DOI: 10.1515/frp-2015-0013
Available online: www.lesne-prace-badawcze.pl

Leśne Prace Badawcze / *Forest Research Papers*
June 2015, Vol. 76 (2): 129–143

ORIGINAL RESEARCH ARTICLE

e-ISSN 2082-8926

The dependence of soil CO_2 fluxes on atmospheric conditions during sub-periods of soil respiration

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Abstract. Soil respiration was measured on rusty soil in a dry forest near Łódź. A two-year series of soil respiration measurements was divided into characteristic sub-periods, and the relationship between soil CO_2 emissions to selected aspects of climatic conditions was examined. The temperature dependence of soil CO_2 fluxes is linear from March to June and exponential during the period of June to March. Dividing the year into a phase of growth and a phase of decline and modelling soil respiration for each of these sub-periods separately does not significantly improve the accuracy of the model. Research shows that soil respiration responds with a delay of three days to changes in temperature and relative humidity, but with a 17-day delay to changes in precipitation.

Keywords: soil respiration, carbon dioxide, temperature, hysteresis

1. Introduction

In modelling the process of soil respiration (soil CO_2 emissions), it is almost universally accepted that an exponential equation best describes the dependence between the amount of soil CO_2 emissions and temperature (of soil and air) (Borken et al., 1999; Rochette et al., 1999; Kutsch et al., 2001; Tang et al. 2003, 2005; Zhaofu et al. 2005). In addition to temperature, soil respiration models also take into account moisture levels (amount of moisture in the soil or amount of precipitation) (Savage, Davidson 2003; Tufekcioglu, Kucuk 2004; Tang et al. 2005). The formulas for calculating soil CO_2 emissions vary among different authors, but these two characteristics are repeatedly found in almost all models. If they relate to an entire year, very good results are achieved.

Sometimes other factors are also taken into account, such as carbon content (Kutsch et al. 2001; Rodeghiero and Cascatti 2005), maximum leaf area index (Doran et al. 1990; Reichstein et al., 2003), pH (Reth et al. 2004), type of land use (Ardo, Olsson 2003), etc.

Meanwhile, more accurate analyses of changes in soil CO_2 emissions under different conditions show that a single formula is insufficient to describe soil respiration for shorter periods of time. For example, Updegraff et al. (1998) (in a laboratory experiment) obtained different regression equations of respiration on temperature with an identical change in temperature depending on whether first generating an increase (from 6° C to 30° C), and then a drop (from 30° C to 6° C), or vice versa. In turn, Moore (1989) noted that in analysing the influence of the depth of groundwater on soil respiration, historical changes in this determinant should also be taken into account because the amount of CO_2 emissions differed at the same depth depending on whether the soil had been saturated with water and then dried, or whether the moisture content of the soil was increasing.

Another phenomenon worth examining is to determine the speed with which soil respiration responds to changes. Factors affecting the size of the population of soil microorganisms, mainly responsible for soil CO_2 emissions, i.e., temperature and moisture, are taken into account in soil respiration models, but a response in the size of this population to changes in these parameters may be delayed to a certain degree. So far, this issue has been studied by Wroński (2013, 2014) over an entire year, and Wroński and Okupny (2012) during the period of respiration growth in spring.

Received: 7.10.2014, reviewed: 1.12.2014, accepted: 10.12.2014.

The purpose of this article was to investigate:

1) the form of the dependence between soil respiration and temperature (linear or exponential) for specific phases of change in soil respiration during the year,

2) whether the 'response'of soil respiration to changes in air temperature, relative humidity and amount of precipitation is immediate or delayed,

3) whether dividing the entire period of soil respiration change into subperiods and modeling soil respiration for each of these subperiods increases the quality of the generated series of theoretical values of respiration.

2. Methodology

Measurements of soil CO_2 emissions were carried out using a closed chamber, which was 23 × 23 cm in size at a height of 6 cm. The lower part of the chamber was a steel frame driven into the ground, the upper part was a Plexiglas cloche. Placed inside was an Airtech vento carbon dioxide meter, manufactured by Gazex, which used the NDIR (Non-Dispersive Infrared) method, allowing CO_2 measurements to be taken at two points in time: 5 minutes and 10 minutes after closing the chamber. The difference in concentrations between the later and the earlier readings was converted to the volume of emitted CO_2 at a given time using the following formula:

$$R = \frac{M_{mol}}{V_{molnorm}} \frac{273 \cdot \Delta X \cdot V_{pow}}{T \cdot P \cdot t}$$

where:

M_{mol} – molar mass of CO_2,

$V_{mol\,norm}$ – the molar volume of air under standard conditions $\left[\frac{dm^3}{mol}\right]$,

ΔX – the difference in meter readings from the beginning to the end of the measurement,

V_{pow} – the volume of air in the chamber (chamber volume minus the volume of the meter) [m^3],

T – temperature [K],

P – area used by the steel frame [m^2],

t – duration of the measurement [h].

CO_2 emissions were measured at irregular intervals, not longer than seven days, depending on changes in the weather. The measurements were started in March 2010 and ended in March 2012. To determine whether intact or poorly distributed needles and leaves lying on the soil surface affect CO_2 emissions, measurements were carried out at two types of sites: soil from which all leaf litter was removed and soil on which the litter was left in place.

Measurement sites were located in a planted pine forest, which can be classified as dry pine habitat. The area is located east of the Olechów district and south of the village of Nery (52º44'36" N, 19º34'57" E, 223 m asl) within the administrative boundaries of Łódź. It is a region where three Wartanian glacial lobes met (Turkowska 2006). The water which flowed from these lobes carried a large amount of fluvioglacial sediments to the area (Klatkowa 1972; Trzmiel, Nowacki 1985, 1987), forming, therefore, favorable conditions for the emergence of a very acidic rusty soil profile (H_2O pH= 4.0, KCl pH=3.5) with a mor type of humus. Sand fraction dominates throughout the soil profile, and texture class of its upper section—the part of soil most affecting the amount of respiration, is loamy sands.

In the statistical analyses, two aspects of the relationship between air temperature and respiration were considered: (1) the result of short-term changes, and (2) the result of seasonal variation.

In the first case, the linear correlation coefficients between filtered series of soil respiration and air temperature were calculated. Filtration was based on subtracting moving average values from the observed values. The occurrence of a delayed reaction in soil respiration in response to changes in air temperature was also tested by calculating the correlation between the filtered series of respiration and filtered series of average temperature of 1, 2, 3, ..., 10 days. The average temperature values were calculated so that the last day of a series was the day of measuring soil respiration, i.e., the calculation of a three-day average temperature included the day of the respiration measurement and the preceding two days.

