JEE ISSN: 2288-1220
https://doi.org/10.5141/jee.24.096
Journal of Ecology and Environment (2025) 49:04

REVIEW

Variation in Q_{10} of soil respiration due to biophysical factors in forest ecosystems

Angom Sarjubala Devi*, Mary Lalremruati, Gospel Lallawmzuali, Naorem Twinkle Devi, Vanlalhmuaka, Khumujam Omeshori Devi and Khumallambam Jyotish

Department of Environmental Science, Mizoram University, Mizoram 796004, India

ARTICLE INFO
Received October 19, 2024
Revised December 27, 2024
Accepted January 26, 2025
Published on February 21, 2025

***Corresponding author**
Angom Sarjubala Devi
E-mail angom75@yahoo.com

Background: Sensitivity of forests to atmospheric warming is greater when compared with other types of landuse. Evaluation on response of soil respiration to increase in temperature is valuable as forest soils emits 75 to 77 PgC yr^{-1}. Sensitivity of soil respiration to climate change varies from a forest to another forests, therefore evaluation of Q_{10} is necessary to provide an unbiased result.
Results: In the present compilation it was found that as latitude increases Q_{10} of forests rises and it correlated negatively with mean annual temperature (MAT) and mean annual precipitation (MAP). The amount of soil organic carbon (SOC) does not correlate with Q_{10} however, higher amount of recalcitrant C and associated microbial population in forest soils at higher latitudes as a result of low MAT and MAP is an important factor in the elevated response of Q_{10}.
Conclusions: The quality of SOC and not the quantity of SOC is an important component in estimating sensitivity of soil respiration to increase in temperature in different forests.

Keywords: boreal, latitude, subtropical, temperate, tropical

Introduction

Forests serves as the largest terrestrial sink of carbon. The natural process of fixing CO_2 through photosynthesis leads to storage in the form of C in different parts of the plant. Incorporation of plant biomass in soil leads to storage of C in soil. The global C stock in forests is estimated to be 861 PgC, with 44% in soil up to a depth of 1 m, 42% in above and below ground live biomass, 8% in deadwood and 5% in litter. Among the forests 55% of the total C is stored in tropical, 32% in boreal and 13% in temperate forests (Pan et al. 2011).

Soil respiration (Rs) is the primary path by which the stored C in soil and plants is returned to the atmosphere and it is estimated to be 75 to 77 PgCyr^{-1}. Rs consists of two main components heterotrophic and autotrophic. Heterotrophic respiration is produced by the free-living soil microorganisms that thrives through decomposition of organic matter in soil and litter. Autotrophic respiration comes from roots, mycorrhizae, and other microorganisms that are in obligate associations with living roots and the organic exudates provided by aboveground parts of the plant through photosynthesis (Ma et al. 2019). Rs in forests respond more sensitively to atmospheric warming compared with other landuse patterns like cropland and grassland soils (Meyer et al. 2018; Zheng et al. 2009). Many studies have evaluated rate of Rs in different forest ecosystems at different temperature and latitudes, as understanding the mode of response of Rs to climate change is necessary. In forest ecosystems large scale variation in Rs was observed due to difference in plant roots, soil organic matter (SOM), soil temperature and soil moisture content. One possibility to overcome the variation of Rs in response to climate change can be overcome by estimation of Q_{10} values (Jung et al. 2015). Q_{10} is the factor by which Rs changes when there is an increase of 10°C in temperature.

Studies reveal that soil organic carbon (SOC) (Vanhala et al. 2008; Zhang et al. 2021), landuse pattern, aggregated soil group, soil texture (Meyer et al. 2018), moisture content (Cusak et al. 2023) are important factors for temperature sensitivity of Rs. The quality and degradability of SOC is also an important regulator of Q_{10} (Lefèvre et al. 2014). Low quality and less easily decomposable organic matter or recalcitrant matter has a stronger temperature sensitivity than that of high quality, easily decomposable substrate (Vanhala et al. 2008). Moreover, according to kinetic theory, more recalcitrant stable SOM should be more sensitive to rise in temperature. Clay and silt particles provide larger reactive sites where SOM are adsorbed and are more stable, whereas sand particles have weak bonding affinity to SOM and are unstable. Therefore, C within sand fraction is allocated as active pool and C in silt and clay fractions is allocated as intermediate and passive pools (Ding et al. 2018). In response to moisture level Cusak et al. (2023) predicted that in future, climate change will lead to drying of fertile and water-logged soils causing an increase in soil CO_2 fluxes while it can lead to reducing CO_2 flux from drier soils.

There are no differences in the relationship of temperature with root associated and non-root associated organism respiration in soil. Therefore, Q_{10} values for the aggregated Rs should be considered while estimating effects of global climate change (Bååth and Wallander 2003). Studies on the response of Q_{10} specifically at latitudinal scale in different forest ecosystems has been undertaken on a very small scale. Therefore, the present work was undertaken to evaluate the impact of biophysical factors consisting of SOC, latitude, altitude, mean annual temperature (MAT) and mean annual precipitation (MAP) on Q_{10}. Collection of published literatures was carried out from a wide latitudinal gradient to carry out the study.

Methodology

A survey of published literatures was carried out using the search engine Google and academic platforms ResearchGate, Google Scholar, Taylor and Francis, Science Direct and Springer. The survey was conducted up to December, 2023. The key words used for collection of the published literatures were, Rs in forest and Q_{10} of Rs in forests. Altogether 73 related published literatures were recorded. The reported procedure for estimation of Rs in the literatures was using Automated Respirometer and Infra-Red Gas Analyzer, SOC using CHNS analyzer and Ignition method.

The equation for determination of Q_{10} is derived from Meyer et al. (2018). The exponential equation used to calculate relationship between temperature and Rs is:

$$Rs_T = a \times \exp^{b \times T}$$

The value of Q_{10} is calculated by substituting the parameter b from the above equation in the following equation:

$$Q_{10} = \exp^{10 \times b}$$

The depth of soil for determination of Rs and SOC was selected up to 0–30 cm although the common soil depth was 0–20 cm. Rate of Rs was converted into mg $m^{-2}hr^{-1}$ and SOC into percentage. Respective data on latitude, MAT, MAP and altitude were collected. The extreme values of SOC 59% (Kukumägi et al. 2017) and 43% (Nakano et al. 2004) respectively were excluded. In order to remove confusion in explaining variations of Rs and Q_{10} data derived from measurements in incubated environment and laboratory experiments were not considered.

