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## Bioenergetical description of selected tundra soils in Hornsund, Svalbard

**ABSTRACT:** Studies were performed in the summer of 1989 in the vicinity of the Polish Polar Station at Hornsund, Svalbard, in an attempt to characterize the functioning of selected tundra soils in terms of bioenergetics. The intensity of bioenergetical processes in the soil was evaluated by the rates of O<sub>2</sub> consumption and CO<sub>2</sub> production, measured in the laboratory under controlled hydrothermic conditions. Soils metabolic processes are markedly correlated with soil water content and dependent upon soil structure, water capacity and character of plant cover. The strongest correlation was observed in the more aerated soils with small water capacity and without vegetation. The respiratory quotient (RQ) decreased with the growth of soil moisture content. Soil metabolic activity began directly after the summer melting of the ground, when the soil temperature reached 0°C, and ceased in autumn, when temperatures fell below 0°C again.

**Key words:** Arctic, Spitsbergen, tundra soils, bioenergetics.

### Introduction

The soil plays the key role in energy and matter flow through the terrestrial ecosystem, hence it holds information on the ecosystem resources and on their utilization. The main environmental factors influencing the soil are temperature and humidity and therefore they are in focus in an ecological evaluation of the soil as biotope (Bunnell *et al.* 1977, Salenius 1978, Howard P.J.A. and Howard D.M. 1979). In severe climatic conditions of Arctic, where biological processes in soil are slow (Tedrow and Douglas 1959, Bliss *et al.* 1973) a question arises what is the effect of temperature and humidity changes in these particular conditions (Billings 1987).

The present study is an attempt to characterize bioenergetically the typical soils in a selected region of Spitsbergen (Hornsund, basin of Fuglebekken stream) with respect to temperature and humidity changes. This area, situated

in the vicinity of the Polish Polar Station, has been an arena for biological studies of the Institute of Ecology P.A.S. since 1979 (Klekowski, Opaliński and Fischer 1988). The studied basin is located between both mountain slopes of Arikammen and Fugleberget and the sea. One of the slopes is inhabited by a colony of Little Auks (*Alle alle*), resulting in a marked input of biogenic elements into basin ecosystems (Krzyszowska 1986). Soil and geomorphological characteristics of the study area can be found in the papers by Kowaliński and Szerszeń (1962), Szerszeń (1965) and Fischer and Skiba (1993); soil fauna was investigated by Byzova, Uvarov and Petrova (1995).

## Material and methods

Investigations were mainly concentrated on three soil types dominating in the study area. Plot 1 was a mineral soil (gelic gleysol), of a dusty clay composition, constantly water saturated, covered with a 0.5 cm thick layer of algae and fungi spawn. This soil is similar to those of a highcentered polygon type described by Szerszeń (1965). Plot 2 was an organic/mineral soil (histic gleysol) composed of a 20–30 cm moss/peat layer and overlying a blue-green-coloured mineral layer. Plot 3 was also an organic/mineral soil (histic regosol type), composed of an organic layer (originating from the living and decaying moss/lichen community) and of a rock debris layer below. This soil is highly water penetrable. A detailed description of the soils under study can be found in the paper of Fischer and Skiba (1993).

The present results were supplemented with data obtained during the expedition in 1984. The research program of 1984 included measurements within 5 plots differing from those investigated later. Two of them were situated on the meadow (*Cetraria hiescens*, *Drepanocladus uncinatus*) close to the base of the bird colony slope. One of them represented a typical organic soil originating from meadow litter decay; another one, being under a similar influence of the bird colony, was of a mineral/organic type. The other 3 plots (fully characterized by Fischer and Bieńkowski 1987) were situated on the slope and included: (1) soils of sea origin, under the cover of lichens and willows (lichenous soils); (2) soils similar to structural ones, but without vegetation cover (structural soils); (3) soils of organic origin, under mosses (mossy soils). For the sake of comparison the results of respiration in Polish soils are quoted.

As indices characterizing the rate of soil bioenergetic processes, the values of oxygen consumption and carbon dioxide production were used, measured in the laboratory under controlled conditions of temperature and air humidity. These indices are known to give only comparative characteristics of different soils. Nevertheless, this method is at present among the few ones allowing to compare the intensity of bioenergetical processes in the subsoil (Edwards 1975, Fischer and Bieńkowski 1987, Fischer 1990, Focht 1990a).

The measurements of O<sub>2</sub> consumption and CO<sub>2</sub> production were done between the end of April and the end of September 1989. A respirometer constructed by Klekowski was used (Klekowski 1975). Soil samples (ca. 10 g wet weight) were taken from a depth of 5 cm, after removing of the living plant layer. We tried to preserve the natural state of water content of the study soil. That parameter was measured in situ in the soil sampled and separately for every sample after the measurement of its respiration, and was expressed in grams of water per g of soil over dry mass (60°C), as well as in percent of the water fully saturating 1 g of dry soil. The content of dry organic matter was determined from the loss on ignition at 500°C.

The measurements were made at stable temperatures of 0, 1, 2, 3, 4, 5, 6 and 8°C during spring and summer periods (when the subsoil water content was very high), and under 6, 4, 3, 2, 1 and 0°C in autumn (with low soil water content). The measurement temperature thus differed from that in situ only by  $\pm 0 - 1.5^\circ\text{C}$ .

Each experiment lasted 3 hours, observations were made after every 30 min, and the average value calculated. It was assumed that no less than 30 3-hour long measurements were needed for statistical analysis in 30 soil samples for each temperature and for each soil. Totally, in 1989, as many as 2200 measurements were carried out. Respirometry of Polish soils was carried out with the same method for a mineral soil and organic soil (decaying mossy litter). Experimental temperatures were also 0° and 2°C. All the studied sites are briefly characterized in Table 1.

Table 1.

General characteristics of the studied soils

Site	Year of research	Plant cover	Organic matter content [%]	Water holding capacity g water/10 g of dry soil
polygonal	1989	40% fungi, lichens	4	39
mossy/peat	1989	100% moss	64	1000
mossy/lichenous	1989	30% lichens, 70% willow	55	40
lichenous	1984	70% lichens	55.5	50.5
structural	1984	no vegetation	5	48.4
mossy	1984	100% moss*	3	23.8
meadow/litter	1984	100% meadow herbs**	83	478.2
meadow/mineral	1984	60% meadow**	70-80	518.1
sandy soil (Poland)		100% grasses	3-9	70.5
peat soil (Poland)		100% moss	2.5	15.5
			22.5	21.5

\* *Calliergon stramineum*\*\* *Cochlearia arctica*, *Saxifraga caespitosa*, *Polygonum viviparum*, etc.

