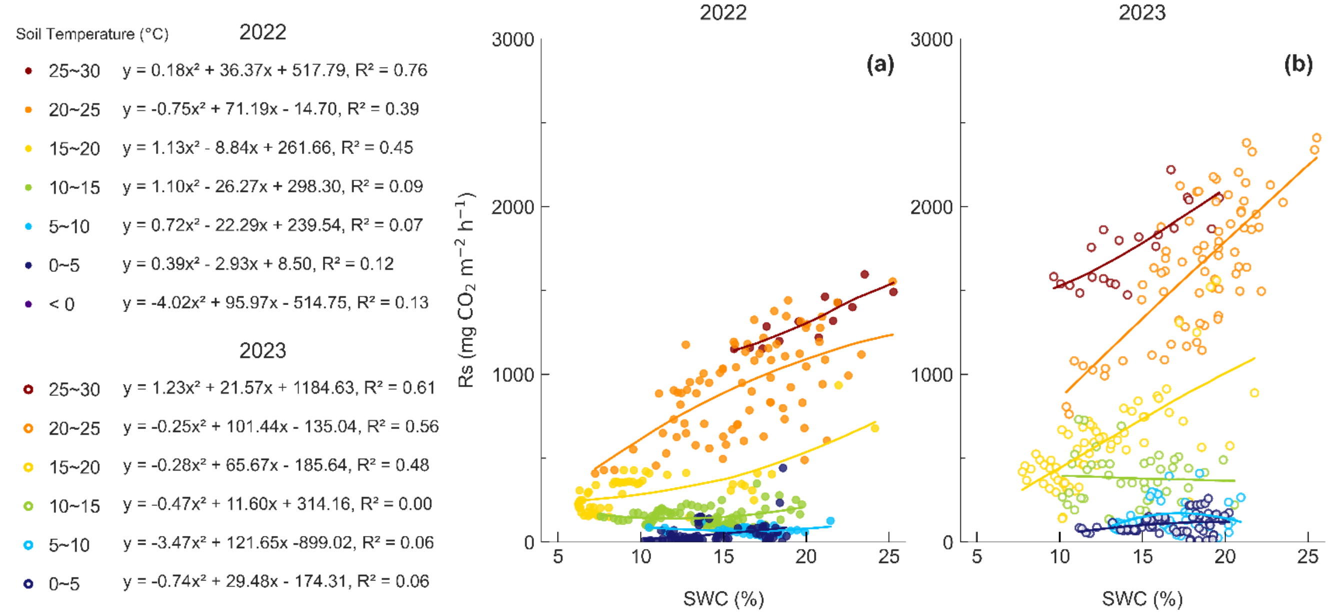


Figure 3: Relationship between ~~SMC~~SWC and Rs across Ts bins in (a) 2022 and (b) 2023. In 2023, no days had Ts below 0°C, so the Ts bins below 0°C were excluded from the analysis.

3.4 Changes in ~~soil moisture~~the contribution ~~by~~of soil water content across soil temperature ~~range~~ranges

To ~~evaluate~~directly test whether the ~~additional~~ contribution of ~~SMC~~SWC to Rs changed across temperature conditions after accounting for ~~the effect of~~ Ts, we compared the Ts~~-~~-only model and the Ts + ~~SMC~~SWC model within each temperature bin and quantified the difference as the ~~SMC~~SWC contribution (ΔAdj. R^2) (Fig. 4). Over the full period, the ~~SMC~~SWC contribution was 0.03 in 2022 and 0.09 in 2023. However, the ~~SMC~~SWC contribution varied substantially among temperature bins. Below 15°C, the ~~SMC~~SWC 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~~SWC) indicated improved fit of the Ts + ~~SMC~~SWC model above 15°C, while the improvement was relatively small below 15°C (Fig. S1).