The data collected were subjected to analysis of variance, Tukey's HSD test, Pearson's coefficient of correlation, student's t-test and summarized by finding out average, maximum, minimum and standard deviation. MS Excel and SPSS version 16 were used for the statistical analysis.

Results and Discussion

There are 3 types of forest based upon latitude (Nordseth 2024). They are: 1. Tropical Forest 2. Temperate Forest and 3. Boreal Forest. The latitudes for tropical forest ranged from 0 to 23.5°. Although subtropical forest is not included in the classification, based upon the data collected from the published literatures it was found that the subtropical forest is situated around latitudes of approx. 23.5° to 30.7° which can also vary (Huang et al. 2017; Wei et al. 2015; Zhang et al. 2021). The forests lying beyond latitudes of subtropical till 50.0° were categorized under the temperate forests however, overlapping between the two types of forests can happen. The boreal forests are located in 50.0 to 60.0° latitudes.

Maximum Rs was recorded from Malaysia with 760.0 mg $m^{-2}hr^{-1}$ situated at a latitude of 2.59° and recorded MAT of 27.0°C (Cindy et al. 2018) (Table 1). Minimum Rs was recorded to be 41.47 mg $m^{-2}hr^{-1}$ from Southwestern China (Xu et al. 2017) situated at latitude of 31.37° and MAT of 8.7°C. Many studies have demonstrated a positive correlation of Rs with MAT (Arroyo and Wood 2020; Gallo et al. 2023; Hu et al. 2001; Jeong et al. 2018; Kumar et al. 2023; Lim et al. 2012; Ma et al. 2005; McGrath et al. 2022; Tomar and Baishya 2020; Yang et al. 2022). The positive correlations recorded are due to enhancing root activities, acceleration of decomposition of plant litter leading to production of more plant biomass at higher temperatures. However, when the compiled data for different types of forests are considered Rs was not able to correlate significantly with MAT. The reason could be attributed to the wide variation in MAT along latitudinal gradient whereas, Rs does not show such a wide variation along the latitudinal gradient. Greater variations of Rs were observed at similar latitudes in different forest having different composition of tree species however, an insignificant inverse correlation between Rs and latitude was recorded ($r = -0.12$, $p < 0.9$) (Table 2). MAP also was not significantly correlated with Rs in the present review. Reports of significant correlation between the two variables were recorded when the soil moisture levels are not too wet or too dry, as Ma et al. (2005) found a

Table 1 Maximum, minimum, mean and standard deviation of latitude, altitude, MAT, MAP, Q_{10}, Rs and SOC in different forests

	Max.	Min.	Mean	Std. Dev.	References
Latitude	60.48	1.50	32.69	14.26	Ma et al. (2019), Kukumägi et al. (2017), Nakano et al. (2004), Cindy et al. (2018), Xu et al. (2017), Kumar et al. (2023), Yang et al. (2022), Tomar and Baishya (2020), Jeong et al. (2018), Lim et al. (2012), Hu et al. (2001), Ma et al. (2005), Arroyo and Wood (2020), Liu et al. (2020), Chen et al. (2014), Schedlbauer and Miller (2022), Wangluk et al. (2013), Verchot et al. (2020), Ito et al. (2007), Inoue et al. (2012), Yang et al. (2023), Hu et al. (2016), Hergoualc'h et al. (2017), Noh et al. (2016), Aini et al. (2020), Wei et al. (2015), Huang et al. (2017), Zhuang et al. (2023), Han and Jin (2018), Mielke et al. (2022), Yan et al. (2015), Zhao and Shi (2022), Jevon et al. (2023), Devi and Lepcha (2023), Kaushal et al. (2023), Pacaldo and Aydin (2023), Zhao et al. (2022), Makhnykina et al. (2020), Ivanov et al. (2018), Ivanov and Momot (2016), Ivanov et al. (2022), Jia et al. (2013), Pandey et al. (2023), Han et al. (2023), Xu and Qi (2001), Hirano et al. (2003), Wangdi et al. (2017), Doff Sotta et al. (2004), Liu et al. (2019), Luan et al. (2013), Yu et al. (2021), Wang et al. (2006), Tan et al. (2013) and Wang et al. (2013)
Altitude (m asl)	3574	66.00	1099	882.06	Ma et al. (2019), Cindy et al. (2018), Xu et al. (2017), Kumar et al. (2023), Yang et al. (2022), Jeong et al. (2018), Ma et al. (2005), Arroyo and Wood (2020), Liu et al. (2020), Chen et al. (2014), Wangluk et al. (2013), Verchot et al. (2020), Ito et al. (2007), Inoue et al. (2012), Huang et al. (2017), Han and Jin (2018), Mielke et al. (2022), Zhao and Shi (2022), Jevon et al. (2023), Devi and Lepcha (2023), Kaushal et al. (2023), Pacaldo and Aydin (2023), Zhao et al. (2022), Jia et al. (2013), Pandey et al. (2023), Han et al. (2023), Xu and Qi (2001), Hirano et al. (2003), Wangdi et al. (2017), Liu et al. (2019) and Luan et al. (2013)
MAT (°C)	28.05	–0.30	12.21	6.40	Ma et al. (2019), Kukumägi et al. (2017), Cindy et al. (2018), Xu et al. (2017), Kumar et al. (2023), Tomar and Baishya (2020), Jeong et al. (2018), Lim et al. (2012), Hu et al. (2001), Ma et al. (2005), Arroyo and Wood (2020), Liu et al. (2020), Chen et al. (2014), Schedlbauer and Miller (2022), Wangluk et al. (2013), Verchot et al. (2020), Inoue et al. (2012), Hu et al. (2016), Hergoualc'h et al. (2017), Noh et al. (2016), Aini et al. (2020), Wei et al. (2015), Huang et al. (2017), Zhuang et al. (2023), Han and Jin (2018), Mielke et al. (2022), Yan et al. (2015), Zhao and Shi (2022), Jevon et al. (2023), Devi and Lepcha (2023), Kaushal et al. (2023), Zhao et al. (2022), Ivanov et al. (2018), Ivanov and Momot (2016), Ivanov et al. (2022), Jia et al. (2013), Pandey et al. (2023), Han et al. (2023), Xu and Qi (2001), Wangdi et al. (2017), Doff Sotta et al. (2004), Liu et al. (2019), Luan et al. (2013), Yu et al. (2021), Wang et al. (2006), Tan et al. (2013) and Wang et al. (2013)
MAP (mm)	2867	83.00	1303	702.48	Ma et al. (2019), Kukumägi et al. (2017), Nakano et al. (2004), Cindy et al. (2018), Xu et al. (2017), Kumar et al. (2023), Yang et al. (2022), Rodtassana et al. (2021), Tomar and Baishya (2020), Jeong et al. (2018), Lim et al. (2012), Hu et al. (2001), Ma et al. (2005), Arroyo and Wood (2020), Liu et al. (2020), Chen et al. (2014), Schedlbauer and Miller (2022), Wangluk et al. (2013), Verchot et al. (2020), Inoue et al. (2012), Hu et al. (2016), Hergoualc'h et al. (2017), Noh et al. (2016), Aini et al. (2020), Wei et al. (2015), Huang et al. (2017), Zhuang et al. (2023), Han and Jin (2018), Mielke et al. (2022), Yan et al. (2015), Zhao and Shi (2022), Jevon et al. (2023), Devi and Lepcha (2023), Kaushal et al. (2023), Zhao et al. (2022), Makhnykina et al. (2020), Ivanov et al. (2018), Ivanov and Momot (2016), Pandey et al. (2023), Han et al. (2023), Xu and Qi (2001), Ivanov et al. (2022), Jia et al. (2013), Hirano et al. (2003), Wangdi et al. (2017), Doff Sotta et al. (2004), Liu et al. (2019), Luan et al. (2013), Yu et al. (2021), Wang et al. (2006), Tan et al. (2013) and Wang et al. (2013)
Q_{10}	6.70	0.70	3.17	1.40	Ma et al. (2019), Kukumägi et al. (2017), Cindy et al. (2018), Xu et al. (2017), Yang et al. (2022), Lim et al. (2012), Hu et al. (2001), Liu et al. (2020), Chen et al. (2014), Schedlbauer and Miller (2022), Yang et al. (2023), Jia et al. (2013), Wangluk et al. (2013), Verchot et al. (2020), Ito et al. (2007), Inoue et al. (2012), Yang et al. (2023), Hu et al. (2016), Noh et al. (2016), Zhuang et al. (2023), Han and Jin (2018), Yan et al. (2015), Zhao and Shi (2022), Makhnykina et al. (2020), Ivanov et al. (2018), Han et al. (2023), Xu and Qi (2001), Wangdi et al. (2017), Liu et al. (2019), Luan et al. (2013), Tan et al. (2013) and Wang et al. (2013)