Finally it should be mentioned that evaluating the intensity of soil metabolism, both aerobic and anaerobic, by measuring soil O<sub>2</sub> consumption or CO<sub>2</sub> production, we obtain the data characterizing the terminal effect of the

process, and expressing a combined action of oxygenous and (to a lesser extent) anoxic types of metabolism. The RQ ratio of CO<sub>2</sub> produced to O<sub>2</sub> consumed, calculated on the base of those data can only show possible disturbances of an equilibrium between the quantity of O<sub>2</sub> consumed and CO<sub>2</sub> released, and may (but not must) give certain information on a relationship between the anaerobic and aerobic metabolic processes. However, the conclusions ought to be drawn very cautiously. If RQ values are stable, the ratio between the intensities of these processes is most likely also constant. Studying soil sites of the same region, it is necessary to compare the extent of similarity of these soils. According to the data obtained, it was possible to make a relative comparison of the intensity of metabolic processes in the soils under study.

## Results

The potential similarity of investigated soils with regard to their metabolic rate at different temperatures, expressed in  $\mu\text{l O}_2$  per hour, per g of dry soil or

Table 2.  
Average rates of soil oxygen consumption in  $\mu\text{l O}_2$  per g dry soil ( $x_1$ ) or per g of soil organic matter ( $x_2$ ) per hour

Site	t°C	n	$x_1$	SE	$x_2$	SE
polygonal, 1989	0	70	0.120	0.040	3.300	1.220
	2		0.175	0.040	4.850	1.350
mossy/peat, 1989	0	60	0.438	0.230	0.730	0.340
	2		0.417	0.180	0.760	0.250
willow/mossy/lichenous, 1989	0	30	0.245	0.050	0.326	0.077
	2		0.278	0.034	0.496	0.060
lichenous, 1984	0	56	0.474	0.186	8.117	2.833
	2		0.214	0.105	4.995	1.280
structural, 1984	0	47	0.170	0.056	6.133	2.063
	2		0.166	0.080	3.940	2.140
mossy, 1984	0	44	1.623	0.356	1.651	0.354
	2		1.690	0.540	2.020	0.550
meadow/litter, 1984	0	42	2.823	0.656	5.168	1.460
	2		13.680	39.890	9.130	2.210
meadow/mineral, 1984	0	51	0.350	0.090	4.046	1.790
	2		0.350	0.090	4.040	1.790
sandy soil (Poland)	0	52	0.109	0.021	4.360	0.960
	2		0.270	0.074	12.420	3.410
peat soil (Poland)	0	42	0.843	0.247	3.770	0.930
	2		1.930	0.450	8.320	2.170

n — number of samples

per g of soil organic matter follows from Tab. 2. As an index for such a comparison, O<sub>2</sub> consumption rate at 0° and 2°C can be used, taking into consideration the commonness of this temperature level in the Arctic soils.

The level of metabolic activity of the Polish soils at 0°C did not differ from the one of the Arctic soils. However, a marked increase in the metabolic intensity correlated with the growth in temperature up to 2°C was registered for the Polish, but not for the polar soils (Tab. 2).

Regarding the foregoing, values of metabolic activity per g of organic matter were calculated as the basis for the following analysis of the results obtained. This index eliminates the differences in the organic matter content for the soils studied. Table 1 allows for other kinds of recalculations.

Table 3 contains a summary of average estimates of soil O<sub>2</sub> consumption and CO<sub>2</sub> production at different temperatures and moisture content for the field season of 1989.

Table 3.

Average rates ( $\mu\text{l}\cdot\text{g}^{-1}$  organic matter  $\cdot\text{h}^{-1}$ ) of soil oxygen consumption, carbon dioxide production and RQ values for the studied soils, 1989

Soil		n	$\bar{x}$	SD	Actual water content % of dry soil	Temperature range °C
structural	O <sub>2</sub>	490	4.69	1.70	20–90	0–10
	CO <sub>2</sub>		1.80	0.90		
	RQ		0.39			
mossy	O <sub>2</sub>	390	0.758	0.28	35–220	0–8
	CO <sub>2</sub>		0.283	0.15		
	RQ		0.39			
willow	O <sub>2</sub>	270	1.25	1.28	40–200	0–8
	CO <sub>2</sub>		0.56	0.63		
	RQ		0.46			

n — number of samples;  $\bar{x}$  — arithmetic average; SD — standard deviation.

### Effects of temperature

The results obtained in 1989 are generally similar to the data of 1984 (Fischer and Bienkowski 1987) and 1987 (Fischer 1990) expeditions. The correlation between the metabolic activity and temperatures is statistically significant, though rather weak (values of “b” index range from 0.02 to 0.25 in different soils). An approximation of that relationship by means of a linear regression equation is presented in Tab. 4. Values of “b” index show the slopes of the curves (i.e. reflect the degree of the dependencer of metabolic processes on temperature changes), being somewhat lower for CO<sub>2</sub> production as compared with O<sub>2</sub> consumption. The O<sub>2</sub> consumption (per g of organic matter) in the

organic (moss/peat) soils is over 5 times lower than that in the mineral (polygonal) soil, whereas the respective value for  $\text{CO}_2$  production is over 7 (Tab. 4, index "a"). However, it should be remembered that the recorded relationships are generally slight. The growth of temperature up to  $10^\circ\text{C}$  is associated with an increase in  $\text{O}_2$  consumption by about 55% and hardly 32% for the mineral and organic soils, respectively (Fig. 1, Tab. 4). To show the pattern of calculation of those figures, according to the regression equation based on the

Table 4.

Dependence of soil oxygen consumption and carbon dioxide production ( $\mu\text{l}\cdot\text{g}^{-1}$  organic matter $\cdot\text{h}^{-1}$ ) upon temperature in the range of  $0^\circ\text{C}$  and  $8^\circ\text{C}$ , expressed in the form of linear regression ( $Y = a + bx$ ), where  $[Y]$  is  $\mu\text{l O}_2$  ( $\text{CO}_2$ )/g of organic matter  $\cdot \text{h}^{-1}$  and  $[x]$  is temperature ( $^\circ\text{C}$ )

Site		n	a	b	Significance level
polygonal 1989	$\text{O}_2$	490	3.911	0.218	$p < 0.01$
	$\text{CO}_2$	490	1.625	0.055	$0.01 < p < 0.05$
mossy/peat 1989	$\text{O}_2$	390	0.681	0.022	$0 < p < 0.01$
	$\text{CO}_2$	384	0.218	0.020	$0 < p < 0.01$
mossy/lichenous 1989	$\text{O}_2$	240	0.341	0.257	$0 < p < 0.01$
	$\text{CO}_2$	237	0.049	0.170	$0 < p < 0.01$

