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Spatial variability of CO_2 fluxes from meadow and forest soils in western part of Wzniesienia Łódzkie (Łódź Hills)

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Abstract. For this study, the rate of soil respiration was estimated based on monthly measurements of 20 research points representing different types of plant communities. Meadows were found to have the highest rates of soil respiration, whereas rates measured in forests were lower. However, the seasonality of leaf and pine needle decomposition caused large variation in the CO_2 fluxes from forest soils. Furthermore, the carbon content at both, the soil surface and 5 cm below ground, affected spatial differentiation of soil respiration in summer and autumn, while the carbon content at 5 cm below ground also affects the spatial variability of annual CO_2 fluxes from the soil. Amazingly, however, results of research indicate that the carbon content throughout the whole humus layer does not impact soil respiration. It was also observed that changes in relief affected rates of soil respiration due to differences in sunlight exposure and the history of land use, which can markedly reduce the impact of the carbon content at 5 cm below ground on soil respiration.

Keywords: soil respiration, carbon dioxide, spatial variability, tree stands, felling areas, relief

1. Introduction

The factors that influence the time variability of soil respiration (CO_2 emission from soil) are relatively well known (Borken et al. 1999; Rochette et al. 1999; Kutsch et al. 2001; Tang et al. 2003, 2005; Savage, Davidson 2003; Tufekcioglu, Kucuk 2004; Zhaofu et al. 2005), but the knowledge about spatial variability of soil respirationis is still incomplete. However, based on the series of studies about single issues, it can express some dependencies. The highest soil respiration is in meadows and other areas with herbaceous vegetation (Reich and Tufekcioglu 2000; Lohila et al. 2003; Reth et al. 2003; Frank et al. 2006; Papińska et al. 2010). Lower soil respiration is observed in forest areas (Reich and Tufekcioglu 2000; Papińska et al. 2010) and cultivated fields (Lohila et al. 2003; Reth et al. 2003; Frank et al. 2006), and the lowest soil respiration is usually observed in areas left fallow (Reth et al. 2003; Trümper and Klik 2008). Derogations from the above relations may be due to the age of trees (Tufekcioglu and Kucuk 2004), the type of crop (Frank et al. 2006) or moisture in research stands (Papińska et al. 2010). However, there are not more accurate studies about the impact of the type of plant communities on CO_2 emissions from the soil.

In addition to the type of plant communities and the type of land use, on spatial variability of soil respiration may affect the carbon content in soil. Many studies indicate the existence of such relationship (Tufekcioglu et al. 2001; Franzluebbers et al. 2002; Harguchi et al. 2002; La Scala et al. 2000); however, there are also different results. Francez et al. (2000) and Reichstein et al. (2003) did not found significant correlation between respiration and organic carbon content in soil. Rodeghiero and Cescatti (2005) speculated that different research results may be due to the fact that the most studies analyze relationship between respiration and concentration of carbon in the topsoil instead of relationship between respiration and amount of carbon expressed in a unit of mass per unit area.

Another issue that was considered during studies about spatial variability of soil respiration in forests is human impact on the intensity of this process. So far, most studies concern on impact of fellings (Concilio 2005, Ohashi et al., 1999, Tang 2005) and rarely dealt with influences of changes in type of trees and changes in relief (Wronski 2014).

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The purpose of this study is to characterise the spatial variability of CO_2 emissions from forest and meadow soils, depending on the most typical factors that may affect soil respiration in Wzniesienia Łódzkie (Łódź Hills):

- type of plant communities in these region,
- organic carbon content in soil,
- human impact on tree stands,
- human impact on relief in forest.

2. Methodology

CO_2 emission from soil was measured by using a closed chamber method. A specially constructed steel frame was driven in soil to a depth of about 3 cm and then a CO_2 sensor was placed on a metal rack. Airtech vento carbon dioxide metre, manufactured by Gazex, was used according to the NDIR (non-dispersive infrared) method. The sensor accuracy is ± 3%, and the response time is approx. 2 min. After inserting the sensor into the chamber, a plexiglass lamp shade was put on the frame. In order to seal the chamber, the groove in frame (in which lamp shade was placed) was filled with water. In this way, the analysed sample of the soil with the air above it was isolated from the external conditions for theshort (10 min) time. The chamber was 23 cm × 23 cm × 6 cm in dimension. CO_2 sensor, which was inside the chamber, measured the concentration of CO_2 for two moments in time: 5min after closing of the chamber and 10 min after closing of the chamber. The 5-min postponement of the initial measure mentis due to the inertia of the CO_2 sensor. The difference in concentration between final measurement and initial measurement was converted to the level of CO_2 fluxes. The sensor shows the ratio of the number of CO_2 particles to the number of whole air particles (hence, the molar fraction) expressed in parts per million,which is given as follows:

$$X = \frac{n_{CO_2}}{n_{\mathrm{air}}} \cdot 1000\,000 \qquad (1)$$

where X is thesensor indicate (ppm)
n_{CO_2} is the number of moles of CO_2
n_{air} is the number of moles of air

Soil respiration is given by

$$R = \frac{\Delta M_{CO_2}}{P \cdot t} \qquad (2)$$

where R is the soil respiration
ΔM_{CO_2} is the difference between CO_2 mass in final measurement and in initial measurement [g]
P is the area of soil under the chamber [m^3]
t is the time between final measurement and initial measurement [h]

We can use the following equation for calculating mass concentration:

$$C_{\mathrm{mass}} = \frac{M_{CO_2}}{V_{\mathrm{air}}} \qquad (3)$$

where C_{mass} is the mass concentration of effluxed CO_2 (g m^{-3})
M_{CO_2} is the CO_2 mass (g)
V_{air} is the volume of air in chamber (volume of air minus volume of sensor) (m^3)

