Analysis and Modeling of Soil Respiration in a Turkey Point Deciduous Forest

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Abstract

Soil water content and temperature are major controls on the soil carbon budget in forest ecosystems. Stored organic matter within the ecosystem is released into the atmosphere through heterotrophic and autotrophic activity referred to as soil respiration (Rs). An appropriate soil respiration model can assist in forest management and improve understanding of major environmental controls under future climate change. We collected and evaluated half-hourly data in the Global Water Futures (GWF) – Southern Forests Water Future (SFWF)'s Turkey Point Deciduous Observatory from a closed-path eddy covariance system as well as automatic soil CO_2 efflux chambers (LI – 8100A) which monitored Rs continuously since July 2014. Observed monthly mean Rs varied from a maximum of 7.50 µmol m^{-2} s^{-1} in July to a low of 1.11 µmol m^{-2} s^{-1} in December and showed a seasonal trend driven by soil temperature and water content. Three models: a general exponential regression model (Rs Ts), Q_{10} with a logistic soil moisture function model (Rs SM), the Q_{10} model (Rs Q_{10}) were used to analyze Rs and soil temperature and soil water content controls. Comparison of the three models showed that the Rs SM model is best with an average yearly coefficient of determination of 0.68. The Rs SM model shows that by incorporating soil water content, it is able to improve upon models such as Q_{10} that utilize soil temperature only to predict respiration. Study results show that Rs measurement and modeling studies should account for seasonal variations of temperature and water content within the soil. In addition, future work could include measurement of Rs during the winter and development of an accurate, predictive model.

1. Introduction

Forests account for 3.7 billion hectares of the planet's surface area and cover around 31% of the world's land surface. They primarily provide vital services at both global regional scales; including the regulation of climate, hydrological

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cycles, air and water quality, and biogeochemical cycles (Apps and Price, 1996; Matsumoto et al., 2008). In addition to these ecosystem services, they provide significant economic resources to various industries related to lumber, pulp, and construction.

Soil respiration (Rs) is the release of CO_2 through heterotrophic and autotrophic activity and accounts for 30 – 80% of net CO_2 release within forests (Davidson and Janssens, 2006; Yiqi Luo and Xuhui Zhou, 2006). Within the carbon cycle, 10% of the atmospheric CO_2 is passed through the soil each year primarily through organic matter decay (Raich and Potter, 1995). Variability of Rs is influenced by diurnal, seasonal, and annual patterns along with multiple factors such as soil moisture and temperature. When compared to the atmosphere and biotic sinks the soil carbon sink is 3.2 and 4 times larger, respectively (Edenhofer, 2014; Lorenz and Lal, 2010). On account of the storage differences, a small change in Rs due to improper management techniques can result in a large release of CO_2 into the atmosphere.

Quantifying Rs can indicate various physiological processes, as well as the ability of soil to support life including plants, animals, and microorganisms (L. Liu et al., 2016). By modeling, mapping, and monitoring flux movement, forest management techniques can be utilized to decrease the amount of CO_2 released into the atmosphere. Changes in Rs rates can also indicate external processes, such as disturbance (for example cultivation) which typically increases Rs (Schlesinger and Andrews, 2000).

Rs models can be classified into two types: empirical and mechanistic. Empirical models typically use regressional analysis of Rs with temperature and moisture which is derived from observed data. Mechanistic models are created using environmental and biological factors that contribute to Rs. These models can be categorized into two parts: the CO_2 production model; which considers factors that produce CO_2, and the CO_2 production-transport models; which considers CO_2 production along with its transport to the soil surface.

The specific objectives of this study are to (1) gain a better understanding of the spatial and temporal dynamics of Rs, (2) determine how Rs responds to its main controlling variables (i.e. soil temperature and soil moisture), (3) help determine the impact of extreme weather events on Rs, (4) to compare several different models with varying complexity using a wide range of parameters, and (5) to determine which model produces the best fit and Rs estimation.

2. Materials and Methods

This study was conducted in a 90 – year old managed deciduous (Carolinian species) forest (TPD) northwest of Long Point Provincial Park in Southern Ontario, Canada (42.64°N, 80.56°W). The forest is naturally regenerated on sandy terrain and abandoned agricultural land, and has been managed (thinned in the past). Predominant tree species include: white oak (*Quercus alba*), sugar and red maple (*Acer saccharum, A. rubrum*), american beech (*Facus grandifolia*), black and red oak (*Q. veluntia, Q. rubra*), and white ash (*Fraxinus americana*). Average tree height is 25.7 m with a diameter at breast height of 22.3 cm. The leaf area index (LAI) of the site was measured by a canopy analyzer (model LAI-2000, LI-COR, Lincoln, Nebraska, USA) and TRAC (Tracing Radiation and Architecture of Canopy, developed by Dr. Jin M. Chen's group at the University of Toronto). This site is part of the Turkey Point Flux Station (TPFS) and associated with Ameriflux and global Fluxnet Networks. Further site information is found in Table 1.

