RESEARCH ARTICLE

Significance of soil respiration from biological activity in the degradation processes of different types of organic matter

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ABSTRACT

Soil respiration is a major component of global carbon cycle. Therefore, it is crucial to understand the environmental controls on soil respiration for evaluating potential response of ecosystems to climate change. In a temperate deciduous forest (located in Northern-Hungary) we added or removed aboveground and belowground litter to determine total soil respiration. We investigated the relationship between total soil CO₂ efflux, soil moisture, and soil temperature. Soil CO₂ efflux was measured at each plot using soda-lime method. Temperature sensitivity of soil respiration (Q₁₀) was monitored *via* measuring soil temperature on an hourly basis, while soil moisture was determined monthly. Soil respiration increased in control plots from the second year after implementing the treatment, but results showed fluctuations from one year to another. The effect of doubled litter was less significant than the effect of removal. Removed litter and root inputs caused substantial decrease in soil respiration. We found that temperature was more influential in the control of soil respiration than soil moisture. In plots with no litter Q₁₀ varied in the largest interval. For treatment with doubled litter layer, temperature sensitivity of CO₂ efflux did not change considerably. The effect of increasing soil temperature is more conspicuous to soil respiration in litter removal treatments since lack of litter causes greater irradiation. When exclusively leaf litter was considered, the effect of temperature on soil respiration was lower in treatments with added litter than with removed litter. Our results reveal that soil life is impacted by the absence of organic matter, rather than by an excess of organic matter. Results of CO₂ emission from soils with different organic matter content can contribute to sustainable land use, considering the changed climatic factors caused by global climate change.

Keywords: carbon cycle, CO₂ efflux, DIRT, Q₁₀, forest soil, and soil biology

1. Introduction

Soil respiration in terrestrial ecosystems plays a critical role in regulating global carbon cycles. Soil contains a

huge and dynamic pool of carbon (C) that is a critical regulator of the global carbon budget (Fekete *et al.*, 2017). Small climatically induced changes in the rate of soil respiration can have a great impact on future

atmospheric CO₂ concentrations. Soil gas release is temperature sensitive; thus, global warming probably creates a positive feedback, causing soils to release more greenhouse gases, which will further exacerbate the problem (Johnston *et al.*, 2004). Soil respiration is the largest terrestrial source of CO₂ to the atmosphere and currently represents an annual flux one order of magnitude larger than that from anthropogenic fossil fuel combustion (IPCC, 2007). Soil carbon accumulation and turnover are important global processes: soils contain about 1.5×10^{12} t C, which is 2-3 times greater than the total amount of C in vegetation (Schlesinger 1990). Thus, any change in rates of soil C turnover will significantly affect to the global C cycle. The quantity and quality of litter input are considered under most scenarios of global climate change (Fekete *et al.*, 2008). With climate change, according to the predicted increase in litter fall, increase the soil CO₂ efflux and the atmospheric CO₂ concentration (Crow *et al.*, 2009; Kotrocó *et al.*, 2009; Prévost-Bouré *et al.*, 2010). Quality and quantity of leaf litter input is considerably different in the soil of various ecosystems (Raich and Nadelhoffer, 1989). Input and output processes are affected by climatic factors (such as temperature and water) and by soil organisms, which simultaneously impact the degradation of organic matter and the abiotic dissolution of nutrients from the soil (Tóth *et al.*, 2013; Juhos *et al.*, 2019). Warming climate increases the activity of soil microorganisms and their soil enzymes (Jin *et al.*, 2010; Fekete *et al.*, 2011a; Kotrocó *et al.*, 2014), which lead to increasing intensity of organic matter degradation (Kotrocó *et al.*, 2020). Degradation processes are under the control of increasing temperature, rather than other processes. Increased degrading yield enhanced soil respiration, which results in decreased organic matter content of soil and, consequently, accelerates deterioration of the habitat (Millard *et al.*, 2010; Béni *et al.*, 2017; Fekete *et al.*, 2020a, 2020b).