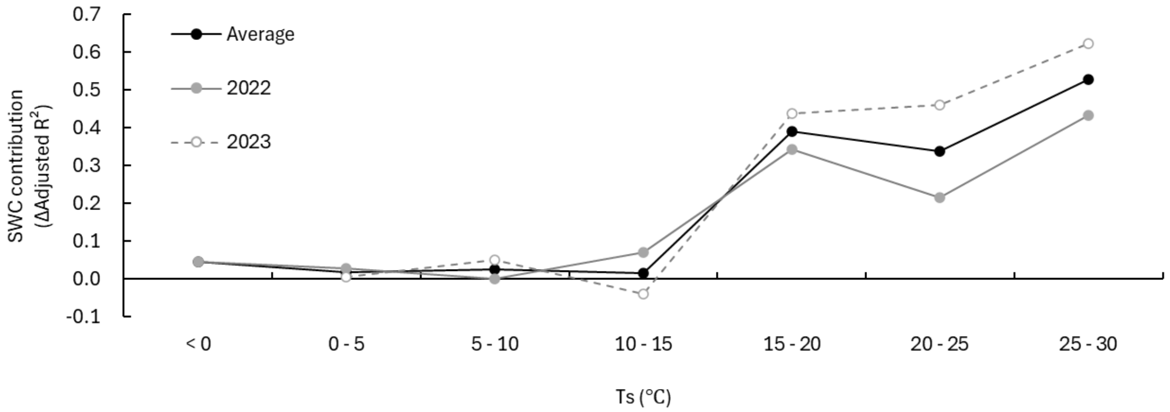


Figure 4: ~~SMC~~SWC contribution (ΔAdj. R^2) by Ts bin. The ~~SMC~~SWC contribution was calculated as the difference in adjusted R^2 between the Ts-only model and the Ts + ~~SMC~~SWC model (ΔAdj. R^2). The gray solid line indicates 2022, the gray dashed line indicates 2023, and the black solid line indicates the mean across both years.

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

The contribution of ~~SMC~~SWC differed across temperature conditions and ~~increased markedly~~became more evident at higher Ts. ~~To estimate the boundary temperature at which this change emerges, we~~We then applied segmented regression to the relationship between Rs and Ts to ~~identify~~examine whether a breakpoint occurred near the temperature range where this pattern emerged (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. To further examine the temperature response across the breakpoint, we analyzed the Ts range, slope, R^2, p-value, and mean SWC for the segments below and above the breakpoint (Table S2). 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, $p < 0.0001$). To provide a more direct visual assessment of the variation not explained by Ts alone, we additionally examined the residuals of the Ts-only model across the Ts range (Fig. S2). In both years, residuals appeared relatively more constrained at lower Ts, but became more widely dispersed in the warmer temperature range, where variation in SWC was also more evident.