In the second case (seasonal variation), the correlation was calculated between (1) the temperature of the number of days for which the strongest correlation was observed with short term variability, and (2) soil respiration and the natural logarithm of soil respiration. On the basis of the correlation coefficient calculated in such a manner, I determined whether the relationship between the variables was linear or exponential for the considered periods. During seasonal variation, the reaction time of soil respiration to temperature change was not tested, because the properties of the correlation coefficient are such that when the curves of temperature and respiration do not exactly agree, a higher correlation is attained when the temperature curve is smoother (that is, the correlation values increase when number of days taken into account in moving average temperature increase regardless of the nature of the relationship). It was assumed a priori that in the case of seasonal variation, the strongest relationship to CO_2 emission occurs for the average air temperature of the same number of days as in the case of short-term variation.

For periods in which a significant correlation between respiration and temperature was observed, the strength of the dependence and the size of the delayed reaction of soil respiration to changes in relative humidity and amount of rainfall were measured. This was done by calculating the linear correlation coefficient between the residuals of the soil respiration model based on temperature values (i.e., the observed variance between soil respiration and the soil respiration model, resulting from the distribution of temperatures), and, respectively: the relative humidity of the atmosphere (the daily average and the average of 2, 3 , ..., 10 days) and amount of precipitation (daily and the average value of 2, 3, ..., 20 days). If, however, the relationship between soil respiration and temperature was exponential, the correlation with the relative humidity of the atmosphere or amount of precipitation was calculated for the residuals from the model of the natural logarithm (ln) of respiration, and not from the model of respiration.

The respiration model was developed using as the independent variables of temperature and the parameter of humidity (relative humidity of the atmosphere or amount of precipitation) which have the stronger correlation to soil respiration (more precisely, to deviations of actual respiration from theoretical respiration resulting from the distribution of temperatures). The value of the delay in the response of soil respiration to changes in these climatic elements was also taken into account. If during the given period, the relationship of soil respiration to temperature was linear, estimates were made using the multiple regression. However, if this relationship was exponential, the quasi-Newton method of estimation was used to determine the model.

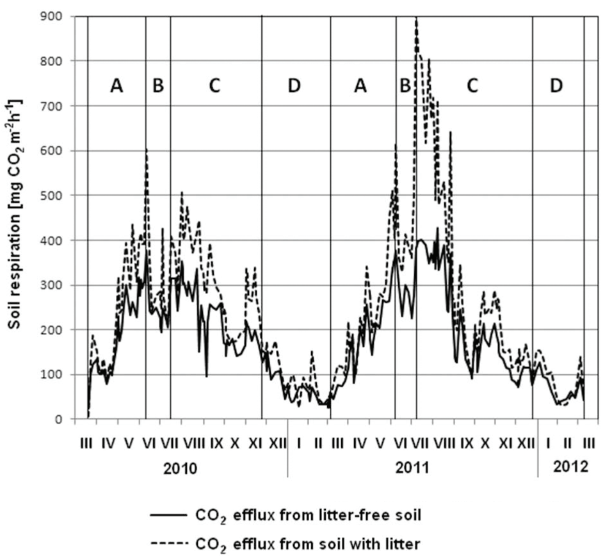


Figure 1. Soil respiration at the study sites and sub-periods (A, B, C and D) of soil respiration

3. Results

Four distinct periods were revealed by the graphed course of soil respiration (Fig. 1). Period A is a time of increasing CO_2 emissions. It usually begins about March 10, after the snow cover melts. It lasts until the end of May or beginning of June, when period B begins with a significant decrease in soil respiration. In period B, the high temperatures should stimulate soil CO_2 emissions but light rains usually occur, reducing soil respiration (Wroński 2013). Period C begins in July. Initially, the value of CO_2 emissions is very high, but over time, it systematically declines. The only exception is when tree leaves and needles are falling on the soil surface and begin to intensively decay, which causes respiration to rise again. Period D was distinguished due to the presence of snow cover (although snowless sub-periods can also occur during this time).

The correlation analysis of short-term changes (Table 1) showed that the strongest relationships to soil respiration usually occur with average daily temperature or average air temperatures of three days. For periods A and D, soil respiration was most strongly correlated with average 3-day temperatures; for periods B and A+B – with the average daily temperature; whereas at other times: for sites without leaf litter – with average 3-day temperature; while at sites with leaf litter – with average daily temperature.

It is worth noting that the observed correlations were relatively strong during periods of increasing respiration (period A) and stagnation of emitted CO_2 amounts (period B), but weak at times of decreasing soil respiration (periods C and D).

It is surprising that for the entire first year of the study (period A+B+C+D), temperature was more strongly correlated with soil respiration than the natural logarithm ln of respiration (Table 2), which is evidence of a linear type of relationship between these variables rather than exponential, as presumed by most authors. This result may have been the effect of the relatively low rainfall in the early summer of 2010, which is the time when soil respiration reaches its highest levels. A smaller amount of water may have reduced soil CO_2 emissions when temperatures were at their highest, which modified the shape of the relationship. In the first year of the study, correlation coefficients with soil respiration (indicating a linear regression) had the greatest advantage over the correlation coefficients of the natural logarithm ln of soil respiration (indicating an exponential dependence) for periods A and A+B – which are times of increasing soil respiration. During periods of decline (periods C, D, B+C), the value of both types of correlation coefficients was similar. The aforementioned sparse rainfall at the beginning of that summer may have

Table 1. Correlation coefficients between (1) filtered series of soil respiration and (2) filtered series of average temperature of 1 day, 2 days, …, 10 days. Filtration consisted of subtracting the moving average temperature of 31 days from the observed temperature values.