Several authors reported a positive correlation between soil respiration and temperature (Lloyd and Taylor, 1994; Ryan *et al.*, 1994). One significant factor, which impacts response of soil respiration to global change, but also determines the direction and magnitude of terrestrial carbon cycle, is related to climate warming. This demonstrates temperature sensitivity of soil respiration (Luo, 2007). Temperature sensitivity of soil respiration (Q₁₀) is important; it enables understanding the effect of ecosystem carbon dynamics to global climate change (Zheng *et al.*, 2009). Q₁₀ shows how many times soil respiration increases with a 10 °C increase in temperature. Soil carbon content is also influenced by human activities, since organic matter decomposition and impending soil erosion can be enhanced by timbering and soil disturbance. Extent of soil respiration

intensity provides input data for large-scale research of carbon circulation, contributes to revealing interactions between biosphere and atmosphere, and promotes the calculation of carbon balance from associations with global levels. Respiration intensity values are also needed for making predictions and for modeling the global climatic change (Ignace, 2019; Zhenfeng *et al.*, 2015).

The aim of the present research is to examine: (i) the amounts of carbon-dioxide efflux in a deciduous oak forest, in relation with temperate variations, over a 5-year period; (ii) changes in CO₂ efflux of the soil under the influence of added litter and litter removal, (iii) effects of litter (i.e., organic matter) removal or of increase of litter input on temperature sensitivity of soil respiration, and (iv) effects of abiotic factors (temperature and humidity) on soil respiration.

2. Methods

The Síkfőkút DIRT Project is a member of a long-term inter-site project (Detritus Input and Removal Treatments, DIRT) organized by the USA ILTER (International Long-Term Ecological Research).

The DIRT Experiment is a long-term study of controls on soil organic matter formation; its goal is to assess how rates and sources of plant litter inputs control the accumulation and dynamics of organic matter and nutrients in forest soils over decadal time scales. Our experimental site is in the southern part of the Bükk Mountains in Northern Hungary (47°55'N, 20°46'E, 320-340 m above sea level). This site is covered by oak forest (*Quercetum petraeae-cerris*) with brown forest soils, with clay illuviation and according to the FAO Soil Classification, the type of soil is Cambisols. Basic meteorological and soil characteristics of the site are presented in Table 1 and Table 2. The annual precipitation amounts to 550 mm.

Table 1. Mean annual soil and meteorological characteristics of Síkfőkút DIRT site, Hungary.

years after estab- lish- ment	Mean annual			
	soil tempera- ture at 10 cm (°C)	soil moisture at 10 cm (v/v%)	air tempera- ture (°C)	precipi- tation (mm)
2	10.3	23.4	11.3	523.3
3	9.6	19.0	10.6	542.7
4	9.5	27.1	10.4	678.6
5	10.2	27.2	10.3	712.1
6	10.1	30.5	10.8	621.3

Plant litter inputs have been manipulated at the DIRT plots in Síkfőkút Forest since year 2000. Six litter treatments (three replicates per treatment, Table 3) were located randomly at the site. Plots sizes are 7×7 m (49 m²). Litter of No Litter plots were transferred to Double Litter plots many times per year. Vegetation was continually removed from the No Roots and No Inputs plots.

Table 2. Mean characteristics of soil at Síkfőkút DIRT site, Hungary.

Parameters	Characteristic value
pH _{H2O}	5.21
C:N (A horizon)	20
C:N (litter)	55
Mean annual litter production (kg ha ⁻¹ yr ⁻¹)	2930
Soil type	Cambisols

Table 3. Treatments of the DIRT (*Detritus Inputs and Removal*) plots (Síkfőkút, Hungary).

Treatment	Method
Control (CO)	Normal litter inputs are allowed.
No Litter (NL)	Aboveground inputs are excluded from plots.
Double Litter (DL)	Aboveground leaf inputs are doubled by adding litter removed from No Litter plots.
Double Wood (DW)	Aboveground wood inputs are doubled based on measured input rates of woody debris fall.
No Roots (NR)	Roots are excluded with impenetrable barriers extending from the soil surface to the top of the C horizon.
No Inputs (NI)	Aboveground inputs are prevented as in No Litter plots, belowground inputs are prevented as in No Roots plots.

