

Article

Temporal Dynamics of CO₂ Fluxes over a Non-Irrigated Vineyard

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Abstract: Some knowledge gaps still remain regarding carbon sequestration in non-irrigated agroecosystems, where plants may experience drought stress during summertime. Therefore, by the combination of the eddy covariance (EC) and soil chamber techniques, we determined the role of a non-irrigated grassed vineyard in carbon sequestration in the Slovak Republic. Based on the EC data, the cumulative net uptake of CO₂ (NEE) for the whole growing season was weak and was ca. −97 (g C m^{−2}). This value resulted from −796 (g C m^{−2}) carbon uptake from the atmosphere through photosynthesis (GEE) and 699 (g C m^{−2}) carbon released to the atmosphere through respiration (Reco). Carbon emissions through Reco were considerable and accounted for ca. 88% of GEE, which points out the importance of Reco for managing non-irrigated agroecosystems. Data from the soil chamber indicated that ca. 302 g C m^{−2} was released by the vineyard through soil respiration (Rsoil) over a growing season, which was constantly lower than Reco and accounted for ca. 44 ± 18% of Reco. This finding implies that the vineyard soil was not a main source of carbon emissions. Rsoil was mainly driven by temperature (exponentially ca. 69–85%). Meanwhile, vapour pressure deficit (VPD) and temperature appeared to be the most important limiting factors for GEE, NEE, and Reco, particularly when they exceeded a certain threshold (e.g., temperature > 17 °C, and VPD > 10 hPa).

Keywords: vineyard; eddy covariance; carbon fluxes; environmental factor; carbon sequestration



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1. Introduction

Anthropogenic emissions of carbon dioxide (CO₂) are on the rise due to human activity and have increased the atmospheric CO₂ by ca. 40% compared to the pre-industrialization period [1,2]. The increase in CO₂ has a direct impact on climate change and global warming by changing the radiation force of the atmosphere [3]. Plants and soil can absorb a substantial part of anthropogenic CO₂ emissions [4]. Therefore, they have the potential to be important carbon sinks, and with proper management, an agroecosystem can sink about 690 and release about 275 g C m^{−2} yr^{−1} to the atmosphere [5,6]. However, carbon dynamics in agroecosystems can also be influenced by harvested yield, soil and crop type, and climate [5,7,8].

Perennial crops, in addition to food production, have the potential to sequester and store carbon on a long-term basis, which can help mitigate the anthropogenic production of CO₂ [9–12]. Viticulture, with an area of ca. 7.3 million hectares, is still one of the most widespread agricultural production systems around the world [13]. Therefore, its potential for carbon capture and storage has gained attention, and researchers have increasingly focused on carbon sequestration in vineyards across the world, particularly in Europe, where 40% of the vineyard area is located [14–20]. On the other hand, undisturbed soil in perennial tree crops, apart from the reduction of carbon emissions [21], can be a good example for assessing carbon emissions from soil in the agroecosystem where the impact of tillage and heavy machines passing on soil respiration (Rsoil) is minimized [22–25]. However, other factors such as temperature, moisture, soil properties, nitrogen fertilizer, and microbial activities can also affect Rsoil as a fraction of ecosystem respiration [26–28]. In general, Rsoil is the largest component of Reco, as evidenced by previous studies [29–31], even though some investigations have reported a lower value of Reco in comparison to Rsoil [32,33]. Nevertheless, the most recent estimations from an Italian vineyard suggest that Rsoil accounts for 83% of Reco [10]. In this context, soil can play an important role as a major carbon reservoir in the global carbon budget, but it is inadequately understood, particularly in the agroecosystem. Therefore, quantifying the amount of Rsoil in parallel with Reco can provide detailed information concerning the main source of the released CO₂ efflux to the atmosphere in the perennial cropland.

Presently, eddy covariance (EC) is the most widely used technique for monitoring the net ecosystem exchange of CO₂ (NEE), which results from two larger fluxes of opposite signs: CO₂ uptake by photosynthesis (GEE) and CO₂ release by Reco [34–38]. Therefore, EC has recently been employed to quantify CO₂ fluxes in vineyards [39,40], particularly in Italy, where vineyards have demonstrated a moderate carbon sink capacity [10,41,42]. However, an irrigated vineyard within an arid region of China acted as a strong carbon sink [39]. In the Slovak Republic, agricultural land covers 46.4% of the total area, and about 5% of agricultural land is given over to perennial tree crops [43]. Although half of the country is covered by agroecosystems, limited studies properly consider the carbon potential of agroecosystems. Furthermore, most studies that have investigated carbon fluxes in vineyards were supplied by irrigation systems. In particular, in areas with hot dry summers where plants may experience drought stress during summertime, carbon fluxes can be affected as a consequence. Therefore, to improve understanding of CO₂ flux patterns in woody crops (with ongoing climate change), this study was conducted in non-irrigated agroecosystems with mild winters and relatively hot and dry summers by employing EC and chamber-based measurements. Considering the potential for drought stress in this area during summer, our specific hypothesis is that a non-irrigated vineyard cannot act as a strong sink of carbon.

In fact, this study aims to determine (i) whether non-irrigated grassed vineyards act as a carbon sequester or emitter; (ii) since soil remains undisturbed for decades in many perennial crops, whether aboveground respiration is the main fraction of Reco, i.e., is Reco consistently higher than Rsoil from daily to seasonal scales because of undisturbed soil; and (iii) how CO₂ fluxes (NEE, GEE, Reco, and Rsoil) respond to environmental variables.

2. Materials and Methods

2.1. Site Description

The study was performed in a 47-year-old vineyard in Nevidzany village, Zlaté Moravce municipality (Tekov region) which is located in the western part of the Slovak Republic (48°16′22″ N and 18°22′35″ E; 220 m a.s.l.). The vineyard under experimentation covered an area of 20 hectares on homogenous terrain with a 5% slope. The planting density was ca. 4000 vines/ha^{−1} with a 3 × 0.8 m distance. The vine varieties were Riesling and Cabernet Sauvignon, grafted on Kober 5BB rootstock. The training system was cordon.