Year	Period	Type of research point	Temperature average from:									
			1 day	2 days	3 days	4 days	5 days	6 days	7 days	8 days	9 days	10 days
1st year	A	litter free	**0.425**	**0.578**	**0.657**	**0.648**	**0.606**	**0.602**	**0.599**	**0.578**	**0.539**	**0.534**
		with litter	**0.622**	**0.743**	**0.794**	**0.775**	**0.725**	**0.699**	**0.667**	**0.630**	**0.585**	**0.584**
	B	litter free	**0.763**	**0.722**	**0.701**	**0.682**	**0.670**	0.645	0.570	0.544	0.567	0.537
		with litter	**0.818**	**0.793**	**0.755**	**0.770**	**0.828**	**0.864**	**0.837**	**0.803**	**0.760**	**0.681**
	C	litter free	**0.569**	**0.617**	**0.596**	**0.533**	**0.441**	**0.339**	**0.298**	**0.268**	**0.240**	**0.201**
		with litter	**0.759**	**0.699**	**0.661**	**0.633**	**0.576**	**0.505**	**0.467**	**0.404**	**0.342**	**0.271**
	D	litter free	0.059	0.038	0.149	0.131	0.099	0.082	0.100	0.127	0.160	0.179
		with litter	**0.471**	**0.426**	**0.442**	**0.393**	0.353	0.303	0.251	0.201	0.157	0.099
	A+B	litter free	**0.426**	**0.523**	**0.583**	**0.583**	**0.568**	**0.576**	**0.568**	**0.546**	**0.521**	**0.500**
		with litter	**0.543**	**0.614**	**0.641**	**0.651**	**0.662**	**0.682**	**0.665**	**0.623**	**0.571**	**0.540**
	B+C	litter free	**0.561**	**0.590**	**0.576**	**0.536**	**0.477**	**0.402**	**0.359**	**0.329**	**0.308**	**0.272**
		with litter	**0.666**	**0.628**	**0.596**	**0.596**	**0.598**	**0.582**	**0.546**	**0.485**	**0.423**	**0.356**
	C+D	litter free	**0.364**	**0.383**	**0.384**	**0.337**	**0.285**	0.238	0.228	0.218	0.212	0.195
		with litter	**0.591**	**0.540**	**0.516**	**0.482**	**0.449**	**0.411**	**0.387**	**0.342**	**0.302**	**0.249**
	B+C+D	litter free	**0.391**	**0.402**	**0.402**	**0.362**	**0.319**	**0.280**	**0.264**	**0.250**	**0.245**	**0.227**
		with litter	**0.544**	**0.505**	**0.480**	**0.461**	**0.453**	**0.445**	**0.423**	**0.375**	**0.332**	**0.281**
	A+B+C+D	litter free	**0.360**	**0.406**	**0.427**	**0.391**	**0.344**	**0.312**	**0.301**	**0.283**	**0.266**	**0.243**
		with litter	**0.522**	**0.524**	**0.520**	**0.499**	**0.476**	**0.464**	**0.443**	**0.394**	**0.342**	**0.291**
2nd year	A	litter free	**0.688**	**0.658**	**0.635**	**0.636**	**0.614**	**0.568**	**0.548**	**0.493**	**0.438**	**0.383**
		with litter	**0.445**	**0.394**	**0.422**	**0.471**	**0.500**	**0.489**	**0.470**	**0.472**	**0.489**	**0.503**
	B	litter free	**0.752**	0.514	0.342	0.246	0.183	0.178	0.205	0.355	0.443	0.390
		with litter	0.628	0.475	0.365	0.244	0.116	0.003	-0.044	0.107	0.198	0.168
	C	litter free	0.154	0.256	**0.369**	**0.365**	**0.343**	**0.304**	0.234	0.196	0.141	0.083
		with litter	**0.262**	**0.262**	**0.262**	0.205	0.171	0.120	0.078	0.080	0.046	0.010
	D	litter free	0.478	0.551	**0.567**	0.545	0.440	0.325	0.252	0.225	0.202	0.178
		with litter	**0.554**	**0.652**	**0.668**	**0.644**	**0.568**	0.495	0.448	0.439	0.418	0.387
	A+B	litter free	**0.679**	**0.595**	**0.527**	**0.492**	**0.456**	**0.416**	**0.405**	**0.383**	**0.352**	0.282
		with litter	**0.438**	**0.351**	**0.316**	0.292	0.256	0.210	0.185	0.215	0.237	0.218
	B+C	litter free	**0.280**	**0.327**	**0.394**	**0.383**	**0.369**	**0.354**	**0.310**	**0.292**	**0.254**	0.195
		with litter	**0.371**	**0.352**	**0.338**	**0.286**	**0.255**	0.216	0.190	0.209	0.188	0.146

Year	Period	Type of research point	Temperature average from:									
			1 day	2 days	3 days	4 days	5 days	6 days	7 days	8 days	9 days	10 days
2ndyear	C+D	litter free	0.169	**0.247**	**0.333**	**0.331**	**0.304**	**0.259**	0.194	0.160	0.118	0.077
		with litter	**0.246**	**0.251**	**0.252**	0.207	0.175	0.129	0.094	0.096	0.072	0.047
	B+C+D	litter free	**0.262**	**0.302**	**0.359**	**0.351**	**0.330**	**0.301**	**0.253**	**0.232**	0.200	0.155
		with litter	**0.330**	**0.319**	**0.314**	**0.272**	**0.241**	0.201	0.175	0.186	0.168	0.135
	A+B+C+D	litter free	**0.242**	**0.284**	**0.340**	**0.329**	**0.307**	**0.279**	**0.235**	**0.213**	**0.178**	0.133
		with litter	**0.307**	**0.298**	**0.289**	**0.240**	**0.208**	**0.170**	**0.149**	**0.160**	**0.140**	0.108
Both years	A	litter free	**0.564**	**0.619**	**0.638**	**0.633**	**0.602**	**0.573**	**0.562**	**0.525**	**0.480**	**0.449**
		with litter	**0.526**	**0.550**	**0.580**	**0.593**	**0.584**	**0.568**	**0.547**	**0.536**	**0.529**	**0.536**
	B	litter free	**0.747**	**0.607**	**0.515**	0.452	0.412	0.406	0.384	0.437	0.485	0.434
		with litter	**0.678**	**0.583**	**0.511**	0.448	0.396	0.364	0.333	0.390	0.408	0.349
	C	litter free	**0.332**	**0.412**	**0.465**	**0.434**	**0.382**	**0.318**	**0.260**	**0.226**	**0.184**	**0.136**
		with litter	**0.388**	**0.370**	**0.358**	**0.309**	**0.270**	**0.217**	**0.179**	**0.164**	**0.127**	**0.084**
	D	litter free	0.221	0.232	0.296	0.269	0.211	0.164	0.151	0.158	0.168	0.171
		with litter	0.504	**0.513**	**0.523**	**0.477**	**0.424**	**0.371**	**0.325**	0.293	0.258	0.209
	A+B	litter free	**0.567**	**0.565**	**0.552**	**0.531**	**0.503**	**0.485**	**0.478**	**0.459**	**0.432**	**0.384**
		with litter	**0.479**	**0.454**	**0.442**	**0.427**	**0.407**	**0.389**	**0.373**	**0.379**	**0.374**	**0.349**
Oba lata / Both years	B+C	litter free	**0.403**	**0.444**	**0.473**	**0.448**	**0.415**	**0.374**	**0.330**	**0.307**	**0.277**	**0.229**
		with litter	**0.458**	**0.434**	**0.415**	**0.382**	**0.362**	**0.333**	**0.307**	**0.297**	**0.264**	**0.215**
	C+D	litter free	**0.261**	**0.310**	**0.352**	**0.326**	**0.288**	**0.243**	**0.208**	**0.186**	0.164	0.137
		with litter	**0.341**	**0.327**	**0.319**	**0.282**	**0.253**	**0.216**	**0.188**	**0.175**	0.150	0.119
	B+C+D	litter free	**0.319**	**0.344**	**0.372**	**0.347**	**0.316**	**0.281**	**0.251**	**0.233**	**0.214**	**0.184**
		with litter	**0.392**	**0.370**	**0.357**	**0.326**	**0.307**	**0.281**	**0.258**	**0.245**	**0.218**	**0.180**
	A+B+C+D	litter free	**0.358**	**0.393**	**0.419**	**0.397**	**0.363**	**0.329**	**0.302**	**0.273**	**0.242**	**0.205**
		with litter	**0.396**	**0.385**	**0.383**	**0.360**	**0.341**	**0.317**	**0.294**	**0.276**	**0.244**	**0.207**

Statistically significant values (at significance level a = 0.05) are indicated with bold numerals

A, B, C, D as in Figure 1

affected the higher correlation with soil respiration compared to the correlation with the natural logarithm ln for respiration during periods C+D and B+C+D.