Table 1 Continued

	Max.	Min.	Mean	Std. Dev.	References
Rs (mg $m^{-2}hr^{1}$)	760.00	41.47	217.57	179.18	Ma et al. (2019), Kukumägi et al. (2017), Nakano et al. (2004), Cindy et al. (2018), Xu et al. (2017), Kumar et al. (2023), Yang et al. (2022), Tomar and Baishya (2020), Jeong et al. (2018), Lim et al. (2012), Hu et al. (2001), Ma et al. (2005), Arroyo and Wood (2020), Liu et al. (2020), Chen et al. (2014), Wangluk et al. (2013), Verchot et al. (2020), Inoue et al. (2012), Yang et al. (2023), Hu et al. (2016), Hergoulch et al. (2017), Noh et al. (2016), Aini et al. (2020), Wei et al. (2015), Huang et al. (2017), Zhuang et al. (2023), Han and Jin (2018), Mielke et al. (2022), Zhao and Shi (2022), Jevon et al. (2023), Devi and Lepcha (2023), Kaushal et al. (2023), Pacaldo and Aydin (2023), Zhao et al. (2022), Makhnykina et al. (2020), Ivanov et al. (2018), Ivanov and Momot (2016), Pandey et al. (2023), Xu and Qi (2001), Hirano et al. (2003), Wangdi et al. (2017), Doff Sotta et al. (2004), Liu et al. (2019), Luan et al. (2013), Yu et al. (2021), Wang et al. (2006), Tan et al. (2013) and Wang et al. (2013)
SOC (%)	29.70	0.40	6.89	7.68	Xu et al. (2018), Kumar et al. (2023), Hu et al. (2001), Arroyo and Wood (2020), Chen et al. (2014), Wangluk et al. (2013), Verchot et al. (2020), Aini et al. (2020), Huang et al. (2017), Zhao and Shi (2022), Devi and Lepcha (2023), Makhnykina et al. (2020), Pandey et al. (2023), Han et al. (2023), Liu et al. (2019), Luan et al. (2013), Tan et al. (2013) and Wang et al. (2013)

MAP: mean annual precipitation; MAT: mean annual temperature; Rs: soil respiration; SOC: soil organic carbon.

Table 2 Pearson's coefficient of correlation (r) of Q_{10} and Rs with different variables in different forests

	Q_{10}	Latitude	Altitude	MAT	MAP	SOC	Rs
Q_{10}	-	0.53[a]	0.38	–0.60[a]	–0.40[a]	0.23	–0.20
Rs	–0.20	–0.12	–0.21	0.03	0.20	0.47[a]	-

MAP: mean annual precipitation; MAT: mean annual temperature; Rs: soil respiration; SOC: soil organic carbon.
[a]Indicates significance at $p < 0.05$.

positive correlation between Rs and soil moisture when water content ranged from 20%–40%. Very high soil moisture content resulting from high MAP leads to reduction in soil oxygen concentrations due to physical barrier created, thereby reducing microbial response (Arroyo and Wood 2020), and very low soil moisture level leads to reduction of microbial activities. The results indicated that positive response of Rs to increase in temperature and intermediate soil moisture level is more pronounced in studies conducted at smaller geographical locations, which have lesser variation in plant species composition and soil nutrients. However, when studies on different types of forests are taken from a wider latitudinal gradient the dependence of Rs to MAT and MAP is reduced. The correlation of Rs with altitude was positive but insignificant showing an uncertainty in their relationship when considered for a wide scale study. The large-scale difference in the type of tree species, microbial activities and physico-chemical properties of the soil at a wider latitudinal gradient resulted in variation of Rs, which does not respond to the corresponding MAT and MAP.