After transformation of the formula,

$$\Delta M_{CO_2} = \Delta C_{\mathrm{mass}} \cdot V_{\mathrm{air}} \qquad (4)$$

where ΔC_{mass} is the difference between mass concentration of CO_2 in final measurement (10 min after closing chamber) and in initial measurement (5 min after closing chamber) (g m^{-3})

After considering (2), we get

$$R = \frac{\Delta C_{\mathrm{mass}} \cdot V_{\mathrm{air}}}{P \cdot t} \qquad (5)$$

The mean problem in determining the variables in the above formula is to determine the difference in mass concentration of CO_2. Because

$$M_{\mathrm{mol}} = \frac{M_{CO_2}}{n_{CO_2}} \qquad (6)$$

where M_{mol} is the molar mass of CO_2 (g/mol)
and after taking into account the differences in units of molar volume and unit of volume,

$$V_{\mathrm{mol}} = \frac{1000 \cdot V_{\mathrm{air}}}{n_{\mathrm{air}}} \qquad (7)$$

where V_{mol} is the molar volume of air (dm^3/mol),
and after considering (3), the mass concentration can be calculated using the following formula:

$$C_{\mathrm{mass}} = \frac{1000 \cdot M_{\mathrm{mol}} \cdot n_{CO_2}}{V_{\mathrm{mol}} \cdot n_{\mathrm{air}}} \qquad (8)$$

After considering (8) and ideal gas law by Clapeyron,

$$p \cdot V_{\mathrm{air}} = n_{\mathrm{air}} \cdot R_g \cdot T \qquad (9)$$

where p is the pressure (Pa)
R_g is the universal gas constant (J mol/K)
T is the temperature (K),
we have

$$\frac{p\, V_{\mathrm{mol}}}{1000\, T} = R_g \qquad (10)$$

and for air in standard condition (under pressure 101,325 hPa and temperature 273 K):

$$\frac{101{,}325 \cdot V_{\mathrm{mol\ norm}}}{1000 \cdot 273} = R_g \qquad (11)$$

where $V_{\mathrm{mol\ norm}}$ is the molar volume of air in standard conditions (dm^3/mol)

On the basis of formulas (10) and (11), we can formulate

$$\frac{p\,V_{\text{mol}}}{T} = \frac{101325 \cdot V_{\text{mol norm}}}{1000 \cdot 273} \tag{12}$$

and after transformation,

$$V_{\text{mol}} = \frac{101325 \cdot T \cdot V_{\text{mol norm}}}{p \cdot 1000 \cdot 273} \tag{13}$$

We can transform (8) by considering (13) as follows:

$$C_{\text{mass}} = \frac{M_{\text{mol}}}{V_{\text{mol norm}}} \cdot \frac{n_{CO_2}}{n_{\text{air}}} \cdot \frac{273}{T} \cdot \frac{p}{101325} \cdot 1000000 \tag{14}$$

Because atmospheric pressure is not usually lower than 990 hPa (99,000 Pa) and is not usually higher than 1040 hPa (104,000 Pa), neglecting the impact of this factor will not cause significant errors in the mass concentration. Thus, we have

$$C_{\text{mass}} = \frac{M_{\text{mol}}}{V_{\text{mol norm}}} \cdot \frac{n_{CO_2}}{n_{\text{air}}} \cdot \frac{273}{T} \cdot 1000000 \tag{15}$$

Taking into account (1), we can write

$$C_{\text{mass}} = \frac{M_{\text{mol}}}{V_{\text{mol norm}}} \cdot \frac{273}{T} \cdot \Delta X \tag{16}$$

where ΔX is the difference between sensor indicate in final measurement and in initial measurement (ppm)

In addition to (2), we have

$$R = \frac{M_{\text{mol}}}{V_{\text{mol norm}}} \frac{273 \cdot \Delta X \cdot V_{\text{air}}}{T \cdot P \cdot t} \tag{17}$$

$$[R] = \left[\frac{\frac{g}{mol}}{\frac{dm^3}{mol}} \frac{K \cdot ppm \cdot m^3}{K \cdot m^2 \cdot h} \right] = \left[\frac{\frac{g}{mol}}{\frac{dm^3}{mol}} \frac{K \cdot \frac{1}{1000000} \cdot m^3}{K \cdot m^2 \cdot h} \right] =$$

$$= \left[\frac{g}{dm^3} \frac{\frac{1}{1000000} \cdot m^3}{m^2 \cdot h} \right] = \left[\frac{mg}{m^3} \frac{\cdot m^3}{m^2 \cdot h} \right] = \left[\frac{mg}{m^2 \cdot h} \right] \tag{18}$$

After taking into account the volume of the chamber and volume of the sensor, soil respiration is estimated using the formula

$$R = \frac{44{,}0095}{22{,}4164} \frac{27341X \cdot (0{,}23 \cdot 0{,}2330{,}06 - 0{,}000154)}{T \cdot 0{,}23 \cdot 0{,}23 \cdot 0{,}0833} =$$