In the second year of the study, values of the two types of correlation coefficients were similar for periods A, B, A+B. On the other hand, a clear exponential dependence was found between soil respiration and temperature for periods C, D, and especially C+D and B+C+D.

Over the whole period under discussion, a linear type of relationship was evident for periods A and A+B (when respiration increased), but it was exponential for periods C, D, B+C, C+D, and B+C+D (times of decreasing respi-

Table 2. Correlation coefficients between (1) soil respiration and the natural logarithm of soil respiration and (2) average daily temperature or average temperature of 3 days

Period	Type of research point	1st year		2nd year		Both years		Number of days of averaging temperature
		Relationship						
		linear	expo-tential	linear	expo-tential	linear	expo-tential	
A	litter free	**0.878**	**0.819**	**0.914**	**0.880**	**0.891**	**0.838**	3
	with litter	**0.911**	**0.788**	**0.854**	**0.866**	**0.869**	**0.791**	3
B	litter free	0.498	0.438	**0.730**	**0.731**	**0.464**	**0.421**	1
	with litter	0.638	0.608	0.398	0.393	0.302	**0.278**	1
C	litter free	**0.863**	**0.821**	**0.736**	**0.758**	**0.757**	**0.755**	3
	with litter	**0.890**	**0.880**	**0.555**	**0.663**	**0.596**	**0.685**	1
D	litter free	-0.203	-0.119	**0.714**	**0.731**	0.123	0.187	3
	with litter	-0.102	-0.089	**0.786**	**0.847**	-0.102	0.268	3
A+B	litter free	**0.703**	**0.644**	**0.903**	**0.877**	**0.801**	**0.755**	1
	with litter	**0.682**	**0.576**	**0.760**	**0.840**	**0.705**	**0.686**	1
B+C	litter free	**0.760**	**0.746**	**0.743**	**0.768**	**0.729**	**0.741**	3
	with litter	**0.701**	**0.709**	**0.557**	**0.679**	**0.548**	**0.657**	1
C+D	litter free	**0.875**	**0.798**	**0.774**	**0.841**	**0.813**	**0.819**	3
	with litter	**0.882**	**0.783**	**0.555**	**0.791**	**0.704**	**0.790**	1
B+C+D	litter free	**0.861**	**0.803**	**0.785**	**0.849**	**0.811**	**0.824**	3
	with litter	**0.836**	**0.775**	**0.557**	**0.802**	**0.684**	**0.789**	1
A+B+C+D	litter free	**0.824**	**0.786**	**0.779**	**0.846**	**0.803**	**0.814**	3
	with litter	**0.794**	**0.708**	**0.543**	**0.797**	**0.681**	**0.753**	1

Statistically significant values (at significance level a = 0.05) are indicated with bold
numerals A, B, C, D as in Figure 1

ration). Both types of correlation coefficient were similar during period B.

Because the correlation with temperature was most often not statistically significant for periods B and D, I examined whether another climatic factor may have had a stronger effect on the amount of soil respiration in these periods (B and D). The analysis was performed in the same manner as was done to determine the dependence between respiration and temperature. However, both atmospheric relative humidity (Table 3), and the amount of precipitation (Table 4), had a not significant effect on the short-term variability of soil respiration. In the case of seasonal variation (Table 5), a significant correlation in both years was found only for relative humidity (9-day average), but at correlation coefficient values of 0.50–0.70 describe only 0.25–0.49% of the variability of soil respiration and this was not suitable to CO_2 emission model.

Given this situation, the most reasonable solution for the purpose of modelling was to divide the entire period of respiration variance into two sub-periods: A and B+C+D or A+B and C+D (Fig. 2). Because higher correlation coefficients were obtained for the first of these possibilities (Table 2), it was used in later stages of the work. I checked whether distinguishing period A, which

Table 3. Correlation coefficients between (1) filtered series of soil respiration and (2) filtered series of average relative humidity of 1 day, 2 days, …, 10 days. Filtration consisted of subtracting the moving averages of the temperature of 31 days from observed temperature values.

Period	Year	Number of days of averaging temperature	Type of research point	Average relative moisture from:									
				1 day	2 days	3 days	4 days	5 days	6 days	7 days	8 days	9 days	10 days
B	1st year	3	litter free	-0.172	-0.234	-0.139	-0.130	-0.069	-0.273	-0.357	-0.494	-0.561	-0.591
		3	with litter	-0.229	-0.485	-0.378	-0.374	-0.343	-0.582	**-0.698**	**-0.758**	**-0.800**	**-0.793**
	2nd year	3	litter free	0.100	0.096	-0.024	-0.059	-0.037	-0.029	-0.016	0.002	0.015	0.046
		3	with litter	-0.044	0.028	-0.035	-0.025	-0.054	-0.077	-0.082	-0.063	-0.046	-0.015
	both years	3	litter free	-0.335	-0.223	-0.179	-0.124	0.059	0.056	0.134	0.097	0.075	0.064
		3	with litter	-0.170	-0.109	-0.089	-0.034	0.132	0.136	0.205	0.182	0.220	0.229
D	1st year	3	litter free	0.100	0.096	-0.024	-0.059	-0.037	-0.029	-0.016	0.002	0.015	0.046
		1	with litter	-0.044	0.028	-0.035	-0.025	-0.054	-0.077	-0.082	-0.063	-0.046	-0.015
	2nd year	3	litter free	-0.004	0.163	0.219	0.290	0.275	0.144	0.050	0.039	0.043	0.089
		1	with litter	0.064	0.308	0.330	0.417	0.379	0.295	0.218	0.237	0.269	0.343
	both years	3	litter free	0.063	0.109	0.055	0.055	0.067	0.031	0.007	0.015	0.024	0.061
		1	with litter	-0.005	0.120	0.100	0.131	0.099	0.057	0.024	0.046	0.072	0.128

Statistically significant values (at significance level a = 0.05) are indicated with bold
numerals B, D as in Figure 1

has a linear increase of CO_2 with temperature, and period B+C+D, when CO_2 respiration decreases exponentially, improves the quality of the soil respiration models in relationship to time.