The topography is undulating, with well − drained, mostly sandy soil (Brunisolic Gray Brown Luvisol) with low to moderate water holding capacity. The soil organic layer depth typically ranged from 2 to 6 cm. In September of 2014, soil cores and litter samples were taken and sent for nutrient analysis (A & L Canada Laboratories, Inc., London, Ontario). The samples were analyzed for total organic matter content, carbon, nitrogen, phosphorus, potassium, magnesium, calcium, and other additional soil characteristics. The soil nutrient content is outlined in Table 2. 30 − year climate normal, based on 1981 − 2010 Environment Canada weather data collected at Delhi, Ontario CDA weather station, indicate a mean annual temperature of 8.0°C and mean annual precipitation (PPT) of 136 mm (906.4 mm of which falls as rain and 129.5 cm as snow).

Continuous Rs was recorded using an automated soil CO_2 flux measurement system, taking half hourly measurements from July 2014 to November 2018 for the snow free growing season. Measurements are comprised of 3 main components: the gas analyzer (hosted in an analyzer control unit) (LI-8100A), long term measurement chambers (LI8100 − 104), and a multiplexer to allow for multiple chamber measurements (LI-8150) (LI-COR Lincoln, Nebraska, USA. Two measurement chambers were deployed from July to December 2014, and increased to five in April 2015. Each chamber extended approximately 15 m from the central analyzer control unit and multiplexer, measuring half − hourly Rs in sequence. Chambers are equipped with a soil temperature (Ts) and soil moisture (SM) probe (LI8150 − 203 and LI8150 − 205 respectively) at 5 cm depth installed outside of the collar.

The soil collars are comprised of thick − walled PVC pipe with an internal diameter of approximately 20 cm, a height of 11.5 cm, and a thickness of 1 cm. Each collar is inserted approximately 7 − 8 cm into the soil surface, with 3 cm remaining above. The measurement chamber is placed directly on the soil collar, remaining open when not taking active measurements. Throughout the growing season, any vegetation growth as removed from inside the collars to eliminate potential photosynthesis effects.

Measurements from the first chamber was removed from 2014 to 2017 due to a wasp nest causing increased CO_2 reports. Data is processed using Soil Flux Pro

(4.0.1) from LI-COR Biosciences, Inc. by analyzing the exponential flux and iteration obtained every 3 – 4 min within the 30 min measurement period. The exponential flux is the CO_2 flux determined by the exponential fit which uses the dilution corrected CO_2 (C) plotted against time in seconds (the difference between the start and stop time) (t) (Equation 1). The resulting plot is fit with a non-linear regression equation that solves for C_∞, t_0, and α where C_o is the starting measured CO_2 concentration. The CO_2 flux based on the slope of the regression equation is reported as the exponential flux.

$$C(t) = C_\infty + (C_0 - C\infty)e^{-\alpha(t-t_0)}$$

Measurements that report a higher exponential iteration (greater than 10) was processed further by changing the start time affecting the overall t value until the exponential iteration is less than 10.

Linear and non-linear analyses are performed on daily measure of measured Rs data for gap filling. Three models are derived to determine the correlation between Rs and its environmental controls, outlined in Table 3. The first is a simple, exponential regression between Rs and Ts (Rs Ts) by Hoff and Lehfeldt (1899), the second is the annual temperature response model (Rs Q_{10}). The third is the Q_{10} model modified with a logistic function (Khomik et al., 2010) to incorporate soil moisture effects (Rs SM). The models are evaluated using 70% of observed measurements for training and 30% of data for model testing.

Each model was used to simulate daily, yearly, and seasonal (spring = March – May, summer = June – August, Autumn = September – November, Winter = December – February) and growing season (March – November) Rs emissions, and compared to ecosystem respiration (RE) data derived from eddy covariance measurements. The models are evaluated using coefficient of determination (R2), error sum of squares (SSE), standard deviation (STD), relative error (RE), slope and intercept of the testing function to Y = x, and yearly fit to observed Rs.

The daily Rs recorded by automated chamber measurements during the study period are shown in Figure 1. The seasonal trend of Rs follow closely that of Ta and Ts, reaching maximum values in the summer months, then followed a declining trend throughout the rest of the year. An increase in Rs during and following precipitation events was observed. For example, on September 2nd, 2014 there was a 22.4 mm precipitation event which caused an increase of SM from 0.1 to 0.28 m^3 m^{-3} and an 88% increase from 6.5 to 12.2 µmol CO_2 m^{-2} s^{-1} (Figure 2).

Rs did not return of pre-rain event Rs until September 8th, 6 days after the rain event. On October 9th, 2017 there was a 11.7 mm precipitation event which caused an SM increase of 0.1 to 0.39 m3m-3 and an 78% in Rs from 5.97 to 10.63 µmol CO_2 m^{-2} s^{-1} (Figure 3) until October 29, 20 days after the rain event. Rs coverage at the site is 36.71%, 55.07%, 55.07%, 50.68%, and 55.62% from 2014 to 2018.