Measurement of soil respiration and determination of Q₁₀ value

Soil respiration was measured by the Soda lime method, based on Kotroczó (2008), who determined the total annual soil CO₂ efflux at each plot, using chamber-based soil respiration measurements. Soil respiration was measured monthly, two chambers being used at every plot. The relation between soil temperature and soil respiration is $R_s = \alpha \times e^{\beta \times T}$, where R_s is the measured

soil respiration rate, T is measured soil temperature at 10 cm depth, while α and β are regression coefficients (β is also called temperature reaction coefficient). From this equation one can calculate Q₁₀ ($Q_{10} = e^{10 \times \beta}$) (Boone *et al.*, 1998). Our measurements were made from year 2002 to 2006.

Measurement of soil temperature and soil humidity

Soil temperature was measured hourly in all 18 plots by Onset StowAway®TidbiT® temperature loggers, at 10 cm soil dept. Soil moisture was measured monthly by TDR 300 (Time Domain Reflectometer) instrument on the field, in volumetric percent. Two measurements were done at each plot.

Statistical analyzes

We used generalized linear models (GLM) to test significant differences among treatments by soil respiration, as dependent variable, and soil temperature and soil moisture as covariates. We used one-way ANOVA to determine significant differences in soil respiration, soil temperature, and soil moisture from one year to another and among treatments. Linear regression was used to evaluate the relationship between soil respiration rates and soil moisture. Statistical analysis was performed by SPSS software (version 19) and significant differences for all statistical tests were evaluated at the level of $p=0.05$.

3. Results

Soil respiration and treatments effect

In the second year after the establishment of the plots, CO₂ efflux in the Control plots was 67.41 mgC m⁻² h⁻¹, and in the next two years the effluxes were lower 57.60 mgC m⁻² h⁻¹ and 57.30 mgC m⁻² h⁻¹, respectively. In the fifth year after its establishment, soil respiration was the highest with 102.43 mgC m⁻² h⁻¹, in the fifth year, and 82.15 mgC m⁻² h⁻¹, in the sixth year (Fig. 1).

Figure 1. Mean soil CO₂ efflux of the control plots between the 2nd and 6th years after establishment (mg C m⁻² year⁻¹ Mean ± SE). Letter a shows significant differences from letter b (years: 2nd $p=0.059$, 3rd $p<0.001$, 4th $p<0.003$).

The soil CO₂ efflux of Control plots showed increasing tendency, but it was not obvious. In this year, the effects of the gypsy moth (*Lymantria dispar* L.) caterpillars' chewing activity could be shown in CO₂ efflux as well. Soil respiration did not differ among treatments ($p=0.362$) over the first year.

In the No Roots plots and No Inputs plots were the Q₁₀ values between 1.7 and 2.6. Temperature sensitivity of soil respiration differed from one year to the next ones. Typically, Q₁₀ value in NR and NI plots was more elevated than in Co plots (Table 4).

Figure 2. Soil CO₂ efflux (mg C m⁻² year⁻¹) between the 2nd and 6th years after the establishment.

Mean soil respiration in the Control plots was 67.41 mgC m⁻² h⁻¹, in the No Litter plots 65.33 mgC m⁻² h⁻¹ and Double Litter plots 80.87 mgC m⁻² h⁻¹. From the third year after its establishment to the sixth year under study, soil respiration differed among treatments ($p<0.05$). The mean soil respiration in the Control plots was 76.66 mgC m⁻² h⁻¹, in the No Litter plots was 64.91 mgC m⁻² h⁻¹ and Double Litter plots was 83.46 mgC m⁻² h⁻¹. According to GLM, soil respiration differed significantly among treatments between the second year to the sixth year ($F_{(5;268)}=10.238$, $p<0.001$). Soil temperature and soil moisture had a strong effect on treatments ($p<0.001$). Soil CO₂ efflux decreased significantly in NL plots ($p=0.022$). In plots, where only belowground litter input (NR) was removed and in plots, where aboveground and belowground litter input (NI) was removed, as well, soil respiration differed from control plots highly significantly ($p<0.001$). In the first years after the establishment of treatments soil CO₂ efflux was greater or almost the same in removal plots than in control plots. Soil CO₂ efflux in DL plots was not significantly higher than in Co, but the difference was close to significant ($p=0.097$). Soil respiration was the same or higher in DW plots as in Co plots, but without significant difference. Soil respiration varied seasonally. Soil CO₂ efflux was the highest during summer and the lowest during winter (Fig. 2).

