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# Soil Type, Topography, and Land Use Interact to Control the Response of Soil Respiration to Climate Variation

Chun Wang
*Chinese Academy of Sciences*

Xiaoming Lai
*Chinese Academy of Sciences*

Qing Zhu
*Chinese Academy of Sciences*

Michael J. Castellano
*Iowa State University*, castelmj@iastate.edu

Guishan Yang
*Chinese Academy of Sciences*

# Soil Type, Topography, and Land Use Interact to Control the Response of Soil Respiration to Climate Variation


## Abstract

The effects of soil and topography on the responses of soil respiration ($R_S$) to climatic variables must be investigated in the southeastern mountainous areas of China due to the rapid land-use change from forest to agriculture. In this study, we investigated the response of $R_S$ to soil temperature (ST), precipitation over the previous seven days (AP7), and soil water content (SWC) across two hillslopes that had different land uses: a tea garden (TG) and a bamboo forest (BF). Meanwhile, the roles of soil properties including soil clay content and total nitrogen (TN), and topography including elevation, profile curvature (PRC), and slope on the different responses of $R_S$ to these climatic variables were investigated. Results showed that mean $R_S$ on the BF hillslope (2.21 umol C $m^{-2}$ $s^{-1}$) was 1.71 times of that on the TG hillslope (1.29 umol C $m^{-2}$ $s^{-1}$). Soil clay content, elevation, and PRC had negative correlations ($p < 0.05$) with spatial variation of $R_S$, and ST was positively correlated ($p < 0.01$) with temporal variation of $R_S$ on both hillslopes. Across both hillslopes ST explained 33%–73% and AP7 explained 24%–38% of the temporal variations in $R_S$. The mean temperature sensitivities ($Q_{10s}$) of $R_S$ were 2.02 and 3.22, respectively, on the TG and BF hillslopes. The $Q_{10}$ was positively correlated ($p < 0.05$) with the temporal mean of SWC and TN, and negatively correlated ($p < 0.05$) with clay and slope. The mean AP7 sensitivities (a concept similar to $Q_{10}$) were greatly affected by clay and PRC. When $R_S$ was normalized to that at 10 °C, power or quadratic relationships between $R_S$ and SWC were observed in different sites, and the SWC explained 12%–32% of the temporal variation in $R_S$. When ST and SWC were integrated and considered, improved explanations (45%–81%) were achieved for the $R_S$ temporal variation. In addition, clay and elevation had vital influences on the responses of $R_S$ to SWC. These results highlight the influences of soil, topographic features, and land use on the spatial variations of the $R_S$, as well as on the responses of $R_S$ to different climatic variables, which will supplement the understanding of controlling mechanisms of $R_S$ on tea and bamboo land-use types in Southeastern China.



## Keywords

greenhouse gas, mountainous area, soil respiration, Southeastern China

## Disciplines

Agriculture | Climate | Forest Sciences | Soil Science

## Comments

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# Soil Type, Topography, and Land Use Interact to Control the Response of Soil Respiration to Climate Variation

**Chun Wang [1,2], Xiaoming Lai [1,2,*], Qing Zhu [1,2], Michael J. Castellano [3] and Guishan Yang [1,2]**

[1] Key Laboratory of Watershed Geographic Sciences, Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences, 73 East Beijing Road, Nanjing 210008, China; springnju@aliyun.com (C.W.); qzhu@niglas.ac.cn (Q.Z.); gsyang@niglas.ac.cn (G.Y.)

[2] University of Chinese Academy of Sciences, Beijing 100049, China

[3] Department of Agronomy, Iowa State University of Science and Technology, Ames, Iowa 50011, USA; castelmj@iastate.edu (M.J.C.)

* Correspondence: xmlai@niglas.ac.cn; Tel.: +86-25-8688-2134

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**Abstract:** The effects of soil and topography on the responses of soil respiration ($R_s$) to climatic variables must be investigated in the southeastern mountainous areas of China due to the rapid land-use change from forest to agriculture. In this study, we investigated the response of $R_s$ to soil temperature (ST), precipitation over the previous seven days (AP7), and soil water content (SWC) across two hillslopes that had different land uses: a tea garden (TG) and a bamboo forest (BF). Meanwhile, the roles of soil properties including soil clay content and total nitrogen (TN), and topography including elevation, profile curvature (PRC), and slope on the different responses of $R_s$ to these climatic variables were investigated. Results showed that mean $R_s$ on the BF hillslope (2.21 umol C $m^{-2}$ $s^{-1}$) was 1.71 times of that on the TG hillslope (1.29 umol C $m^{-2}$ $s^{-1}$). Soil clay content, elevation, and PRC had negative correlations ($p < 0.05$) with spatial variation of $R_s$, and ST was positively correlated ($p < 0.01$) with temporal variation of $R_s$ on both hillslopes. Across both hillslopes ST explained 33%–73% and AP7 explained 24%–38% of the temporal variations in $R_s$. The mean temperature sensitivities ($Q_{10s}$) of $R_s$ were 2.02 and 3.22, respectively, on the TG and BF hillslopes. The $Q_{10}$ was positively correlated ($p < 0.05$) with the temporal mean of SWC and TN, and negatively correlated ($p < 0.05$) with clay and slope. The mean AP7 sensitivities (a concept similar to $Q_{10}$) were greatly affected by clay and PRC. When $R_s$ was normalized to that at 10 °C, power or quadratic relationships between $R_s$ and SWC were observed in different sites, and the SWC explained 12%–32% of the temporal variation in $R_s$. When ST and SWC were integrated and considered, improved explanations (45%–81%) were achieved for the $R_s$ temporal variation. In addition, clay and elevation had vital influences on the responses of $R_s$ to SWC. These results highlight the influences of soil, topographic features, and land use on the spatial variations of the $R_s$, as well as on the responses of $R_s$ to different climatic variables, which will supplement the understanding of controlling mechanisms of $R_s$ on tea and bamboo land-use types in Southeastern China.

**Keywords:** greenhouse gas; mountainous area; soil respiration; Southeastern China

## 1. Introduction

The carbon dioxide ($CO_2$) released from soil respiration ($R_s$) is the second largest carbon flux in the terrestrial carbon cycle, only surpassed by $CO_2$ uptake through photosynthesis [1,2]. Hence, small changes in $R_s$ rate may induce large changes in atmospheric $CO_2$ concentration [1]. Temporal and spatial variations of $R_s$ are determined by the interactions of multiple environmental variables, including soil temperature (ST), precipitation, soil water content (SWC), vegetation cover, topography, and soil texture, etc. [3–6]. Therefore, to accurately predict the future changes in atmospheric $CO_2$ concentration, we must understand the response of $R_s$ to environmental variables including potential feedbacks with future changes in climate and land use.