3. Results

A comparison of modeled and observed daily mean Rs during the growing season for all years are shown in (Figure 4). The modeled vs observed regression analysis and the coefficient of determination of each model is shown in Table 4. Model relative error is shown in (Figure 6) and standard deviation with error sum of squares are shown in Table 5. In all years (with the exception of 2014 and 2016) the Rs SM model produced the highest correlation coefficient and the lowest SSE. The relative error between the Rs Ts and Rs Q_{10} is relatively similar with a standard deviation

To better visualize the temporal trends in model fit, the daily relative error of each fitted models is plotted in a stacked bar plot over the study period (Figure 6). There were clear seasonal trends for all of the models. In all of the years, the models produced a positive relative error values during the summer months (June, July, and August), representing an underestimation of Rs values. Towards April/May to the summer months and at the end of August towards the end of the measurement period, the models were produced negative relative error indicating an overestimation of Rs. There were large relative error values at the end of 2014 and at the beginning of 2016 to 2018 which could be the result of instrumentation problems resulting in a loss of Rs data, inhibiting the ability to produce a model that accurately predicts Rs during that season. Another possibility could be due to high temperatures in 2016 which is followed by a high precipitation event in 2017 and the re-addition of another chamber in 2018.

When daily relative error is plotted against a function of temperature, (Figure 5) Rs Ts and Rs Q_{10} is shown to have similar relative error values with all models resulting in positive relative errors during high temperatures and negative relative errors at low temperatures (with the exception of 2017 and 2018). In 2017, relative error was uniform at higher temperatures indicating better model prediction. In 2018, relative error was consistent throughout temperature ranges due to the addition of another chamber and increased training sample size.

Each model was used to simulate seasonal and growing seasonal Rs emissions which are summarized in Table 6. Across the three models, spring had the lowest carbon emissions. The highest estimates were in the summer season, with emissions declining again the autumn and winter. No model estimated below 1200 m^{-2} s^{-1} in 2014, 2017 and 2018.

4. Discussion and Conclusion

The effect of temperature on Rs can be expressed using the Q_{10} model coefficients, R_{10} and Q_{10} (Table 4. The basal respiration rate at 10°C (R_{10}) is related to the volume of the soil column that is biologically active, i.e. the size and activity of microbial and root population (Mo et al., 2005).The Q_{10} value is the temperature sensitivity of Rs to warming (Jia et al. (2013)). The Q_{10} values obtained at our site were found to range from 1.70 to 2.36 (Table 4) and R_{10} values ranged from 2.84 to 4.73. This was found to be within range of literature – reported values (Greco and Baldocchi, 1996; Tang et al., 2014; Xu et al., 2004) and followed distinct seasonal trends.

Few studies have quantified the total contributions of Rs pulses following rain events to total Rs. Lee et al. (2002) reported an increase in Rs rates of 16 – 21% following rain events in a temperate deciduous forest in Japan. B. Liu et al. (2016) conducted a meta – analysis on precipitation treatments across multiple biomes and found that precipitation events in temperate forests cause an increase in Rs of 17 – 30%. Furthermore, drought can also influence soil respiration. The study concluded that longer drought periods showed an increase in soil and heterotrophic respiration in accordance to the period of drought. This is shown in (7) where after a long period of drought in September 2017 (a period of 19 days; Figure 8), a precipitation event caused a spike in Rs greater than those seen in early to mid – summer.

2014 models produced a poor yearly fit and coefficient of determination mainly because of 3 factors: the lack of data coverage from measurement later within the season, the removal of one chamber due to high CO_2 measurement from a wasp nest, and the number of chambers (3 in 2014 compared to 5 in 2015). This resulted in dependent on time series data training to produce a worse fit. More complex models (Rs SM) produced a spike in Rs during the measurement period and low Rs before the period. Whereas models such as Rs Ts and Rs Q_{10} produced a constant increase and decrease throughout the year. This is likely due to seasonal bias causing the equations to underestimate indicating that in years with no extreme events or anomalies, a simpler model is suitable for estimation.

2015 models on average produced a higher coefficient of determination with the addition of more chambers. However, the Rs Q_{10} and Rs Ts model produced a much lower increase indicating that the annual Q_{10} model may not reflect true temperature sensitivity since it can be obscured by other seasonally – varying factors such as root biomass, photosynthesis rates, and litter inputs (Curiel yuste et al., 2004; Gaumont-Guay et al., 2006). When incorporating soil moisture, the models produced a better yearly fit. Soil moisture has numerous effects on ecosystem metabolism and growth, and thus is an important factor influencing low Rs. Low soil moisture conditions can decrease the temperature sensitivity and lower the overall rate of Rs (Davidson and Janssens, 2006; van der Molen et al., 2011; Xu and Qi, 2001). High soil moisture can limit the diffusion of oxygen to microbial communities for relative humidity (Pumpanen et al., 2008).