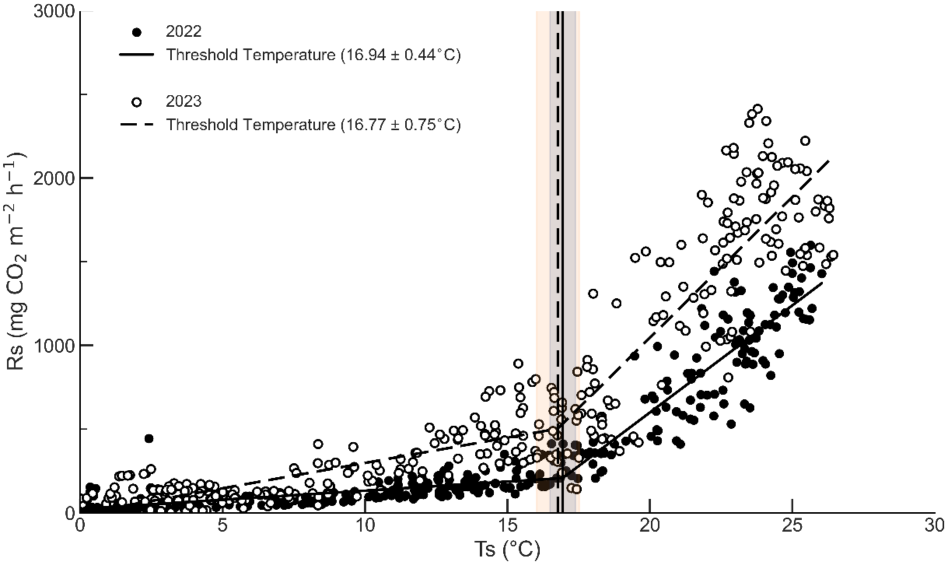


Figure 5: Soil temperature breakpoint estimated by applying segmented regression to the relationship between Rs and Ts. Vertical lines indicate the estimated breakpoint temperatures (16.94°C in 2022 and 16.77°C in 2023), and shaded areas indicate the 95% confidence intervals for each breakpoint.

4 Discussion

~~This study shows~~Our results indicate that the effect of ~~SMC~~SWC on Rs ~~is~~ depends on soil temperature ~~dependent. In particular, the presence~~, with SWC exerting a stronger influence under warmer conditions. This pattern suggests that the relative importance of ~~a~~ SWC is not constant across temperature ~~range in which~~ conditions and that the relative ~~contribution~~importance of ~~SMC changes supports the possibility that the control structure governing~~controls on Rs ~~variability~~ may ~~shift. Therefore, to identify~~differ between cooler and warmer conditions. To examine temperature dependent ~~patterns~~changes in the contribution of ~~SMC~~SWC and whether a breakpoint in the ~~key~~Rs response to Ts occurs near the temperature range ~~at which a transition occurs~~where this contribution becomes more evident, we quantified ~~moisture~~SWC effects within discrete temperature conditions and evaluated the presence of a breakpoint. However, this pattern should be interpreted cautiously because the breakpoint in the Rs response to Ts does not directly represent a threshold in SWC sensitivity.

4.1 Relationship between soil ~~moisture~~water 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~~Although SWC was ~~low,~~significantly associated with ~~values of 0.29~~Rs, variation in ~~2022 and 0.21 in 2023 (Fig. 2). These results support previous findings that~~ SWC alone explained only a limited portion of Rs variability. The wide dispersion of Rs within similar SWC ranges indicates that the influence of SWC is strongly conditioned by other environmental drivers. This interpretation is consistent with previous studies showing that temporal variation in Rs is difficult to explain using ~~soil moisture~~SWC alone (Liang et al., 2010; Yu et al., 2021). Soil respiration is influenced by environmental drivers beyond ~~SMC~~SWC, 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.~~the response of Rs to SWC should be interpreted in relation to the combined effects of temperature and SWC rather than as an independent effect of SWC. The close seasonal correspondence between Rs and Ts in our data further supports temperature as a primary background control, which may obscure a simple direct relationship between SWC and Rs (Matsumoto et al., 2023).

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

These ~~results suggest~~findings indicate that the ~~effect~~influence of ~~SMC is not~~SWC on Rs varies across temperature conditions rather than being expressed uniformly ~~across~~over 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~~ . This temperature dependence suggests that SWC becomes a more effective regulator of Rs under warm conditions, whereas its influence is weaker or less consistent ~~relationships between SMC and Rs~~under cooler conditions.

Under sufficiently warm conditions, microbial and root activity ~~becomes more active~~ increase (Birgander et al., 2013; González-García et al., 2023), and Rs may respond more sensitively to changes in ~~moisture status. In forests such as~~SWC. At our forest site, rainfall events during warm periods ~~can produce large~~likely generated short term ~~changes in SMC (Fig. 1), and these moisture~~ fluctuations ~~can act as an important regulator of Rs. For example, under~~ in SWC, and these fluctuations may have contributed substantially to temporal variation in Rs. One possible explanation is that dry soil conditions~~,~~ restrict solute transport and substrate ~~movement decline, and under extreme drought~~diffusion, while severe moisture limitation can suppress microbial and root activity ~~can decrease or shift toward~~or induce dormancy (Huang et al., 2005; Wang et al., 2014). ~~Under wet conditions, Rs can be suppressed as~~At the wetter end of the SWC range, Rs may also become constrained if oxygen diffusion ~~is limited~~declines and gas diffusion resistance increases (Yan et al., 2018).