Significant correlation of Rs was observed with SOC having Pearson's coefficient of correlation r = 0.47 ($p < 0.05$) (Table 2, Fig. 1). Significant positive correlation of Rs with SOC was reported in many studies (Liu et al. 2020; Rodtassana et al. 2021; Vanhala et al. 2008; Zhang et al. 2021). The maximum record of SOC with 29.7% was reported from a primary forest in Eastern Tibetan Plateau in China situated at latitude of 36.54° (Chen et al. 2014) and minimum was recorded from Puerto Rico with 0.4% at latitude of 18.24° (Arroyo and Wood 2020). However, SOC does not correlate significantly with latitude (r = 0.08, $p < 0.8$) indicating the distribution of SOC along different forests does not linearly follow the latitudinal gradient. As Rs also does not significantly correlate with latitude, the relationship of SOC with Rs in forests depends upon the optimum amount of soil moisture level and active soil organic pools at smaller geographical locations. The results also indicates that the composition of tree species in the different types of forests is an important factor in storing SOC as

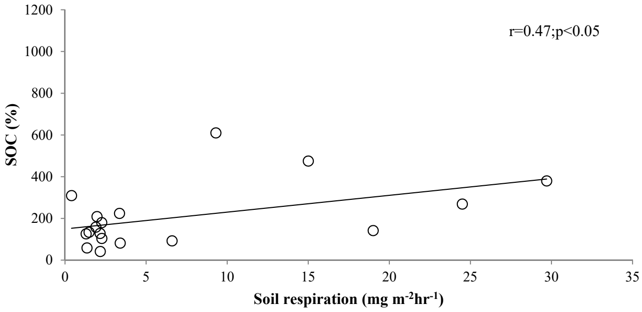

Fig. 1 Correlation of Rs with SOC in different types of forests. Rs: soil respiration; SOC: soil organic carbon.

mixed forest stands store more SOC than pure stands (Devi 2021).

Q_{10} largely determines the feedback mechanism between global warming and cycling of carbon (Pokharel et al. 2018). Therefore, change in Q_{10} along with their influencing factor is an important factor in simulating and predict key parameters of carbon cycles, leading to clarification of the relationship between Rs and its Q_{10} (Yang et al. 2022). Among the data collected for Q_{10}, 55% were recorded from temperate forest, 30% from tropical + subtropical and 15% from boreal forest. In the tropical + subtropical forest Q_{10} varied from 0.7 to 5.13 (mean = 2.21 ± 0.93) (Table 3). In temperate forest it ranged from 1.71 to 6.7 (mean = 3.33 ± 0.88) and in boreal forest it ranged from 3.5 to 6.7 (mean = 4.81 ± 1.12). Maximum Q_{10} was reported from the Tibetan plateau with 6.7 situated at latitude of 36.54° and a recorded MAT of 12.6°C (Chen et al. 2014) from temperate forest and, the same maximum value was also reported from a boreal forest from Northeast China situated at latitude of 50.5° and MAT of –2.9°C (Yang et al. 2023). A minimum Q_{10} of 0.7 was recorded from Malaysia situated at latitude of 2.59° and MAT of 27°C (Cindy et al. 2018) from tropical forest. A one-way ANOVA of the Q_{10} values in the three different types of forests reveal a significant variation at $p < 0.001$. The correlation between Q_{10} and latitude was recorded to be significant with r = 0.53 ($p < 0.05$) (Fig. 2) indicating a higher value of Q_{10} in forest situated at higher latitudes. Similar trend was also reported by Zheng et al. (2009) and Schedlbauer and Miller (2022).

No significant correlation of Q_{10} with altitude was recorded with r = 0.38 ($p < 0.08$). However, the correlation of Q_{10} with MAT and MAP was significant and negative with r = –0.60, ($p < 0.05$) (Fig. 3) and r = –0.40, ($p < 0.05$) (Fig. 4) respectively. The results indicates that response of Q_{10} of forests to increase in latitude is closely related with the decrease in MAT and MAP in the forests along the latitudinal gradient. However, Q_{10} was not correlated significantly with SOC (r = 0.23, $p < 0.08$). As SOC does not correlate with latitude, Q_{10} is not simulated by SOC. The negative response of Q_{10} to MAP and MAT along the latitudinal gradient can be related to microbial activities as more mi-

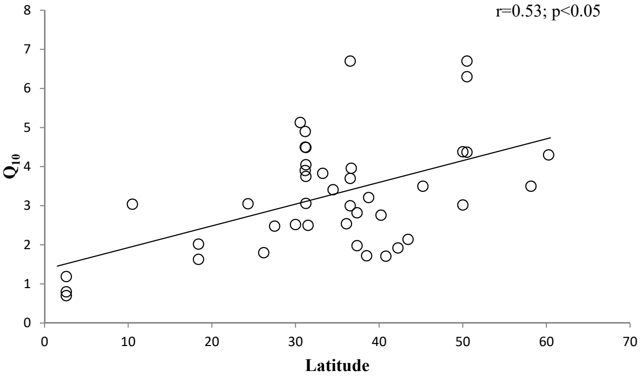

Fig. 2 Correlation of Q_{10} with latitude in different types of forests.

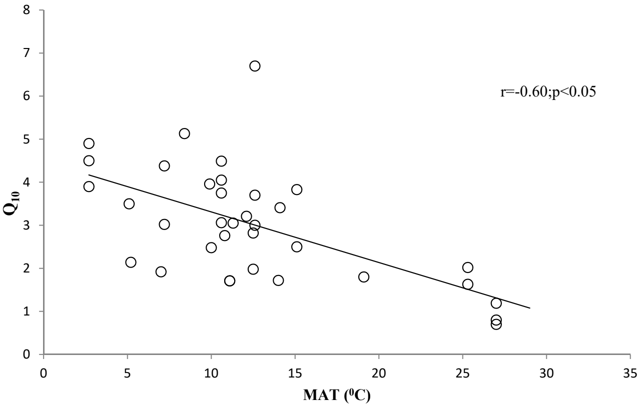

Fig. 3 Correlation of Q_{10} with MAT in different types of forests. MAT: mean annual temperature.

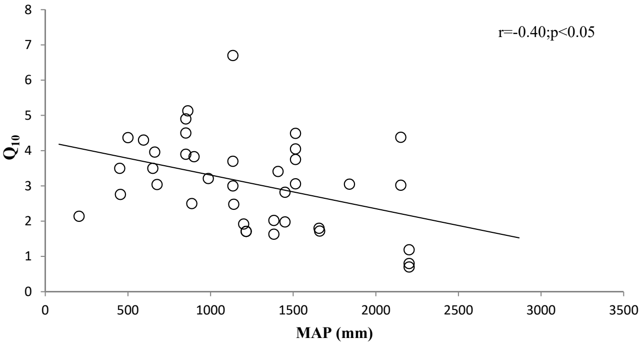

Fig. 4 Correlation of Q_{10} with MAP in different types of forests. MAP: mean annual precipitation.