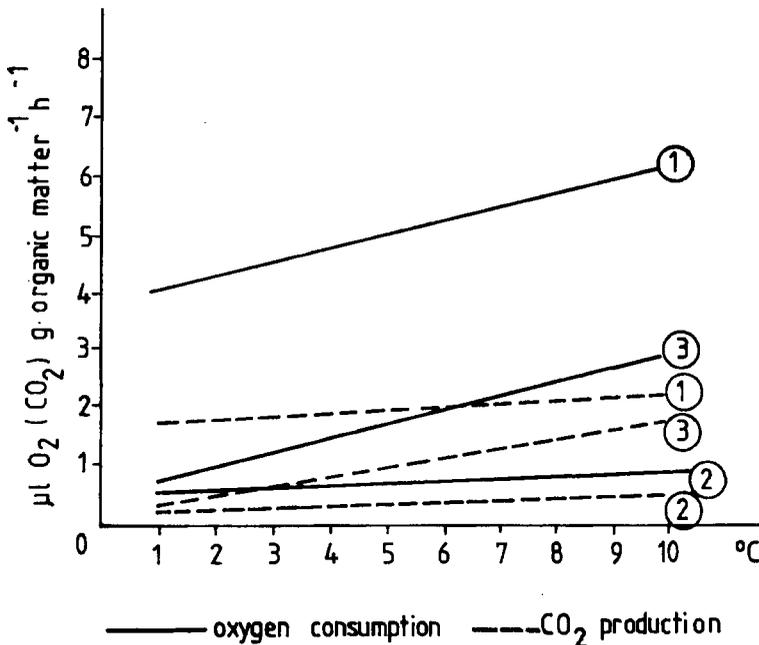


Fig. 1. Oxygen consumption and carbon dioxide production of the examined soils as related to temperature, presented in the form of linear regression: 1 — locality 1; 2 — locality 2; 3 — locality 3; ——— oxygen consumption; - - - - -  $\text{CO}_2$  production

estimates of soil metabolic rate at different temperatures, Fig. 2 presents a comparison between two extremely different soils, mineral and organic in origin.

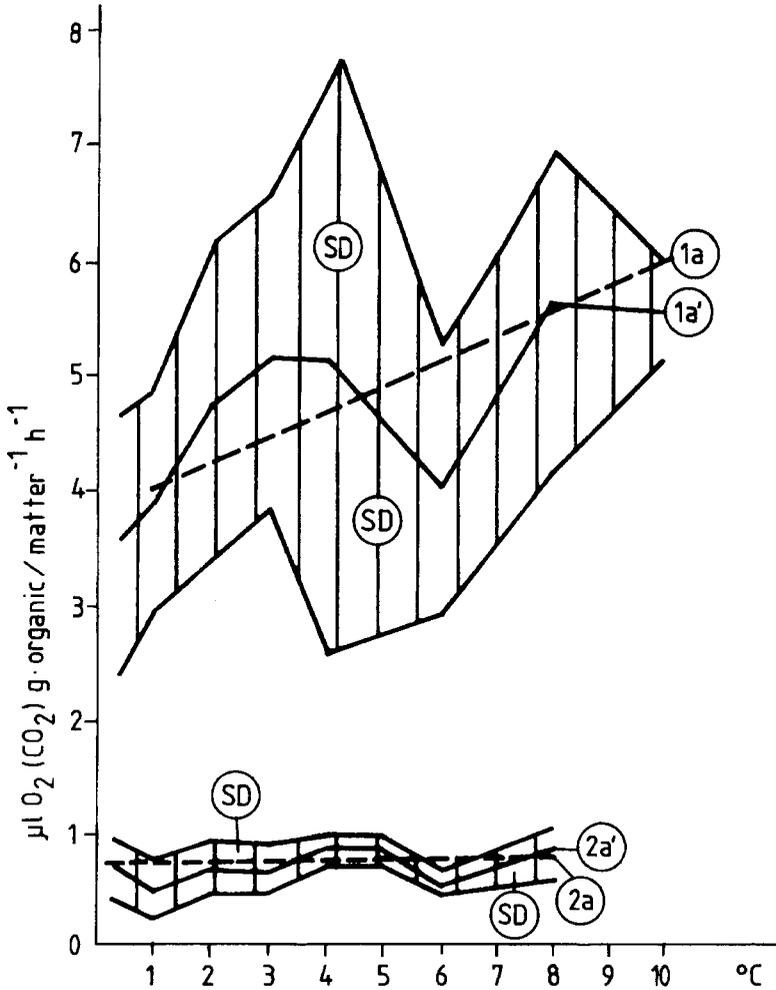


Fig. 2. Comparison of the relationship between oxygen consumption and CO<sub>2</sub> production and temperature in soil at localities 1 and 2, calculated from regressive formulae (1a, 2a) and that obtained empirically (1a', 2a'); SD — standard deviation

Materials so far presented for the Arctic soils refer only to the season of 1989. The previous years did not give sufficient data for any wide comparison. However, it seems that comparisons are possible between average values of O<sub>2</sub> consumption for the most common temperatures of the study region, namely for 0° and 2°C (Fig. 3). Contrary to the general positive correlation between the O<sub>2</sub> consumption and temperature, deviations can be noticed for soils 4 and 5,

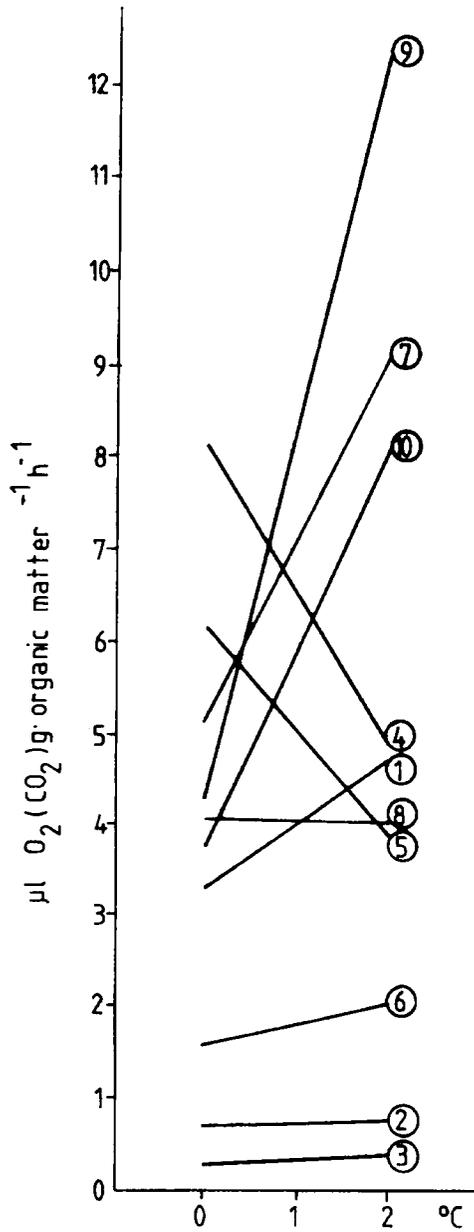


Fig. 3. Comparison of oxygen consumption of various Arctic soils relative to temperature in the range 0°–2°C:

- |                            |                               |
|----------------------------|-------------------------------|
| 1 — polygonal 1989;        | 6 — mossy 1984;               |
| 2 — mossy/peat 1989;       | 7 — meadow/litter 1984;       |
| 3 — willow/lichenous 1989; | 8 — meadow/mineral 1984;      |
| 4 — lichenous 1989;        | 9 — sandy soil (from Poland); |
| 5 — structural 1984;       | 10 — peat soil (from Poland). |

i.e. the one of the lichenous tundra studied in 1984, and the structural one. Oxygenous metabolic rate in these soils at 0° was higher than at 2°C. It can only mean that the dominant microflora populations have their thermic optimum at low temperatures (Fischer and Bieńkowski 1987). All the other Arctic soils, except for soil No. 7, are characterized by a very slight reaction to temperature changes. The only one soil, No. 7, representing a meadow at the foot of the bird colony slope and being heavily N-fertilized (Krzyszowska 1986), exhibits a very strong temperature-induced reaction similar to the one in the Polish soils. Figure 3 shows that within a relatively small study area the soils are evidently differentiated by their biological properties. Averages of RQ calculated on the basis of the measurements at all the temperatures were quite similar being 0.40, 0.38 and 0.41 for the soils of polygonal structure, under moss cover and under moss/lichen cover, respectively. However, RQ values were much more different when compared for every given temperature (Fig. 4). For instance, in the organic soil under moss cover, RQ values rised with temperature growth up to +6°C (Fig. 4.2).

The data obtained proved the existence of a correlation between temperature and the RQ vaeus, allowing to conclude that the trend in their changes is similar for all the soils studied within the range of +2° and +8°C.

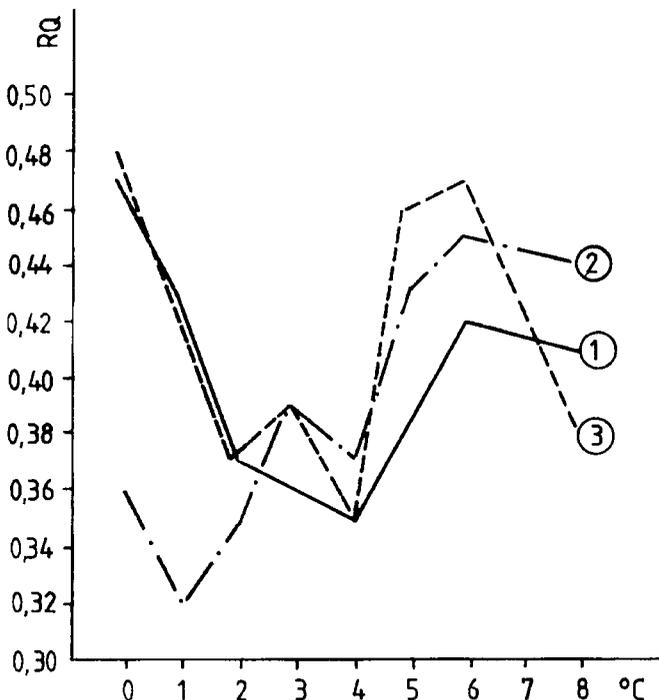


Fig. 4. Relationship between the respiratory quotient (RQ) of the examined soils and temperature; 1 — locality 1; 2 — locality 2; 3 — locality 3

The correlation between metabolic activity of soil organic matter and temperature changes was very weak. To the minimal extent it was expressed in the soil under the moss cover, i.e. being naturally isolated from oxygen supply, and existing at lower and more stable temperature regime, as compared to the other soils (Angiel, *unpubl.*).

The character of dynamics of metabolic processes in the organic matter of the studied soils varies and is highly mosaic, suggesting a considerable variety of communities inhabiting those genetically different soil systems.

### Effects of soil moisture content

The results obtained during the expeditions of 1984 and 1987 (Fischer and Bieńkowski 1987, Fischer 1990) gave evidence of a relationship between soil metabolic rate and moisture content. Calculations carried out for each temperature separately (0, 1, 2, 3, 4, 6, 8, 10°C) gave a significant correlation between O<sub>2</sub> consumption (or CO<sub>2</sub> production) and water content in the subsoil for 70% of the data analyzed. However, from this analysis no single-valued trend or relationship emerges. Having considered the previous on a low-degree dependence of the rate of metabolism from temperature changes, we calculated these correlations for large body of measurements carried out in different temperature conditions (from 0 to 8°C). The correlations are expressed in the form of linear regressions (Tab. 5). Two patterns of recalculation of moisture content in the subsoil are shown in Fig. 5. They are based on an analysis of the relationship between the rate of O<sub>2</sub> consumption (or CO<sub>2</sub> production) and: (1) actual moisture content of the subsoil (Fig. 5A), i.e. quantity of water per certain amount of dry soil; (2) moisture content as per cent of the soil maximal water capacity (Fig. 5B). The comparison of these patterns seems to be informative. From Fig. 5 (A and B) incorporating the range of the values of

Table 5.

Dependence of soil oxygen consumption and carbon dioxide production ( $\mu\text{l} \cdot \text{g}^{-1}$  of organic matter  $\cdot \text{h}^{-1}$ ) upon subsoil moisture content, expressed in the form of linear regression ( $Y = a + bx$ )

Site		$x_1$ actual moisture content [%]				$x_2$ % of saturation			
		n	a	b	sl	n	a	b	sl
polygonal, 1989	O <sub>2</sub>	490	1.51	0.075	p<0.01	490	1.52	0.092	p<0.01
	CO <sub>2</sub>	441	1.02	0.2	p<0.01	451	1.08	0.006	p<0.01
mossy/peat, 1989	O <sub>2</sub>	390	0.49	0.0036	p<0.01	390	0.5	0.035	p<0.01
	CO <sub>2</sub>	390	0.21	0.0009	p<0.01	384	0.2	0.01	p<0.01
mossy/lichenous, 1989	O <sub>2</sub>	240	1.0	0.19	p<0.01	240	1.1	0.018	p<0.01
	CO <sub>2</sub>	234	0.5	0.01	p<0.01	234	0.5	0.005	p<0.01

sl — significance level.

moisture content obtained in the course of a polar day, it can be concluded that a complete water saturation of the organic type of soil (under moss cover) cannot be achieved in principle during the field season (Fig. 5B) and, at the same time, that the quantity of water per g dry soil increased by 2.5 times (Fig. 5A), amounting to 2.5 g of water per g of dry soil. On the other hand, in the mineral soil with a low level of water-holding capacity (Tab. 1), the opposite tendency is evident. During the whole vegetational season (from May till September), this soil was fully saturated with water (moisture content of over 100%) (Fig. 5B—1a). However, calculation of the absolute quantity of water (Fig. 5A—1a) revealed that soil hydration in principle did not exceed 100%, meaning that 1 g of dry soil took up less than 1 g of water. A comparison of Figs. 5A and 5B also shows that hardly 1 gram of water exceeded 2.5 times the saturation level of the polygonal soil. The following increase in water supply will only lead to an increase in the amount of water not taken up by the soil, i.e. covering soil surface. From Fig. 5 it is also evident that the rate of  $\text{CO}_2$  release depends on the soil moisture content to a lesser extent, as compared with the rate of  $\text{O}_2$  consumption. According to a decrease in the sensitivity to changes in moisture content, the soils can be arranged in the following order: polygonal soil — soil under moss/lichen cover — peat soil under moss cover. The response of the latter soil to the level of water saturation (%) is more intensive than in the other soils (Fig. 5B—2); however, it requires much more water in comparison with them.