$$= 367{,}2075 \frac{\Delta X}{T} \tag{19}$$

Measurements were made at monthly intervals at 20 research points in 6 research areas that represented different typesof forest and meadow ecosystems. The study was made in the most typical habitats for the western part of the Wzniesienia Łódzkie (Łódź Hills): medio-European hornbeam-oak forest with European hornbeam (*Carpinus betulus*) and pedunculate oak (*Quercus robur*: research points: ‘Wiączyń 2’51°46'14"N, 19°39'00"E and ‘Wiączyń 4’ 51°46'22"N, 19°39'05"E), acidophilous oak wood with pedunculate oak (*Q. robur*: ‘Wiączyń 1’51°46'10"N, 19°38'58"E; ‘Justynów 1’51°43'18"N, 19°41'03"E; ‘Justynów 2’51°43'12"N, 19°41'11"E; ‘Rokiciny 2’51°41'01"N, 19°47'14"E), acidophilous beech forest with European beech (*Fagus Sylvatica*: ‘Rokiciny 4’51°41'03"N, 19°47'01"E), colline fir forest with black alder (*Abies alba*: ‘Rokiciny 3’51°41'03"N, 19°46'53"E) and alluvial forest with black alder (*Alnus glutinosa*: ‘Zielona Góra 2’51°42'10"N, 19°40'52"E). Very near to Lódź, there are also small forests planted few decades ago. Examples of such forests are forest with scots pine (*Pinus sylvestris*) in the area where potential natural vegetation is oak wood (‘Olechów 1’ 51°44'41"N, 19°34'54"E) and forest with silver birch (*Betula pendula*) in the area where potential natural vegetation is hornbeam-oak forest (‘Olechów 4’51°44'12"N, 19°34'57"E) (Matuszkiewicz 1995). One research point located in after-agricultural area where, approximately 15 years ago, scots pine (*P. sylvestris*) and silver birch (*B. pendula*) started to appear through natural succession (‘Olechów 2’51°44'43"N, 19°34'53"E). Felling areas represent the research point: ‘Wiączyń 3’ (51°46'18"N, 19°39'02"E) (after felling hornbeam-oak forest) and ‘Rokiciny 1’ (51°40'58"N, 19°47'22"E) (after felling oak wood).

In order to investigate what is the level of soil respiration in forests in comparison to areas that covered herbaceous vegetation, studies were also conducted on periodically flooded meadow (‘Zielona Góra 1’ 51°42'07"N, 19°40'52"E), in old headwaters niche (‘Feliksin 3’51°43'55"N,19°36'32"E) and on the old agricultural area where grassy vegetation appeared as a result of natural succession (‘Olechów 3’ 51°44'01"N, 19°35'00"E).

In the research area ‘Feliksin’, the influence of human impact on relief on soil respiration was analysed. Research point ‘Feliksin 1’ (51°43'56"N, 19°36'33"E) was at the top of artificially hill, which was created during the development of the Łódź railway junction during World War II. Research point ‘Feliksin 2’ (51°43'56"N, 19°36'32"E) was located at the foot of the hill. Research point ‘Feliksin 3’ (51°43'55"N, 19°36'32"E) was located in old headwaters niche, but pouring off the hill stopped surface runoff; hence, there is a permanent high soil moisture. Research point ‘Feliksin 4’ (51°43'55"N, 19°36'31"E) has unchanged relief by human. The time of development of the Łódź railway junction should also be identified with the beginning of forest formation in this area.

Measurements (except stands after cutting trees, stands with changed relief in ‘Feliksin’ and stands with planted forests in ‘Olechów’) were done in areas where forests have been occurring constantly since at least 19th century (as part of old Łódź Forest). Table 1 shows soil characteristics in research points.

In each of the 20 points, measurements were made on two types of positions: on the soil with litter and litter-free soil to see how litter affects the CO_2 fluxes. In litter-free stands, litter was removed from soil surface approximately 25 min before measurement and it was redeposited after measurement. Similarly, a layer of turf was removed in soils with grassy vegetation. On each study site, measurement was done on this same square with an area of 23 cm × 23 cm. In order for measurements to be relatively representative for each habitat, each location of this square was chosen in such way that this square was neither too close nor too distant from the trees, which could be the main reason of spatial differences of soil respiration in microscale (Stoyan et al. 2000). As a rule, places without low plants were chosen. However, it was necessary to remove vegetation in meadow stands.

The measurements were done between December 2009 and November 2011 in monthly intervals. To avoid the situation that time variability during the day affect spatial variability results, measurements in different sites should be done in a relatively short period at a precise moment during the day. Therefore, measurements in each site were made once between 9 am and 12 am suntime. Values read at this time are similar to the average daily soil respiration (Savage, Davidson 2003; Lohila et al. 2003). Because of the time consumed for each measurement (in addition to 10 min for measurement, it was necessary to wait about 15 min between measurements to compensate the CO_2 concentration between the atmospheric air above the soil and inside the sensor), measurements were made in five possible allowing days. In order to compare data from different sites, estimated annual soil respiration values using the model, which as an input data uses an average temperature of 3 days and average precipitation of 17 days. This model was previously verified by Wronski (2015) for the much more numerous data series:

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

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

Organic carbon content on soil surface and 5 cm below ground and in whole humus were investigated by using the Tiurin method, and but organic carbon content in organic soils were estimated by using loss on ignitron method. The relationship between soil respiration and carbon content was calculated using the Pearson correlation coefficient.

3. Results

The influence of plants on soil respiration

Generally higher soil respiration was observed in meadows (Fig. 1, Table 2). This regularity is visible especially in summer (Fig. 2). In winter, soil respiration could be even lower than that in forests, so differences between these types of ecosystems are smaller for the entire year but high respiration in meadows is still visible.

Particularly high respiration was observed in research point 'Zielona Góra 1'. However, probably, this value is overstated, because the annual value was calculated only based on these periods when the stand was not flooded. Studies by Chimner and Cooper (2003) and Turbiak and Miatkowski (2010) shows that soil respiration can be even twice lower whensoil surface is under water.

Forest ecosystems can be arranged in terms of volume of respiration as follows: for litter-free sites: beech forest < pine forest < oak wood < hornbeam-oak forest on silt < alluvial forest < birch forest < fir forest < hornbeam-oak forest on loam; for sites with the litter: pine forest < oak wood ≈ fir forest ≈ beech forest ≈ birch forest < hornbeam-oak forest on silt < alluvial forest < hornbeam-oak forest on loam (Fig. 2). However, the differences between different types of plant communities in sites with litter are in general small.