Responses of $R_s$ to climatic variables including the ST, precipitation, and SWC and their interactions have been well documented in previous studies using field measurements, incubation experiments, model simulations, and a meta-analysis [3,7–9]. In general, the decomposition rate of soil organic matter—which accounts for ~50% of $R_s$—increases exponentially with ST [3,7,10]. However, high ST is often associated with low SWC. Liu et al. [11] found that at extremely high ST (e.g., >28 °C), $R_s$ declined due to insufficient SWC. Carey et al. [12] reported a universal decline in the temperature sensitivity ($Q_{10}$) of $R_s$ with ST > 25 °C, and this result may be due to low SWC at high ST. Precipitation influences $R_s$ through two related mechanisms: one is stimulating the exchanges of substrates and gases in soil pores by rain dripping; the other is improving the connectivity of substrates through increasing SWC [11,13]. Generally, increased precipitation has a positive effect on $R_s$ [8,13,14]. However, in regions with high precipitation inputs or soils with low water-holding capacity, increased precipitation can reduce the $R_s$ because $R_s$ declines at SWC exceeding field capacity due to slow diffusion of $O_2$ [11,15,16]. In contrast, in dry conditions, water in soil pores is disconnected, and dissolved organic C supply limits the metabolic activity of microbial communities [4,17]. Therefore, the relationship between SWC and $R_s$ is typically quadratic, and the optimal SWC for $R_s$ is near the field capacity due to the balance between substrate and $O_2$ diffusion [11,15,16,18].

Previous studies generally focused on the responses of $R_s$ to the climatic variables, like ST, precipitation, and SWC at plot scales [8,13]. Despite these generalizations across regions within hillslope scales, soil properties and topographic features create great spatial heterogeneity [3,19] that change the spatial distribution of SWC, soil gas concentration, soil nutrients, and even the ST, and thus can induce the spatial heterogeneity of $R_s$ [4,7]. By considering the effect of these spatial variables on the responses of $R_s$ to the temporal variables (ST, precipitation, and SWC), there is a significant opportunity to improve our ability to predict and explain the response of $R_s$ to land-use and climate changes [19].

The southeastern mountainous area occupies over 11.8% of the area of national land in China [20]. Much of this area suffers from intensive agricultural development, and tea plantations are a common vegetation type for the developed lands which have rapidly expanded in recent decades [21–23]. In this region, the expansion of tea plantations generally occurs at the expense of natural forested land like bamboo forest (BF) [24,25]. However, only few studies have investigated the feedback of $R_s$ to the environmental variables in these two land-use types [21,26,27].

Here, we selected adjacent tea garden (TG) and bamboo forest (BF) hillslopes in the southeastern mountainous area of China as the study sites. The objectives of this study were to: (1) compare the temporal and spatial variations of $R_s$ on these two hillslopes; (2) reveal the different responses of $R_s$ to the ST, precipitation and SWC on these two hillslopes; and (3) determine the roles of soil properties and topographic features on the responses of $R_s$ to the ST, precipitation, and SWC.

## 2. Materials and Methods

### 2.1. Study Hillslopes

The adjacent TG and BF hillslopes are located in the northern margin of the southeastern mountainous areas of China (31°21′N, 119°03′E) (Figure 1). The vegetation types on the TG and BF hillslopes were green tea (*Camellia sinensis* (L.) O. Kuntze) and Moso bamboo (*Phyllostachys edulis* (Carr.) H. de Lehaie), respectively. The region has a subtropical monsoon climate and the annual mean temperature and precipitation over the period from 2006 to 2016 were 1157 mm and 15.9 °C, respectively. The foot of the hillslope was near a pond. Lai et al. [28] provides detailed descriptions of the soil and topographic features of the TG and BF hillslopes.

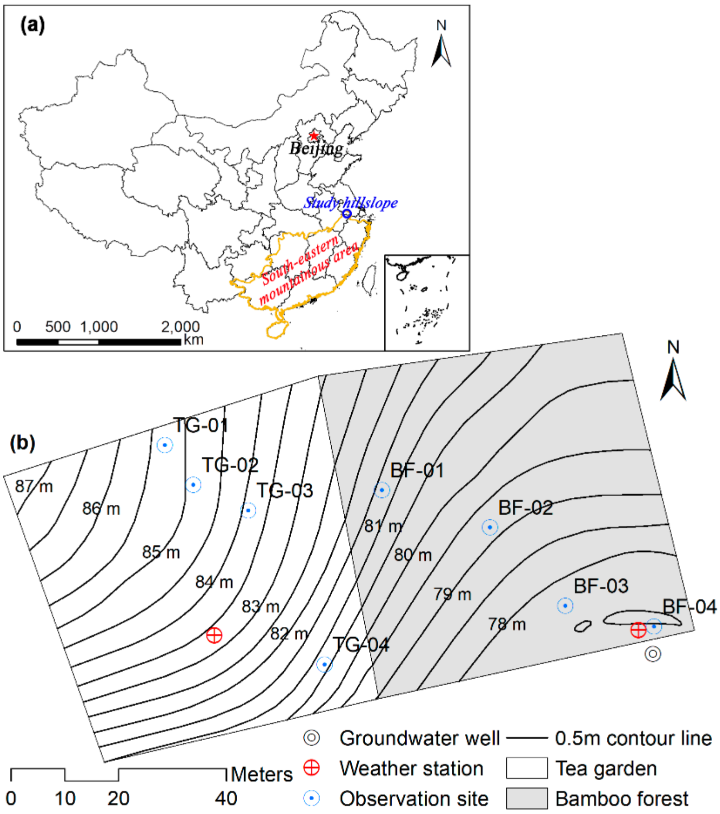


**Figure 1.** (**a**) The geographic location of the tea garden (TG) and bamboo forest (BF) hillslopes in the southeastern mountainous areas of China, and (**b**) the spatial distributions of the observation sites and weather stations as well as the groundwater well on the study hillslopes.

The TG hillslope was planted with green tea for ~15 years, replacing from bamboo forest, while the BF hillslope was un-managed for >35 years. Fertilizers were applied twice per year on the TG hillslope: spring fertilizer applied in March (urea: 209 kg N $ha^{-1}$), and basal fertilizer was applied in October (urea: 174 kg N $ha^{-1}$; organic fertilizer: 1792 kg C $ha^{-1}$ and 120 kg N $ha^{-1}$). Tea leaf was pruned in May every year, and left on the soil surface. No fertilizer or tillage was applied on the BF hillslope.

## *2.2. Data collection*

Four observation sites were respectively allocated along the slope transects on the TG and BF hillslopes (TG-01, TG-02, TG-03, and TG-04; BF-01, BF-02, BF-03, and BF-04) (Figure 1b). Paired EC-5 and MPS-6 sensors (Decagon Devices Inc., Pullman WA, USA) were installed at 10-cm depths at these observation sites to measure SWC and ST. Before sensor installation, at all observations sites, soil samples were collected from depths of 0–20 cm. After being dried, weighted, ground, and sieved through a 2-mm polyethylene sieve, contents of clay (<0.002 mm), silt (0.002–0.05 mm), and sand (0.05–2 mm), soil organic carbon (SOC), and total nitrogen (TN) were then measured. The soil samples were collected in October, long after the application of spring fertilizer and just before the basal fertilization to minimize effects of inorganic nutrient inputs on SOC and TN. Thus, these measured SOC and TN values could be considered the initial SOC and TN values on the TG and BF hillslopes. The depth to bedrock (DB) was measured in excavated soil profiles. In addition, the topographic features including elevation, slope, and profile curvature (PRC) at these observation sites were extracted from a local elevation survey with 1-m spatial resolution. Weather stations (Decagon Devices Inc., Pullman WA, USA) were installed on the TG and BF hillslopes to record precipitation under the canopies. All these measurements including ST, SWC, and precipitation were collected with a frequency of 5 min. Soil properties and topographic features at observation sites of the TG and BF hillslopes were presented in Table 1.