The vineyard soil was covered by grasses and classified as brown soil type, subtype: Pseudogley brown soil, with signs of anthropic activity in the humus horizon. The original

parent material that formed the soil-forming substrate for the emerging soil was loess, and in some parts of the area of interest, loess and polygenetic clays (soil survey taken by the Department of Pedology and Geology, Institute of Agronomic Sciences, Faculty of Agrobiological and Food Resources, Slovak Agricultural University in Nitra, 2022). The climate, in general, is dry and warm with mild winters, and the area receives an average annual precipitation of 662 mm; the mean annual temperature is 9 °C [44].

During the measurement period, a combination of *B. megaterium* and micro-dosed NPK fertilizer was applied once on the leaves, and pesticide spraying was used for pest-control purposes three times. Dormant pruning was performed in March, and prunings were chopped (into smaller pieces) or mulched in the vineyard alleys and used as a source of nutrients for the covered grass, soil, and grapevines. In addition, the cover grass was mowed three times in April, July, and November, and grass clippings were also used as soil surface mulch in the vineyard alleys. The grape production was 5.5 tons per hectare for the year 2022.

To provide an overview of the soil's chemical and physical characteristics, we quantified parameters such as soil organic carbon and nitrogen, soil pH, bulk density, soil porosity, and soil water retention. The results of these measurements are presented in detail in Table 1. Additionally, our assessment of soil texture demonstrated that ca. 68% of the soil proportion was clay-silt (0.001–0.05 mm; Table A1).

Table 1. The mean value of soil carbon (C) and nitrogen (N) stocks, soil pH; soil bulk density (BD), soil porosity, and soil water retention capacity.

	Soil C (kg C m ⁻²)	Soil N (kg N m ⁻²)	Soil pH	BD (g cm ⁻³)	Soil Porosity (%)	Soil Water Retention Capacity (%)
Mean	3.04	0.23	6.31	1.32	47	29
Standard deviation (SD)	0.41	0.06	0.20	0.06	4	3

2.2. Instrumentation and Measurements

2.2.1. Eddy Covariance

An eddy covariance tower was mounted at 3.0 m height above the soil surface to quantify the CO₂ fluxes' exchange between the vineyard ecosystem and atmosphere (NEE). The measurement was performed for a growing season (April–September 2022). The EC consisted of an enclosed-path infrared gas analyzer (IRGA analyzer Li-7200 from LI-COR Biosciences, Lincoln, NE, USA) to monitor GHG fluxes continuously, a 3-dimensional sonic anemometer (CSAT3, Campbell Scientific Inc., Logan, UT) to collect wind velocities and sonic temperature, and a datalogger to store 10 Hz raw data (CR3000, Campbell Scientific Inc., Logan, UT, USA). To calculate the 30 min average fluxes of CO₂, the high-frequency binary data (TOB1) was converted into the ASCII format with a 30 min timestep, using LoggerNet (Campbell Scientific Inc., Logan, UT, USA). Then, its output (ASCII files) was processed by the Eddypro software packages developed by the Li-Cor Company (LI-COR, Lincoln, NE, USA). After calculating the 30 min average fluxes (of CO₂, LE and H), the data were quality-checked [45], de-spiked [46,47], and filtered according to friction velocity [48,49], and double coordinate rotation was used to tilt correction [50]. The *u** threshold was detected using the R package REddyProc [46]. Gap filling was carried out using the techniques outlined by Falge et al. [51] and Reichstein et al. [49], and the uncertainty of the gap-filled half-hourly data was estimated. Partitioning of NEE into GEE and Reco was also done by REddyProc [46], based on the nighttime method [49]. Then, biological flux parameters (NEE, GPP, Reco) were aggregated into daily and monthly values, and those for the whole growing season [46,52]. All steps of post-processing were done by the REddyProc package in R [46].

2.2.2. Soil Chamber

Soil respiration (R_{soil}) measurements were conducted in parallel with EC continuously (1 h intervals) using an Automated Soil CO_2 Exchange System (ACE, ADC BioScientific Ltd., Hoddesdon, UK). The measurements were taken within the footprint of the EC tower in the vine rows, as it was not possible to measure in the alleys due to machine passage. Measurements were taken using the measured CO_2 concentration by soil chamber; then, soil CO_2 effluxes were measured as follows [53], (Equation (1)):

$$R_{\text{soil}} = u_s \times (-\Delta c) \quad (1)$$

where R_{soil} is soil respiration ($\mu\text{mol m}^{-2} \text{s}^{-1}$); u_s is the molar flow of air per square meter of soil ($\text{mol m}^{-2} \text{s}^{-1}$); and Δc is the difference in CO_2 concentration through the soil chamber.

The nonlinear least squares (NLS) regression is the most widely used method for the gap-filling of soil CO_2 efflux [54]. Therefore, to fill the gaps in soil CO_2 efflux, we applied (i) the Q_{10} [55] (Equation (2)), and (ii) the logistic model [56] (Equation (3)), by using the nls package in R software [57]. The best-fitted models were used to fill the gaps in R_{soil} (based on Akaike's Information Criterion (AIC), R-squared (R^2), Mean Absolute Error (MAE), and Root Mean Squared Error (RMSE)). The Q_{10} model was also used to estimate the Q_{10} value.

$$R_{\text{soil}} = R_{\text{ref}} \cdot Q_{10}^{\left(\frac{T - T_{\text{ref}}}{10}\right)} \quad (2)$$

where R_{soil} is the soil respiration; R_{ref} is the fitted R_{soil} at the reference temperature of 10°C (T_{ref}); Q_{10} is the temperature sensitivity of R_{soil} , defined as the factor by which R_{soil} increases with a 10°C temperature increase; and T is soil temperature.

$$R_{\text{soil}} = \frac{a}{(1 + b \cdot \exp(-k \cdot T))} \quad (3)$$

where R_{soil} is soil respiration; a is the maximum value of R_{soil} ; b determines the elongation of the R_{soil} curve along the x-axis; k is the logistic growth rate or steepness of the R_{soil} curve along the x-axis; and T is soil temperature.

After computing Reco and R_{soil} , the aboveground respiration (RAG) was calculated as below [Equation (4)]:

$$\text{RAG} = \text{Reco} - R_{\text{soil}} \quad (4)$$

2.2.3. Soil Properties and Meteorological Variables

To analyze soil properties, we collected 15 soil samples at a depth of 10 cm. Soil samples were oven-dried (at $110 \pm 5^\circ\text{C}$), weighed, and sieved (2 mm mesh size) in the laboratory. Soil bulk density was determined by dividing the weight of dried soil by the sample volume [58]. The pipette method was used for soil texture determination [59]. Soil porosity and soil water retention were determined as described by Spasić et al. [60]. The determination of soil nitrogen (N) was done by the Kjeldahl Method [61], and soil organic carbon (C) was estimated by the Walkley and Black Method [62]. Soil pH was measured by a pH meter with soil having a deionized water ratio of 1:2.5 (m:v; ino Lab pH 730, Carl Stuart Limited, Tallaght Business Park, Dublin 24, Ireland).