It should be noted, however, that the potential model could provide better results if a satisfactory formula for the calculation of soil respiration in winter could be found in the future. However, most likely it will take into account neither weather conditions nor even the physical processes of the soil, but its biological processes. The research of Zimov et al. (1993) found that the high variability of CO_2 flow in this period is accompanied by relatively stable physical parameters. Figure 2 shows how changes occur in the relationship of soil respiration to average 3-day temperatures over a year, divided into these three periods (A, B+C and D). While respiration increases quite rapidly with increasing temperatures in period A, the decrease in respiration during period B+C is gradual, especially in late autumn. It is impossible, therefore, to formulate a single equation to calculate the amount of CO_2 emissions based on temperature, but the configurations of this variable over time result in a graph presenting a quasi-hysteresis loop.

Air temperature served as the basis for the model. In addition to temperature, the most important factor affecting the amount of soil respiration is moisture, which is why the model was supplemented with the relative humidity of the atmosphere or the amount of precipitation. An approximately 3-day delay was confirmed in the response of soil respiration to changes in relative humidity (in both periods A and B+C+D, as well as in the entire year) (Table 6). The delay is greater in the relationship of soil respiration to level of precipitation, usually ranging approximately 17–18 days in periods B+C+D and the entire year. In the second year of the study, soil respiration reacted more quickly in period A, amounting to 7–8 days (Table 7).

It was also noted that soil respiration (more precisely, the deviations of soil respiration from theoretical respiration, resulting from the temperature distribution) had a stronger relationship to the amount of precipitation than to the relative humidity of the atmosphere. An exception

Table 4. Correlation coefficient between (1) filtrem series of soil respiration and (2) filtred series of average 1-daily. 2-daily. …. 10-daily precipitation. Filtration consisted in substraction moving average 31-daily temperature from observed values of temperature.

Period	Year	Number of days of averaging temperatur	Type of research point	Average precipitation from:									
				1 day	2 days	3 days	4 days	5 days	6 days	7 days	8 days	9 days	10 days
B	1st year	3	litter free	-0.096	-0.281	-0.230	-0.366	-0.418	-0.563	-0.580	-0.616	-0.608	-0.726
		3	with litter	0.202	-0.003	-0.097	-0.164	-0.216	-0.448	-0.558	-0.571	-0.550	-0.635
	2nd year	3	litter free	-0.268	0.017	0.321	0.160	0.137	0.152	0.146	0.095	0.187	0.228
		3	with litter	0.348	0.627	0.597	0.196	0.189	0.166	0.129	0.116	0.014	0.022
	both years	3	litter free	-0.291	-0.249	-0.322	-0.311	-0.111	-0.116	0.125	0.145	0.164	0.087
		3	with litter	-0.217	-0.172	-0.258	-0.258	0.037	0.018	0.221	0.233	0.240	0.179
D	1st year	3	litter free	-0.268	0.017	0.321	0.160	0.137	0.152	0.146	0.095	0.187	0.228
		1	with litter	0.348	**0.627**	**0.597**	0.196	0.189	0.166	0.129	0.116	0.014	0.022
	2nd year	3	litter free	0.112	0.239	0.211	0.349	0.406	0.119	-0.017	-0.058	-0.056	0.020
		1	with litter	0.162	0.107	0.095	0.289	0.330	0.166	-0.002	0.066	0.008	0.044
	both years	3	litter free	-0.103	0.086	0.266	0.215	0.204	0.137	0.095	0.048	0.103	0.146
		1	with litter	0.265	**0.450**	**0.374**	0.220	0.221	0.165	0.091	0.101	0.015	0.035

Statistically significant values (at significance level a = 0.05) are indicated with bold numerals B. D as in Figure 1

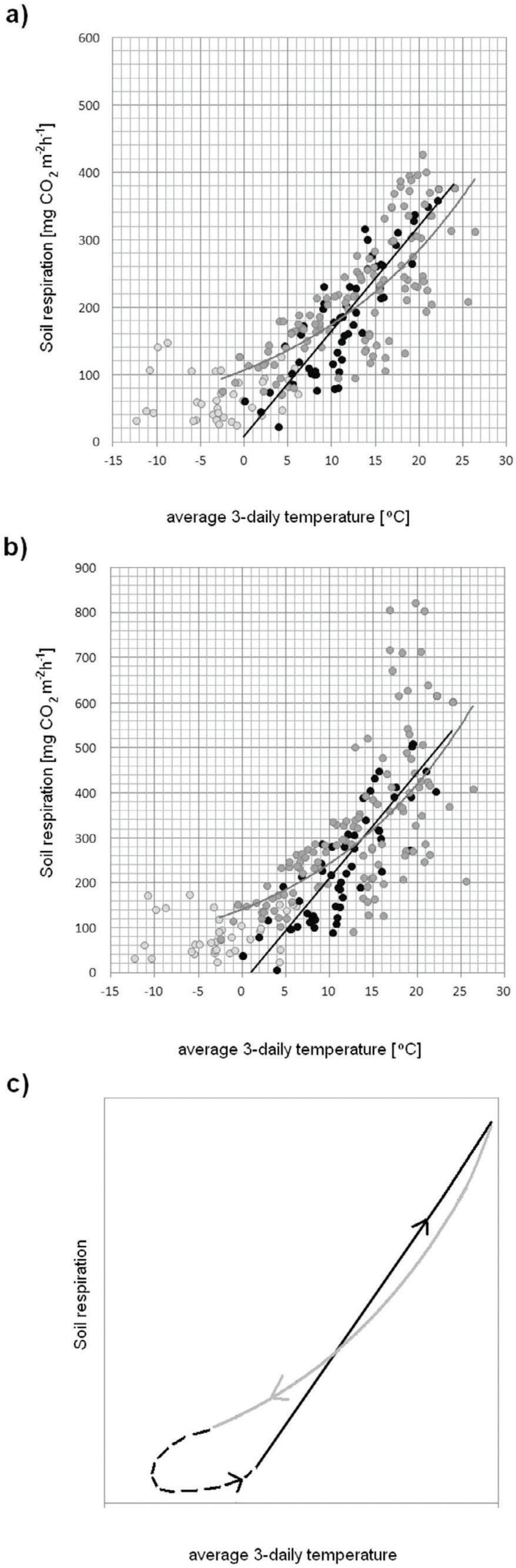
Table 5. Correlation coefficients between (1) soil respiration and (2) average 9-daily relative moisture and average 3-daily precipitation

Period	Type of research point	Average 9-daily relative moisture			Average 3-daily precipitation		
		1st year	2nd year	both years	1st year	2nd year	both years
B	litter free	0.131	0.196	0.215	0.299	-0.312	0.007
	with litter	-0.122	**0.679**	0.495	0.360	0.023	0.234
D	litter free	**0.500**	**0.617**	**0.527**	**0.558**	0.164	**0.405**
	with litter	**0.510**	**0.687**	**0.510**	**0.706**	0.144	**0.706**

Statistically significant values (at significance level a = 0.05) are indicated with bold numerals B. D as in Figure 1

to this rule was noted for period A only in the first year of the study.