**Table 1.** Soil and topographic properties of the four observation sites on the tea garden (TG) and bamboo forest (BF) hillslopes. DB: depth to bedrock; SOC: soil organic carbon content; TN: soil total nitrogen content; PRC: profile curvature. The percentages of sand, silt, clay, SOC, and TN were defined by weight.

| **Properties** | **TG Hillslope** | | | | **BF Hillslope** | | | |
|---|---|---|---|---|---|---|---|---|
| | **TG-01** | **TG-02** | **TG-03** | **TG-04** | **BF-01** | **BF-02** | **BF-03** | **BF-04** |
| Sand (%) | 10.28 | 12.27 | 8.39 | 13.3 | 19.24 | 15.85 | 5.96 | 6.26 |
| Silt (%) | 75.86 | 71.22 | 71.71 | 71.99 | 68.5 | 71.26 | 81.71 | 82.02 |
| Clay (%) | 13.86 | 16.51 | 19.90 | 14.71 | 12.26 | 12.89 | 12.33 | 11.72 |
| DB (cm) | 41.07 | 40.32 | 41.73 | 58.12 | 28.27 | 86.12 | 59.08 | 71.12 |
| SOC (%) | 1.32 | 1.43 | 0.96 | 0.76 | 1.24 | 1.35 | 1.40 | 1.47 |
| TN (%) | 0.13 | 0.13 | 0.08 | 0.07 | 0.12 | 0.14 | 0.15 | 0.14 |
| Elevation (m) | 86.03 | 85.14 | 83.8 | 80.71 | 81.36 | 79.14 | 77.63 | 77.5 |
| Slope (%) | 9.59 | 9.28 | 12.84 | 17.92 | 15.99 | 8.31 | 5.27 | 0.22 |
| PRC | −0.28 | 1.63 | 2.93 | −0.21 | −8.21 | −1.00 | −0.76 | 0.00 |

Gas sampling was performed between 09:00 and 11:00 h from 13 April 2016 to 22 March 2018, with a frequency of once or twice a month (a total of 28 times). Around each observation site, three closed chambers were installed to collect the gas samples with a space of 0.50 m between each other. Thus three replicates of gas samples could be obtained for one site. At each chamber, gas samples were collected at 0, 10, 20, and 30 min after chamber closure, and the $CO_2$ and $N_2O$ concentrations in each gas samples were analyzed using a gas chromatograph (7890B, Agilent Technologies, Santa Clara, California, USA). The measurements of $R_s$ ($CO_2$ emission flux) and $N_2O$ emission flux were described in detail by Fu et al. [23] and Liao et al. [29], respectively.

In addition, three zero-tension lysimeters were also installed around each observation site to collect the soil leachates of up to 30 cm in depth. Soil leachate samples were collected at the gas sampling date and were filtered through 0.45-mm paper. The $NO_3^-$-N and total organic carbon (TOC) concentrations in leachates were measured respectively using the continuous flow analyzer (San$^{++}$, Skalar, Breda, The Netherlands) and the total organic carbon analyzer (Torch, Teledyne Tekmar, Cincinnati, Ohio, USA). In addition, around each site, three soil samples at 0–20 cm soil depths were collected at the same date with gas and leachate sampling, and the soil $NO_3^-$-N and $NH_4$-N concentrations were determined by extracting with 2 mol $L^{-1}$ KCl solution. The averaged $R_s$, $N_2O$ emission flux, leachate $NO_3^-$-N and TOC concentrations, and soil $NO_3^-$-N and $NH_4$-N concentrations of three replicates for each site were used as the final measurements. The ground water table depth at each site was calculated on each sampling date, based on the difference between the elevation of each site and the ground water table depth measured in the groundwater well (Figure 1b).

### *2.3. Data Analysis*

One-way analysis of variance with Tukey's HSD test was used to test the differences of different variables among different observation sites and on the TG and BF hillslopes. Statistical significance was identified at the 0.05 level. Correlation analyses were conducted to investigate the relationships between $R_s$ and soil $N_2O$ emission flux, leachate $NO_3^-$-N and TOC concentrations, soil $NO_3^-$-N content, SWC, ST, groundwater table depth, and the antecedent precipitation. The cumulative antecedent precipitation amount during previous the 7 days (AP7) was used as the antecedent precipitation, as better correlations were found between $R_s$ and AP7 as compared to using smaller day length for calculating the antecedent precipitation.

An exponential function was used to explore the relationship between $R_s$ and ST at a 10–cm depth:

$$R_s = \alpha \times e^{\beta \times ST} \quad (1)$$

where $\alpha$, $\beta$ are coefficients fitted by the least-square method.

The temperature sensitivity $Q_{10}$, described as a proportional change in $R_s$ with a 10 °C increase in temperature, was calculated by:

$$Q_{10} = e^{10 \times \beta} \quad (2)$$

Similarly, an exponential function was also used to detect the relationship between $R_s$ and AP7, and precipitation sensitivity $P_{10}$, was proposed as a proportional change in $R_s$ with a 10-mm increase in AP7:

$$R_s = m \times e^{n \times AP7} \quad (3)$$

$$P_{10} = e^{10 \times n} \quad (4)$$

The $R_s$ was normalized to 10 °C ($R_{s10}$) to minimize the effect of ST and investigate the relationship with the SWC at a 10-cm depth:

$$R_{s10} = R_s \times e^{\beta \times (10 - ST)} \quad (5)$$

where $\beta$ is the coefficient derived from Equation (1).

Power and quadratic functions were used to explore the relationship between $R_{s10}$ and the SWC, and the fitted function with best accuracy was selected.

To detect the relationships between $R_s$ and the interactions of ST and SWC, two-factor regression model analyses were performed as follows:

$$R_s = a + b \times ST + c \times SWC \quad (6)$$

$$R_s = a \times ST^b \times SWC^c \quad (7)$$

$$R_s = a \times e^{b \times ST} \times SWC^c \quad (8)$$

where *a*, *b*, *c* are coefficients fitted by the least-square method.

Spearman rank correlation analyses were conducted to investigate the relationships between the temporal mean $R_s$, $Q_{10}$, $P_{10}$, coefficient *c* in Equations (6), (7), and (8), spatial variables including soil texture, DB, SOC, TN, elevation, slope, and PRC, and temporal mean SWC and ST. All statistical analyses were conducted with SPSS 18.0 (SPSS Inc., Chicago, IL, USA) or Origin Pro 8.5 (OriginLab, Northampton, MA, USA).

