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Interannual variation of soil heat flux in a grass-dominated alpine tundra. Preliminary study from the Jeseníky Mts.

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Abstract

Soil heat flux (G) is an important component of the surface energy balance of terrestrial ecosystems. In polar and alpine tundra, G enters the subsurface layers during summer and relatively high G is released from soil during winter. Measuring of energy cycle in polar and alpine treeless ecosystems is challenging due to complex physics of seasonal changes associated with freeze-thaw cycle. That is why field data on G are much less abundant compared to the other World regions. In our 2 year study, we quantified soil heat flux in two alpine plots differing in the characteristics of vegetation cover. The first one was a wind-swept alpine grassland, while the other one was the same vegetation cover localized in a close neighbourhood of a patchy *Pinus mugo* stand. Our results suggest that both sites had similar yearly time courses of G with peak values of the heat flux to the soil recorded in spring season after the snow melt (April/May). Maxima of heat flux from the soil were found in the December-January period. In summer season (April-October), proportion of G to global radiation (R) reached low values, typically below 10%. Regression analysis revealed that in spite of similar vegetation cover and microrelief of the two study plots, the site neighbouring to the *P. mugo* stand responded to R more sensitively than the open plot dominated by a grassland community exclusively. Data recorded and the relationships presented in the paper are discussed with the results of similar studies performed in polar and treeless alpine regions.

Key words: alpine ecosystems, thermal regime, grassland, *Nardus* sp., *Pinus mugo*

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Introduction

Soil heat flux (G) is an important component of the surface energy balance equation comprising net radiation (Rn), sensible (H), and latent heat (L) fluxes. Soil heat flux is of particular importance in the regions with arid, bare, or thinly vegetated soil surfaces. For polar and alpine regions with no or limited vegetation, G represents an important parameter of energy exchange (Choi et al. 2008, Alves and Soares 2016). Soil heat flux (G) consists of two components representing heat advection and heat conduction. Thermal properties of soil affect G and depend mainly on bulk soil heat capacity of soil. Heat capacity of soil consist of three components, *i.e.* volumetic capacities of (1) water, (2) solid mineral constituents, and (3) solid organic matter. These parameters are used when G is modelled (for mountainous ecosystems, *see* e.g. Votrubová et al. 2012).

In polar and alpine regions G yearly performance is seasonal, *i.e.* soil serves as a heat source (winter season) or a heat sink (summer season) (Prošek and Brázdil 1994). Measurements of G in such regions are typically accompanied by extreme climatic conditions and heterogeneity in surface properties, vegetation cover in particular.

Generally, the most common technique for determining G is the calorimetric method, which uses the soil heat flux plate (for review *see* e.g. Gao et al. 2017) as a part of the energy balance calculation (Russell et al. 2015). Despite its importance, direct measurement of G is not performed routinely in the field, particularly in remote areas such as mountainous and polar regions. Prošek et al. (2000) measured the components of energy balance in an Antarctic vegetation oasis at the Polish Station (King George Island, Antarctic region). Long-term studies covering several years have been performed only on few spots such as *e.g.* Zackenberg study site (Lund et al. 2014, 2017). Another techniques to evaluate G for polar and alpine regions are modelling based on the surface energy balance (*e.g.* Yao et al. 2020) and the use of remote sensing thermal data from satellites (*e.g.* Cristóbal et al. 2017).

Recently, global warming-induced changes in local climate in Arctic regions lead to the changes in vegetation cover, such as shrub *e.g.* encroachment and wetland expansion, with implications for altered soil heat fluxes in these ecosystems (Jushak et al. 2016). In our study, we measured G and its proportion to global radiation input in a mountainous location for a grassland locality in alpine zone in order to evaluate soil heat fluxes yearly variability. The hypothesis we tested was that G would differ between open grassland alpine tundra and the locality with the same vegetation cover in proximity with dwarf pine (*Pinus mugo*) stand. We hypothesized that snow cover is thinner in the *P. mugo*-sheltered then open grassland site and thus lasts for a shorter time (melts earlier) in the early spring season. Therefore, G values are affected by the above factors in the early spring season. However, due to similar composition of vegetation cover, we expected that the yearly dynamics in G does not differ between the two sites.