Table 3 Maximum, minimum, mean and standard deviation for Q_{10} in the three different forests

	Q_{10}				
	Max.	Min.	Mean	Std. Dev.	References
Tropical +Subtropical	5.13	0.7	2.21	0.93	Cindy et al. (2018), Yang et al. (2022), Wangluk et al. (2013), Hu et al. (2016), Han and Jin (2018), Wangdi et al. (2016), Liu et al. (2019) and Tan et al. (2013)
Temperate	6.7	1.71	3.33	0.88	Ma et al. (2019), Lim et al. (2012), Hu et al. (2001), Liu et al. (2020), Chen et al. (2014), Schedlbauer and Miller (2022), Ito et al. (2007), Noh et al. (2016), Zhuang et al. (2023), Han and Jin (2018), Yan et al. (2015), Zhao and Shi (2022), Han et al. (2023), Xu and Qi (2001), Jia et al. (2013), Hirano et al. (2003), Wangdi et al. (2017), Luan et al. (2013) and Wang et al. (2013)
Boreal	6.7	3.5	4.81	1.12	Kukumägi et al. (2017), Yang et al. (2022), Inoue et al. (2012), Yang et al. (2023) and Makhnykina et al. (2020)

crobial activities occurs in hot and wet soil conditions. More microbial activities associated with mixed types of tree species leads to storage of more labile organic C in wetter forests in lower latitudes. The segment of SOC that increase Rs is mainly the labile organic C (Karhu et al. 2014).

The value of Q_{10} does not depend upon the quantity of SOC but on level of degradability of SOC. Soils with large proportion of SOC resistant to degradation are more sensitive to rise in temperature than soils with large proportions of easily degradable SOC (Meyer et al. 2018). The tropical and boreal forests store the most C, however, there is a difference in their carbon structures. Tropical forests have 56% of C stored in biomass and 32% in soil, whereas boreal forest have only 20% in biomass and 60% in soil (Pan et al. 2011). The boreal forest litter tends to be composed of phenol, chitin, lignin and waxes which contributes to more amount of recalcitrant organic C in soil when compared to tropical soils (Nilsson et al. 2008; Wangluk et al. 2013). The recalcitrant organic matter is associated with ectomycorrhizal fungi which have more C per unit of N than in soil dominated by arbuscular mycorrhizal fungi. Majority of N is locked in various organic forms and are protected from decomposition (Schmidt et al. 2011) leading to more SOC accumulation in the boreal soils. The higher sensitivity of forests at higher latitudes to increase in temperature cannot be solely responsible by the recalcitrant C but it is also indirectly associated with the simulated response of the microbial population and ectomycorrhizal fungi which may lead to loss of more carbon in future. At the same time the process of loss of carbon due to global warming from forests at lower latitudes cannot be overruled by the higher Q_{10} of forests at higher latitudes.

Conclusions

The present review reveals that simulating effect of MAT and MAP to Rs in forest ecosystems is more pronounced when studies are undertaken at smaller geographical locations where variations in SOC, soil nutrients and plant species composition is low. When, comparative studies on forests situated at greater latitudinal variations are undertaken, the role of MAT and MAP on Rs declined. Whereas, reverse response happened in Q_{10} as it rises with increase in latitude along with the associated decrease in MAT and MAP. SOC does not correlate significantly with Q_{10} indicating the quality of SOC, not the quantity of SOC is an important component in estimating sensitivity of Rs to increase in temperature in different forests. The recalcitrant carbon and the associated microbial population, along with ectomycorrhizal fungi are indirectly responsible for the simulated response of Q_{10} to rise in temperature in forests occurring at higher latitudes. The results do not indicate that response of forests lying at lower latitudes to climate change should not be taken care of. The limitations of the present review work are, only the average data of Rs and Q_{10} collected from soil depth of 0–30 cm was considered. Studies on measurements of Rs, its temperature sensitivity at seasonal scale for different soil depths and the role of biophysical factors for different kinds of forests is highly recommended.

Abbreviations

MAP: Mean annual precipitation
MAT: Mean annual temperature
Rs: Soil respiration
SOC: Soil organic carbon

Authors' contributions

The corresponding author has done the main part of collecting data and writing and the remaining authors help in writing and typing the manuscript.

Funding
None.

Availability of data and materials

Not applicable.

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

References

Aini FK, Hergoualc'h K, Smith JU, Verchot L, Martius C. How does replacing natural forests with rubber and oil palm plantation affect soil respiration and methane fluxes? Agroecosys. 2020;11(11):e03284. https://doi.org/10.1002/ecs2.3284.

Arroyo OG, Wood TE. Large seasonal variation of soil respiration in a secondary tropical moist forest in Puerto Rico. Ecol Evol. 2020; 11(1):263-72. https://doi.org/10.1002/ece3.7021.

Bååth E, Wallander H. Soil and rhizosphere microorganisms have the same Q_{10} for respiration in a model system. Glob Change Biol. 2003;9(12):1788-91. http://doi.org/10.1046/j.1365-2486.2003.00692.x.

Chen Y, Luo J, Li W, Yu D, She J. Comparison of soil respiration among three different subalpine ecosystems on eastern Tibetan Plateau, China. Soil Sci Plant Nutr. 2014;60(2):231-41. https://doi.org/10.1080/00380768.2013.873991.

Cindy US, Hazandy AH, Ahmed-Ainuddin N, Mohd-Kamil I. Soil CO_2

efflux in relation to soil temperature and relative humidity in Gmelina, Mahogany and pine stands in Malaysia. J Trop For Sci. 2018; 30(2):207-15.

Cusak DF, Dietterich LH, Sulman BN. Soil respiration responses to throughfall exclusion are decoupled from changes in soil moisture for four tropical forests, suggesting processes for ecosystem models. Global Biogeochem Cycles. 2023;37(4):e2022GB007473. https://doi.org/10.1029/2022GB007473.

Devi AS. Influence of trees and associated variables on soil organic carbon: a review. J Ecology Environ. 2021;45(5). https://doi.org/10.1186/s41610-021-00180-3.