Temperature sensitivity

Temperature sensitivity (Q₁₀) varied in the Control plots from 1.1 to 2.7, in the Double Litter plots from 1.1 to 2.3, and in the No Litter plots from 1.0 to 2.8. In the removed aboveground litter input plots the temperature sensitivity varied in the highest range.

Table 4. Annual Index of Respiration Response to Seasonal Change (IRRSC) values of the DIRT plots (Síkfőkút, Hungary).

	Years after establishment									
	IRRSC					R2				
	2nd	3rd	4th	5th	6th	2nd	3rd	4th	5th	6th
DL	1.6	1.3	1.3	2.7	1.4	0.15	0.38	0.10	0.75	0.07
DW	1.4	1.3	1.6	3.0	1.7	0.12	0.38	0.38	0.84	0.15
CO	1.5	1.1	1.3	2.9	2.0	0.14	0.09	0.25	0.77	0.24
NL	1.5	1.5	2.0	2.7	2.0	0.15	0.47	0.71	0.85	0.37
NR	2.1	1.8	2.0	2.5	2.4	0.83	0.89	0.93	0.92	0.62
NI	1.7	1.8	2.2	2.5	2.3	0.49	0.79	0.93	0.91	0.55

Treatment effects on soil temperature

Soil temperature varied seasonally, the highest was during summer and the lowest during winter (Fig. 3). We did not find significant differences in the monthly average soil temperature among treatments ($p>0.05$). The five-year average soil temperature was Co: 9.9 °C, NR: 10.1 °C, NI: 9.8 °C, NL: 9.7 °C, DL: 10.2 °C and DW: 9.8 °C. We measured both the lowest (-0.37 °C) and the highest (21.45 °C) temperature in the No Inputs plots. The Doubled Litter input had an insulating effect. For DL plots, soil temperature never fell under 0 °C (in December, January, and February), while in summer (June, July, and August) the soil temperature increased. The minimum soil temperature was 2.85 °C and the maximum 19.20 °C in the DL plots, against the removed litter inputs plots, where we measured always the highest

Figure 3. Soil moisture (%) between the 2nd and 6th years after the establishment.

temperature (NL: 20.39 °C, NR: 20.74 °C, NI: 21.45 °C) (Fig. 2). During the warm-up period (spring and summer months) the soil was warmer in the NL, NR, and NI plots than in the Co, DW, and DL plots. Soil temperature varied over the warm-up period among treatments in the order DL < DW < Co < NL < NR < NI. This warm-up sequence ceased gradually in fall (September and October).

Then it turned with the weakening of diurnal warming. The soil temperature decreased in the NL, NR, and NI plots more than in Co, DW, and DL plots. Again, soil temperature varied among treatments during wintertime in the order NI < NL < NR < DW < Co < DL. In control plots, the annual average temperature range was 19 °C.

found between monthly values of soil respiration and soil moisture. Soil moisture content in the NR and NI plots was higher as for other treatments and significantly different from control plots ($p < 0.000$) (Fig. 4). Moisture conditions were more balanced in NR and NI plots. Lowest soil moisture content was of 22% in NR plots and 20% in NI plots, while in DL plots of only 10%. The maximum value of soil moisture did not vary significantly among treatments. Soil moisture content was 51.5% in NI plots and 46% in DL plots. The difference among the minimum and maximum values of the soil moisture content was 2.5-fold in NI plots, while we found five-fold difference in DL plots (Co, DW and NL plots varied similarly to DL plots).

Figure 4. Soil temperature (°C) between the 2nd and 6th years after the establishment.

Temperature range was the highest in the removed litter inputs plots (NI: 22 °C, NR: 21 °C, NL: 21 °C). The temperature range of DW plots was the same as for Co plots (19 °C). The temperature range of DL plots was lower by 1 °C (18 °C).