## 3. Results

### 3.1. Differences in Environmental Variables on TG and BF Hillslopes

Soil properties and topographic features differed among the observation sites on the TG and BF hillslopes (Table 1). Among the eight sites, greater sand contents were found in BF-01 and BF-02, while BF-03 and BF-04 had greater contents of silt. The TG-03 site also had lower sand content and greater clay content among these sites. Relative to the TG hillslope, the clay content on the BF hillslope was lower. Deeper soil depths (i.e., DB) were observed on the BF hillslope, while the shallowest soil depth was found in BF-01. The initial soil SOC and TN values were slightly greater on the BF hillslope than on the TG hillslope. The elevation of BF hillslope was generally lower than that on the TG hillslope. Greater slope was found in the TG-03, TG-04, and BF-01 sites, while the TG-01, TG-02, and BF-02 sites had a medium slope, and the BF-04 site had the gentlest slope. The positive PRC were found in TG-02 and TG-03, which indicated a convergent terrain, while the PRC in TG-01, TG-04, BF-01, BF-02, and BF-03 were negative, which indicated a divergent terrain.

Soil $N_2O$ emission flux, leachate $NO_3^-$-N and TOC concentrations, soil $NO_3^-$-N, water contents, and temperature at a 10-cm depth also differed among observation sites on the TG and BF hillslopes (Table 2 and Figure 2). Soil $N_2O$ emission flux, leachate $NO_3^-$-N and TOC concentrations, and soil $NO_3^-$-N content were significantly greater ($p < 0.05$) on the TG hillslope than on the BF hillslope (Table

2). Mean soil $N_2O$ flux, leachate $NO_3^-$-N and TOC concentrations, and soil $NO_3^-$-N content on the TG hillslope were respectively 3.25, 4.29, 1.66, and 1.55 times of those on the BF hillslope. The greatest soil $N_2O$ flux, leachate $NO_3^-$-N concentration, and soil $NO_3^-$-N content were found in TG-03. The ST at 10-cm depths were similar between the TG and BF hillslopes ($p > 0.05$), while slightly higher ST was observed on the TG hillslope during warm seasons and on the BF hillslope during cooler seasons (Figure 2a). The SWC at 10-cm depths on the TG hillslope was significantly lower ($p < 0.05$) than that on the BF hillslope (Table 2). The mean SWC on the TG hillslope was 0.72 times of that on the BF hillslope (Figure 2b). Significant correlations ($r > 0.43$, $p < 0.05$) between SWC and AP7 were observed on the TG hillslope, while the correlations were non-significant ($r < 0.31$, $p > 0.05$) on the BF hillslope. In addition, the ground water table depth in BF-04 ranged from 0.18 to 1.10 m (Figure 2). The temporal variations of ground water table depth were opposite to those of the SWC; a low SWC and a deep ground water table were observed from July to September 2016 and from November to December 2017 (Figure 2). The ground water table was shallow in BF-03 and BF-04, which caused the high SWC in these two sites (Table 2).

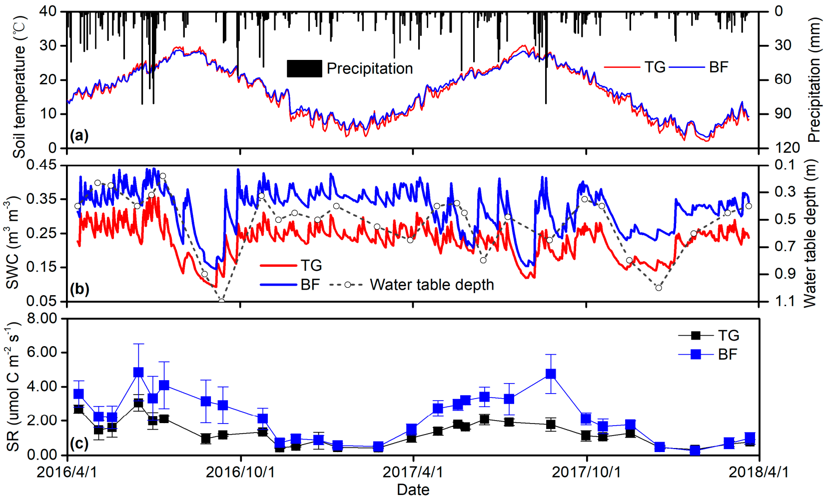


**Figure 2.** Temporal variations of (**a**) the mean soil temperature at 10-cm depths of the observation sites on the tea garden (TG) and bamboo forest (BF) hillslopes; (**b**) the mean soil water content (SWC) on the TG and BF hillslopes and the water table depth at site BF-04; and (**c**) the mean soil respiration (SR) on the TG and BF hillslopes. The error bar represents the standard deviation.

**Table 2.** Statistical summaries of the soil respiration rate (i.e., $CO_2$ flux) and $N_2O$ emission flux, leachate $NO_3^-$-N and total organic carbon (TOC) concentrations, soil $NO_3^-$-N content, soil water content (SWC), and soil temperature (ST) at 10-cm soil depths. Statistical summaries of the measured data at different observation sites and on hillslopes with different land uses are shown by the means ± standard deviations. One-way ANOVA and Tukey's test were used to compare the data among different observation sites and hillslopes with different land uses. Different letters indicate significant differences at the $p < 0.05$ level.

| | ***Gas Emission*** | | ***Leachate*** | | ***Soil*** | | |
|---|---|---|---|---|---|---|---|
| ***Site*** | **$CO_2$ umol C $m^{-2}$ $s^{-1}$** | **$N_2O$ g N $ha^{-1}$** | **$NO_3^-$-N mg N $L^{-1}$** | **TOC mg C $L^{-1}$** | **$NO_3^-$-N mg N $kg^{-1}$** | **ST °C** | **SWC $m^3$ $m^{-3}$** |
| TG-01 | 1.25 ± 0.7$^a$ | 6.3 ± 8.7$^{bcd}$ | 13.7 ± 6.5$^{bc}$ | 31.0 ± 14.3$^{cd}$ | 24.3 ± 14.5$^{ab}$ | 16.9 ± 7.3$^a$ | 0.16 ± 0.03$^a$ |
| TG-02 | 1.35 ± 0.8$^a$ | 7.2 ± 9.1$^{cd}$ | 17.7 ± 9.0$^c$ | 36.6 ± 14.9$^d$ | 21.6 ± 16.5$^{ab}$ | 16.9 ± 7.2$^a$ | 0.25 ± 0.05$^b$ |
| TG-03 | 1.22 ± 0.7$^a$ | 7.9 ± 9.1$^d$ | 16.0 ± 8.7$^c$ | 15.3 ± 9.7$^a$ | 29.7 ± 30.3$^b$ | 16.9 ± 7.5$^a$ | 0.35 ± 0.06$^d$ |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| TG-04 | 1.35 ± $0.7^{a}$ | 4.4 ± $6.6^{abcd}$ | 10.8 ± $6.1^{b}$ | 24.8 ± $10.9^{bc}$ | 16.6 ± $25.6^{ab}$ | 16.8 ± $6.2^{a}$ | 0.15 ± $0.04^{a}$ |
| BF-01 | 2.27 ± $1.4^{bc}$ | 1.1 ± $0.7^{a}$ | 3.7 ± $2.6^{a}$ | 19.1 ± $9.2^{ab}$ | 17.9 ± $21.4^{ab}$ | 16.7 ± $6.6^{a}$ | 0.22 ± $0.06^{b}$ |
| BF-02 | 2.45 ± $1.5^{c}$ | 1.9 ± $1.0^{ab}$ | 4.3 ± $2.4^{a}$ | 13.6 ± $6.1^{a}$ | 16.9 ± $13.4^{ab}$ | 16.8 ± $6.4^{a}$ | 0.30 ± $0.07^{c}$ |
| BF-03 | 2.54 ± $1.7^{c}$ | 2.8 ± $2.0^{abc}$ | 3.5 ± $2.9^{a}$ | 17.0 ± $7.1^{a}$ | 15.8 ± $11.7^{ab}$ | 17.4 ± $6.4^{a}$ | 0.37 ± $0.06^{d}$ |
| BF-04 | 1.57 ± $1.0^{ab}$ | 2.1 ± $1.5^{ab}$ | 2.2 ± $1.6^{a}$ | 15.1 ± $7.0^{a}$ | 9.2 ± $6.0^{a}$ | 16.8 ± $5.5^{a}$ | 0.39 ± $0.09^{d}$ |
| ***Land use*** | | | | | | | |
| TG | 1.29 ± $0.7^{A}$ | 6.5 ± $8.5^{B}$ | 14.6 ± $8.0^{B}$ | 26.9 ± $14.8^{B}$ | 23.1 ± $22.9^{B}$ | 16.9 ± $7.0^{A}$ | 0.23 ± $0.10^{A}$ |
| BF | 2.21 ± $1.3^{B}$ | 2.0 ± $1.5^{A}$ | 3.4 ± $2.5^{A}$ | 16.2 ± $7.6^{A}$ | 14.9 ± $14.5^{A}$ | 16.9 ± $6.2^{A}$ | 0.32 ± $0.09^{B}$ |