It should be noted that the above relations relate to the average values for the whole year. These dependencies may be different for monthly values. The characteristic is that very similar results were obtained for all research points in oak woods, regardless of the physical and chemical properties of soils. On the other hand, both research points in hornbeam-oak forest were significantly different in terms of size of soil respiration. The reason of lower amount of CO_2 emission in point 'Wiączyń 2' (with silt loam as soil texture) in comparison to respiration in point 'Wiączyń 4' (with sandy loam as soil texture) was probably lower amount of wide macropores (Table 1) and thus limiting the flow of CO_2 through soil.

The influence of carbon content on soil respiration

Organic carbon content in research point is shown in Fig. 1. Correlation coefficients between soil respiration and carbon content are given in Table 3.

Statistically significant values (at significance level $\alpha=0.05$) are indicated in bold.

A significant correlation between CO_2 efflux from soil and carbon content at soil surface (0–1 cm below ground) was found only in four autumn months: in September 2010 and in September, October and November 2011. A significant correlation with carbon content at a depth of 5 cm below ground was also found in few other months: August, October and November 2010 and June 2011. Thus, effect of this parameter is visible also in summer. A stronger relationship with an annual value of soil respirationis also observed. In contrast, it is surprising that the quantity of organic car-

Table 1. Characteristics of soils in research points

Site	Soil type	Soil separates (%)			Soil texture	Porosity [%]	The content of wide macro-pores (>50 µm) [%]	The content of narrow macro -pores (10–50 µm) [%]	The content of mezo-pores (0,2–10 µm) [%]	The content of micro-pores (<0,2 µm) [%]
		Sand	Silt	Clay						
Wiączyń 1	gley soil	70	29	1	Sandy loam	69.7	4.1	17.0	26.0	22.6
Wiączyń 2	gley soil	42	57	1	Silt loam	65.1	5.2	14.6	40.0	5.3
Wiączyń 3	gley soil	48	48	4	Sandy loam	61.5	3.8	11.3	34.7	11.7
Wiączyń 4	brown soil	54	44	2	Sandy loam	64.4	15.4	16.8	27.9	4.3
Ziel. Góra 1	stagnosols	90	3	7	Sand	82.8	34.2	12.5	31.3	4.8
Ziel. Góra 2	peat-marshysoil	59	32	9	Sand	80.5	7.6	12.1	22.4	38.4
Justynów 1	rusty soil	89	10	1	Sand	63.1	17.3	16.8	17.8	11.2
Justynów 2	rusty soil	77	22	1	Sandy loam	57.1	9.9	18.6	23.4	5.2
Rokiciny 1	gley soil	71	24	5	Sandy loam	60.1	21.2	10.3	25.5	3.1
Rokiciny 2	podzols	74	24	2	Sandy loam	65.8	16.0	13.9	33.2	2.7
Rokiciny 3	gley-podzols	77	18	5	Sandy loam	88.3	39.9	17.2	12.1	19.2
Rokiciny 4	gley soil	82	16	2	Sandy loam	71.5	33.1	15.5	19.2	3.7
Olechów 1	rusty soil	83	16	1	Sandy loam	58.8	19.1	13.8	19.9	6.1
Olechów 2	rusty soil	89	10	2	Sand	46.2	7.4	9.7	26.4	2.7
Olechów 3	gley soil	82	17	1	Sandy loam	49.9	12.0	10.3	21.8	5.9
Olechów 4	rusty soil	91	8	1	Sand	61.8	15.0	16.5	25.0	5.3
Feliksin 1	rusty soil	92	7	1	Sand	49.9	17.3	11.2	16.0	5.4
Feliksin 2	gley soil	77	21	2	Sandy loam	50.7	10.2	11.3	23.6	5.6
Feliksin 3	stagno sols	63	29	8	Sandy loam	63.0	26.0	7.3	25.4	4.3
Feliksin 4	gley soil	74	23	4	Sandy loam	42.6	3.5	6.5	25.3	7.3

Table 2. Annual CO_2 emission from soil in research points (w kg CO_2 $m^{-2}year^{-1}$)

Habitat	Research point	Annual soil respiration		The average soil respiration for type of plants	
		research point litter-free	research point with litter	research point litter-free	research point with litter
Acidophilous beech forest	Rokiciny 4	1.32	2.18	1.32	2.18
Acidophilous oak wood	Wiączyń 1	1.69	2.19	1.67	2.19
	Justynów 1	1.61	2.19		
	Justynów 2	1.65	2.21		
	Rokiciny 2	1.73	2.19		
Medio-European hornbeam-oak forest	Wiączyń 2	1.84	2.42	2.31	2.65
	Wiączyń 4	2.78	2.88		
Colline fir forest	Rokiciny 3	2.24	2.30	2.24	2.30
Alluvial forest with alder	Zielona Góra 2	2.01	2.57	2.01	2.57
Dry pine forest	Olechów 1	1.51	2.11	1.51	2.11
Pine and birch forest	Olechów 2	1.35	1.57	1.35	1.57
Birch forest	Olechów 4	2.19	2.54	2.19	2.54
Meadows and areas with herbaceous plants	Feliksin 3	1.74	1.74	3.04	3.33
	Olechów 3	2.74	2.77		
	Zielona Góra 1	4.63	5.49		
Felling area after hornbeam-oak forest	Wiączyń 3	1.62	2.50	2.08	2.38
Felling area after oak forest	Rokiciny 1	2.53	2.26		
Maple-sycamore maple-elm forest	Feliksin 1	1.85	2.52	1.47	2.00
	Feliksin 2	1.36	1.87		
	Feliksin 4	1.20	1.60		

bon in the whole humus do not affect the spatial differences of soil respiration in any of these periods.

The correlation between these factors for onlyforest sites unchanged by human (i.e. excluding felling areas, areas where there was human interference in relief and the stands where tree stands are unsuitable to potential natural vegetation) was also examined. The influence of carbon content at soil surface on the spatial variability of soil respiration within these positions was almost imperceptible, but the impact of carbon content at 5 cm below ground was very visible (Table 4). Correlation coefficient with soil respiration in site without litter was 0.82 and in site with litter was 0.75. In addition to the summer and autumn months, this impact was also marked in spring of 2010, but similar dependence was not observed in the following year. It is surprising that strong negative correlation was observed in March 2010. It can be due to the uneven melting of snow at different sites in this month.