Climate variables including soil temperature (at 10 cm depth; PT100/8, EMS, Czech Republic), air temperature, relative humidity (at a height of 2 m above ground level; HMP155C probe, Vaisala Corporation, Helsinki, Finland), and the global radiation (R_g ; CMP 6 pyranometer, AZO, Czech Republic) were collected in 30 min intervals (April–September 2022). Daily sum precipitation (MR3H-01s, METEOSERVIS, Czech Republic) was collected from the nearest meteorological station (meteorological station in Mochovce; 2 km). Vapour pressure deficit (VPD) was estimated by ReddyProc from air temperature and RH [46]. The estimation of the energy budget closure was not possible due to the absence of sensors for net radiation and soil heat flux.

2.3. Data Analysis

All statistical comparisons were performed by the ANOVA (normally distributed data; Tukey test, $p < 0.05$) or the Kruskal–Wallis test (non-normally distributed data; Dunn test, $p < 0.05$) after assessing the normality of the data and homogeneity of the variance [63,64]. All statistical analyses were performed by R version 4.1.12 [65]. The regression analyses were used to examine the response of NEE, GEE, Reco, and Rsoil to the environmental factors.

3. Results

3.1. Meteorological Variables

Seasonal patterns of daily averages of the main environmental variables over a growing season (April–September) are presented in Figure 1. Overall, the air and soil temperature ($^{\circ}\text{C}$), vapour pressure deficit (VPD, hPa), global radiation (R_g ; $\text{MJ m}^{-2} \text{d}^{-1}$), and latent (LE; $\text{MJ m}^{-2} \text{d}^{-1}$) and sensible heat flux (H ; $\text{MJ m}^{-2} \text{d}^{-1}$) values gradually increased as the growing season progressed; once they reached their peak in June/July/August, they started to decline again and reached their lowest value at the end of the growing season. At the same time, an opposite pattern was detected for relative air humidity (RH%) (Figure 1).

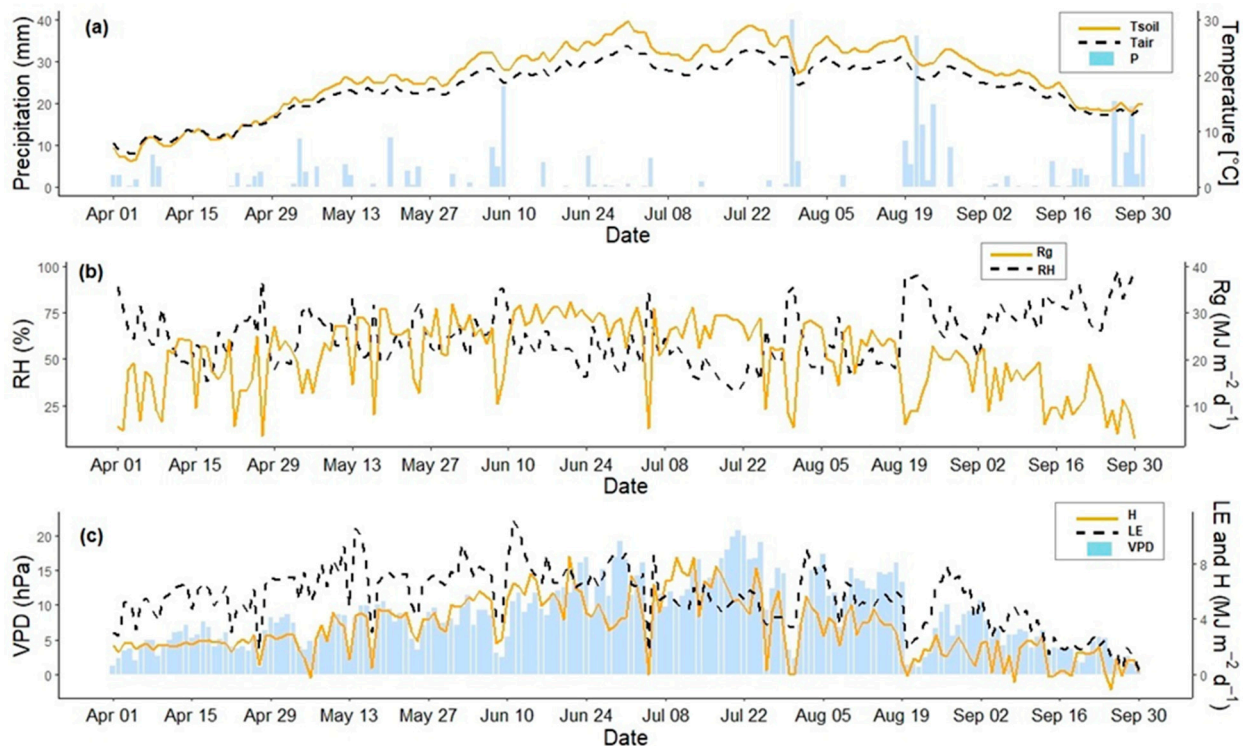


Figure 1. Seasonal course of daily averages of the main environmental variables over a growing season (April–September, 2022): (a) sum daily precipitation (P , mm d^{-1}), (b) air temperature (T_{air} , $^{\circ}\text{C}$) and soil temperature (T_{soil} at 10 cm depth), (c) relative air humidity (RH%) and global radiation (R_g , $\text{MJ m}^{-2} \text{d}^{-1}$), (c) vapour pressure deficit (VPD, hPa), latent (LE) and sensible heat flux (H , $\text{MJ m}^{-2} \text{d}^{-1}$).