### *3.2. Spatial and Temporal Variations of $R_s$*

The $R_s$ varied among observation sites and on the TG and BF hillslopes (Table 2). The greatest $R_s$ was found in BF-03 (2.54 umol C $m^{-2}$ $s^{-1}$), and a relatively greater $R_s$ was also found in BF-01 and BF-02 (>2.25 umol C $m^{-2}$ $s^{-1}$). However, small and similar amounts of $R_s$ were found in TG-01, TG-02, TG-03 and TG-04 (1.22–1.35 umol C $m^{-2}$ $s^{-1}$). The $R_s$ on the BF hillslope was significantly higher ($p < 0.05$) than that on the TG hillslope (the mean $R_s$ on BF hillslope was 1.71 times of that on the TG hillslope). The temporal variations of the $R_s$ both on the TG and BF hillslopes were generally in accordance with the temporal changes of the measured ST at 10 cm depths (Figure 2). The $R_s$ ranged from 0.34 to 3.06 umol C $m^{-2}$ $s^{-1}$ on the TG hillslope, and from 0.25 to 4.84 umol C $m^{-2}$ $s^{-1}$ on the BF hillslope during the observation period. When a higher $R_s$ was observed, greater differences between the mean $R_s$ on the TG and BF hillslope were observed (Figure 2). Greater spatial variations of $R_s$ among observation sites could be found on the BF hillslope due to relatively low $R_s$ in BF-04. The standard deviations (SD) of $R_s$ ranged from 0.01 to 0.56 umol C $m^{-2}$ $s^{-1}$ on the TG hillslope, and from 0.06 to 1.67 umol C $m^{-2}$ $s^{-1}$ on the BF hillslope (Figure 2).

### *3.3. Relationships Between $R_s$ and Environmental Variables*

Soil clay content, elevation, and PRC were all negatively correlated ($r = -0.71$, $-0.74$ and $-0.74$, respectively, $p < 0.05$) with $R_s$. There was also a positive relationship between $R_s$ and TN ($r = 0.64$, $p = 0.09$), while low $r$ values (absolute value of $r < 0.45$) were found between $R_s$ and sand, DB, SOC, slope, temporal mean SWC, and ST.

Correlations between temporal variations in $R_s$ and the temporal factors varied among different observation sites and on the TG and BF hillslopes (Table 3). Both $N_2O$ flux and ST were positively correlated ($p < 0.05$) with the mean $R_s$ on the TG and BF hillslopes. The $r$ value between $R_s$ and ST was great (>0.70) in all observation sites and on the TG and BF hillslopes. The $r$ values between $R_s$ and $N_2O$ flux and ST were greater on the BF hillslope than on the TG hillslope. Likewise, positive correlations ($p < 0.05$) were found between $R_s$ and leachate TOC concentration and AP7 on the BF hillslope, while no such relationship was found on the TG hillslope. Specifically, significant correlations ($p < 0.05$) between $R_s$ and leachate TOC concentration were found in BF-01 and BF-04, while significant correlations ($p < 0.05$) between $R_s$ and AP7 were found in BF-01 and BF-02. Positive correlations between $R_s$ and AP7 were significant ($p < 0.05$) in TG-01 and TG-04. In addition, the negative correlation between $R_s$ and leachate $NO_3^-$-N concentration was significant ($p < 0.05$) on the TG hillslope, but non-significant on the BF hillslope. In general, correlations between $R_s$ and soil $NO_3^-$-N content, SWC, and ground water table depth were non-significant ($p > 0.05$).

**Table 3.** Correlation coefficients between the soil respiration and ancillary variables at different observation sites on the tea garden (TG) and bamboo forest (BF) hillslopes. Ancillary variables included soil $N_2O$ emission flux, leachate $NO_3^-$-N and total nitrogen carbon (TOC) concentrations, soil $NO_3^-$-N content, soil water content (SWC), soil temperature (ST) at 10-cm depths, groundwater table depths (GWTD), and the antecedent precipitation during previous 7 days (AP7).

| *Site* | $N_2O$ flux | Leachate | | Soil | | | GWTD | AP7 |
|---|---|---|---|---|---|---|---|---|
| | | $NO_3^-$–N | TOC | $NO_3^-$–N | SWC | ST | | |
| TG–01 | 0.337 | −0.493* | −0.145 | 0.300 | 0.243 | 0.708** | −0.338 | 0.378* |
| TG–02 | 0.362 | −0.463* | −0.040 | 0.384* | 0.015 | 0.720** | −0.343 | 0.361 |
| TG–03 | 0.444* | −0.255 | −0.069 | 0.072 | 0.083 | 0.722** | −0.131 | 0.224 |
| TG–04 | 0.234 | −0.438* | 0.054 | −0.035 | 0.368 | 0.630** | −0.211 | 0.389* |
| BF–01 | 0.525** | −0.338 | 0.401* | 0.208 | −0.225 | 0.844** | −0.242 | 0.516** |
| BF–02 | 0.620** | −0.473* | 0.254 | −0.029 | −0.122 | 0.877** | −0.227 | 0.474* |
| BF–03 | 0.453* | −0.005 | 0.388 | −0.120 | −0.285 | 0.858** | 0.101 | 0.302 |
| BF–04 | 0.407* | 0.133 | 0.447* | −0.410* | −0.376* | 0.817** | 0.022 | 0.348 |
| ***Land use*** | | | | | | | | |
| TG | 0.379* | −0.425* | −0.081 | 0.184 | 0.218 | 0.734** | −0.273 | 0.357 |
| BF | 0.571** | −0.240 | 0.399* | −0.022 | −0.263 | 0.895** | −0.091 | 0.431* |

Note. The symbols of * and ** denote significant correlations at $p < 0.05$ and $p < 0.01$, respectively.