The influence of human impact on species of trees on soil respiration

Relatively low respiration is noted within area with planted pine ('Olechów 1'), but relatively high respiration is

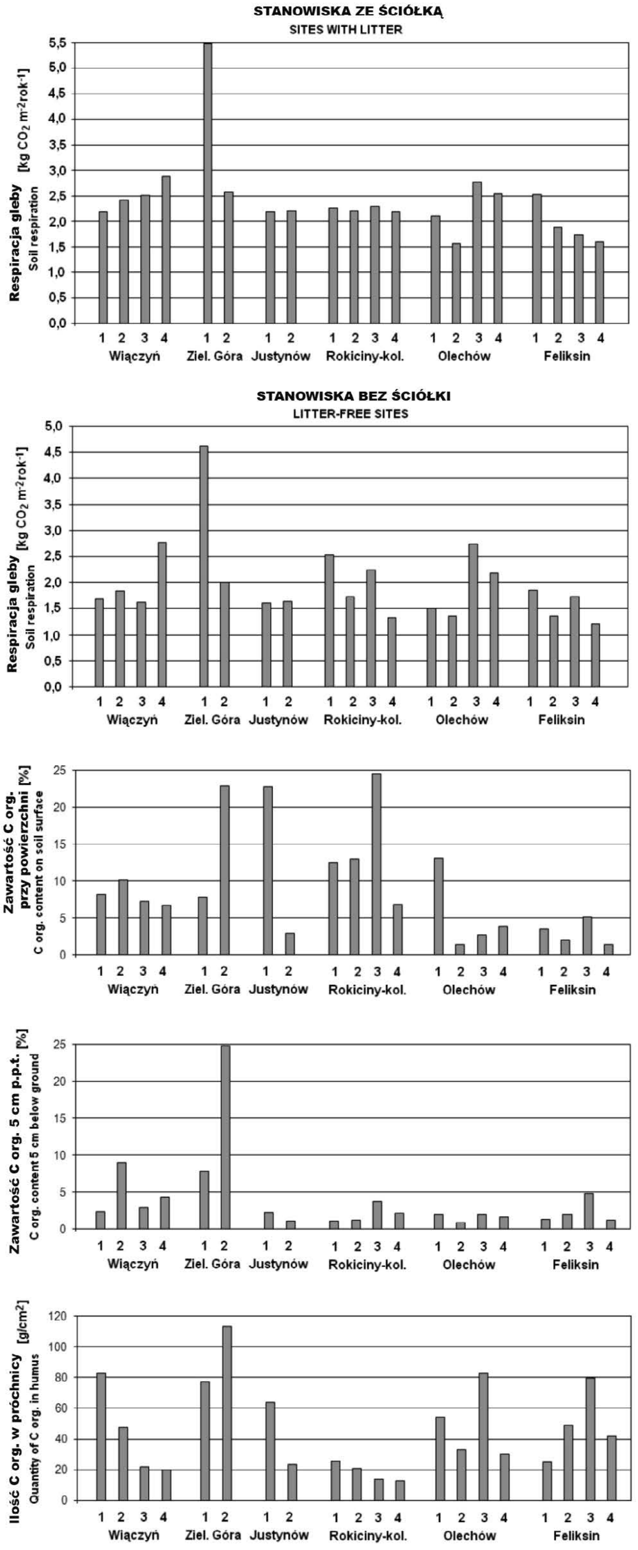

Figure 1. Annual soil respiration on research points, organic carbon content on research points on soil surface, 5 cm below ground and quantity of organic carbon in humus

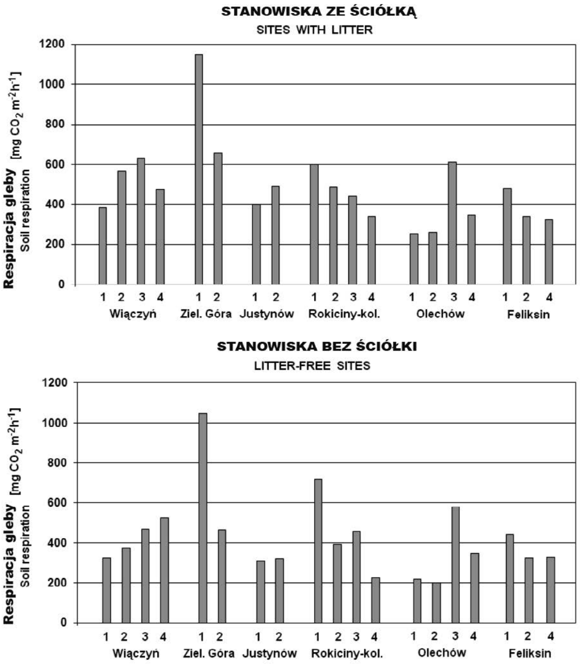

Figure 2. CO_2 emissions from soils in the beginning of July 2010

noted in area with planted birch (‘Olechów 4’). However, these values are not significantly different from the level of respiration in oak forests and hornbeam-oak forests (which are potential natural vegetation in these areas). Very low values are observed in after-agricultural area, where pine and birch appeared as a result of natural succession (‘Olechów 2’).

The influence of human impact on relief on soil respiration

It was also noted that human impact on relief may significantly affect soil respiration. In research area ‘Feliksin’, higher values was noted in points where there was an interference in relief (‘Feliksin 1’ and ‘Feliksin 2’) than in sites unchanged (‘Feliksin 4’). The highest respiration was on the top of the anthropogenic hill (‘Feliksin 1’).