A relationship was also analysed between the soil water content and RQ index. The calculations carried out on the basis of the linear regression confirm the dependence of soil respiration upon the water content in the subsoil (Tab. 5). The results are shown in Fig. 6. All the curves indicate that RQ values decrease according to the growth of subsoil water content. Assuming, as above, that the proportion of oxygenous metabolism in the total one positively correlates with the values of RQ index, we obtain that the rate of the former process increased along with a rise in moisture content. A comparison of Figs. 5 and 6 shows that the polygonal soil reacts most intensively to a high-level water content by an enhanced rate of metabolic processes, especially oxygenous ones. It should be remembered that this soil is practically deprived of vegetation cover and is therefore better provided by oxygen than the other soils studied. Instead, in the case of a wet mossy cover (Plot 2), gaseous exchange is inhibited and an increase in the rate of anoxic processes can be less expressed (Fig. 6). It is evident from Fig. 5 that a very weak correlation exists between metabolic processes and moisture content in the soil of the mossy-peat plot.

We found that water conditions are significantly important for the estimates of the intensity of metabolic processes (Tab. 5, Figs. 5, 6) depending upon the soil structure, its water holding capacity and the character of plant cover. The influence of soil moisture content on the level of metabolic rate was higher in the soil of low water holding capacity and without plant cover, i.e. in the best conditions of oxygen supply.

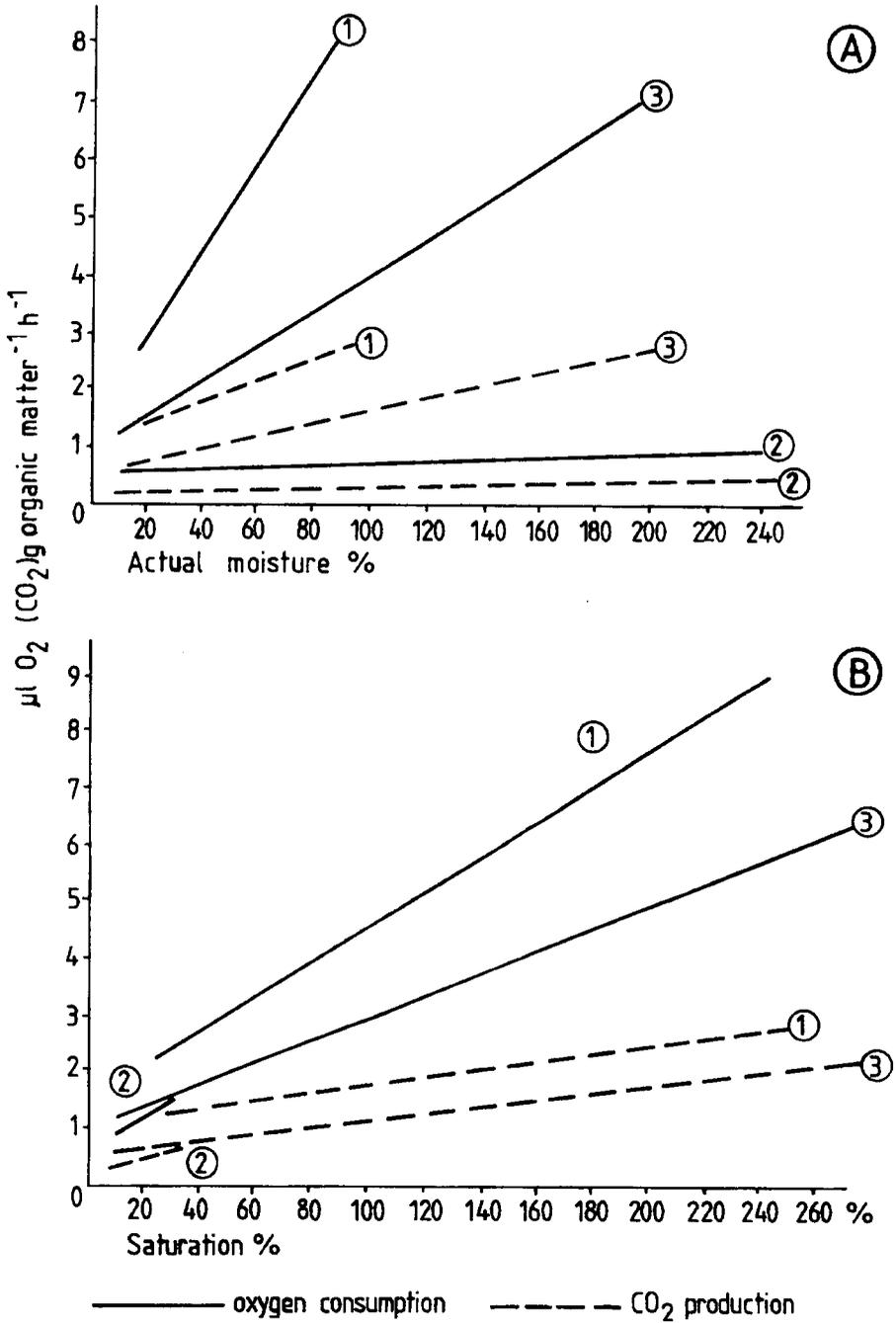


Fig. 5. Influence of soil humidity on oxygen consumption and carbon dioxide production: A — moisture in weight per cent; B — moisture in saturation per cent; 1 — locality 1; 2 — locality 2; 3 — locality 3; — oxygen consumption; - - - - CO<sub>2</sub> production