Devi NB, Lepcha NT. Carbon sink and source function of Eastern Himalayan forests: implications of change in climate and biotic variables. Environ Monit Assess. 2023;195(7):843. https://doi.org/10.1007/s10661-023-11460-x.

Ding F, Sun W, Huang Y, Hu X. Larger Q_{10} of carbon decomposition in finer soil particles does not bring long-lasting dependence of Q_{10} on soil texture. Eur J Soil Sci. 2018;69(2):336-47. https://doi.org/10.1111/ejss.12530.

Doff Sotta E, Meir P, Malhi Y, Nobre AD, Hodnett M, Grace J. Soil CO_2 efflux in a tropical forest in the central Amazon. Glob Change Biol. 2004;10(5):601-17. https://doi.org/10.1111/j.1529-8817.2003.00761.x.

Gallo AC, Holub SM, Littke K, Lajtha K, Maguire D, Hatten JA. Short-term effects of organic matter and compaction manipulations on soil temperature, moisture, and soil respiration for 2 years in the Oregon Cascades. Soil Sci Soc Am J. 2023;87(1):156-71. https://doi.org/10.1002/saj2.20485.

Han M, Jin G. Seasonal variations of Q_{10} soil respiration and its components in the temperate forest ecosystems, northeastern China. Eur J Soil Biol. 2018;85:36-42. https://doi.org/10.1016/j.ejsobi.2018.01.001.

Han Y, Wang G, Zhou S, Li W, Xiong L. Day-night discrepancy in soil respiration varies with seasons in a temperate forest. Funct Ecol. 2023;37(7):2002-13. https://doi.org/10.1111/1365-2435.14358.

Hergoualc'h K, Hendry DT, Murdiyarso D, Verchot LV. Total and heterotrophic soil respiration in a swamp forest and oil palm plantations on peat in Central Kalimantan, Indonesia. Biogeochemistry. 2017;135:203-20. https://doi.org/10.1007/s10533-017-0363-4.

Hirano T, Kim H, Tanaka Y. Long-term half-hourly measurement of soil CO_2 concentration and soil respiration in a temperate deciduous forest. J Geophys Res Atmos. 2003;108(D20). https://doi.org/10.1029/2003JD003766.

Hu R, Kusa K, Hatano R. Soil respiration and methane flux in adjacent forest, grassland, and cornfields soils in Hokkaido, Japan. Soil Sci Plant Nutr. 2001;47(3):621-7. https://doi.org/10.1080/00380768.2001.10408425.

Hu Z, Liu S, Liu X, Fu L, Wang J, Liu K, et al. Soil respiration and its environmental response varies by day/night and by growing/dormant season in a subalpine forest. Sci Rep. 2016;6:37864. https://doi.org/10.1038/srep37864.

Huang YH, Hung CY, Lin IR, Kume T, Menyailo OV, Cheng CH. Soil respiration patterns and rates at three Taiwanese forest plantations: dependence on elevation, temperature, precipitation, and litterfall. Bot Stud. 2017;58(1):49. https://doi.org/10.1186/s40529-017-0205-7. Erratum in: Bot Stud. 2017;58(1):60. https://doi.org/10.1186/s40529-017-0215-5.

Inoue T, Nagai S, Inoue S, Ozaki M, Sakai S, Muraoka H, et al. Seasonal variability of soil respiration in multiple ecosystems under the same physical-geographical environmental conditions in central Japan. Forest Sci Technol. 2012;8(5):52-60. https://doi.org/10.1080/21580103.2012.672012.

Ito A, Inatomi M, Mo W, Lee M, Koizumi H, Saigusa N, et al. Examination of model-estimated ecosystem respiration using flux measurements from a cool-temperate deciduous broad-leaved forest in central Japan. Tellus B: Chem Phys Meteorol. 2007;59(3):616-24. https://doi.org/10.1111/j.1600-0889.2007.00258.x.

Ivanov AV, Braun M, Tataurov VA. Seasonal and daily dynamics of the CO_2 emission from soils of *Pinus koraiensis* forests in the South of the Sikhote-Alin Range. Eurasian Soil Sci. 2018;51:290-5. https://doi.org/10.1134/S1064229318030043.

Ivanov AV, Momot AA. Carbon emission from the soil surface of floodplain forests in the south of PrimorskyKrai. Vestn Povolzh Gos Tekhnol Univ Ser Les Ekol Prirodopol'zovanie. 2016;1:69-78.

Ivanov AV, Salo MA, Tolstikova VY, Bryanin SV, Zamolodchikov DG. Effects of windfall on soil surface carbon emission and fine root stocks in the central Sikhote-Alin. Eurasian Soil Sci. 2022;55:1405-13. https://doi.org/10.1134/S1064229322100052.

Jeong SH, Eom JY, Park JY, Lee JH, Lee JS. Characteristics of accumulated soil carbon and soil respiration in temperate deciduous forest and alpine pastureland. J Ecology Environ. 2018;42(1):1-10. https://doi.org/10.1186/s41610-018-0063-6.

Jevon FV, Gewirtzman JG, Lang AK, Ayres MP, Matthes JH. Tree species effects on soil CO_2 and CH_4 fluxes in a mixed temperate forest. Ecosystems. 2023;26:1587-602. https://doi.org/10.1007/s10021-023-00852-2.

Jia X, Zha T, Wu B, Zhang Y, Chen W, Wang X, et al. Temperature response of soil respiration in a Chinese pine plantation: hysteresis and seasonal vs. diel Q10. PLoS One. 2013;8(2):e57858. https://doi.org/10.1371/journal.pone.0057858.

Jung SH, Kwon DJ, Park CW, Kim SD. Appropriate sampling points and frequency of CO_2 measurements for soil respiration analysis in a pine (*Pinus densiflora*) forest. Anim Cells Syst. 2015;19(5):332-8. https://doi.org/10.1080/19768354.2015.1069209.

Karhu K, Auffret MD, Dungait JAJ, Hopkins DW, Prosser JI, Singh B, et al. Temperature sensitivity of soil respiration rates enhanced by microbial community response. Nature. 2014;513(7516):81-4. https://doi.org/10.1038/nature13604.

Kaushal S, Rao KS, Uniyal PL, Baishya R. Patterns and determinants of soil CO_2 efflux in major forest types of central Himalayas, India. Environ Monit Assess. 2023;195(7):876. https://doi.org/10.1007/s10661-023-11470-9.