4. Discussion

The influence of plants on soil respiration

The research confirms the observations of many studies that soil respiration in meadows is higher than that in forests (Reich and Tufekcioglu 2000; Papińska 2010). Reich and Tufekcioglu (2000) estimated that the rate of soil respiration in meadows are approximately 20% higher than that in

Table 3. Linear correlation coefficients between soil respiration and organic carbon content in soil for all research points

Year	Month	Organic C content on soil surface (0–1 cm below ground) [%]		Organic C content 5 cm below ground [%]		Quantity of organic C in humus [g/cm²]	
		litter-free	with litter	litter-free	with litter	litter-free	with litter
2009	XII	0.28	0.27	0.29	0.43	-0.25	-0.12
2010	I	0.34	0.39	0.04	-0.06	-0.14	-0.16
	II	-0.33	-0.42	-0.14	-0.11	-0.20	-0.37
	III	-0.01	0.16	-0.17	-0.26	-0.15	-0.05
	IV	0.18	0.17	0.33	0.43	-0.03	0.06
	V	-0.06	-0.20	0.33	0.37	0.18	0.02
	VI	0.06	0.34	0.21	0.11	-0.10	0.13
	VII	0.03	0.08	0.32	0.28	0.06	0.14
	VIII	0.26	0.39	0.36	**0.57**	-0.03	-0.09
	IX	**0.52**	0.41	0.04	0.01	0.12	0.04
	X	0.14	0.27	**0.53**	0.32	0.16	0.06
	XI	0.25	0.28	**0.53**	**0.48**	0.06	0.45
	XII	0.10	0.29	0.31	0.27	-0.22	0.07
2011	I	0.45	0.20	0.29	0.38	0.29	0.07
	II	0.12	0.02	0.38	0.44	0.03	-0.18
	III	0.03	-0.12	0.01	-0.02	0.37	0.45
	IV	0.28	0.27	0.15	0.20	-0.40	-0.42
	V	0.23	0.07	0.07	0.11	-0.11	0.40
	VI	0.22	0.13	**0.57**	**0.50**	0.35	-0.01
	VII	-0.06	-0.04	-0.01	-0.04	0.08	0.38
	VIII	0.09	0.00	0.18	0.12	-0.18	-0.32
	IX	**0.52**	0.41	0.30	0.28	0.07	0.08
	X	0.73	**0.50**	0.43	0.03	0.17	0.09
	XI	**0.52**	0.45	0.34	0.33	-0.02	0.34
Annual respiration		0.18	0.19	0.41	**0.52**	0.04	0.13

Statistically significant values (at significance level α=0.05) are indicated in bold

Table 4. Linear correlation coefficients between soil respiration and organic carbon content in soil for forest sites unchanged by human (i.e. without felling areas, without areas in which relief has changed and without stands in which there was planting trees on habitats wrong for them)

Year	Month	Organic C content on soil surface. [%]		Organic C content 5 cm below ground [%]		Quantity of organic C in humus [g/cm²]	
		litter-free	with litter	litter-free	with litter	litter-free	with liter
2009	XII	-0.02	-0.21	**0.81**	**0.76**	-0.26	-0.06
2010	I	-0.08	-0.07	-0.38	-0.64	-0.48	-0.35
	II	-0.36	-0.48	-0.17	0.05	-0.42	-0.43
	III	-0.02	-0.28	-0.68	**-0.88**	-0.01	-0.04
	IV	0.18	0.32	**0.74**	**0.73**	-0.42	-0.18
	V	0.03	-0.23	**0.83**	**0.75**	-0.31	-0.28
	VI	-0.04	0.37	0.53	0.46	-0.35	0.15
	VII	0.04	-0.03	**0.74**	0.35	0.04	0.31
	VIII	0.28	0.37	**0.81**	0.54	-0.33	-0.23
	IX	0.44	0.40	0.32	-0.02	0.31	0.31
	X	0.02	-0.08	**0.81**	**0.72**	-0.05	0.00
	XI	0.05	-0.12	**0.88**	0.30	0.15	0.60
	XII	-0.28	0.13	0.52	0.04	-0.54	-0.20
2011	I	0.25	-0.40	-0.02	0.05	0.23	-0.16
	II	-0.22	-0.47	0.36	0.32	0.28	-0.02
	III	0.15	0.06	-0.03	-0.04	0.49	0.58
	IV	0.23	0.26	0.44	0.27	-0.60	-0.51
	V	0.61	0.27	0.64	0.46	0.04	0.48
	VI	0.30	0.21	**0.78**	0.69	0.12	-0.38
	VII	0.25	0.25	**0.72**	0.06	0.12	0.43
	VIII	0.11	0.05	0.43	**0.71**	-0.47	-0.28
	IX	0.48	0.36	0.28	-0.06	-0.02	0.13
	X	**0.69**	0.40	0.42	0.00	0.03	0.17
	XI	0.20	0.05	**0.71**	0.29	0.00	0.32
Annual respiration		0.15	-0.01	**0.82**	**0.75**	-0.10	0.08

Statistically significant values (at significance level α=0.05) are indicated in bold forests. Also in Załęcze Landscape Park, soil respiration in meadow in position without litter was 20% higher than that in the nearby alluvial forest but CO_2 fluxes in meadow in point with litter was about 3% higher than that in forest (Papińska 2010). In the western part of Wzniesienia Łódzkie, the respiration noted in all meadow sites was higher than that in the nearest research points located in forests. However, the differences between forests and meadows are higher. For research points with litter, respiration in meadows was 8–14% higher than that in forests, whilst for research points without litter, CO_2 emission in meadow was 25–45% higher than that in forests.

On higher soil respiration rate in meadows can affect a large amount of biomass produced by herbaceous plants. This biomass there goes into the soil, where it is decomposed. In addition, a large amount of roots and higher temperatures in the open area contribute to higher CO_2 emission in these sites (Tufekcioglu and Kucuk 2004). High soil respiration was observed even in research points where there is a grassy vegetation but low amount of carbon in soil (‘Olechów 3’). This state of affairs can explain the results of studies by Reichstein et al. (2003), according to which site productivity affects soil respiration more than soil carbon stocks.