Treatment effects on soil moisture

The range of soil moisture varied from 8% to 50% in the control plots from the second year to the sixth year. Significant correlation ($r = 0.310$ $p < 0.000$ $N = 573$) was

4. Discussion

Treatment effects on soil respiration

In a temperate deciduous forest in Sikkökút, Hungary, we measured the soil CO₂ efflux between the second year to the sixth year, after establishment. Soil respiration increased from the beginning of measurement, but results fluctuated from one year to another. Differences in soil respiration among years were affected by temperature, moisture, and organic matter input,

similarly to results reported by Yu and co-workers (2015). Variation of soil organic carbon content, especially in the topsoil, changes soil microbial activity (Villányi *et al.*, 2006; Yan *et al.* 2020) and, accordingly, CO₂ efflux from the soil. In our study, we either added to or removed litter inputs from the soil. Removed litter and root inputs caused the most significant change in soil respiration among treatments. Doubled litter input increased soil respiration, but its extent was not as big as the effect of removing litter (Prévost-Bouré *et al.*, 2010). DL plots had greater nutrient supplies, which – under appropriate circumstances, e.g., optimal moisture content for decomposing organisms, increase the intensity of soil respiration (Wan-Luo, 2003; Fekete *et al.*, 2011b).

In the 5th year of the establishment, additional amounts of organic matter fell down to the soil, as a result of gypsy moth caterpillars' (*Lymantria dispar*) chewing activity. As an effect of organic fragments and caterpillar frass, intensity of soil respiration exhibited a larger increase over this period as compared to other years. Caterpillar frass was quickly washed into the soil by precipitates. It formed large and easily available organic food supply for microorganisms. Therefore, it also increased soil respiration *via* enhancing decomposition processes (Kagata and Ohgushi, 2012).

Over the initial three years after treatment establishment, CO₂ efflux was higher in plots with root- and leaf-litter removal than in Co plots. For NL treatments, CO₂ efflux did neither exceed the Co plots, nor the values of NR and NI plots. If one assigns a value 100% to Co plots, CO₂ efflux of NL plots was 95% over the initial three years. In case of NR and NI treatments, these values were 110% and 102%, respectively. On one hand, it can be explained by the amount of plant roots, which remained in the plot soil after the establishment, their decomposition serving as a continuous nutrient supply. As a result, roots increased the CO₂ efflux of microorganisms. On the other hand, greater humidity of NR and NI plots ensured favorable conditions for decomposing microorganisms. Similar processes were revealed by Schindlbacher *et al.* (2008), who examined the CO₂ efflux on artificially heated parcels, surrounded by ditches. Their short-term examinations revealed considerably increased release of CO₂ from the soil, in the first period of heating. Bond-Lamberty *et al.* (2011) found that trenching a plot causes unavoidable disturbance; authors observed on the short-term, spatial variability of soil respiration doubled.

Five years after the establishment of treatments, efflux of NR (99%) and NI (93%) decreased as compared to Co, likely triggered by the continuous decomposition in the soil of a few years old leaf-litter. These results agreed with experiments by Crow *et al.* (2006), who measured the soil respiration in the H. J. Andrews

Experimental Forest (Oregon, USA), and found that decreasing CO₂ efflux of NI plots showed up a few years after the manipulation. An explanation is that treatments need time to be effective. According to Sayer *et al.* (2010), when leaf litter and roots were missing from the soil, the connection between humidity and CO₂ efflux becomes less evident. Soils of litter removal treatments had lower nutrient basis since organic matters got into the soil in different quantities. Therefore, despite of favorable soil moisture and because of poorer nutrient supply, metabolism of decomposing soil microorganisms (Hooper and Vitousek, 1998) and subsequent intensity of soil respiration did not increase as much as in the other three treatments.

Relation between soil respiration and soil temperature, Q₁₀ value

Temperature sensitivity of soil respiration has been studied widely across the temperate forest ecosystems (Wang *et al.*, 2006) and described by an exponential equation (Q₁₀). Temperature sensitivity of soil respiration varied among soils with different soil organic carbon contents (Zheng *et al.*, 2009). Because of various annual average temperatures, yearly examination of Q₁₀ values showed differences (Table 4). The Q₁₀ value in NR and NI plots was greater than in Co plots. Soil respiration responded to changes in temperature more sensitively in trenched treatments, than in control plots (Bond-Lamberty *et al.*, 2011).