Material and Methods

The measurements of G were performed at the Tabulové skály rocks (Jeseníky Mts., 1 445 m a.s.l., 50.0867 N, 17.2311 E) which belongs to the biotope of wind-swept alpine grasslands (*Juncion trifidi*) and closed alpine grasslands (Nardo-Caricion rigidae) formed by the anemoorographic system. The locality is typical by rocky outgrowhts surrounded by natural stand of alpine grasses and dwarf pine (*Pinus mugo*) stands originally planted in the period 1880–1900 (Hošek 1964, 1984). The presence of dwarf pine plantation, however, strongly influenced environmental conditions compared to natural stands (Zeidler et al. 2010). Local climate is typical for treeless area of the Jeseníky Mts. It is harsh, wet and windy with average annual temperature of 0.9°C and an annual precipitation of 1029 mm reported for the neighbouring (200 m distant) peak of the Praděd Mt. (Šafář et al. 2003).

In our study, soil heat flux, (G), was measured by a Hukseflux HFP01 plates located at a depth of 0.05 m and 0.01 m below soil surface (Fig. 1). The HFP01 plates (soil heat flux plates, Hukseflux, the Netherlands linked to a datalogger Micrologг V3A - Environmental Measuring Systems, Brno, Czech Republic) were installed in two lacalities, one representing an open area, *i.e.* alpine grassland with no tree vegetation. The second one was located in a grassland but in close proximity (5 m distant) of *P. mugo* stand. The two localities are abbreviated as (1) OPEN and (2) PMUGO. In the period of May 2020 to October 2022, G was masured in 30 min. interval. Therefore, daily courses of G was plotted against time of the experimental period. From the G data set, monthly means of G were calculated as well as the monthly mean of G daily maximum.

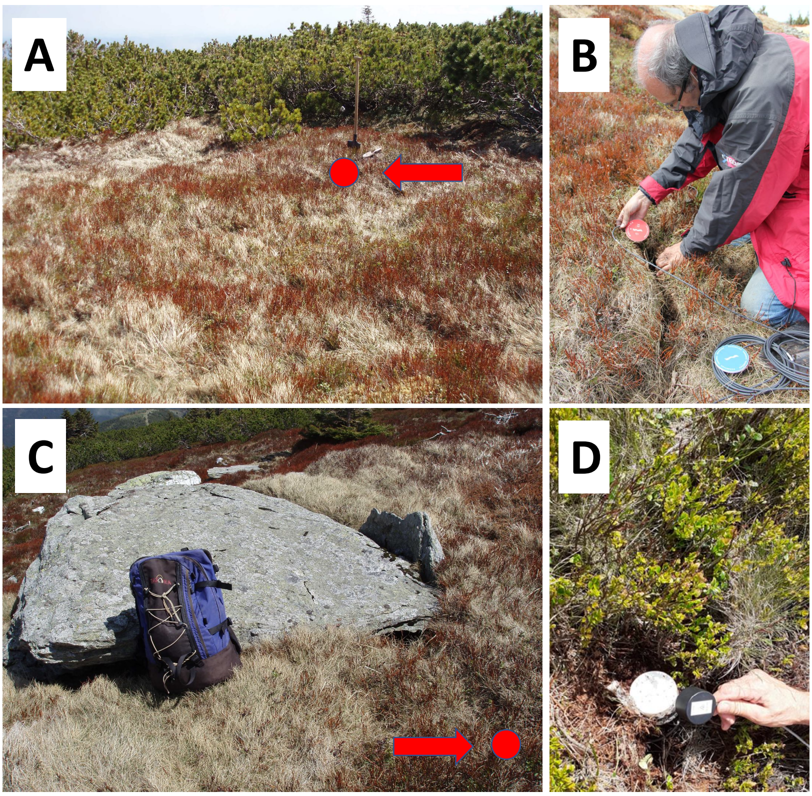

Fig. 1. The sites at which the heat flux sensors were installed in May 2020 in the Jeseníky Mts., 1 445 m a.s.l. The sites are indicated by a red dot. A – the spot located close to a *Pinus mugo* stand (abbreviated as PMUGO in the text), B – insertion of the sensor plate into a soil profile, C – the spot denoted as OPEN in the text, D – dowloading data from a datalogger by an IR port.

Global radiation was measured by a microclimatological station at the Švýcárna site localized 2 km from the Tabulové skály study site. The station is referred as the Q541 ICP Forest meteorological site that monitors air temperature and humidity, precipitation, global radiation, wind speed and direction. In our study, global radiation (R) data were used for analysis of G to R ratio.