The results also indicate that the type of trees can significantly influence CO_2 emissions from soil. Trees shape soil conditions by providing the organic material (dead leaves and needles) into soil. But the following question arises: how differences in tree species affect the spatial variation of soil respiration. Earlier studies have suggested that the CO_2 emission is higher in deciduous forests than that in conifers forests (Longdoz et al. 2000). The results of this study do not fully confirm it. Low respiration in a pine forestwas noted, but the respiration was more lower in beech stand (for positions without litter). In turn, the rate of soil respiration in fir forest is higher than that in most positions with deciduous trees. The research may point to the significant role of the rate of decomposition of organic matter in shaping differences in CO_2 release from soil between different ecosystems. The 95-percentage time of decomposition of beech leaves (known from the literature) is 37.45 years, pine needles is 14.27 years, oak leaves is 4.76 years and hornbeam leaves is 2.83 years(Weiner 2006). It is, therefore, evident that this factor may influence on low respiration from litter-free soil in beech forest, higher respiration in the pine forest and the oak forest and very high respiration in hornbeam-oak forest. The correlation coefficient between average time of decomposition of leaves and needles in these habitats and average soil respiration in positions without litter is negative and amounts to –0.74 (although, because of the small number of elements in variables, there was no statistical significance of this coefficient). However, it should take into account that the rate of decomposition, even in small areas, is very diverse (Horodecki et al. 2015). Therefore, the potential relationship between soil respiration and rate of decomposition should be investigated in future studies.

From the obtained results, the level of CO_2 emission from soil with litter in different types of forests is more unified than that from soil without litter. An influence of type of habitats for level of soil respiration is also less visible. This situation can probably explain the fact that in forests with slow decomposition of leaves (e.g. in beech forest) or needles, soil is slowly enriched in organic carbon and more organic matter is there in litter. CO_2 emission in sites with litter is, therefore, much greater than that from sites without litter. In forests with fast decomposition of leaves and needles (e.g. in hornbeam-oak forest), CO_2 is rapidly released from these leaves and needles and also these needles and leaves are quickly crushed and soil is quickly enriched with carbon. Larger amount of carbon in soil results in smaller differences between respiration from soil with litter and that from soil without litter compared with sites with slow decomposition of organic matter. This is illustrated in Fig. 3. Greater uniformity of soil respiration on position with litter is the result of taking into account the release of carbon contained both in the litter and in the soil itself.

If the scheme described in the figure is true, there should be a combination of the following relationships:

- negative correlation between soil respiration (in sites without litter) and time of decomposition of organic matter;
- high uniformity of soil respiration in sites with litter;
- positive correlation between soil respiration (in sites without litter) and carbon content in soil;
- negative correlation between decomposition time of organic matter and carbon content in soil.

The first two of above dependences were mentioned already. The correlation between carbon content at 5 cm below

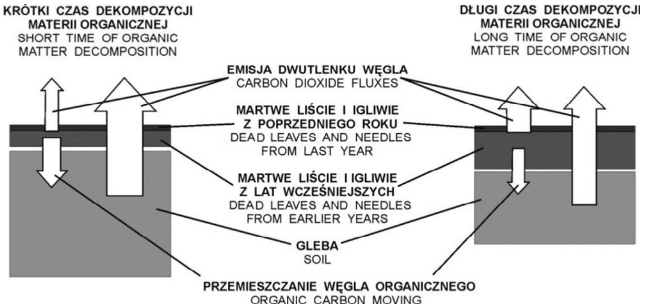

Figure 3. Schematic figure illustrating carbon streams in the short time and the long time of organic matter decomposition. The size of rectangles is the quantity of carbon. The width of arrows means the level of CO_2 emissions and organic carbon moving.

ground in unchanged forest stands and soil respiration for whole year is very strong and is 0.82 (Table 4). The veracity of the scheme can also be attributed to a negative relationship between the average time of decomposition of needles and leaves (Weiner 2006) and the carbon content at 5 cm below ground (−0.44). It would be advisable, however, to verify this model in separate studies.

The influence of carbon content on soil respiration

Several studies have shown a relationship between soil respiration and carbon content in soil. Tufekcioglu et al. (2001) found a strong correlation between these factors (0.75) on farmland in Iowa and Franzluebbers et al. (2002) for areas in prairie in Kansas, USA (0.84). High correlation (0.70) was obtained by Harguchi et al. (2002) during their research in petland in central Japan. Gough and Seiler (2004) found a small but significant correlation (0.16) between carbon content and soil respiration in a pine forest in South Carolina in the Unites States. Correlation of 0.30–0.47 between CO_2 emissions from tropical bare soils near Sao Paulo, Brazil, and the carbon content in soil was noted by La Scala et al. (2000). Rodeghiero and Cescatti (2005) observed a positive linear relationship between carbon content in the layer 0–30 cm below ground and an average annual soil respiration and exponential correlation between carbon content and soil respiration at 10 ° C. Much less studies indicate no effect of carbon in soil respiration (Francez et al. 2000, Reichstein et al. (2003).

Therefore, a surprising result of the research is that significant correlation between soil respiration and carbon content was not observed in all year but only in a few months. It can point at two periods when the impact of carbon content on soil respiration is stronger: autumn and summer. Varying sensitivity of soil respiration to organic matter content has been noticed by Moncrieff and Fang (1999) for pine plantations in Florida. The biggest reaction to a 5% increase in soil organic matter content they observed in summer. These authors explained it with moderate soil moisture and high temperatures. In central Poland, the relationship between these variables is more visible during autumn. It can be the result of fall of leaves and needles during this period and a beginning of its decay.