During our measurement period, the warmest months were June, July, and August, and April was the coldest (Figure 2a,b; $p < 0.001$). Further, we found that the soil temperature at a depth of 10 cm exceeds the atmospheric temperature (Figure 1a). The highest value of R_g was recorded for June and the lowest value for September (Figure 2c). LE in May and June was significantly higher than in other months, while June and July were the months with the highest value of H (Figure 2d,e). The driest period of our measurement period was between April–July, and the amount of precipitation during April–July was

significantly lower than in August and September; the majority of the precipitation fell at the end of the growing season (Figure 2f). RH showed the opposite pattern to VPD; RH reached its lowest value in July when the highest value of VPD was recorded. On the other hand, September was the month with the lowest value of VPD and the highest value of RH (Figure 2g,h).

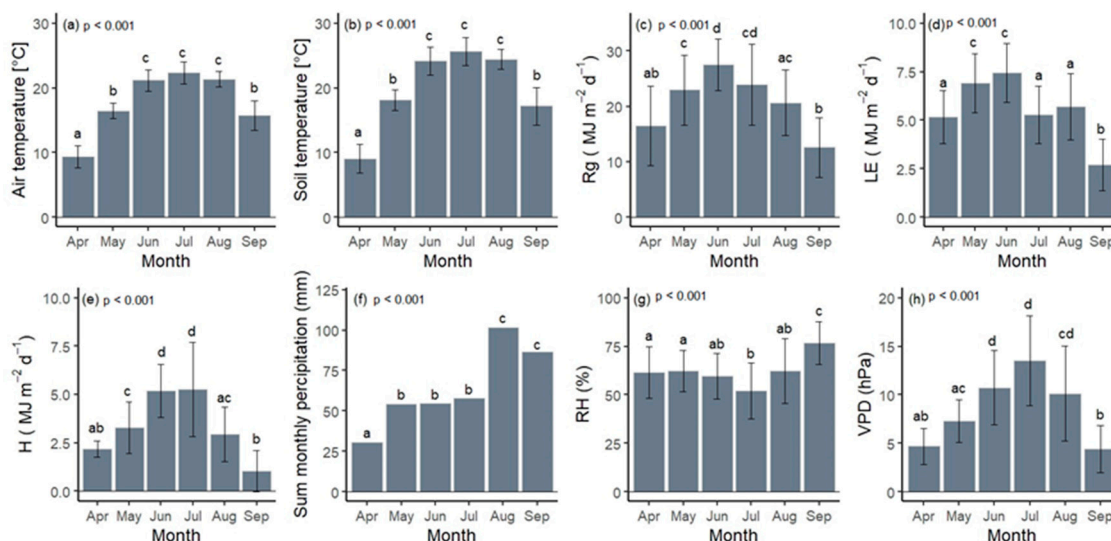


Figure 2. The daily mean value of (a) air temperature, (b) soil temperature (10 cm depth), (c) Rg, (d) LE, (e) H, (f) sum monthly precipitation, (g) RH, and (h) VPD. Error bars indicate standard deviation. Significant differences were found between months for all environmental variables ($p < 0.001$) and month-to-month variations are indicated by different letters.

3.2. Dynamics of CO₂ Fluxes

In total, NEE or the net uptake of CO₂ for the whole growing season was ca. -97 g C m^{-2} . Our case study ecosystem uptake was ca. -799 g C m^{-2} from the atmosphere through photosynthesis (by convention, CO₂ uptake from the atmosphere has a negative sign; therefore, NEE and GEE < 0). On the other hand, it released ca 699 g C m^{-2} to the atmosphere through respiration (Reco), for the whole growing season. Diurnal averaged NEE fluxes were $-0.53 \pm 1.03 \text{ g C m}^{-2} \text{ d}^{-1}$, which varied between -4.06 and $3.36 \text{ g C m}^{-2} \text{ d}^{-1}$. Its value was almost negative during May–September; in contrast, it acted as a source of CO₂ during April, which is indicated by the positive values. The mean daily value of GEE was $-4.35 \pm 1.30 \text{ g C m}^{-2} \text{ d}^{-1}$, and the mean daily value of Reco was $3.82 \pm 0.72 \text{ g C m}^{-2} \text{ d}^{-1}$ (Figure 3).

The highest value of the net CO₂ uptake was during May ($-1.44 \pm 1.27 \text{ g C m}^{-2} \text{ d}^{-1}$) and was significantly higher than in April and August. The lowest value was recorded for April ($1.27 \pm 0.69 \text{ g C m}^{-2} \text{ d}^{-1}$; Figure 3a) which was significantly lower than other months. In the meantime, the highest amounts of gross productivity and ecosystem respiration were also recorded for May and the lowest value for April (Figure 3b).