In addition, the shift in Rs response around 15°C cannot be fully explained by Ts or SWC alone and may also reflect seasonal biological changes, including increases in fine root biomass and activity and enhanced microbial activity during warmer phenophases (Schindlbacher et al., 2015; Heinzle et al., 2023).

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

In contrast, under low Ts conditions, ~~metabolic activity of~~ microbial and root ~~respiration~~activity generally ~~declines~~decline (Chen et al., 2021; Schnecker et al., 2023), and the magnitude of the Rs response to ~~moisture change can be constrained~~ changes in SWC may therefore remain limited even ~~for~~under similar changes in ~~SMC~~SWC. Consistent with this interpretation, the ~~SMC and~~influence of SWC on Rs ~~relationship~~ was weak and ~~not consistently evident for~~less consistent under Ts below 15°C. In addition, during cold periods, lower rainfall frequency and weaker evapotranspiration effects can reduce the amplitude of ~~SMC~~SWC variability. This ~~low~~limited variability ~~can reduce~~may also make the ~~precision~~estimated effect of ~~slope estimates for SMC effects~~SWC less stable and more difficult to detect statistically in regression analyses.

4.3 ~~Soil moisture contribution~~Contribution of soil water content to soil respiration after accounting for the temperature effect

Under field conditions, Ts and ~~SMC~~SWC 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~~ Accordingly, the ~~SMC~~stronger SWC and Rs relationship observed during warm periods must be interpreted carefully to determine whether it reflects ~~a direct moisture~~an independent SWC effect or ~~an apparent strengthening driven by~~arises partly from 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. R²) 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~~When the effect of temperature was constrained within comparable Ts ranges, the influence of SWC on Rs became clearer under warm conditions. This comparison further indicates that SWC can provide explanatory power beyond temperature alone, but primarily under sufficiently warm conditions.

The stronger contribution of SWC under Ts above 15°C suggests that SWC explains additional variation in Rs under warm conditions beyond that captured by temperature alone, although seasonal covariance between Ts and SWC cannot be fully excluded. By contrast, ~~for Ts below 15°C, SMC contribution and model improvement were~~under cooler conditions, the independent role of SWC appears limited. This ~~pattern~~interpretation is consistent with reduced ~~biological~~microbial and root activity under low Ts, which ~~can reduce moisture~~ may suppress the sensitivity of Rs to SWC (Huang et al., 2005). ~~In addition, reduced SMC~~Reduced SWC variability during cold periods ~~can limit~~may also weaken the extent to which ~~moisture~~SWC related changes are expressed in Rs variability. Overall, these ~~results show~~findings support the view that the contribution of ~~SMC can differ across Ts~~SWC to Rs is temperature dependent and becomes more pronounced only under sufficiently warm conditions~~ and suggest a potential transition in moisture contribution around 15°C~~.

4.4 Effect of soil ~~moisture~~water content on soil respiration ~~before~~below and ~~after~~above 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~~ consistently detected near 17°C~~, the~~ in both years (Fig. 5). The relative contribution of ~~SMC~~SWC to Rs variability ~~changed, supporting the possibility that the dominant controls on Rs shift from primarily~~differed between cooler and warmer temperature ~~driven regulation to a combined control structure involving both Ts and SMC~~conditions, with the influence of SWC becoming more evident under warmer conditions. A breakpoint in the Rs response to Ts was also detected near the temperature range where this pattern emerged. These results suggest a possible shift in the relative importance of the controls on Rs between cooler and warmer conditions (Johnston et al., 2021). This breakpoint ~~can be interpreted as emerging from~~may reflect the combined effects of ~~increasing~~enhanced plant and microbial activity ~~with warming and changes~~under warmer conditions and greater variation in ~~moisture supply and variability~~SWC during warm periods, which together ~~strengthen~~increase the relative influence of ~~SMC~~SWC on Rs (Kaisermann et al., 2017; Wang et al., 2022; Li et al., 2025b). The location of such a breakpoint may vary with regional climate, vegetation characteristics, and soil environmental conditions, including soil moisture ~~status~~regimes (Lellei-Kovács et al., 2016; Almagro et al., 2025). However, because this study was conducted at a single site, the extent to which the identified breakpoint near 17°C can be generalized remains limited. In addition, the breakpoint may reflect not only moisture related constraints on microbial activity but also seasonal changes in root activity.