The study also shows that carbon content at 5 cm below ground better reflects the spatial differences in soil respiration (in relation to both the annual value and the individual months) than the carbon content on soil surface, as evidenced by the results for the unchanged forest stands. Low correlation between CO_2 emissions from soil and carbon content on soil surface in these stands may seem surprising, but it should take into account that the process of soil respiration also include CO_2 released from deeper levels of soil and spatial differences of carbon content at soil surface may be different from that in other depths in a soil. However, human interference in relief, tree stand or interference by earlier agricultural cultivation may impair strong correlation with carbon content at 5 cm below ground (as evidenced by the comparison of Tables 4 and 3). It is then more noticeable influence of other factors. A more detailed analysis of human impact on the process of soil respiration is presented in the following sections.

Surprising research resultis that quantity of organic carbon in whole humus is very poorly correlated with soil respiration. According to Rodeghiero and Cascatti (2005) calculating correlation between respiration and carbon content in topsoil instead of correlation with carbon mass per unit areais a mistake. However, in this study, significant correlation between quantity of carbon in the whole humus and soil respiration has not been detected.

The influence of human impact on tree stand on soil respiration

A very common situation in the Polish forests is planting trees on habitats that do not suit them. Researches indicate that in these areas, as well as in the forests in which there was no human interference with tree stands, intensity of soil respiration depends on the rate of decomposition of leaves and needles. Higher respiration rate was observed in birch forest, than in pine forest, where the semi-annual amount of decomposition is, respectively, 29–34% and 21–25% (Horodecki et al. 2015). These differences cannot be explained by differences in physical properties of soil, which are very similar in both positions, or by differences in carbon content (Fig. 1).

But the number of factors affecting CO_2 emissions from soil in areas with changed tree stands is greater. The most important of them is history of land use, although its effect is noted with varying intensity, depending on the time from last change of use. Usually small monoculture forests occur on areas of old farmlands. Intensive farming reduces the number of elements in soil, reduce an amount of carbon and causes decreasing of CO_2 emissions. Many studies point to very low respiration on fallow areas (Frank et al. 2006; Trümper and Klik 2008). It was also observed at research point ‘Olechów 2’, where pine and birch entered as a result of natural succession. Observation at research point ‘Olechów 2’ shows that even approx. 15 years after entering the forest, soil respiration is still very low. However, in the areas of older planting forests (in site ‘Olechów 1’ after planting pine and in site ‘Olechów 4’ after planting birch), the impact of reducing carbon in soil is already invisible. Soil respiration in these research points is similar to that in oak forests and hornbeam-oak forests, which are natural habitats for these areas, respectively.

The impact of felling on the process of soil respiration in research areas had already been analysed by Wroński (2014). At this point, therefore, I only quote, as many studies indicated (Concilio 2005), that in young felling areas, the increase of release of carbon from soil is observed, because of making fissures during planting new trees (Rykowski 1999) and an increase in temperature in the open places (Houghton and Hackler 1999, Schlesinger and Andrews 2000; Hirsh et al. 2004) and increasing nutrient availability (Tang et al. 2005). For example, in the area of young felling area after oak wood ('Rokiciny 1'), soil respiration was about 46% higher than in the area with trees ('Rokiciny 2'). But as the amount of carbon in soil is reduced, the soil respiration is decreased. Therefore, CO_2 emissions on old felling areas from the litter-free soil are lower than those from areas around.

The influence of human impact on relief on soil respiration

The author has analysed the impact of changes in relief on the process of soil respiration in research area'Feliksin 4' (Wroński 2014), but he had a much shorter data series and estimated annual level of CO_2 emissions from soil based on other, less precise models. He has not disposed some measurements of chemical soil properties. Therefore, the following interpretation is different to the interpretation in article from 2014.

Presented studies show that the impact of human on relief may significantly affect soil respiration. CO_2 emissions at the top of artificial hill ('Feliksin 1') are clearly higher than those in not changed position ('Feliksin 4'). A similar effect, although smaller, is visible at the foot of the hill ('Feliksin 2'). The reasons cannot be associated with more organic matter in the hill, because that matter is less in this place in soil profile. The reason is rather higher light intensity and, hence, more favourable conditions for the growth of crowns of trees, and thus the greater amount of leaves, which are the sources of organic matter for soil after their falling in autumn. The correctness of such explanation confirms the distribution of organic carbon in soil profiles. Although carbon content 5 cm below ground on the top of the hill is the smallest, lower at the foot of the hill, and the highest is in the unchanged place, the situation is reversed for carbon content on soil surface. The hill was made from much lighter material than that occurred naturally in this area. This material also has significantly less organic carbon. Increasing the amount of carbon near soil surface is, therefore, a result of carbon accumulation, which was initiated relatively recent (approx. 70 years ago). Large growth of tree crowns on the top of the hill provided a large dose of carbon supplied to the soil, which began to form on the hill.

5. Conclusions

This study confirmed the highest soil respiration in meadow. Within the forest, the presence of a certain scheme can be observed: in ecosystems with the fast rate of decomposition of organic matter, there is a greater supply of carbon to the soil and higher CO_2 emissions from soil without litter (in positions with litter soil respiration is more uniform) is observed. However, amongst the indicators, taking into account the amount of carbon in soil, not the total quantity of carbon in humus but the carbon content at 5 cm below ground have the strongest correlation with soil respiration. The study also showed that the influence of carbon content at 5 cm below ground varies during the year and the strongest impact of this factor is observed in summer and autumn. However, human can modify the above-described general scheme. The history of land use can be visible by reducing carbon content in soil and thus by decreasing the correlation between soil respiration and carbon content at 5 cm below ground. The rate of decomposition of leaves and needles from planted trees will have then a stronger impact on after-agricultural land. Interference in relief can affect soil respiration by changing the intensity of sunlight, whereas the volume of soil respiration in felling areas is affected by the age of felling area.

Conflict of interest

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

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