2016 models produced an average low fit because of low precipitation and higher yearly temperatures creating relatively low Rs compared to previous years causing models dependent on soil temperature and moisture to underestimate. 2017 models produced a slightly better fit compared to 2016, however because of an extremely high precipitation event, the overall fit is comparably less than 2014 and 2015. All models have a close relationship with Ts and follows the Ts curve accordingly each year. However, because of the high amount of Ts early within the season due to a high precipitation event (57.39 mm), the models based on only Ts overestimated Rs early within the growing season (Rs Ts, Rs Q_{10}).

This event was closely followed with another, slightly lower precipitation event (39.70 mm) which caused Rs to rapidly increase and models to underestimate. In October 9th, there was an extreme precipitation event of 81.44 mm causing Rs to spike to 11.86 µmol CO_2 m^{-2} s^{-1}. However, because the soil moisture did not increase as high due to excess saturation of the ground and runoff, models dependent on both soil temperature and soil moisture underestimated Rs (Rs SM).

2018 models are able to produce a better yearly fit because of a one measurement chamber being re-introduced increasing the amount of training data. The year showed relatively similar soil temperature and moisture to 2014 and 2015 with no extreme precipitation events. There were two spikes in Rs in July and September corresponding to two precipitation events the first of which (July) caused underestimation in models using only Ts and SM. The second spike in Rs (September) was able to be accurately predicted by all models involving soil moisture.

This study has provided important insight on the temporal and spatial dynamics of Rs. The addition of temporal and SM considerations have shown to increase the modeling accuracy of traditional models such as Q_{10}. Many future climate change scenarios predict an increased probability of intense precipitation events (Edenhofer, 2014), and a quantitative understanding of the Rs rain response is a necessary consideration in the development of an accurate global carbon cycle model. Future work could include a quantification of the contribution of precipitation – induced pulses in Rs to annual total Rs in temperate deciduous forests, considering the measurement of Rs during the winter, as well as the further development of an accurate, predictive model through improved understanding of spatial and temporal dynamics of Rs.

Tables and Figures

Table 1: Site description of a 90 - year old managed deciduous (Carolian species) forest.

Characteristic	Description
Water Table Depth (m)	2 - 3.5
Stand Density (Trees Ha^{-1})	504±5
Area (Ha)	49
LAI (m^2m^{-2})	8.00
Elevation (m)	210.60
Climate	Cool, temperate
Mean Temperature (^{o}C)	7.80
Precipitation (mm)	1010
soil pH	5.00

Table 2: Selected values of soil nutrient content of litter fall horizon (LFH), Turkey Point Deciduous (TPD).

Soil Layer	OM (%)	P (ppm)	K (ppm)	Mg (ppm)	Ca (ppm)	pH	C/N Ratio
Litter	28.80	93.00	127.00	274.30	2186.00	6.00	15.90
0 to 15 cm	3.50	126.00	24.00	52.00	458.00	4.90	13.30
15 to 35 cm	1.30	170.00	10.00	33.00	315.00	5.30	12.70

Table 3: Selected values of soil nutrient content of litter fall horizon (LFH), Turkey Point Deciduous (TPD).

Model	Formula	References
Rs Ts	Rs = ae^{bTs}	Hoff and Lehfeldt (1899)
Rs Q_{10}	Rs = $R_{10}Q_{10}$ $^{(Ts-10)/10}$	Curiel Yuste et al. (2004)
Rs SM	Rs SM = $R_{10}Q_{10}$ $^{(Ts-10)/10}$ * (1/1+e^{a+b*SM})	Chan et al. (2018)

Table 4: Training results and coefficient of determination (R^2) for the Rs Ts, Rs Q_{10}, Rs SM models from 2014 to 2018.

Models	Variables	2014	2015	2016	2017	2018	All
Rs Ts	a	2.29	1.79	1.67	2.61	1.49	2.25
	b	0.072	0.056	0.053	0.052	0.085	0.054
	R^2	0.71	0.54	0.44	0.48	0.74	0.38
Rs Q_{10}	R_{10}	7.43	3.14	2.84	4.36	3.51	3.87
	Q_{10}	2.06	1.76	1.70	1.67	2.36	1.72
	R^2	0.71	0.54	0.44	0.48	0.75	0.38
Rs SM	R_{10}	6.07	3.87	2.77	4.30	3.97	4.12
	Q_{10}	2.51	2.32	2.03	1.89	2.76	2.14
	a	1.17	0.89	1.46	0.90	0.029	0.49
	b	-17.67	-17.55	-87.91	-63.23	-18.65	-26.90
	R^2	0.82	0.76	0.54	0.64	0.85	0.52

Table 5: Statistics for applied Rs models; error sum of squares (SSE) and standard deviation (STD).

Year	Rs Ts		Rs Q_{10}		Rs SM	
	SSE	STD	SSE	STD	SSE	STD
2014	86.86	2.49	86.91	2.50	111.20	2.63
2015	72.15	1.26	72.23	1.25	54.52	1.63
2016	41.32	1.10	41.35	1.10	42.16	1.24
2017	57.18	1.56	57.08	1.55	56.83	1.68
2018	233.60	2.63	233.40	2.63	152.70	2.73

Table 6: Estimated seasonal and total Rs over the growing season from 2014 to 2018.