## 4. Discussion

### 4.1. Factors Influencing $R_s$ response to ST

The ST at 10-cm depth explained 33%–45% and 59%–73% of the temporal variations in $R_s$ on the TG and BF hillslopes, respectively, using the exponential functions (Figure 3). The temporal trends of $R_s$ were mainly controlled by ST, which were consistent with many previous studies [3,7,10]. However, the exponential relationships between ST and $R_s$ were poor when ST was high, especially on the TG hillslope (Figure 3). This was because when ST was low, the $R_s$ was mainly constrained by ST, while under high ST conditions, other environmental variables like the SWC and substrate supplies would have a great influence on $R_s$ [3]. Because of the lower SWC on the TG hillslope, the $R_s$ was more likely to be constrained by SWC under high ST conditions, especially in TG-04 with the lowest SWC (Table 2). This result was consistent with that of Liu et al. [11] and Carey et al. [12]. Li et al. [3] also indicated that when the $R_s$ values from the days with extreme low SWC were discarded, the explanation rates of ST on $R_s$ increased.

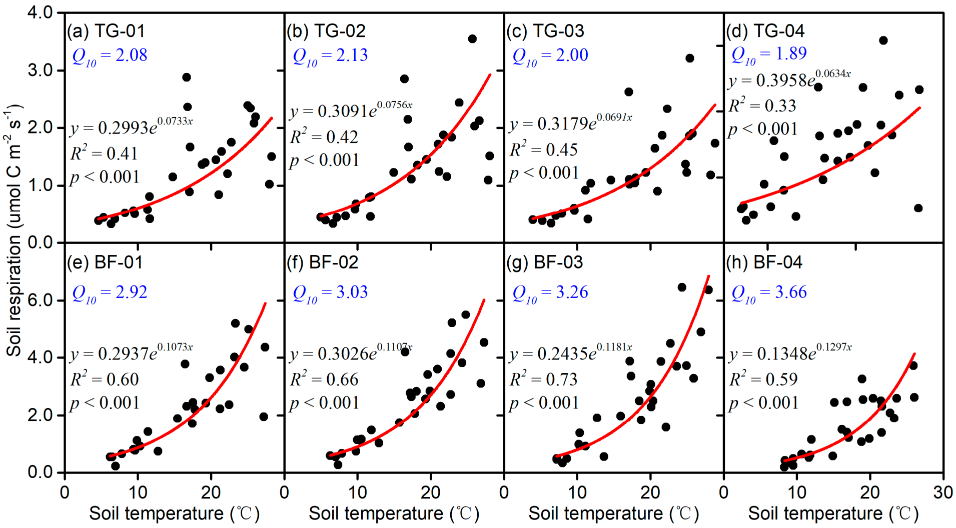


**Figure 3.** Exponential relationships between soil respiration and soil temperature at a 10-cm depth at different observation sites on the tea garden hillslope and bamboo forest hillslope. The $Q_{10}$ is the temperature sensitivity of soil respiration.

The mean $Q_{10}$ was 2.02 on the TG hillslope and ranged from 1.89 to 2.13, lower than that on the BF hillslope (mean $Q_{10}$: 3.22, range from 2.92 to 3.66) (Figure 3). The $Q_{10}$ on the TG hillslope in our study was consistent with that observed in Zhejiang, China (range from 1.86 to 1.98) [30], greater than that observed in Sichuan, China (range from 1.15 to 1.40) [31], and lower than that observed in Yunnan, China (5.7) [32]. In addition, the $Q_{10}$ of the BF hillslope was a little higher than that observed in a BF in Zhejiang, China (2.80) [26], and lower than that observed in a BF in central Taiwan, China (4.09) [33]. The different $Q_{10}$ on the TG and BF hillslopes derived from this study and the other studies might be attributed to the different soil water availability, temperature range, substrate quality, or microbial community [34].

The lower $Q_{10}$ on the TG hillslope relative to that on the BF hillslope might be due to lower initial soil C and N contents and higher soil clay content (Table 1). Positive correlations between $Q_{10}$ and TN ($r = 0.88$, $p < 0.01$), temporal mean SWC ($r = 0.74$, $p < 0.05$), and negative correlations between $Q_{10}$ and clay ($r = -0.81$, $p < 0.05$), slope ($r = -0.86$, $p < 0.01$) were observed in this study. Higher initial soil C and N availability induced abundant microbial communities and enhanced soil enzyme activities, which was highly related to the $R_s$ as well as $Q_{10}$ [35]. Although excess N fertilizer was applied on the TG hillslope (Table 2), this would not substantially improve the soil microbial communities due to the N consumption by tea plantation and high N losses through gas and solute pathways (Table 2). In addition, excess inorganic N fertilization tended to suppress microbial activities, as revealed by Mahal et al. [36]. A positive relationship between $Q_{10}$ and SWC was found by Flanagan and Johnson [37] and Zhou et al. [38], while a negative correlation or no effect were found in other studies [6,39,40]. One of the reasons for this might be whether the observed ranges of SWC covered the optimum SWC for $R_s$ (near to field capacity) [15,18]. Previous studies have indicated the inhibition effects of clay on $R_s$ by impeding mineralization of soil organic matter, and thus posed negative on $Q_{10}$ [4,41]. In addition, large slope was always companied by low soil water and nutrient-holding capacities [19], which would result in low $R_s$ and the negative effects on $Q_{10}$.

### *4.2. Factors Influencing $R_s$ Response to Precipitation*

Relationships between $R_s$ and AP7 could also be described by the exponential functions in this study (Figure 4). The AP7 explained 24%–37% (mean: 31%) and 28%–38% (mean: 35%) of the temporal variations in $R_s$ on the TG and BF hillslopes, respectively. Positive relationships between $R_s$ and precipitation were also found by Chen et al. [13] and Zhou et al. [8], while some other studies demonstrated that increased precipitation could reduce $R_s$ due to the slow gas diffusion [15,42]. In this study, the relative lower explanation rates (<30%) of AP7 on $R_s$ in TG-03, BF-03, and BF-04 were due to the wet soil conditions at these sites (Table 2). This confirmed the inhibition effects of high SWC on the responses of $R_s$ to AP7. In addition, negative correlations between clay ($r = -0.82$, $p < 0.05$), PRC ($r = -0.79$, $p < 0.05$) and $P_{10}$ also indirectly confirmed the inhibition effects. High clay content was always associated with high water-holding capacity [43], and large PRC represented the depressions where it was easy to accumulate water [44], inducing a low sensitivity of $R_s$ to precipitation.