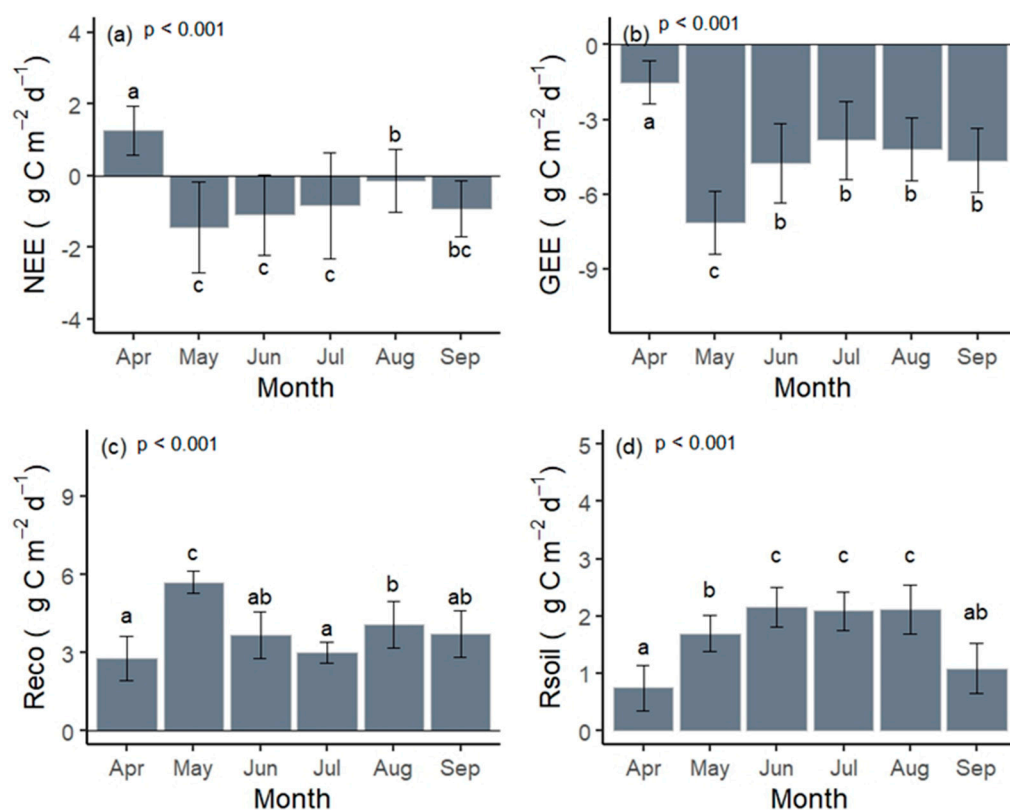


Figure 3. The mean diurnal cumulative (a) net ecosystem exchange (NEE), (b) gross ecosystem exchange (GEE), (c) ecosystem respiration (Reco), and (d) soil respiration (Rsoil). Negative flux represents CO₂ uptake and a positive one is the reverse. Different letters indicate significant month-to-month differences.

3.3. Diurnal and Seasonal Variability in Rsoil

The cumulative carbon loss by the vineyard soil was ca. 302 g C m^{-2} for a growing season, and the mean diurnal cumulated Rsoil was $1.65 \pm 0.37 \text{ g C m}^{-2} \text{d}^{-1}$. The lowest value of Rsoil was observed in April ($0.75 \pm 0.39 \text{ g C m}^{-2} \text{d}^{-1}$) and the highest value in June ($2.15 \pm 0.35 \text{ g C m}^{-2} \text{d}^{-1}$). The Rsoil values in June, July, and August were significantly greater than in April, May, and September (Figure 3d). Overall, Rsoil exponentially followed the trend of soil temperature, and 69–85% of the variation in Rsoil was explained by temperature (Table A2).

3.4. Comparing Reco and Rsoil

Overall, Rsoil accounted for ca. $44 \pm 18\%$ of Reco for the whole measurement period and was consistently lower than Reco (Figure 4b). The proportion of Rsoil to Reco varied between months (27% to 70%; Table 2): Rsoil in Jul accounted for the highest fraction of Reco (70%; Table 2), while in April, Rsoil accounted for 27% of Reco. Aboveground respiration (RAG) accounted for ca. $56 \pm 27\%$ of Reco. May (4.01 ± 0.11) reached the highest value of RAG, and the lowest value of RAG was recorded for July (0.90 ± 0.06 ; Table 2).

Further, our result indicated that the temperature sensitivity (Q_{10}) of both Reco and Rsoil is similar during the cooler months (April and September), but during the warmer months (May, June, July, and August), the Q_{10} value from Rsoil is almost twice that of Reco. In contrast, computed Rref from Reco is notably higher than Rsoil for all six months (Table 2).

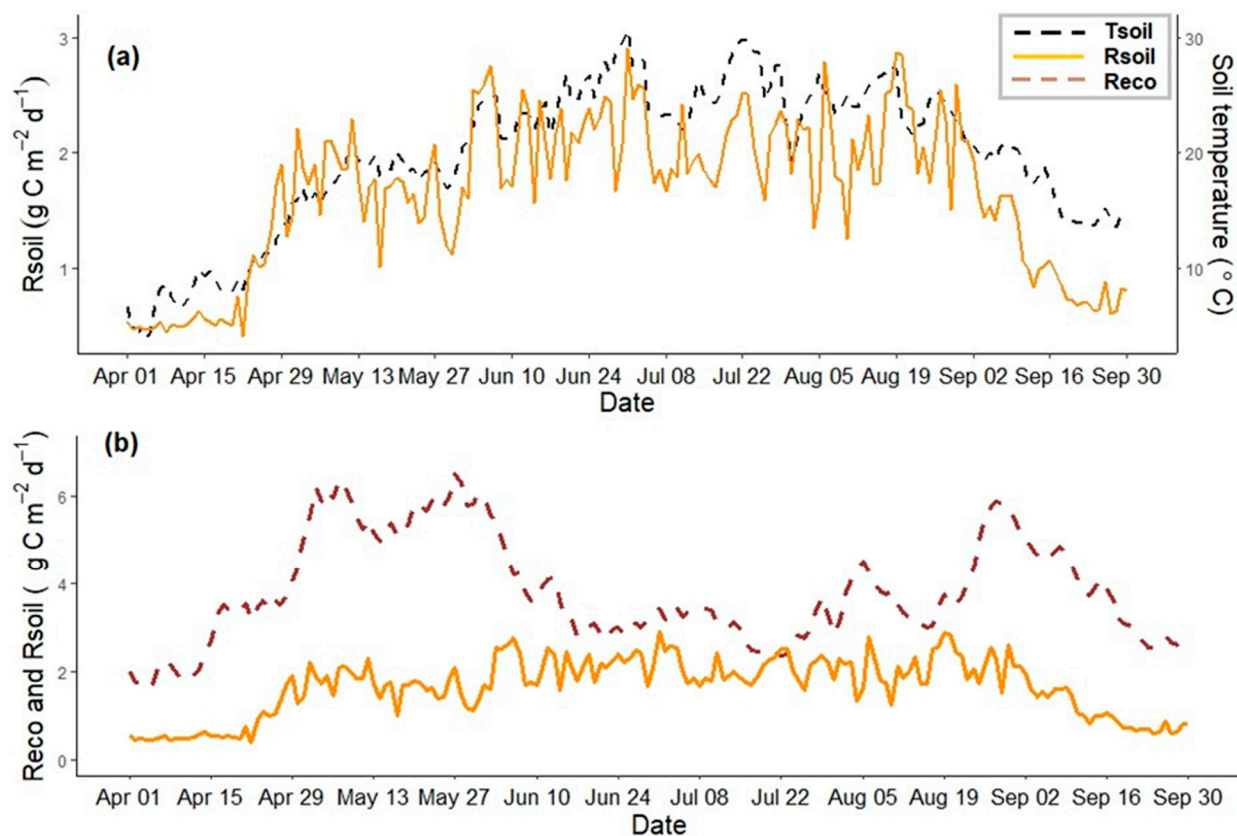


Figure 4. (a) Seasonal patterns of daily averages of Rsoil and soil temperature, (b) comparison of Reco to Rsoil over a growing season.