Season	2014(in thousands)			2015 (in thousands)			2016 (in thousands)			2017 (in thousands)			2018 (in thousands)		
Model	RsTs	RsQ_{10}	RsSM	RsTs	RsQ_{10}	RsSM	RsTs	RsQ_{10}	RsSM	RsTs	RsQ_{10}	RsSM	RsTs	RsQ_{10}	RsSM
Spring	3.33	3.33	3.16	2.40	2.40	2.14	2.32	2.32	2.14	3.61	3.61	3.50	2.53	2.53	2.57
Summer	7.49	7.49	6.47	4.43	4.43	4.77	4.13	4.13	4.77	6.00	6.00	5.92	6.80	6.80	6.43
Autumn	4.99	4.99	4.98	3.42	3.42	2.92	3.22	3.13	2.92	4.64	4.64	4.38	4.34	4.34	4.56
Winter	2.34	2.24	1.67	1.62	1.62	1.08	1.28	1.28	1.08	2.59	2.59	2.31	1.52	1.52	1.38
Total	18.05	18.05	16.27	11.86	11.87	10.92	10.86	10.86	10.84	16.85	16.85	16.11	15.19	15.19	14.93

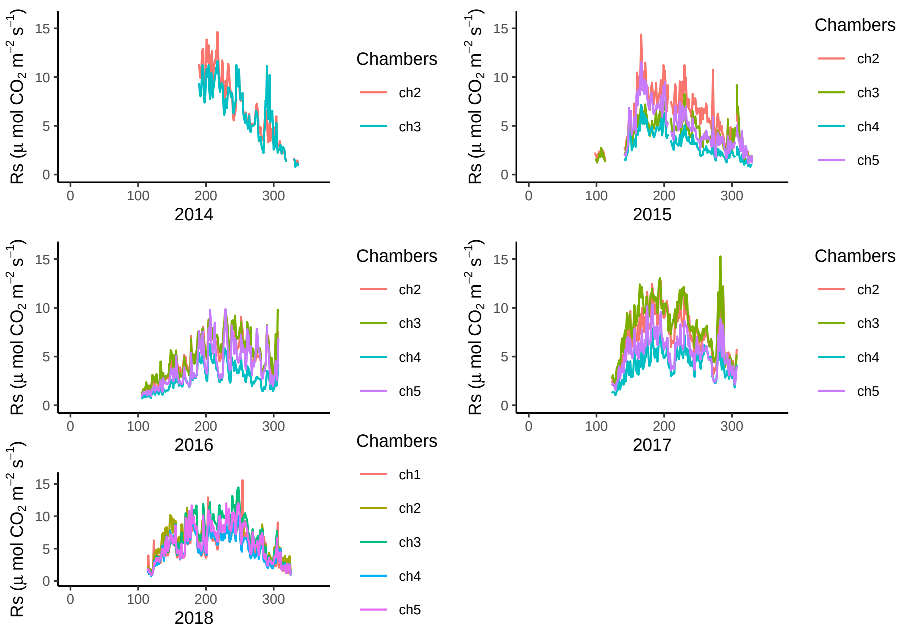

Figure 1: Daily average soil respiration (Rs) in µmol CO_2 m^{-2} s^{-1} measured by automated soil CO_2 chamber systems over a 5 year study period