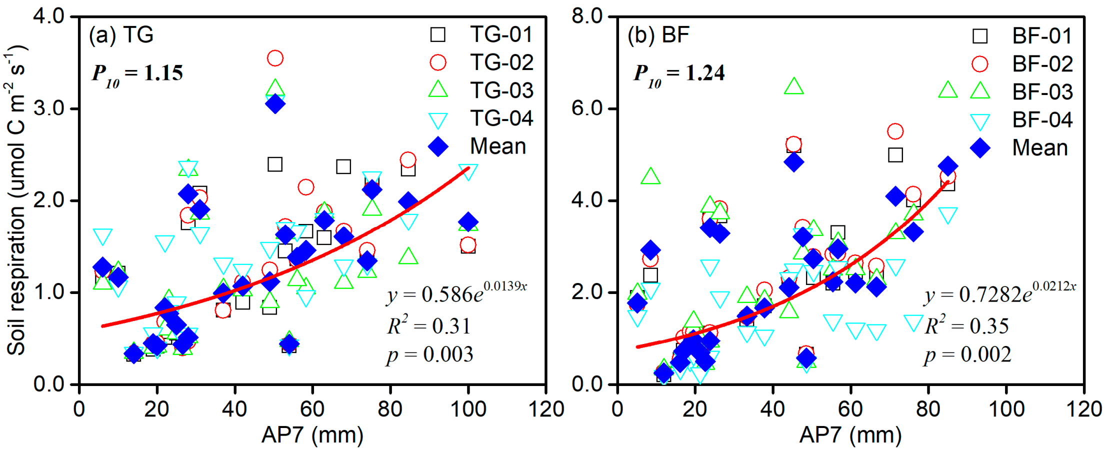


**Figure 4.** Relationships between soil respiration at the observation sites on the (**a**) tea garden (TG) and (**b**) bamboo forest (BF) hillslopes and their corresponding antecedent precipitation during previous 7 days (AP7). The exponential correlations between the spatial mean values and the AP7 are also shown. The $P_{10}$ is the precipitation sensitivity of soil respiration.

## *4.3. Factors Influencing $R_s$ Response to SWC*

In this study, correlations between $R_s$ and SWC were relatively poor (Table 3). However, when $R_s$ was normalized to that at 10 °C, power relationships between $R_s$ and SWC were observed in TG-01, TG-02, TG-04, and quadratic relationships were observed in TG-03, BF-01, BF-02, and BF-04, while an ambiguous power relationship was found in BF-03 (Figure 5). The SWC explained 12%–32% of the temporal variations of $R_s$ except in BF-03 (Figure 5). The different curves fitting the relationships between SWC and $R_s$ could be attributed to the different ranges of SWC observed in these sites. The quadratic relationships between SWC and $R_s$ have been demonstrated by previous studies including those of Liu et al. [11], Hursh et al. [9], and Han et al. [15]. The optimum SWC for $R_s$ was near the field capacity [15,18]. Therefore, when the observed SWC was below the optimum value (e.g., TG-01, TG-02, and TG-04), only positive power relationships between SWC and $R_s$ could be extracted. When the observed SWC covered the optimum value (e.g., TG-03, BF-01, BF-02, and BF-04), the quadratic relationships could be captured. In BF-03, as the observed SWC was kept around the optimum value; thus, an ambiguous negative power relationship was observed, and also the largest mean $R_s$ was found (Table 2).

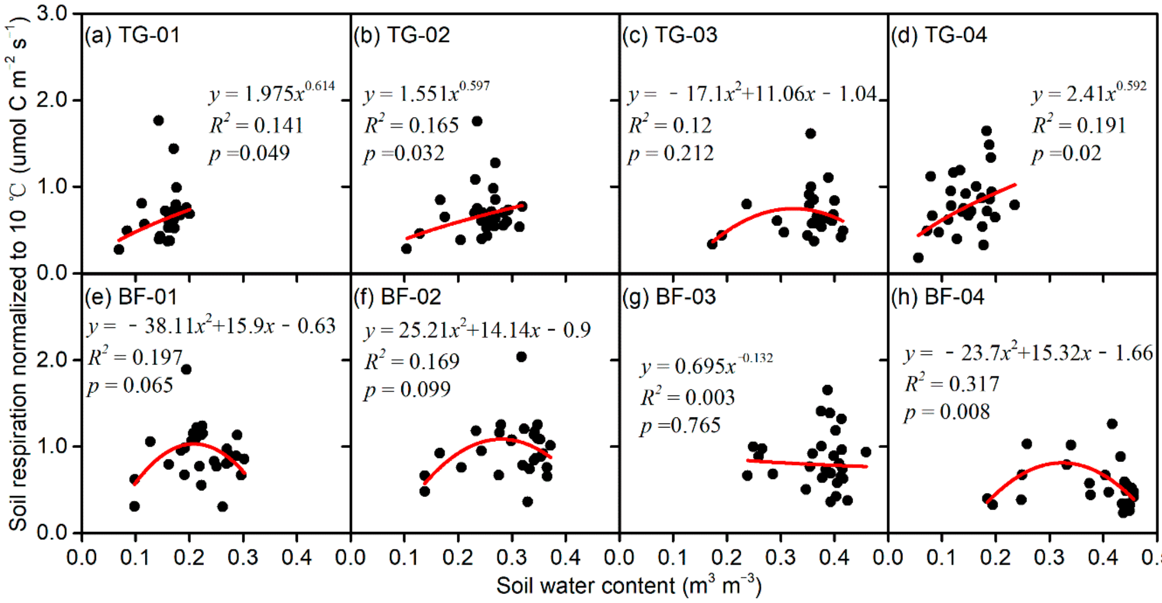


**Figure 5.** Power or quadratic relationships of the soil respiration normalized to 10 °C with the soil water content at a 10-cm depth of the observation sites on the tea garden (TG) and bamboo forest (BF) hillslopes.

In order to extract the combined effect of ST and SWC on $R_s$, we integrated both ST and SWC into three two-factor regression models (Equations (6)–(8)). The ST and SWC together explained 45%–81% of the temporal variations in $R_s$ in different observation sites and on the TG and BF hillslopes, with a relatively higher explanation rate acquired by Equation (7) (Table 4). The combined effects of ST and SWC on $R_s$ temporal variations were consistent with previous studies [3,7,11], which also reported better explanation rates with these two-factor regression models than with one-factor regression models. In addition, for large spatial scales, previous studies also indicated that ST alone was insufficient to accurately predict the $R_s$, and that other factors such as SWC or TN should be considered also [6,7].