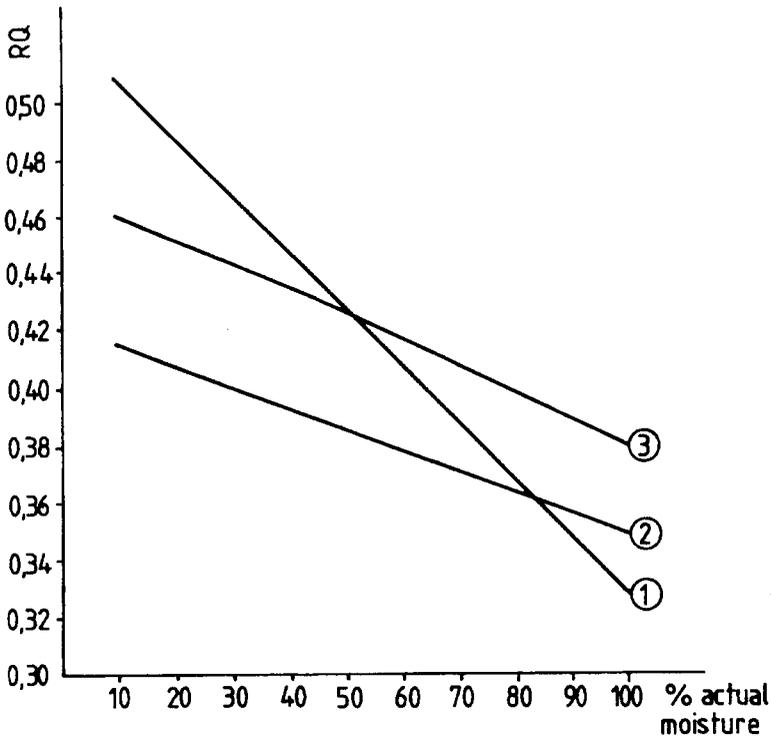


Fig. 6. Influence of soil humidity on the respiratory quotient (RQ): 1 — polygonal; 2 — mossy/peat; 3 — mossy/lichenous

## Discussion

Dynamics of soil metabolic activity in the course of a Svalbard polar day is presented for 2 plots extremely different from one another by physico-chemical properties, as well as by the character of plant cover, namely the polygonal and the mossy-peat plots. The polygonal plot had no, or very scarce, vegetation while the mossy-peat plot was uniformly covered with a thick moss layer. Samples were taken similarly in relation both to the globe quarters and to the mountain slope.

Soil bioenergetic processes at 5 cm depth were characterized by RQ values,  $O_2$  consumption and  $CO_2$  production. A comparison of the results is presented in Fig. 7. It can be seen that microclimatic conditions in the course of the polar day were very different between plots studied. Snow cover disappeared from the polygonal plot by a month earlier, and therefore its soil was warmer, as compared to the other plot. Maximal average daily temperatures during the summer period were  $+15^\circ$  and  $+9^\circ C$  in the polygonal and mossy-peat soil, respectively. Figure 7 shows the course of average temperatures approximately

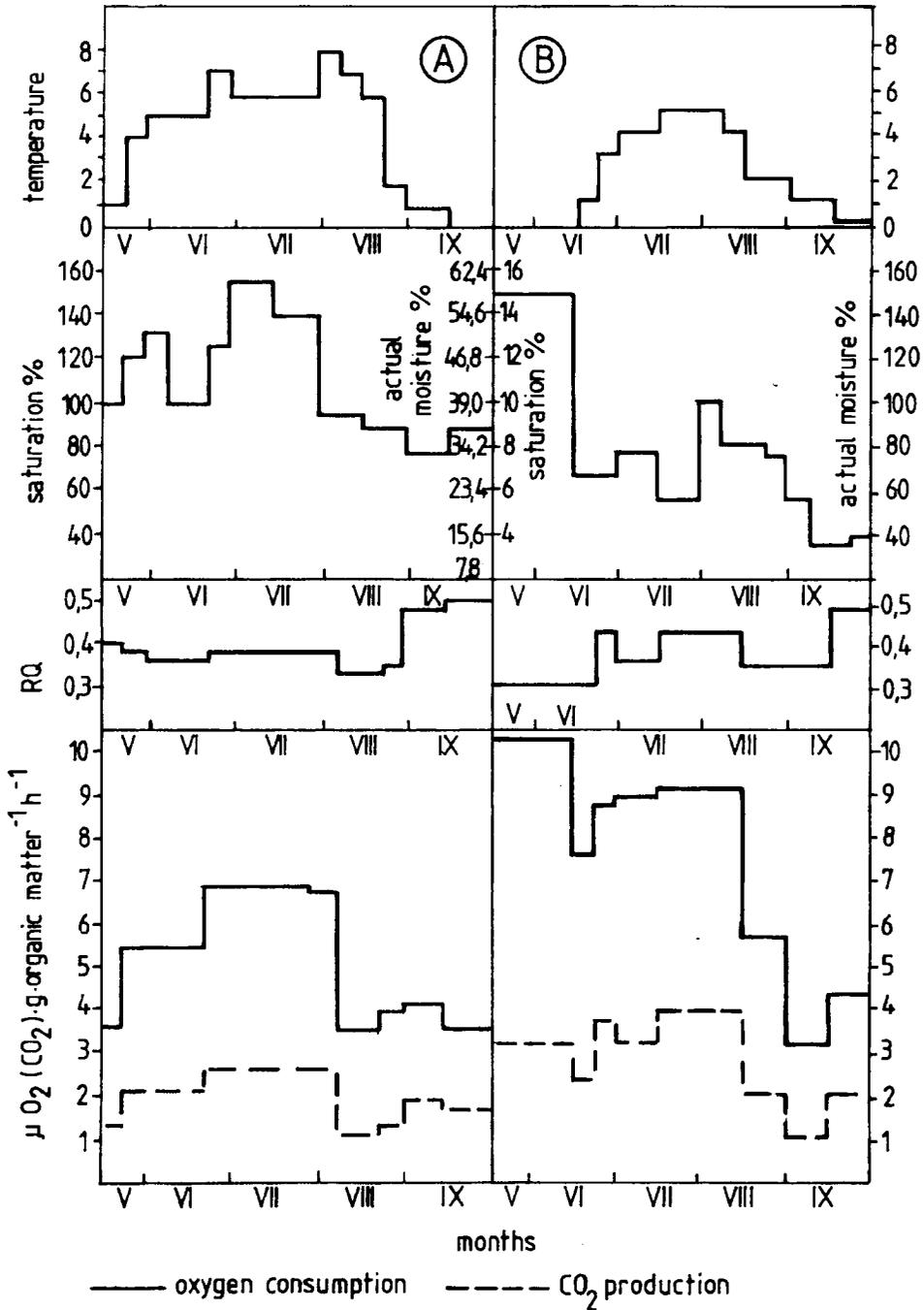


Fig. 7. Theoretical oxygen consumption, carbon dioxide production and respiratory quotient (RQ) calculated for the organic matter of some Arctic soils in the vegetative period in relation to soil temperature and humidity: A — locality 1; B — locality 2; ——— oxygen consumption; - - - - CO<sub>2</sub> production

calculated for every 10-day interval. Under moss cover the level of soil temperatures is lower and the duration of the period of temperatures about 0°C longer. On the other hand, the character of autumn temperature decreases in the both soils is similar. It begins on the turn of July, and by the middle of September soil temperature in both plots reaches 0°C. Seasonal dynamics of soil moisture content for the two plots is also different (Fig. 7). The soil of the polygonal plot is fully saturated with water from the middle of May till the end of July. At the beginning of autumn drop in August, soil moisture content declines to the level lower than 100% of the water holding capacity. Thus, 'autumn' in this soil begins with the decrease in both temperature and moisture content. It should be also noted that due to small water holding capacity even maximal saturation of this soil requires small quantities of water (100% of water saturation corresponds to 39 g of water per 100 g of dry soil).