4.5 Implications and considerations

This study suggests that Rs variability is not governed consistently by a single factor ~~but~~and that the relative importance of key controls may ~~be reorganized~~vary depending on Ts conditions. In particular, the ~~change in the~~greater relative contribution of ~~SMC near 17°C~~SWC under warm conditions indicates that understanding and predicting Rs variability during warm periods requires consideration of not only Ts but also the ~~moisture~~seasonal water regime, including ~~moisture~~variation in SWC and water 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 Q_{10} alone. Accordingly, carbon cycle modeling and predictions based on field observations should explicitly represent the role of ~~moisture~~SWC terms under warm conditions or adopt a structure that allows ~~moisture~~the sensitivity of Rs to SWC to differ with Ts, such as interaction terms or models fitted within temperature bins. Although short term increases in Rs were observed following rainfall, daily averaged data were used to reduce the influence of these transient responses and to more clearly evaluate the broader effect of SWC on Rs across temperature conditions.

At the same time, because breakpoint location can shift with regional climate, vegetation, and soil environmental conditions, caution is required when ~~generalizing~~interpreting our results ~~as a universal~~beyond the hydroclimatic setting of this study. In particular, in temperate deciduous forests, monsoon climates tend to maintain relatively high soil water availability during the warm season because precipitation is concentrated in this period, whereas non monsoon climates tend to experience intensified seasonal drying with increasing temperature ~~threshold.~~ (Chae, 2011; Prigoliti et al., 2023). In this context, our findings should be interpreted within the hydroclimatic setting of monsoon influenced temperate forests where soil water availability remains relatively high during the warm season, and the same pattern may not occur in non-monsoon temperate forests where water availability is seasonally limited. In addition, because Ts and ~~SMC~~SWC can covary seasonally under field conditions, and because Rs was not partitioned into autotrophic and heterotrophic components, the breakpoint may reflect combined seasonal drivers~~.~~, including phenological changes in root activity, rather than a purely physiological ~~boundary.~~ moisture threshold.

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~~Clarifying the processes underlying breakpoint formation ~~and control structure reorganization. This can be approached by~~will require further studies incorporating phenological 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~~relative contribution of SWC to Rs ~~may be reorganized~~variability changes across ~~a~~ temperature ~~boundary~~conditions. Although the explanatory power of the ~~SMC~~SWC only regression was limited, we found a consistent pattern in which the relationship between ~~SMC~~SWC and Rs ~~strengthened and the relative contribution of SMC increased~~became stronger above a certain Ts. In addition, ~~the Ts~~a breakpoint in the Rs response to Ts was estimated near 17°C in both years, and ~~the relative contribution of SMC differed across~~ this breakpoint~~. Together~~ was located near the temperature range where the relative contribution of SWC became more evident. Taken together, these ~~results indicate~~findings suggest that the ~~dominant~~ relative importance of controls on Rs ~~variability may shift from primarily Ts driven regulation below the breakpoint to a combined control structure in which Ts~~may differ between cooler and warmer soil conditions, with the contribution of SWC becoming greater under warm soil conditions and ~~SMC jointly influence Rs above the breakpoint~~remaining limited or less evident under cool soil conditions.

Code availability

The segmented regression analyses were performed in R using standard packages. Custom 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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