As a result of the above analysis, the average temperature of 3 days and the average precipitation of 17 days were adopted as the independent variables for the model. Although a better fit was obtained with average daily temperature and average precipitation of 5, 7, 8, 18 days in some periods, the differences in the strength of the correlation with soil respiration (or with the deviations of soil respiration from theoretical respiration resulting from the temperature distribution in the case of amount of precipitation) are not large. It was therefore accepted that for period A, the relationship of soil respiration to temperature is described by a linear equation, while in period B+C+D, by



exponential equation. In both sub-periods, it was accepted that high precipitation limits CO_2 emissions, so for period A, the equation describing respiration is:

$$R = a+bT+cW+dW^2$$

while for period B+C+D, it is:

$$R = a + e^{b+cT+dW+fW^2}$$

where: R – the theoretical respirations of the soil for the given day,
T – average temperature of 3 days,
W – average precipitation of 17 days,
a, b, c, d, f – empirical coefficients.

It is assumed that period A starts on March 11 and ends on June 10, while period B+C+D begins on June 11 and ends on 10 March. Such a proposed model was compared with a model for the entire study period, which took into account the exponential form of the dependence between CO_2 emissions and temperature, as well as the limiting effect of high precipitation on soil respiration. This model takes the following form:

$$R = a + e^{b+cT+dW+fW^2}$$

Dividing the whole period of soil respiration variability by the time of its growth (period A) and decrease (period B+C+D) in modelling the process of soil respiration improved the accuracy of the theoretical values of respiration to some extent. This is especially evident for values from May and early June (Fig. 3). However, the standard error of the estimate and the coefficients of determination R^2 for both considered models are almost identical (Table 8, Fig. 4). This means that including the different shapes of the dependence of CO_2 emission amounts in periods A and B+C+D does not significantly improve the quality of the respiration model, so the use of a single formula for the entire period of variability provides satisfactory results.

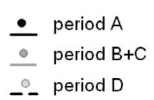


Figure 2. Regression curve of soil respiration and average temperature of 3 days in distinguished periods A and B+C at study sites without leaf litter (a) and with litter (B) and a schematic diagram presenting how the relationship between soil respiration and average 3-day temperature changes during the year. A, B, C, D / as in Figure 1.

Table 6. Correlation coefficients between (1) average relative humidity of 1 day. 2 days. …. 10 days and (2) residuals of the respiration model based on average temperature values of 3 days (during period A) and the residuals of the natural logarithm model of respiration based on average daily or average 3-day temperatures (in periods B+C+D and A+B+C+D)

Period	Year	Number of days of averaging temperatur	Type of research point	Average precipitation from:									
				1 day	2 days	3 days	4 days	5 days	6 days	7 days	8 days	9 days	10 days
A	1st year	3	litter free	**0.556**	**0.633**	**0.703**	**0.652**	**0.584**	**0.543**	**0.507**	**0.495**	**0.479**	**0.483**
		3	with litter	**0.559**	**0.620**	**0.749**	**0.717**	**0.660**	**0.607**	**0.566**	**0.547**	**0.537**	**0.546**
	2nd year	3	litter free	-0.090	0.047	0.158	0.163	0.154	0.088	0.079	0.046	-0.015	-0.051
		3	with litter	0.105	0.229	0.284	0.215	0.136	0.035	0.060	0.056	-0.011	-0.092
	both years	3	litter free	0.235	**0.266**	**0.318**	**0.307**	**0.269**	0.231	0.213	0.194	0.167	0.153
		3	with litter	**0.296**	**0.316**	**0.365**	**0.337**	**0.285**	0.229	0.223	0.210	0.183	0.155
B+C+D	1st year	3	litter free	**0.391**	**0.451**	**0.462**	**0.430**	**0.398**	**0.376**	**0.345**	**0.325**	**0.313**	**0.307**
		1	with litter	**0.447**	**0.476**	**0.485**	**0.460**	**0.424**	**0.396**	**0.359**	**0.335**	**0.328**	**0.330**
	2nd year	3	litter free	0.154	**0.241**	**0.266**	**0.247**	**0.272**	**0.242**	**0.223**	0.186	0.166	0.151
		1	with litter	**0.234**	**0.316**	**0.300**	**0.275**	**0.294**	**0.274**	**0.254**	**0.224**	0.220	0.211
	both years	3	litter free	**0.289**	**0.359**	**0.375**	**0.353**	**0.348**	**0.323**	**0.295**	**0.268**	**0.252**	**0.240**
		1	with litter	**0.342**	**0.397**	**0.396**	**0.376**	**0.369**	**0.345**	**0.313**	**0.287**	**0.279**	**0.274**
A+B+C+D	1st year	3	litter free	**0.408**	**0.446**	**0.454**	**0.423**	**0.386**	**0.362**	**0.325**	**0.304**	**0.297**	**0.296**
		1	with litter	**0.424**	**0.409**	**0.401**	**0.380**	**0.341**	**0.311**	**0.270**	**0.247**	**0.247**	**0.254**
	2nd year	3	litter free	0.061	0.175	**0.225**	**0.209**	**0.209**	0.179	0.165	0.145	0.128	0.114
		1	with litter	0.232	0.330	0.343	0.320	0.310	0.280	0.266	0.250	0.243	0.229
	both years	3	litter free	**0.243**	**0.302**	**0.325**	**0.305**	**0.286**	**0.260**	**0.233**	**0.214**	**0.202**	**0.194**
		1	with litter	**0.321**	**0.346**	**0.342**	**0.321**	**0.299**	**0.269**	**0.242**	**0.224**	**0.220**	**0.216**

Statistically significant values (at significance level a = 0.05) are indicated with bold
numerals A. B. C. D as in Figure 1

4. Discussion

Soil respiration, like any other phenomenon in nature, defies attempts to be described with simple mathematical formulas. However, mathematical modelling makes it easier to predict changes in soil CO_2 emissions, thus increasing the need to improve these models.