Table 2. The values of Q_{10} (temperature sensitivity) and Rref (soil respiration at the temperature of 10 °C), aboveground respiration (RAG), and Rsoil fraction to Reco.

Parameters	Flux	April	May	June	July	August	September
Q_{10}	Rsoil	3.24	2.41	2.36	2.54	1.88	2.98
	Reco	3.20	1.30	1.32	1.63	1.35	3.16
Rref	Rsoil	0.70	0.75	0.67	0.60	0.98	0.64
	Reco	3.96	5.80	4.80	2.40	4.65	2.01
RAG		2.03 ± 0.46	4.01 ± 0.11	1.51 ± 0.54	0.90 ± 0.06	1.94 ± 0.47	2.62 ± 0.47
Rsoil fraction to Reco (%)		27	30	59	70	52	29

3.5. Response of CO₂ Fluxes to Major Environmental Variables

All flux parameter (NEE, GEE, Reco, Rsoil) responses were almost significant to temperature, VPD, and Rg. On the contrary, no significant correlations were detected between precipitation and CO₂ fluxes (Figure 5). The net and gross uptake of CO₂, and Reco tended to increase with the increasing temperature and VPD. They reached their peak at specific values of temperature (ca. 17 °C) and VPD values (10 hPa). Then, their value started to decline with further increases in temperature and VPD. Based on the R-square (R^2) values, Rg ($R^2 = 0.32$) and VPD ($R^2 = 0.29$) were identified as the most important driving factors for NEE. Meanwhile, temperature and VPD were detected as the main driving factors for Rsoil, Reco, and GEE (Figure 5).

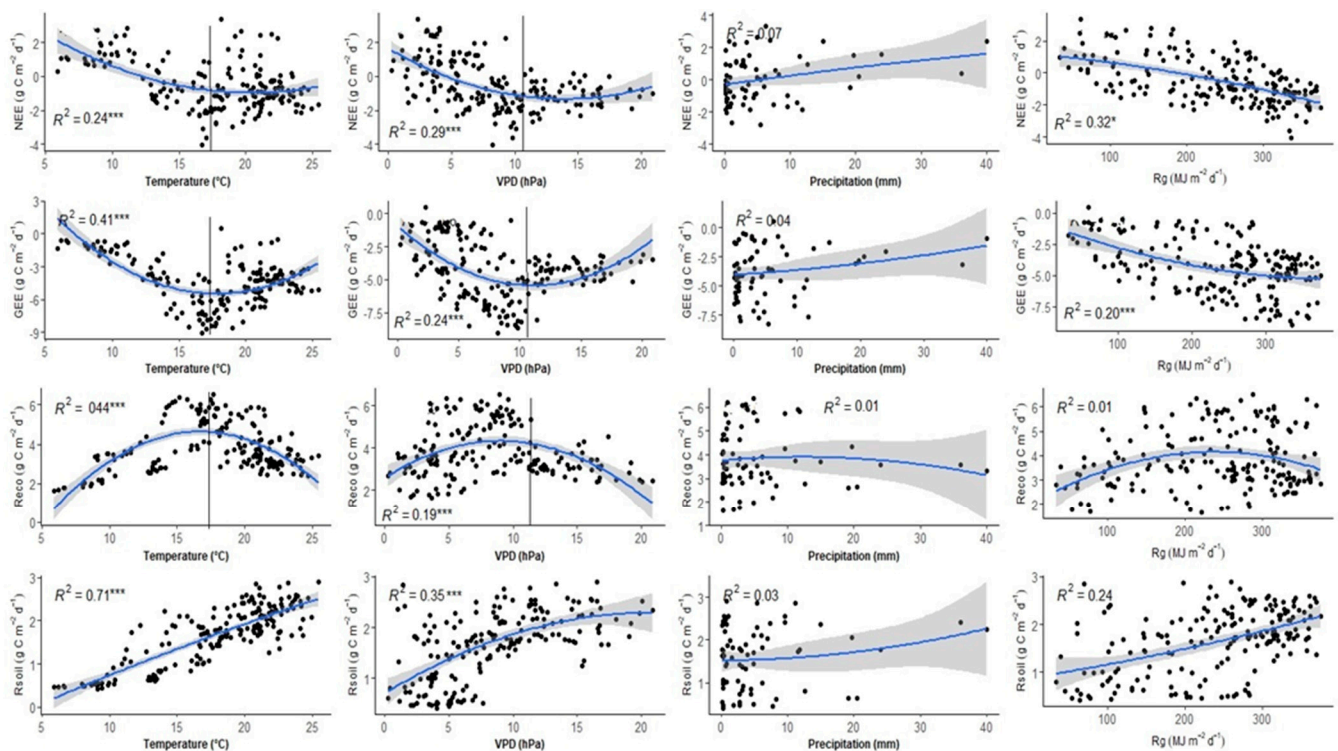


Figure 5. Response of NEE, GEE, Reco, and Rsoil to the environmental variables ($n = 183$). The asterisks indicate significance levels of R-square at the 95% (*), 99.9% (***)

4. Discussion

4.1. Variability in NEE, GEE, and Reco

The reported amounts of annual net carbon accumulation in vineyards ranged between -69 to -961 g C m⁻² yr⁻¹ [10,19,23,39,40,42,66], and some of them were considerably higher than our finding (-97 g C m⁻²). In fact, the higher values of NEE in these research findings resulted from the lower values of Reco. For instance, in the arid area of China where a vineyard reached the highest value of NEE [-961 g C m⁻² yr⁻¹; 39], the annual GEE was ca. -1274 g C m⁻² yr⁻¹, which is not considerably more than our finding (-796 g C m⁻² for a growing season). But they could record the highest amount of NEE due to a lower value of Reco (286 g C m⁻² yr⁻¹), which was much smaller than our finding (699 g C m⁻² for a growing season). Therefore, despite a higher amount of GEE, the role of our vineyard in carbon sequestration was weak [41], because ca. 88% of carbon uptake was released again into the atmosphere through respiration. However, this value was ca. 90% of GEE in an irrigated vineyard in Italy [10], while it accounted for just 22% of GEE in China and made it a strong carbon sink [39]. This finding suggests the importance of Reco for agroecosystem management for carbon sequestration.