**Table 4.** Fitted Equations (6), (7), and (8) of soil respiration ($R_s$) against soil temperature (ST) and soil water content (SWC) in different observation sites and on tea garden (TG) and bamboo forest (BF) hillslopes, with the corresponding determination coefficients ($R^2$). In these equations, *a*, *b*, *c* are coefficients fitted by the least-square method.

| *Site* | **Equation (6) $R_s$ = $a + b$ST + $c$SWC** | $R^2$ | **Equation (7) $R_s$ = $a$ST$^b$ SWC$^c$** | $R^2$ | **Equation (8) $R_s$ = $ae^{b\text{ST}}$ SWC$^c$** | $R^2$ |
|---|---|---|---|---|---|---|
| TG-01 | $R_s$ = – 0.977 + 0.073ST + 6.427SWC | 0.57 | $R_s$ = 0.262ST$^{0.986}$ SWC$^{0.650}$ | 0.60 | $R_s$ = 1.741e$^{0.057\text{ST}}$ SWC$^{0.729}$ | 0.55 |
| TG-02 | $R_s$ = – 0.989 + 0.087ST + 3.546SWC | 0.56 | $R_s$ = 0.125ST$^{1.124}$ SWC$^{0.559}$ | 0.60 | $R_s$ = 1.051e$^{0.065\text{ST}}$ SWC$^{0.652}$ | 0.56 |
| TG-03 | $R_s$ = – 0.826 + 0.072ST + 2.333SWC | 0.56 | $R_s$ = 0.110ST$^{1.055}$ SWC$^{0.546}$ | 0.59 | $R_s$ = 0.793e$^{0.062\text{ST}}$ SWC$^{0.663}$ | 0.56 |
| TG-04 | $R_s$ = – 0.478 + 0.069ST + 4.607SWC | 0.48 | $R_s$ = 0.235ST$^{0.953}$ SWC$^{0.484}$ | 0.54 | $R_s$ = 1.468e$^{0.055\text{ST}}$ SWC$^{0.550}$ | 0.52 |

| | | | | | | |
|---|---|---|---|---|---|---|
| BF-01 | $R_s = -1.667 + 0.194ST + 3.165SWC$ | 0.72 | $R_s = 0.055ST^{1.538} SWC^{0.419}$ | 0.76 | $R_s = 0.998e^{0.086ST} SWC^{0.477}$ | 0.72 |
| BF-02 | $R_s = -2.230 + 0.215ST + 3.596SWC$ | 0.79 | $R_s = 0.048ST^{1.556} SWC^{0.404}$ | 0.81 | $R_s = 0.899e^{0.087ST} SWC^{0.454}$ | 0.77 |
| BF-03 | $R_s = -0.693 + 0.225ST - 1.840SWC$ | 0.74 | $R_s = 0.014ST^{1.750} SWC^{-0.117}$ | 0.75 | $R_s = 0.411e^{0.093ST} SWC^{-0.042}$ | 0.74 |
| BF-04 | $R_s = -0.107 + 0.140ST - 1.760SWC$ | 0.69 | $R_s = 0.017ST^{1.555} SWC^{-0.077}$ | 0.66 | $R_s = 0.318e^{0.087ST} SWC^{-0.033}$ | 0.62 |
| ***Land Use*** | | | | | | |
| TG | $R_s = -0.073 + 0.074ST + 0.520SWC$ | 0.49 | $R_s = 0.121ST^{0.941} SWC^{0.176}$ | 0.51 | $R_s = 0.676e^{0.053ST} SWC^{0.196}$ | 0.46 |
| BF | $R_s = -0.667 + 0.191ST - 1.128SWC$ | 0.68 | $R_s = 0.024ST^{1.616} SWC^{0.077}$ | 0.68 | $R_s = 0.501e^{0.088ST} SWC^{0.115}$ | 0.65 |

The coefficient *c* of SWC in Equations (6)–(8) was negative in BF-03 and BF-04, and positive in other observation sites, which indicated the general inhibition effects of SWC in BF-03 and BF-04, and promotion effects in other sites (Table 4). This also could be approximately reflected in Figure 5. Negative relationships ($r = -0.86$, $p < 0.01$) were observed between SWC and the coefficient *c* in Equation (6), which indicated that the influences of SWC on $R_s$ always ranged from promotion (positive) to inhibition (negative) with the increasing of SWC [4,15]. In addition, both clay ($r = 0.71$ and 0.74, respectively, $p < 0.05$) and elevation ($r = 0.95$ and 0.93, respectively, $p < 0.01$) were positively correlated with the coefficient *c* in Equations (7) and (8). Clay improved the soil water-holding capacity and prevented soil organic matters from decomposition [41,43], and thus the dependence of $R_s$ on the ST declined and the importance of SWC increased. Elevation determined the depth to groundwater level in different observation sites, and thus indirectly altered the SWC. Regions with high elevation were always featured by dry soil condition, this resulted in the great dependence of $R_s$ on SWC.

### *4.4. Relation Between Land Use and $R_s$*

Land use was recognized as one key factor determining the spatial variations of $R_s$ [6,30,34]. In addition, land-use change from natural forestland to agricultural land has been a common phenomenon in the mountainous area in recent decades [25,45]. Different root biomass and exudates between the forestland and agricultural land determined the differences of the characteristics of root autotrophic respiration and the rhizosphere condition; the latter could change soil microbial community compositions [13,34]. In addition, the intensive human management of agricultural land, including fertilization and tillage, could change soil conditions like soil structure and soil C and N availability. The changes of soil condition thus could affect the root autotrophic respiration and change the soil microbial communities and activities, which directly determined the soil heterotrophic respiration [34]. In this study, higher $R_s$ and $Q_{10}$ were observed on the BF hillslope than on the TG hillslope (Table 2 and Figure 3). Reasons for the higher $R_s$ on the BF hillslope were identified as the higher soil water content and C and N availabilities in this study. High soil water content and C and N availabilities could enhance the root and microbial activities and respiration [19]. However, the direct factors of soil microbial community compositions as well as the root respiration properties were not investigated in this study, and need to be considered to reveal the relationship between land use and $R_s$ in further work.

## 5. Conclusions

In this study, responses of $R_s$ to the ST, precipitation, and SWC and their relationship with soil and terrain properties were investigated in different observation sites and among different land-use types. The mean $R_s$ on the BF hillslope was 2.21 umol C $m^{-2}$ $s^{-1}$, significantly larger than that on the TG hillslope (1.29 umol C $m^{-2}$ $s^{-1}$) during the observation period. Spatial variations of $R_s$ were negatively correlated ($p < 0.05$) with clay, elevation, and PRC. Temporal variations of $R_s$ were correlated ($p < 0.05$) with ST and soil $N_2O$ flux on both the TG and BF hillslopes. The ST was the dominant temporal factor of the $R_s$, and explained 33%–45% and 59%–73% of the $R_s$, on TG and BF hillslopes, respectively. The mean $Q_{10}$ on the TG hillslope was 2.02, which was lower than that on the BF hillslope (mean: 3.22). Positive correlations ($p < 0.05$) were found between $Q_{10}$ and TN and SWC, and negative correlations ($p < 0.05$) were found between $Q_{10}$ and clay and slope. The AP7 explained 24%–37% and 28%–38% of the $R_s$ on the TG and BF hillslopes, respectively, and both clay and PRC were significantly negatively correlated ($p < 0.05$) with $P_{10}$ (a proportional change in $R_s$ with a 10-mm increase in AP7). Power or quadratic relationships between $R_s$ and SWC were detected in different sites, and the SWC explained 0%–32% of the temporal variations of $R_s$. Improved explanation rates (45%–81%) were achieved when both ST and SWC were considered together in the two-factor regression models. The temporal mean SWC, clay, and elevation had great influences ($p < 0.05$) on the dependencies of $R_s$ on SWC. The study highlights the roles of soil and topographic features in inducing the spatial variations of $R_s$ and the responses of $R_s$ to climatic variables in the mountainous area. These results can supplement the knowledge of response mechanisms of $R_s$ to different climatic variables on TG and BF hillslopes, facilitating modelling prediction of $R_s$ at large scales.

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**Conflicts of Interest:** The authors declare no conflict of interest.

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