Soil water content in the mossy-peat plot is many times higher than the polygonal one. Its maximal values attain 140% (Fig. 7); however, full saturation is never reached. The autumn drying of soil begins also in August, along with the temperature decrease. It seems that the humidity level of this soil is determined during the spring period when the moss layer absorbs water of melting snow; later on, in summer, evaporation proceeds very slowly. The relative influence of precipitation is probably of low significance.

Regarding thermal characteristics of the plots we should suggest that their vegetational seasons, i.e. periods of biological activity of the studied soils, are different. Under moss cover at lower temperature level and with the period of positive temperatures of hardly 3 months long, rates of biological processes must be less intensive as compared with the polygonal plot (4 months of positive temperatures in soil). Analyzing bioenergetical activity of organic matter (and therefore levelling differences in its content in the studied soils), we observe that the rate of gaseous exchange does not correlate with the dynamics of microclimate. True, the level of organic matter respiration in soil of the polygonal plot is almost 10 times higher than in soil under moss cover; however, temperature dynamics does not affect the changes in soil activity, especially in the mossy-peat soil (Fig. 7). Besides, we should also remember the high level of soil respiration activity in spring, when soil temperature is still about 0°C whereas moisture content is maximal. These conditions seem to effect, in particular, the process of O<sub>2</sub> consumption that, accompanied by a moderate intensity of CO<sub>2</sub> production, determines low level of RQ values. It is possible that in spring, under the conditions of low temperature and high water content, the rate of soil oxygenous respiration rises. According to Fig. 7, O<sub>2</sub> consumption under moss cover depends to a greater extent on soil moisture content than on temperature; on the other hand, the rate of CO<sub>2</sub> production decreases only late in autumn. In the polygonal site of the dynamics of soil O<sub>2</sub> consumption and CO<sub>2</sub> production is similar, reaching maximal values in the warmest period, from the end of June till the end of August. In August and September soil

metabolic activity drops (especially the rate of  $O_2$  consumption), later remaining stable until the end of September, despite continuing temperature decrease. In the soil of polygonal plot the values of RQ index rise in September that probably means an increase in anoxic respiration. Under moss cover, in the second part of September there begins also a rise of RQ up to the values registered in the polygonal plot. It can be suggested that in spring, under sufficient water supply, oxygenous processes prevail in the both soil types, whereas in autumn intensity of anoxic processes grows, following the decrease in temperature and moisture content (Fig. 7). This consideration is supported by the data on the abundance and biomass of soil invertebrates in the same plots, both parameters beginning to diminish from August (Byzova, Uvarov and Petrova 1995).

Regarding other soils without wet moss cover inhibiting the rate of soil gaseous exchange, a somewhat different pattern is observed. At low temperatures, 0 and 1°C, anoxic respiration rate is relatively intensive. These temperatures correspond to the natural conditions of the end of winter, when the soil is covered with a layer of snow or water originating from the melting of the former. Later on, oxygen becomes more accessible, water runs away, temperature rises, and a reorganization of microbial communities begin. From 2 to 4°C the role of oxygen metabolism increased, according to the drop in RQ values. In the following period the proportion of anoxic metabolism grows again. It may be associated with an enhanced moisture content favouring mainly the development of anoxybiotic microflora, or simply with the stabilization of soil processes. True, the considerations can only serve as hypotheses for future research programmes. The RQ is only the ratio between  $CO_2$  released and  $O_2$  consumed, and can tell nothing about the origin of the substrates.

Up to this point we have only analysed the activity of soil organic matter. Taking into account very different contents of organic matter in the soil studied, another pattern of comparison for the polar day of 1989 is obtained (Fig. 8). It is evident that due to a small content of organic matter soil activity in the polygonal tundra is over 2 times less than in the mossy-peat soil. The biomass of soil invertebrates was shown to be, respectively, 1100 and 8100  $mg\ m^{-2}$  (Byzova, Uvarov and Petrova 1995). Autumn drop in metabolic activity of the polygonal tundra soil is less pronounced but begins earlier than in the mossy-peat soil. A tendency of gradual decrease in the rate of  $O_2$  consumption in the soil under moss cover and lack of that tendency in the polygonal tundra soil during the polar day are more distinguished in Fig. 8 than in Fig. 7.

It can be concluded that metabolic activity of tundra soil, as well as of its organic matter, varies greatly. It does not precisely correlate with temperature conditions, being a result of a combined influence of soil temperature and moisture regimes, the latter one often playing the leading role. Soil becomes active in May, being still covered with snow. The activity begins to decrease on the turn of July, that is apparently indicated by the drop in the soil moisture