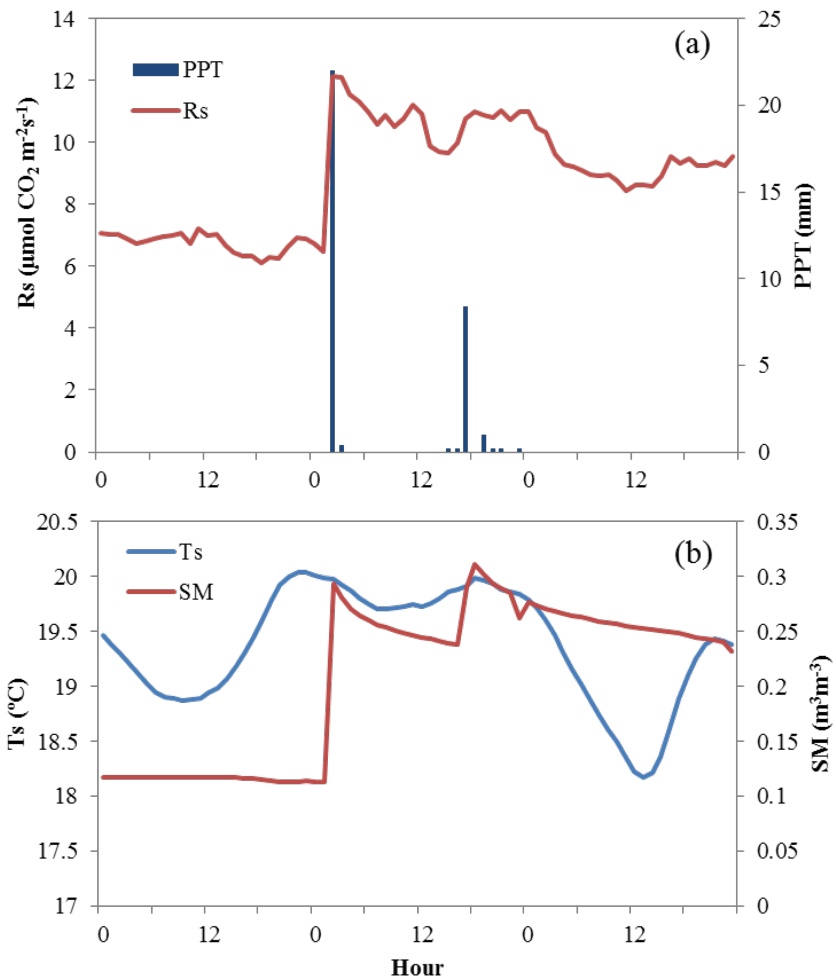

Figure 2: (a) Half hourly soil respiration (Rs) and precipitation (PPT) and (b) half hourly soil temperature (Ts) and soil moisture (SM) at 5 cmd depth before, during, and after following a 22.4 mm precipitation event on September 2, 2014

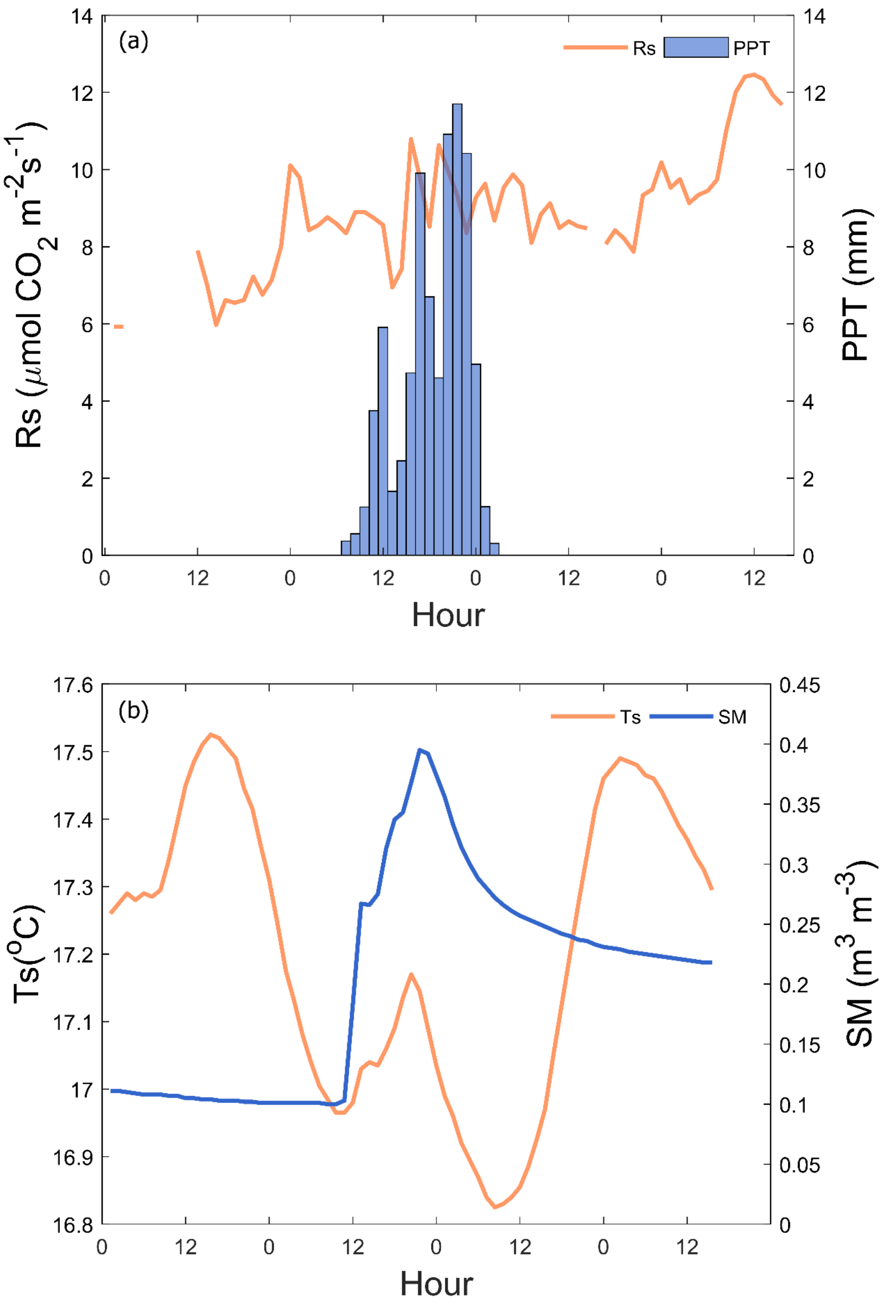

Figure 3: (a) Half hourly soil respiration (Rs) and precipitation (PPT) and (b) half hourly soil temperature (Ts) and soil moisture (SM) at 5 cm depth before, during, and after following a 11.7 mm precipitation on October 7, 2017