Kukumägi M, Ostonen I, Uri V, Helmisaari HS, Kanal A, Kull O, et al. Variation of soil respiration and its components in hemiboreal Norway spruce stands of different ages. Plant Soil. 2017;414:265-80. https://doi.org/10.1007/s11104-016-3133-5.

Kumar S, Kumar M, Verma AK, Joshi RK, Hansda P, Geise A, et al. Seasonal dynamics of soil and microbial respiration in the banj oak and chir pine forest of the central Himalaya, India. Appl Soil Ecol. 2023;182:104740. https://doi.org/10.1016/j.apsoil.2022.104740.

Lefèvre R, Barré P, Moyano FE, Christensen BT, Bardoux G, Eglin T, et al. Higher temperature sensitivity for stable than for labile soil organic carbon--evidence from incubations of long-term bare fallow soils. Glob Chang Biol. 2014;20(2):633-40. https://doi.org/10.1111/gcb.12402.

Lim H, Choi WJ, Ahn K, Lee KH. Ecosystem respiration and tree growth influenced by thinning in a red pine forest in southern Korea. Forest Sci Technol. 2012;8(4):192-204. https://doi.org/10.1080/21580103.2012.704977.

Liu S, Luo D, Cheng R, Yang H, Wu J, Shi Z. Soil-atmospheric exchange of greenhouse gases from typical subalpine forests on the eastern Oinghai-Tibetan Plateau: effects of forest regeneration patterns. Land Degrad Dev. 2020;31:2019-32. https://doi.org/10.1002/ldr.3586.

Liu X, Chen S, Yang Z, Lin C, Xiong D, Lin W, et al. Will heterotrophic soil respiration be more sensitive to warming than autotrophic respiration in subtropical forests? Eur J Soil Sci. 2019;70(3):655-63. https://doi.org/10.1111/ejss.12758.

Luan J, Liu S, Wang J, Zhu X. Factors affecting spatial variation of annual apparent Q_{10} of soil respiration in two warm temperate forests. PLoS One. 2013;8(5):e64167. https://doi.org/10.1371/journal.pone.0064167.

Ma M, Zang Z, Xie Z, Chen Q, Xu W, Zhao C, et al. Soil respiration of four forests along elevation gradient in northern subtropical China. Ecol Evol. 2019;9(22):12846-57. https://doi.org/10.1002/ece3.5762.

Ma S, Chen J, Butnor JR, North M, Euskirchen ES, Oakley B. Biophysical controls soil respiration in the dominant patch types of an old growth, mixed-conifer forest. For Sci. 2005;51(3):221-32. https://doi.org/10.1093/forestscience/51.3.221.

Makhnykina AV, Prokushkin AS, Menyailo OV, Verkhovets SV, Tychkov II, Urban AV, et al. The impact of climatic factors on CO_2 emissions from soils of middle-Taiga forests in Central Siberia: emission as a function of soil temperature and moisture. Russ J Ecol. 2020;51:46-56. https://doi.org/10.1134/S1067413620010063.

McGrath CR, Prices CEH, Nguyen N, Glazer B, Lio S, Crow SE. Minerals limit the deep soil respiration response to warming in a tropical Andisol. Biogeochemistry. 2022;161:85-99. https://doi.org/10.1007/s10533-022-00965-1.

Meyer N, Welp G, Amelung W. The temperature sensitivity (Q10) of soil respiration: controlling factors and spatial prediction at regional scale based on environmental soil classes. Glob Biogeochem Cycles. 2018;32(2):306-26. https://doi.org/10.1002/2017GB005644.

Mielke LA, Ekblad A, Finlay RD, Fransson P, Lindahl BD, Clemmensen KE. Ericaceous dwarf shrubs contribute a significant but drought-sensitive fraction of soil respiration in a boreal pine forest. J Ecol. 2022;110(8):1928-41. https://doi.org/10.1111/1365-2745.13927.

Nakano T, Inoue G, Fukuda M. Methane consumption and soil respiration by a birch forest soil in West Siberia. Tellus B: Chem Phys Meteorol. 2004;56(3):223-9. https://doi.org/10.3402/tellusb.v56i3.16421.

Nilsson MC, Wardle DA, DeLuca TH. Belowground and aboveground consequences of interactions between live plant species mixtures and dead organic substrate mixtures. Oikos. 2008;117(3):439-49. https://doi.org/10.1111/j.2007.0030-1299.16265.x.

Noh NJ, Lee SJ, Jo W, Han S, Yoon TK, Chung H, et al. Effects of experimental warming on soil respiration and biomass in *Quercus variabilis* Blume and *Pinus densiflora* Sieb. et Zucc. seedlings. Ann For Sci. 2016;73:533-45. https://doi.org/10.1007/s13595-016-0547-4.

Nordseth A. 2024. Types of forests: definitions, examples and importance. https://www.treehugger.com/types-of-forests-definitions-examples-5180645. Accessed 7 Aug 2024.

Pacaldo RS, Aydin M. Soil respiration in a natural forest and a plantation during a dry period in the Philippines. J For Res. 2023;34(6):1975-83. https://doi.org/10.1007/s11676-023-01636-z.

Pan Y, Birdsey RA, Fang J, Houghton R, Kauppi PE, Kurz WA, et al. A large and persistent carbon sink in the world's forests. Science. 2011;333(6045):988-93. https://doi.org/10.1126/science.1201609.

Pandey R, Rawat M, Singh R, Bala N. Large scale spatial assessment, modelling and identification of drivers of soil respiration in the Western Himalayan temperate forest. Ecol Indic. 2023;146:109927. https://doi.org/10.1016/j.ecolind.2023.109927.

Pokharel P, Kwak JH, Ok YS, Chang SX. Pine sawdust biochar reduces GHG emission by decreasing microbial and enzyme activities in forest and grassland soils in a laboratory experiment. Sci Total Environ. 2018;625:1247-56. https://doi.org/10.1016/j.scitotenv.2017.12.343.

Rodtassana C, Unawong W, Yaemphum S, Chanthorn W, Chawchai S, Nathalang A, et al. Different responses of soil respiration to environmental factors across forest stages in a Southeast Asian forest. Ecol Evol. 2021;11(21):15430-43. https://doi.org/10.1002/ece3.8248.