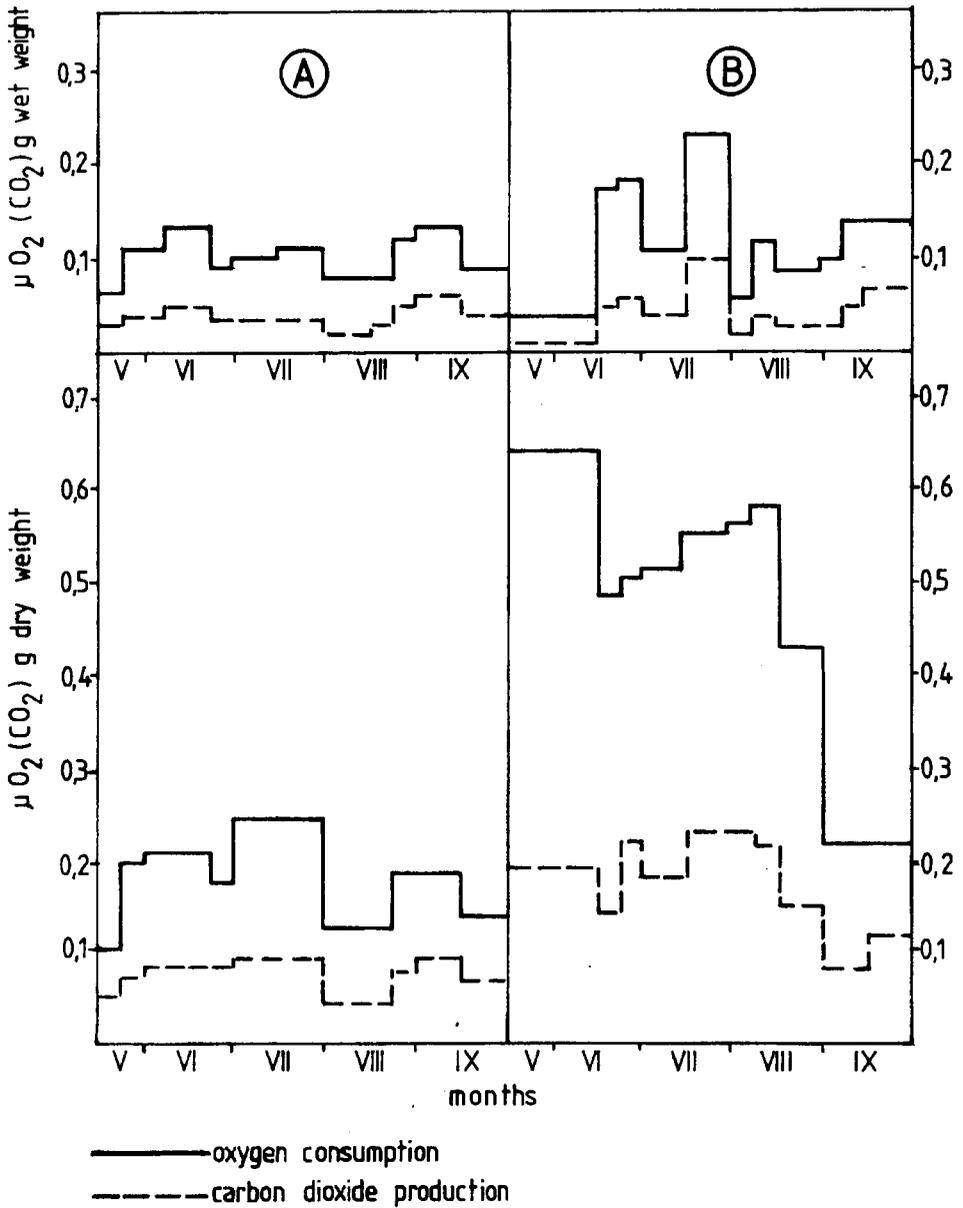


Fig. 8. Theoretical metabolic activity of some Arctic soils: A — locality 1; B — locality 2; ——— oxygen consumption; - - - - CO<sub>2</sub> production

content. It seems possible that in autumn the processes of oxygenous metabolism are somewhat disturbed, the main role passing to anoxic one, that is indicated by the growth in the values of RQ.

It is generally assumed that the level of biological activity of Arctic soils is very low, being restricted by unfavourable temperature conditions and short summer period (Tedrow and Douglas 1959, Szerszeń 1965, Bliss *et al.* 1973). The results of our research, confirming these statements, make it possible to perform somewhat more detailed interpretations.

Nelson and Edwards (1975) obtained that the rate of CO<sub>2</sub> release by a deciduous forest soil in the western Tennessee amounted from 0.09 to 24.5 g CO<sub>2</sub> m<sup>-2</sup> day<sup>-1</sup> at 6.8°C in December and 20.1°C in September, respectively. Expressing our data on the Arctic soils per unit of soil surface, we derived the values lower by an order of magnitude than the minimal values of Nelson and Edwards. On the other hand, estimates of biological activity of some Polish soils, having been obtained for the same temperature range (Focht 1992b), gave the results similar to the data on the Spitsbergen soils. The problem is, what is the reason for the low general activity of biological processes in Spitsbergen tundra soils and whether indeed it is as low as it is usually assumed.

Indisputable is the prolonged Spitsbergen winter period (from October till May, about 7 months), when the biological processes do not proceed in tundra soil. However, in May the activity of soils (still under snow) develops intensively; its reached level is later on maintained till the end of September. Thus, the characteristic gradual spring awakening and growing of the rate of soil metabolic processes is not observed in Spitsbergen tundra. It seems that these soils, using minimum of environmental resources tend to function at their maximal possibilities. Biological strategy of soil ecosystems is directed towards the overcoming the 'limiting factor' of below zero temperatures. Above this threshold, soil metabolic processes function at the maximal level of their activity, being practically independent of temperature fluctuations and hardly reacting to the changes in soil moisture content. According to our data, aerobic and anaerobic groups of microflora certainly interchange in the course of the vegetative season, that suggests a possibility of their optimal strategy of functioning in the soil ecosystems. This hypothesis is not as yet correctly confirmed, basing on the obtained values of RQ (Fig. 7).

This type of biological activity results in a relatively effective and prolonged (from May till September) functioning of tundra soil ecosystems. An extreme diversity is one of the basic characteristics of the polar soils. In such a small area as the basin of Fuglebekken stream, 8 different soil types were found. These types are greatly dissimilar by their microclimatic regimes, due to variations in physical structure and plant cover. Consequently, bioenergetical activity of the soils must be also different. Undoubtedly, there can be found soil ecosystems functioning very actively and quite comparable bioenergetically with those in the temperate climate. That can be connected with a number of adaptations enabling such ecosystems function at the maximal level of their possibilities. This type of strategy is forced by the conditions of a very short vegetative period.

## Conclusions

1. Dependence of metabolic processes upon soil moisture content varies relatively strongly with soil structure, soil water capacity and character of plant cover. It is more pronounced in the soils of small water capacity and without vegetation, i.e. being better aerated.
2. The values of RQ decrease with the growth of soil moisture content.
3. Soil metabolic activity begins under snow cover directly after spring melting of the ground, when soil temperature reaches 0°C, and ceases after the repeated temperature reduction below 0°C.
4. Metabolic processes in the soils studied are only slightly determined by temperature in the range from 0° to 10°C. This relationship is the least marked for the soils covered with moss layer and therefore isolated from aboveground air.
5. The Arctic soils studied are characterized by a great heterogeneity resulting in a mosaics of different soil environments within the study area.
6. In the course of polar day, levels of soil metabolic activity are very different, depending on soil quality. For individual soils, rates of this activity are relatively stable from May till August, later on becoming slightly dependent upon climatic changes.

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## Streszczenie

Celem pracy była próba bioenergetycznej charakterystyki gleb wybranego rejonu Spitsbergenu (Tab. 1). Jako wskaźnik charakteryzujący intensywność procesów bioenergetycznych w badanych glebach zastosowano pomiar zużycia tlenu i wydalania dwutlenku węgla, mierzone eksperymentalnie w warunkach laboratoryjnych, w kontrolowanej temperaturze i wilgotności (Tab. 2–5; Rys. 1–3).

W wyniku badań stwierdzono, że:

- wartość wskaźnika RQ maleje wraz ze wzrostem wilgotności (Rys. 4–7);
- aktywność metaboliczna gleb stwierdzana jest jeszcze pod śniegiem, gdy temperatura gleby wynosi około 0°C;
- procesy metaboliczne w granicach temperatur 0–10°C są słabo uzależnione od termiki gleby;
- w ciągu lata polarnego aktywność metaboliczna gleb jest zmienna i uzależniona od jakości gleb; w niektórych przypadkach jest ona ustabilizowana (w czasie od maja do sierpnia), w innych zaś siedliskach glebowo-roślinnych aktywność gleby zmienia się w zależności od zmian termiczno-wilgotnościowych.