Exceptions to the exponential shape of the relationship between soil respiration and temperature has been observed, among others, by Rodeghiero and Cascatti (2005). According to these authors, soil respiration is lower at the highest temperatures than would be expected from the exponential equation due to the decrease in humidity at high temperatures. Chapman and Thurlow (1996), Fang and Moncrieff (2001) and Falge et al. (2002) believe that the relationship between soil respiration and temperature is best described by the Arrhenius equation. On the other hand, Tufekcioglu and Kucuk (2004) treat this as a rectilinear relationship. I believe that the dependence of soil respiration to air temperature is fairly well described by

Table 7. Correlation coefficients between (1) average precipitation of 1 day. 2 days. …. 20 days and (2) residuals of the soil respiration model based on average temperature values of 3 days (in period A) and residuals of the natural logarithm soil respiration model based on average 1-day or average 3-day temperatures (in periods B+C+D and A+B+C+D)

Period	Year	Number of days of averaging temperatur	Type of research point	Average precipitation from:									
				1 day	2 days	3 days	4 days	5 days	6 days	7 days	8 days	9 days	10 days
A	1st year	3	litter free	0.325	**0.552**	**0.664**	**0.680**	**0.674**	**0.620**	**0.592**	**0.628**	**0.635**	**0.604**
		3	with litter	0.269	**0.493**	**0.602**	**0.653**	**0.728**	**0.682**	**0.648**	**0.685**	**0.687**	**0.656**
	2nd year	3	litter free	-0.148	0.136	0.303	**0.448**	**0.453**	**0.482**	**0.533**	**0.506**	**0.466**	**0.467**
		3	with litter	-0.014	**0.425**	**0.585**	**0.535**	**0.445**	**0.416**	**0.573**	**0.588**	**0.528**	0.484
	both years	3	litter free	0.142	**0.349**	**0.462**	**0.525**	**0.529**	**0.493**	**0.476**	**0.501**	**0.495**	**0.461**
		3	with litter	**0.132**	**0.379**	**0.473**	**0.484**	**0.500**	**0.463**	**0.477**	**0.511**	**0.496**	**0.454**
B+C+D	1st year	3	litter free	-0.020	0.036	0.121	0.223	**0.265**	**0.315**	**0.306**	**0.312**	**0.358**	**0.370**
		1	with litter	0.197	**0.297**	**0.349**	**0.386**	**0.400**	**0.426**	**0.412**	**0.423**	**0.450**	**0.460**
	2nd year	3	litter free	0.093	0.204	**0.337**	**0.374**	**0.403**	**0.393**	**0.427**	**0.417**	**0.392**	**0.383**
		1	with litter	**0.230**	**0.327**	**0.425**	**0.447**	**0.482**	**0.488**	**0.517**	**0.530**	**0.534**	**0.516**
	both years	3	litter free	0.007	0.117	**0.211**	**0.281**	**0.316**	**0.338**	**0.340**	**0.332**	**0.352**	**0.359**
		1	with litter	**0.184**	**0.314**	**0.376**	**0.401**	**0.422**	**0.429**	**0.426**	**0.425**	**0.438**	**0.444**
A+B+C+D	1st year	3	litter free	0.040	0.143	**0.218**	**0.291**	**0.323**	**0.328**	**0.309**	**0.327**	**0.367**	**0.371**
		1	with litter	**0.197**	**0.286**	**0.327**	**0.358**	**0.370**	**0.344**	**0.319**	**0.350**	**0.379**	**0.380**
	2nd year	3	litter free	0.030	0.185	**0.321**	**0.375**	**0.381**	**0.387**	**0.417**	**0.409**	**0.384**	**0.378**
		1	with litter	**0.206**	**0.359**	**0.454**	**0.460**	**0.463**	**0.472**	**0.506**	**0.505**	**0.507**	**0.498**
	both years	3	litter free	0.030	**0.160**	**0.252**	**0.316**	**0.337**	**0.335**	**0.327**	0.333	0.351	0.351
		1	with litter	**0.181**	**0.312**	**0.364**	**0.385**	**0.389**	**0.364**	**0.352**	**0.367**	**0.385**	**0.383**

Period	Year	Number of days of averaging temperatur	Type of research point	Average precipitation from:									
				11 days	12 days	13 days	14 days	15 days	16 days	17 days	18 days	19 days	20 days
A	1st year	3	litter free	**0.627**	**0.649**	**0.621**	**0.614**	**0.678**	**0.684**	**0.685**	**0.688**	**0.656**	**0.637**
		3	with litter	**0.674**	**0.698**	**0.703**	**0.700**	**0.724**	**0.720**	**0.728**	**0.713**	**0.647**	**0.612**
	2nd year	3	litter free	**0.448**	**0.498**	**0.496**	**0.487**	**0.484**	**0.465**	**0.450**	**0.438**	**0.420**	**0.401**
		3	with litter	**0.431**	**0.488**	**0.489**	**0.524**	**0.510**	**0.430**	**0.431**	**0.446**	**0.437**	**0.392**
	both years	3	litter free	**0.457**	**0.485**	**0.473**	**0.466**	**0.504**	**0.506**	**0.505**	**0.505**	**0.477**	**0.456**
		3	with litter	**0.435**	**0.471**	**0.486**	**0.494**	**0.500**	**0.475**	**0.480**	**0.478**	**0.443**	**0.410**

Period	Year	Number of days of averaging temperatur	Type of research point	Average precipitation from:									
				11 days	12 days	13 days	14 days	15 days	16 days	17 days	18 days	19 days	20 days
B+C+D	1st year	3	litter free	**0.383**	**0.387**	**0.394**	**0.406**	**0.419**	**0.447**	**0.474**	**0.484**	**0.477**	**0.456**
		1	with litter	**0.507**	**0.524**	**0.533**	**0.539**	**0.537**	**0.559**	**0.580**	**0.582**	**0.568**	**0.547**
	2nd year	3	litter free	**0.390**	**0.395**	**0.407**	**0.414**	**0.411**	**0.417**	**0.424**	**0.404**	**0.421**	**0.418**
		1	with litter	**0.509**	**0.502**	**0.525**	**0.537**	**0.534**	**0.527**	**0.527**	**0.513**	**0.519**	**0.513**
	both years	3	litter free	**0.372**	**0.377**	**0.382**	**0.394**	**0.403**	**0.423**	**0.443**	**0.442**	**0.442**	**0.430**
		1	with litter	**0.471**	**0.479**	**0.488**	**0.498**	**0.500**	**0.510**	**0.525**	**0.521**	**0.513**	**0.503**
A+B+C+D	1st year	3	litter free	**0.390**	**0.402**	**0.407**	**0.415**	**0.432**	**0.456**	**0.475**	**0.487**	**0.480**	**0.460**
		1	with litter	**0.421**	**0.442**	**0.453**	**0.454**	**0.457**	**0.469**	**0.481**	**0.487**	**0.477**	**0.461**
	2nd year	3	litter free	**0.386**	**0.397**	**0.405**	**0.410**	**0.410**	**0.414**	**0.420**	**0.403**	**0.416**	**0.413**
		1	with litter	**0.492**	**0.493**	**0.516**	**0.525**	**0.523**	**0.511**	**0.515**	**0.503**	**0.511**	**0.504**
	both years	3	litter free	**0.366**	**0.377**	**0.381**	**0.389**	**0.403**	**0.419**	**0.434**	**0.435**	**0.431**	**0.418**
		1	with litter	**0.408**	**0.420**	**0.433**	**0.439**	**0.444**	**0.446**	**0.456**	**0.455**	**0.445**	**0.435**

Statistically significant values (at significance level a = 0.05) are indicated with bold numerals A. B. C. D as in Figure 1

the exponential equation in the period of decreasing respiration (from June to March) and by the linear equation when respiration is increasing (March to June). Parkin and Kaspar (2003) noted a similar shape to the course of CO_2 soil emissions and the phenomenon of hysteresis, but in a diurnal cycle. When the temperature rose between 6:00 and 12:00, soil respiration increased very quickly, stabilizing at approx. 13:00 despite further increases in temperature, and the exponential shape of the relationship between soil CO_2 emissions and temperature occurred only as respiration decreased.