Schedlbauer JL, Miller J. Edge effects increase soil respiration without altering soil carbon stocks in temperate broadleaf forests. Ecosphere. 2022;13(6):e4092. https://doi.org/10.1002/ecs2.4092.

Schmidt MW, Torn MS, Abiven S, Dittmar T, Guggenberger G, Janssens IA, et al. Persistence of soil organic matter as an ecosystem property. Nature. 2011;478(7367):49-56. https://doi.org/10.1038/nature10386.

Tan ZH, Zhang YP, Liang N, Song QH, Liu YH, You GY, et al. Soil respiration in an old-growth subtropical forest: patterns, components, and controls. J Geophys Res Atmos. 2013;118(7):2981-90. https://doi.org/10.1002/jgrd.50300.

Tomar V, Baishya R. Seasonality and moisture regime control soil respiration, enzyme activities, and soil microbial biomass carbon in a semi-arid forest of Delhi, India. Ecol Process. 2020;9:50. https://doi.org/10.1186/s13717-020-00252-7.

Vanhala P, Karhu K, Tuomi M, Björklöf K, Fritze H, Liski J. Temperature sensitivity of soil organic matter decomposition in southern and northern areas of the boreal forest zone. Soil Biol Biochem. 2008;40(7):1758-64. https://doi.org/10.1016/j.soilbio.2008.02.021.

Verchot LV, Dannenmann M, Kengdo SK, Njine-Bememba CB, Rufino MC, Sonwa DJ, et al. Land-use change and biogeochemical controls of soil CO_2, N_2O and CH_4 fluxes in Cameroonian forest landscapes. J Integr Environ Sci. 2020;17(3):45-67. https://doi.org/10.1080/1943815X.2020.1779092.

Wang C, Yang J, Zhang Q. Soil respiration in six temperate forests in China. Glob Change Biol. 2006;12(11):2103-14. https://doi.org/10.1111/j.1365-2486.2006.01234.x.

Wang W, Zeng W, Chen W, Yang Y, Zeng H. Effects of forest age on soil autotrophic and heterotrophic respiration differ between evergreen and deciduous forests. PLoS One. 2013;8(11):e80937. https://doi.org/10.1371/journal.pone.0080937.

Wangdi N, Mayer M, Nirola MP, Zangmo N, Orong K, Ahmed IU, et al. Soil CO_2 efflux from two mountain forests in the eastern Himalayas, Bhutan: components and controls. Biogeosciences. 2017;14(1):99-110. https://doi.org/10.5194/bg-14-99-2017.

Wangluk S, Boonyawat S, Diloksumpum S, Tongdeenok P. Role of soil temperature and moisture on soil respiration in a teak plantation and mixed deciduous forest in Thailand. J Trop For Sci. 2013; 25(3):330-49.

Wei H, Chen X, Xiao G, Guenet B, Vicca S, Shen W. Are variations in heterotrophic soil respiration related to changes in substrate availability and microbial biomass carbon in the subtropical forests? Sci Rep. 2015;5:18370. https://doi.org/10.1038/srep18370.

Xu M, Qi Y. Spatial and seasonal variations of Q_{10} determined by soil respiration measurements at a Sierra Nevadan forest. Glob Biogeochem Cycles. 2001;15(3):687-96. https://doi.org/10.1029/2000GB001365.

Xu Z, Yin H, Zhao C, Xiong P, Liu Q. Responses of soil respiration to warming vary between growing season and non-growing season in a mountain forest of southwestern China. Can J Soil Sci. 2017; 98(1):70-6. https://doi.org/10.1139/cjss-2017-0036.

Yan M, Guo N, Ren H, Zhang X, Zhou G. Autotrophic and heterotrophic respiration of a poplar plantation chronosequence in northwest China. For Ecol Manag. 2015;337:119-25. https://doi.org/10.1016/j.foreco.2014.11.009.

Yang L, Zhang Q, Jin H, Ma Z, Jin X, Marchenko SS, et al. CO_2 and CH_4 fluxes from forest soil in the northern Da Xing'anling Mountains in Northeast China during the freezing and thawing periods of near-surface soil in 2018–2019. Scan J For Res. 2023;38(4):275-85. https://doi.org/10.1080/02827581.2023.2208874.

Yang L, Zhang Q, Ma Z, Jin H, Chang X, Marchenko SS, et al. Seasonal variations in temperature sensitivity of soil respiration in a larch forest in the Northern Daxing'an Mountains in Northeast China. J For Res. 2022;33:1061-70. https://doi.org/10.1007/s11676-021-01346-4.

Yang Z, Luo X, Shi Y, Zhou T, Luo K, Lai Y, et al. Controls and variability of soil respiration temperature sensitivity across China. Sci Total Environ. 2023;871:161974. https://doi.org/10.1016/j.scitotenv.2023.161974.

Yu JC, Chiang PN, Lai YJ, Tsai MJ, Wang YN. High rainfall inhibited soil respiration in an Asian monsoon forest in Taiwan. Forests. 2021;12(2):239. https://doi.org/10.3390/f12020239.

Zhang Y, Zou J, Dang S, Osborne B, Ren Y, Ju X. Topography modifies the effect of land-use change on soil respiration: a meta-analysis. Ecosphere. 2021;12(12):e03845. https://doi.org/10.1002/ecs2.3845.

Zhao R, He M, Liu F. Differential linkages between soil respiration components and microbial community structures under long-term forest conversion. J Soils Sediments. 2022;22(4):1252-62. https://doi.org/10.1007/s11368-022-03160-9.

Zhao Z, Shi F. Influence of temperature and moisture on autotrophic and heterotrophic respiration in a semi-arid highland elm sparse forest. Eurasian Soil Sc. 2022;55:1384-94. https://doi.org/10.1134/S1064229322100180.

Zheng ZM, Yu GR, Fu YL, Wang YS, Sun XM, Wang YH. Temperature sensitivity of soil respiration is affected by prevailing climatic conditions and soil organic carbon content: a trans-China based case study. Soil Biol Biochem. 2009;41(7):1531-40. https://doi.org/10.1016/j.soilbio.2009.04.013.

Zhuang W, Liu M, Wu Y, Ma J, Zhang Y, Su L, et al. Litter inputs exert greater influence over soil respiration and its temperature sensitivity than roots in a coniferous forest in north-south transition zone. Sci Total Environ. 2023;886:164009. https://doi.org/10.1016/j.scitotenv.2023.164009.