In perennial systems, cover crop mowing can raise the amount of greenhouse gas (GHG) emissions even up to 10–20 times after subsequent irrigation or precipitation [67,68]. Therefore, a possible explanation for the higher amount of Reco could be frequent mowing and surface mulching by grass clippings and pruned branches. The retention of grass clippings on the soil surface during April, July, and November, and returning pruned branches as the surface mulch in March, probably increased carbon emission (Reco) in our study site due to rapid decomposition [19]. A study from the USA also found a significant effect of mowing on Rsoil, particularly after rainfall [21]. However, in our study, mulching may not affect the Rsoil, because Rsoil measurements were performed on the vine rows, and grass clippings were left on the tractor row (alleys) surface. More work is needed to verify the mulching effect on Rsoil, and consequently, Reco.

4.2. CO₂ Flux Response to Environmental Variables

May was the month that reached the highest value of NEE (negative value), GEE, and Reco (Figure 3). An increase in NEE is expected with increasing GEE; on the other hand, with an increase in GEE, larger crop biomass is also expected, which provides more respiring tissues [69]. Therefore, an increase in GEE consequently increased NEE and Reco. However, in contrast to our finding, the highest value of NEE in the irrigated vineyards was reported for the mid-growth stage [19,39]. A study in a forest area attributed the lower value of NEE at the mid-growth stage to the high Rsoil [70]; this might also be a reason for our case study, as we found the highest amount of Rsoil for the mid-growth stage (Figure 3d). Besides the high values of Rsoil, the water limitation in combination with heat stress can be the most important reason that June, July, and August acted as weak sinks of carbon in our case study [49,71]. As Figure 5 has shown, VPD and temperature can be limiting factors when they exceed a certain threshold, e.g., once the temperature is higher than ca. 17 °C and VPD is higher than ca. 10 hPa (Figure 5) [72]. Therefore, a higher amount of NEE and GEE in May could be induced by the coupling of warmer weather (16.5 ± 1.5 °C; Figure 2a) with a lower value of VPD/water stress (7.3 ± 2.2 hPa); [28,73–75]. Meanwhile, based on our result, 75% of Reco is explained by GEE (Figure A1); [29,76]. In this context, the highest amount of Reco in May is also reasonable [74]. May was the month with the lowest rainfall (Figure 2f); nevertheless, the highest values of NEE, GEE, and Reco were found for this month. Probably, the lower value of VPD maintains higher stomatal conductance, thereby potentially triggering an increase in the photosynthesis rate and subsequently leading to higher NEE and Reco values [73,77]. Alternatively, a higher amount of Rg could be another influencing factor, considering the significant correlations observed between NEE and GEE with Rg (Figure 5); [23]. Conversely, the high VPD associated with high temperatures and low rainfall during the summer months might suppress the photosynthesis rate and decrease productivity in our non-irrigated vineyard, particularly in July (Figures 2a,f,h and 3). This observation implies the importance of water availability in carbon sequestration [69,78–80] and aligns with the findings of Marras et al. [19], who suggested that a vineyard can reach relatively high values of NEE during the summer months (June, July, and August) if the vineyard is provided with supplementary irrigation.

4.3. Rsoil and Reco Comparison

We found that Rsoil accounted for ca. $44 \pm 18\%$ of Reco for the whole measurement period, and it was consistently lower than Reco, which answers our second research question (Figure 4b). However, according to the most recent estimations in a vineyard in Italy, Rsoil accounts for 83% of Reco [10]. As we described before, the higher fraction of Rsoil could be due to the higher amount of fine roots in that 14-year-old vineyard [81,82].

A similar temporal pattern for Reco and Rsoil has been reported [10,33], but we could not find a similar pattern for these two effluxes (Figure 4b). In particular, July, being a hot and dry month, approached the highest value of Rsoil, while Reco in July was significantly lower than in other hot months (June, August, and May; Figure 3c). This finding may imply that the influence of temperature on Reco is much smaller than on Rsoil, which may emphasize the much lower sensitivity of Reco to climate warming [83,84]. This fact is also confirmed by the lower Q₁₀ values for Reco, compared to Rsoil (Table 2), suggesting that soil is more vulnerable to losing carbon through respiration as a result of global warming compared to Reco. But if we remove the effect of temperature on respiration (Rref), CO₂ emission through the ecosystem (Reco) reaches values 4–7 times larger than soil CO₂ efflux, and may suggest higher sensitivity of Reco to non-temperature factors [84]. Furthermore, our result indicated that 75% of Reco variation is explained by GEE (Figure A1); in this context, the variables that influenced GEE, such as water availability, could indirectly influence Reco [29,76]. Meanwhile, the Rsoil was more sensitive to temperature [27,29,85]. Reco and Rsoil showed different patterns probably because of the different driving variables.

4.4. Dynamics of Rsoil and Its Environmental Responses

In comparison to other vineyards, we found a similar value of Rsoil ($1.65 \pm 0.37 \text{ g C m}^{-2} \text{ d}^{-1}$) to irrigated vineyards in China ($2.28 \text{ g C m}^{-2} \text{ d}^{-1}$); [86], and in Chile ($2.74 \text{ g C m}^{-2} \text{ d}^{-1}$) [81]. On the other hand, the Rsoil value in our study was notably lower than the reported Rsoil in the Mediterranean vineyards ($11.92 \text{ g C m}^{-2} \text{ d}^{-1}$ Lardo et al. [87], ca. $10.37 \text{ g C m}^{-2} \text{ d}^{-1}$ Escalona et al. [88] and Callesen et al. [10]). The lower value of Rsoil can be attributed to the lower productivity in our study (Figure 3b), which could not provide the substrate for respiration, particularly during the summertime [27,28,73,89]. It is well known that temperature has a regulating role on Rsoil [33]. Besides temperature, Rsoil can also be affected by soil properties, including soil organic carbon, bulk density, and pH [90–93]. Therefore, the higher amount of soil organic carbon which was reported by Callesen et al. ([10]; $14.1 \pm 0.7 \text{ kg C m}^{-2}$) could be a reason for the conflicting result, as their report was notably greater than our result (Table 1; $3.04 \pm 0.41 \text{ kg C m}^{-2}$). Alternatively, the difference in fine root biomass or age could also explain the variation in Rsoil, as the decline in Rsoil with increasing stand age has been reported [94,95]. Rsoil can decrease with stand age because of decreasing fine root production [96,97]. Our site is an old-growth vineyard (47 years old) and older than other sites (1 year old, Escalona et al. [88], 14 years old, Callesen et al. [10]). Therefore, a decline in fine root production in our mature site may be another reason for the lower value of Rsoil [81,82]. Moreover, finding a strong influence of temperature (exponentially ca. 69–85%) on Rsoil and a positive correlation between Rsoil and VPD (Figure 5) may confirm the regulating role of temperature and a minor role of the soil moisture on Rsoil [20,86]. Ceccon et al. [83] also found a similar trend of Rsoil to temperature (as the main driver) and water content (a negative correlation) in a 27-year-old apple orchard in Italy.