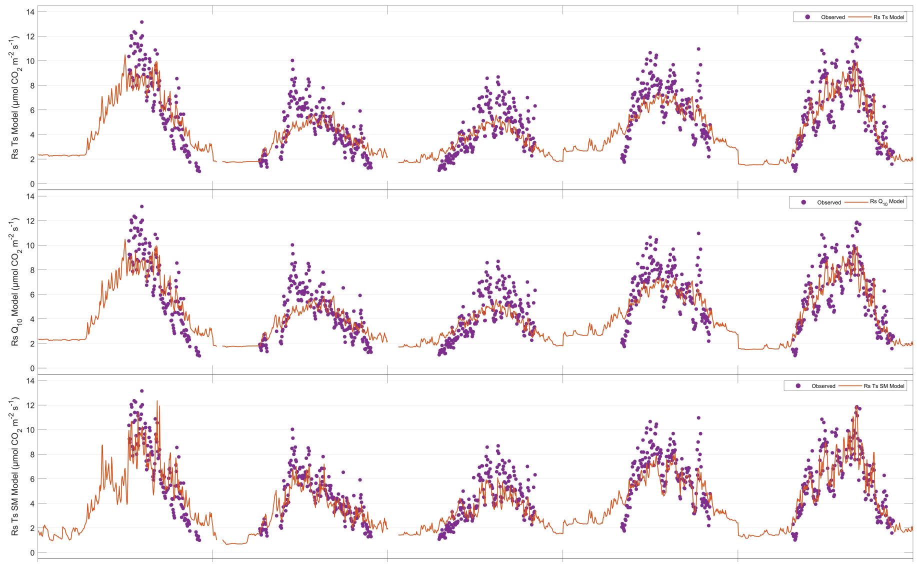

Figure 4: Annual observed Rs values compared with predicted values using three models (Rs Ts, Rs Q_{10} Rs SM) from 2014 to 2018 recoreded in µmol CO^2 m^{-2} s^{-1}

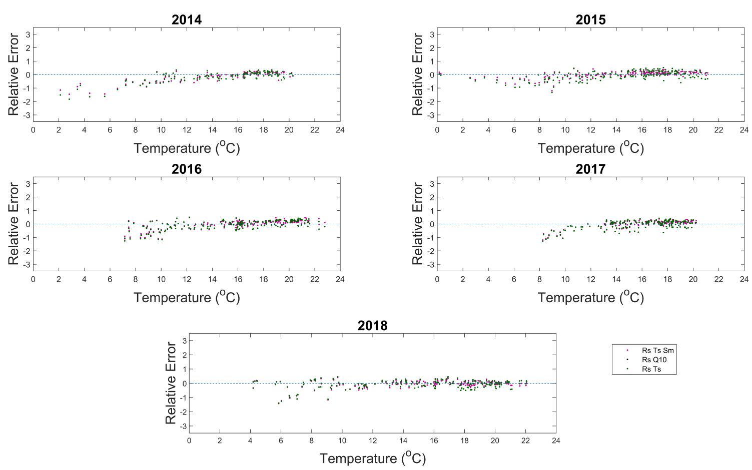

Figure 5: The daily relative error of Rs Ts, Rs Q_{10}, and Rs SM plotted against temperature (^oC) for the growing season from 2014 to 2018.

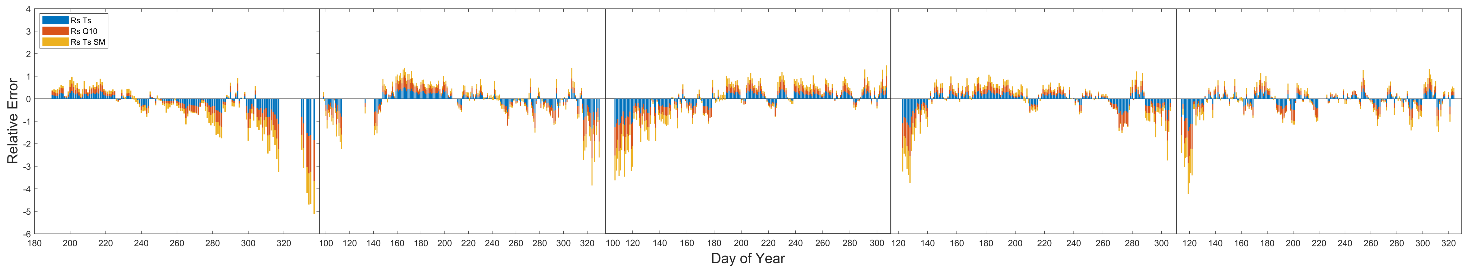

Figure 6: Stacked bar plot showing the daily relative error of Rs Ts, Rs Q_{10}, Rs SM models over the 2014 to 2018 measurement period