Variation among Q₁₀ values was the most evident in No Litter plots, where the insulating effect of the litter was not overcome by the removal of aboveground litter. Should the litter input decrease, soil CO₂ efflux would respond to the change of temperature more sensitively. For treatments with doubled litter inputs, temperature sensitivity of CO₂ efflux did not change to a large extent (Wan and Luo, 2003) because of leaf-litter isolation. In these plots, effect of litter removal treatments on soil respiration was larger as compared to added litter inputs. This is an important finding, given that activity of soil microorganisms and intensity of decomposition processes (i.e., soil respiration) were less affected by the equable temperatures (lower fluctuation in temperature), relative to treatments, with greater temperature fluctuations. Chen *et al.* (2010) found that lower temperature may render active microbes dormant, hence, may decrease the variety of microbial species. Vardavakis *et al.* (1990) reported that seasonal changes in abundance or frequency of fungal species might be a result of seasonal fluctuations of pedological and environmental factors (moisture, temperature, and nutrient elements).

In treatments, where aboveground litter and belowground litter were removed (NR and NI), Q₁₀ values exhibited less fluctuations. These plots were

trenched; accordingly, moisture and soil temperature were higher (contrary to other treatments) over the warm-up period. These conditions favored microbiological processes. Nevertheless, this difference in temperature response between the abiotic and mineralization stages of decomposition could result in limitations of substrate supply at higher temperatures (Cooper *et al.*, 2011). On their turn, Fang *et al.* (2001) mentioned one possible reason, namely an adaptation of microbes to the desert habitat by decreasing their respiration rate at high temperatures. By this, microbes protect themselves from exhaustion.

Other researchers reported that different ecosystem types, even different vegetation types within one ecosystem, also exhibited different Q_{10} values. Hence, Chen *et al.* (2010) found a mean Q_{10} value between 1.16 and 24.3 in sub-alpine forest ecosystems. Zheng *et al.* (2009) studied different ecosystem types, where determined average Q_{10} values were in the following order: forest (2.51 ± 0.78) > grassland (2.15 ± 0.44) > cropland (1.99 ± 0.24) ecosystems, with significant differences among these three ecosystem types. According to scientific data, Raich and Schlesinger (1992) found Q_{10} values between 1.3 and 3.3. In laboratory experiments, Kirschbaum (1995) determined the proportion of Q_{10} between 2.5 (20 °C) and 8.0 (0 °C), needed for avoiding the disturbing effects of factors like soil humidity or the quality of leaf-litter.

Relation between soil respiration and soil moisture

In our experiments, we found a significant correlation between monthly values of soil respiration and soil moisture, from the second year to the sixth year after the establishment of treatment. Soil moisture content in the NR and NI plots was as high as in the other treatments and differed significantly from the control plots. A greater soil moisture content found in NR and NI plots was caused by the removal of vegetation and lack of transpiration. These plots were trenched by impenetrable barriers to block root growth, while allowing additional water flow. Bond-Lamberty *et al.* (2011) stated that in trenched plots the soil moisture test was marginally significant. Several papers dealt with the connection between soil respiration and soil moisture, however, results were different. Sulzman *et al.* (2005) did not find a significant correlation between soil respiration and moisture, except for an extreme water content (when biological activity or physical diffusion are limited). In case of extremely low or extremely high water-content, Bowden *et al.* (1998) measured lower CO_2 efflux, in forest soils (deciduous vegetation), which were incubated in the laboratory.

Annual average soil respiration increased from the beginning of the measurement, but results showed fluctuations from one year to the next. Our results

revealed that temperature changes expected for the upcoming decades would play a more important role in the control of soil respiration, than changes in soil moisture. Temperature sensitivity of soil respiration considerably determines the effects of warming through the amount of carbon, which is released from the soil into the atmosphere. According to our experiments, increasing soil temperature led to increasing soil respiration for all treatments. This relation is more noticeable in litter removal treatments since the lack of litter causes higher irradiation. As a result of isolation effects of leaf litter, the effect of temperature on soil respiration was lower in treatments with added litter relative to litter removal treatments.

5. Conclusion

Nowadays we can state that climate change will increase or decrease with litter production. We found that doubled organic matter inputs caused an increase in soil respiration, but the effect of doubled organic matter was not as significant as the effect of removal. Removed litter and root inputs caused the biggest change in soil respiration. Our results demonstrate that soil life is affected by absence of organic matter, rather than by its excess. Overall, we can conclude that examining the amount of organic matter in soils contributes to a better understanding of the effects of climate change on soils. By this one can also adapt to future climate changes, a practical way of adaptation being enabled by sustainable land use.

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