4.5. Limitations of the Study

The results obtained in this study should be extrapolated with caution to other non-irrigated vineyards. In fact, cultivated ecosystems display specific responses to agronomic practices, fertilization, genetic variability of plant and rootstock material, and training systems. The presence and management of cover crops further complicate the ecosystem response. In addition, this experiment lasted one single season; therefore, is not possible to extrapolate these findings in a longer time frame, and it also relies upon a limited set of measurement replicates. Therefore, further work, including multiple soil respiration measurements along the vines and alleys, is required to validate our results. Nevertheless, this study represents a novel insight into Central Europe vineyard cultivation functioning.

5. Conclusions

In our conditions, the sink capacity of a non-irrigated vineyard was proved, which aligns with findings in other studies. However, it is important to note that a non-irrigated vineyard cannot be considered a strong sink of CO₂, particularly in areas with dry and warm summers. We further conclude that Rsoil, which accounts for 44% of the Reco, is not the main contributor of carbon emission in a mature vineyard. Our results also suggest that the combination of rising air temperature with VPD may have a positive impact on plant productivity during spring or the humid season, particularly in May. Conversely, during summer, water availability can be the most important factor; thus, coupling high temperature with high VPD can cause productivity to decline in a non-irrigated agroecosystem during summer or dry season.

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Appendix A

Table A1. The relative proportions of soil aggregate at the 0–20 cm depth.

Soil Aggregation Size Class (mm)	<0.001	0.001–0.01	0.01–0.05	0.05–0.25	>0.25
The proportions of aggregate fractions (%)	31	15	22	22	10

Table A2. Mean values of MAE (Mean Absolute Error), Root Mean Squared Error (RMSE), R² (R-square), and AIC (Akaike information criterion) for each model (logistic and Q₁₀).

	April	May	June	July	August	September
AIC Q ₁₀ model	26	228	237	140	228	142
AIC logistic model	25	163	196	137	194	118
R ² Q ₁₀ model	0.83	0.68	0.80	0.66	0.57	0.64
R ² logistic model	0.84	0.80	0.85	0.69	0.70	0.73
MAE Q ₁₀ model	0.21	0.41	0.45	0.50	0.60	0.42
MAE logistic model	0.21	0.30	0.39	0.47	0.49	0.35
RMSE Q ₁₀ model	0.30	0.52	0.54	0.61	0.71	0.50
RMSE logistic model	0.29	0.41	0.47	0.59	0.60	0.44

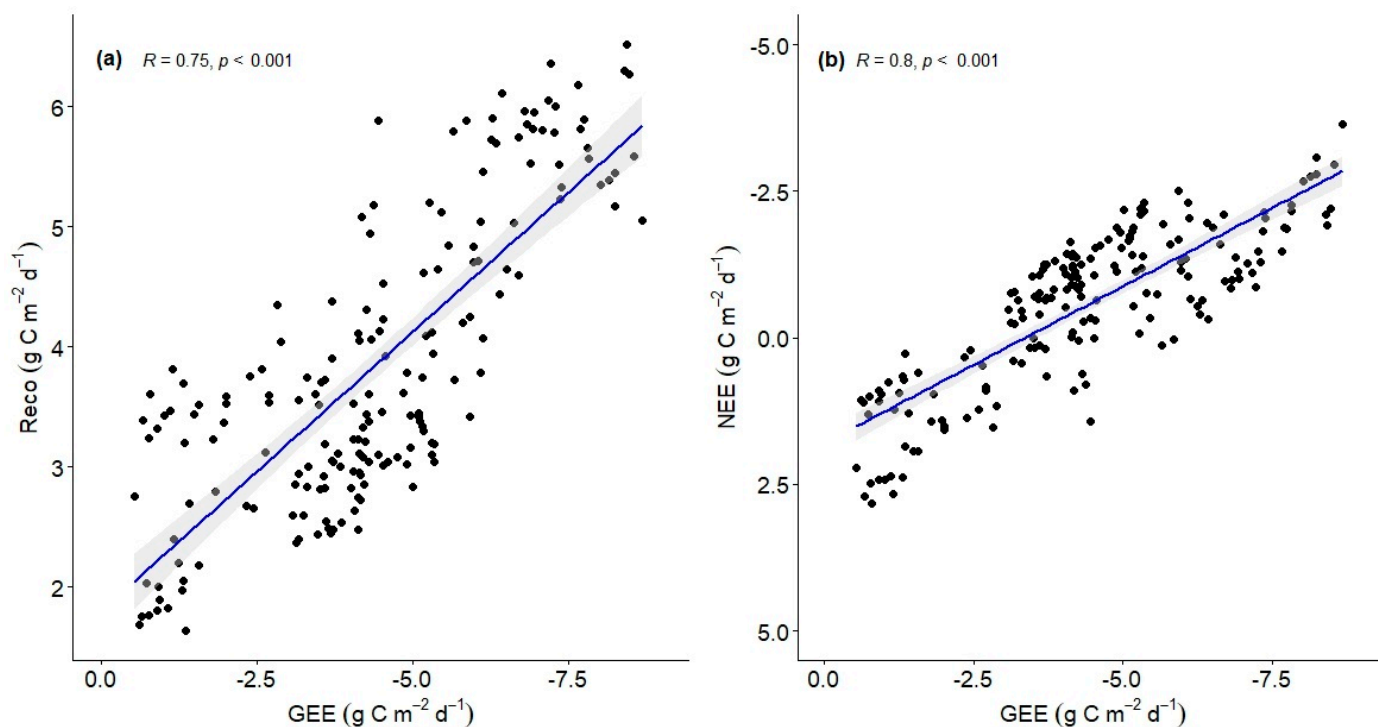


Figure A1. The relationship between GEE with (a) Reco, and (b) NEE.

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