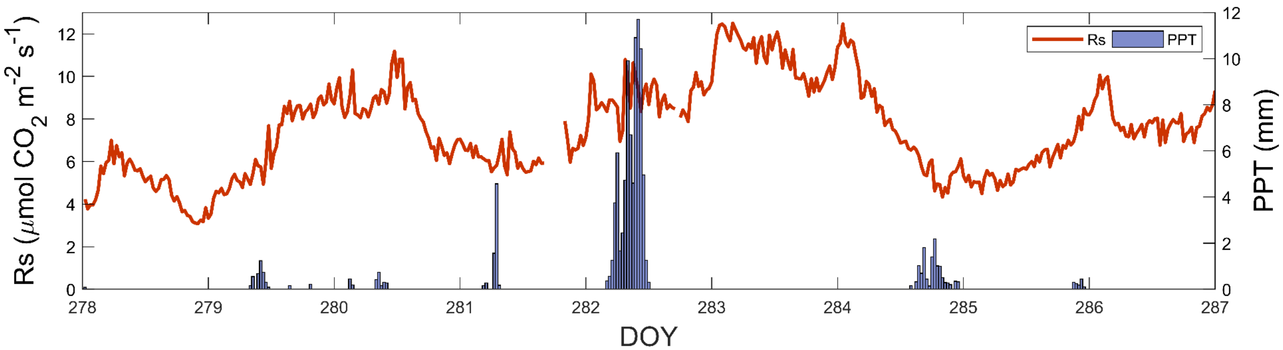

Figure 7: Precipitation event (mm) and Rs (µmol CO^2 m^{-2} s^{-1}) from October 5 to 13 in 2017 following a drought of 19 days

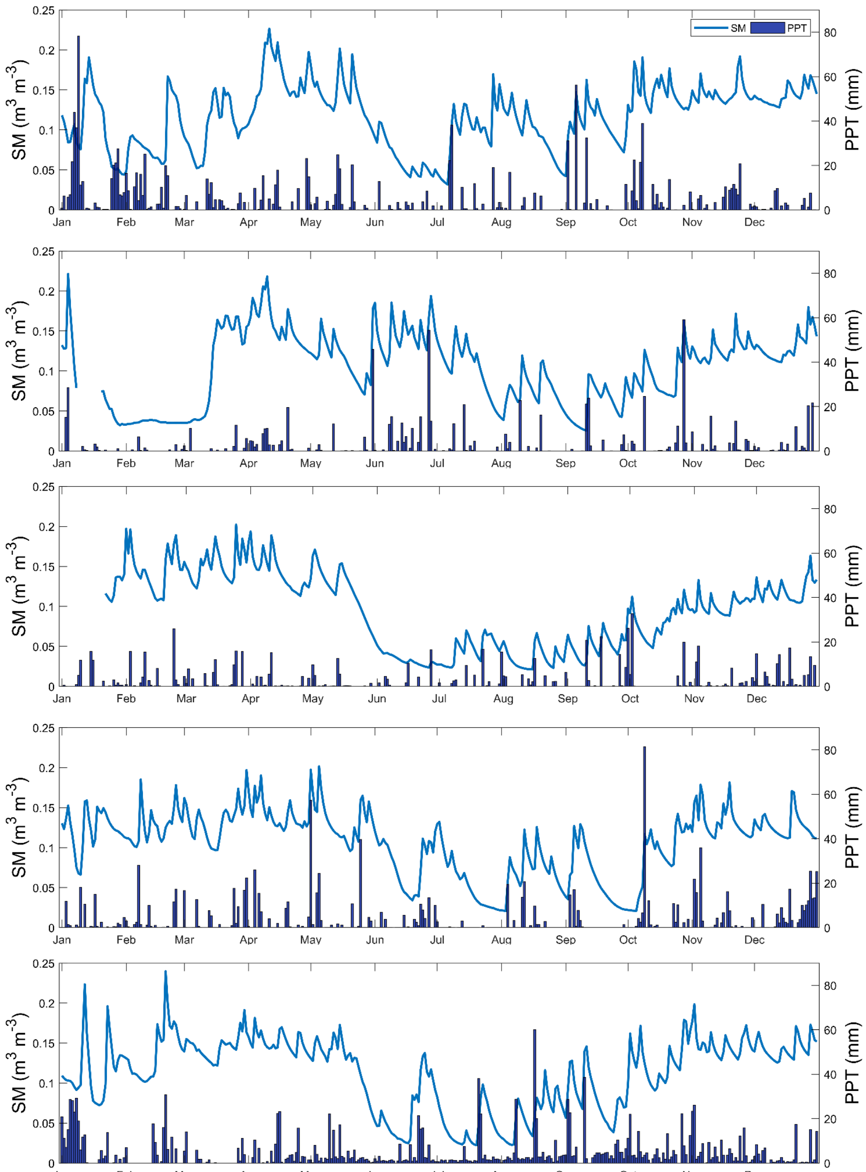

Figure 8: Comparison of daily mean soil mositure content (SM) at 5 cm depth in m^3 m^{-3} and cumulative daily average precipitation (PPT) in mm during (a)2014, (b)2015, (c)2016, (d)2017, and (e)2018

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