My research also indicated that soil respiration is best correlated with temperature when it is increasing. Slightly different results were obtained by Moncrieff and Fang (1999), who state that the reaction of soil respiration to changes in temperature is certainly highest in summer, but soil CO_2 emissions are more strongly determined by temperature in spring than in autumn.

The problem of soil respiration response time to changes in temperature and relative humidity has hardly been studied thus far. This should probably be explained by the fact that it takes a certain amount of time for the population of soil microbes to change due to reaction to improving or deteriorating environmental conditions. The three day delay observed in this study corresponds to the 2–8 day periodicity in the amount of CO_2 emissions found in the tundra (Zimov et al. 1993), which was also associated with the life cycle of microorganisms.

In the case of the relationship of soil respiration to amount of precipitation, a 17-18 day delay is most likely due to the shape of these averages, which fairly well describes the changes in soil moisture directly affecting the number of soil microorganisms.

So far, no attempt has been made to model soil respiration by dividing the period of variability in the amount of CO_2 emissions into sub-periods. Attempts to do so in this study did not improve the model significantly, despite providing a better representation of the course of soil respiration in May and early June. Another problem is finding the right formula for the calculation of soil respiration in winter. Most researchers omit this period, beginning their studies in spring and ending in autumn. The use of the exponential model for the entire period of soil respiration variation may be useful for estimating the amount of CO_2 emitted in an entire the year, but it does not reflect the dynamics of the changes, because the period of winter is considered separately.

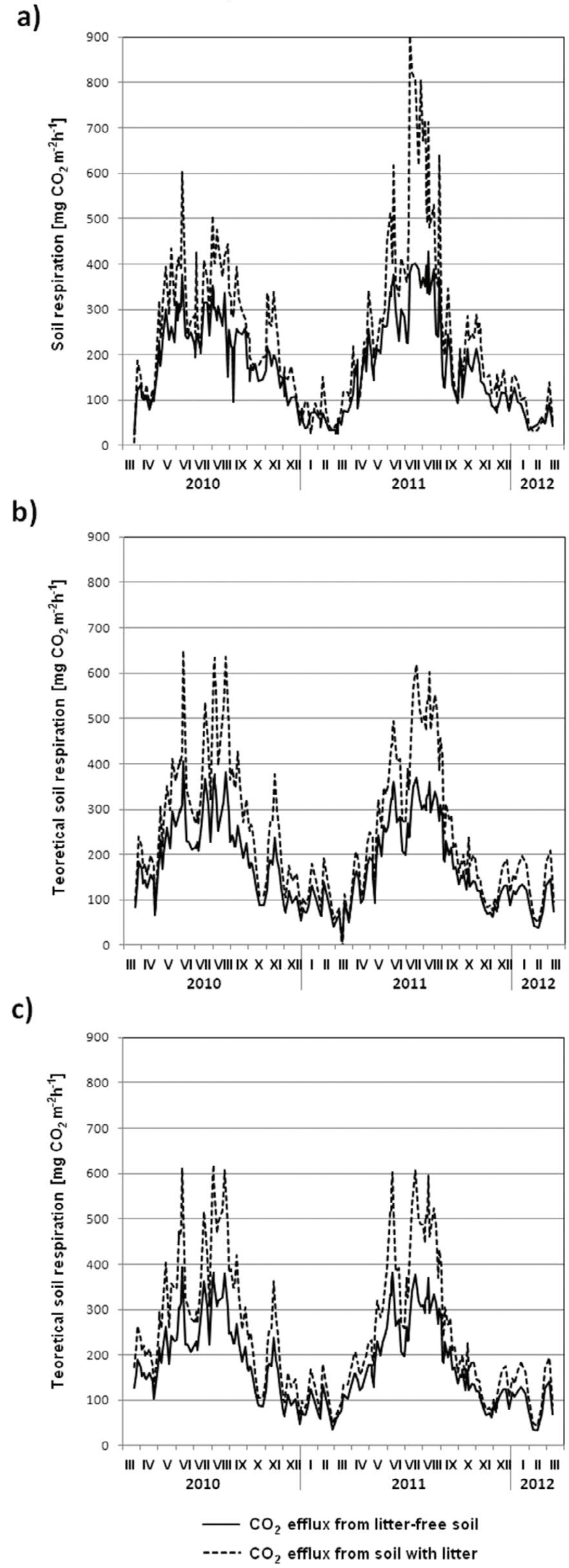


Figure 3. Observed soil respiration at the study sites (a) and theoretical soil respiration values based on the model taking into account a division between the period of increasing soil respiration and the period of decreasing soil respiration (b) and a single model for the entire research period (c)

Table 8. Values of R^2 and standard error of the estimate for the two tested models

Model	Research point without litter		Research point with litter	
	R^2	Standard error of estimation	R^2	Standard terror of estimation
$R = a+bT+cW+dW^2$ in period A; $R = a + e^{b+cT+dW+fW^2}$ in period B+C+D	0.83	41.28	0.81	85.33
$R = a + e^{b+cT+dW+fW^2}$ in whole research period	0.75	42.85	0.73	88.3

Explanation: *R*—theoretical soil respiration of the day; *T*—average temperature of 3 days; *W*—average precipitation of 17 days; *a. b. c. d. f*—empirical coefficients; A. B. C. D as in Figure 1.

5. Conclusions

The following conclusions can be made from the study presented in this paper:

1. Between approx. March 10 to approx. June 10, soil respiration increases linearly as temperature increases.
2. When respiration decreases (from approx. June 10 to approx. March 10), the relationship of soil respiration to air temperature takes the shape of an exponential curve.
3. Soil respiration responds with a delay of approx. 3 days to temperature changes and relative humidity, and with a delay of approx. 17 days to changes in amount of precipitation.
4. Dividing the period of soil respiration variation into a period of increasing respiration and a period of decreasing respiration, as well as modelling soil respiration for each of these periods alone does not significantly improve the quality of the generated series of theoretical values of respiration.

The research carried out by the author also shows that there is very little knowledge available about the determinants of soil respiration in winter. Future research should focus also on this issue.

Conflict of interest

The author declares that there are no potential conflicts of interest.

Acknowledgements and funding sources

The study was funded by the author. The author would like to thank the Department of Physical Geography, University of Łódź for the free use of a carbon dioxide meter.

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Translated by: Barbara Przybylska