Results

The courses of G presented in Figs. 2 and 3 show several important phenomena. Heat flux from the soil to the above surface during winter season was interrupted with several episodes of warm weather when there was heat flux to the soil detected. These episodes are indicated by arrows in Fig. 2. The two plot differed in the time of snow cover which lasted longer in the PMUGO plot. This was reflected in the earlier switch of the G from negative (heat flux from the soil) to positive values (heat flux to the soil).

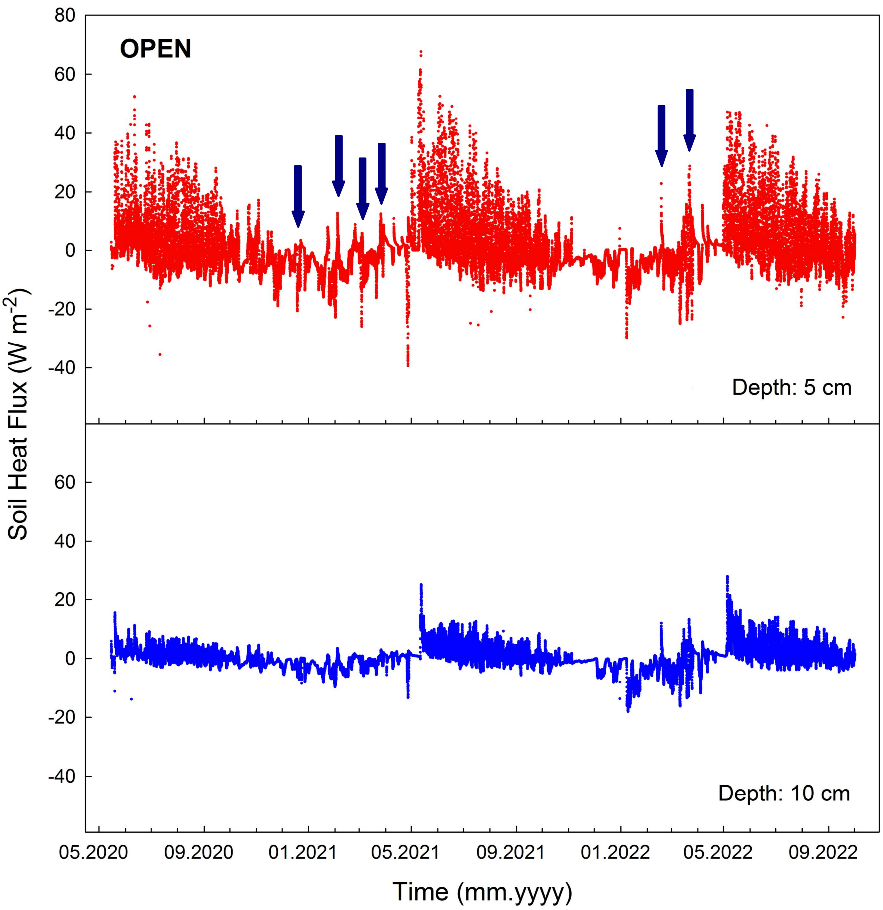

Fig. 2. Yearly courses of Soil Heat Flux (G) at the alpine tundra grassland plot (*abbr.* OPEN). The G values are presented for the soil depth of 5 (red) and 10 cm (blue).

During the period without snow cover (spring-summer-autumn), soil heat fluxes did not differ too much between the OPEN and PMUGO sites, presumably due to similarly timed development of new leaves in the vegetation cover (non-woody vascular plants), foliage which typically become standing dead during winter season. Some plants species of the locality, however, are capable to maintain green and partially functioning leaves over winter period, such as *e.g. Luzula sylvatica*. The species however, was not present at the experimental plot.

Daily means of G shows the phenomenon of cooling the soil profile during the winter months (*see* Fig. 4, the periods indicated by circles). The heat flow from soil remained more or less constant in the depth of 10 cm, while the G recorded at the depth of 5 cm showed daily variability and generally higher values for the same period. Maximum values of daily mean of G (heat flux to the soil) were found in May after the snow melt, more apparently in 2021 when the peak value reached about 25 W m^{-2} for the sensor at the depth of 5 cm, while much lower values were found for the rest of the spring-summer season.

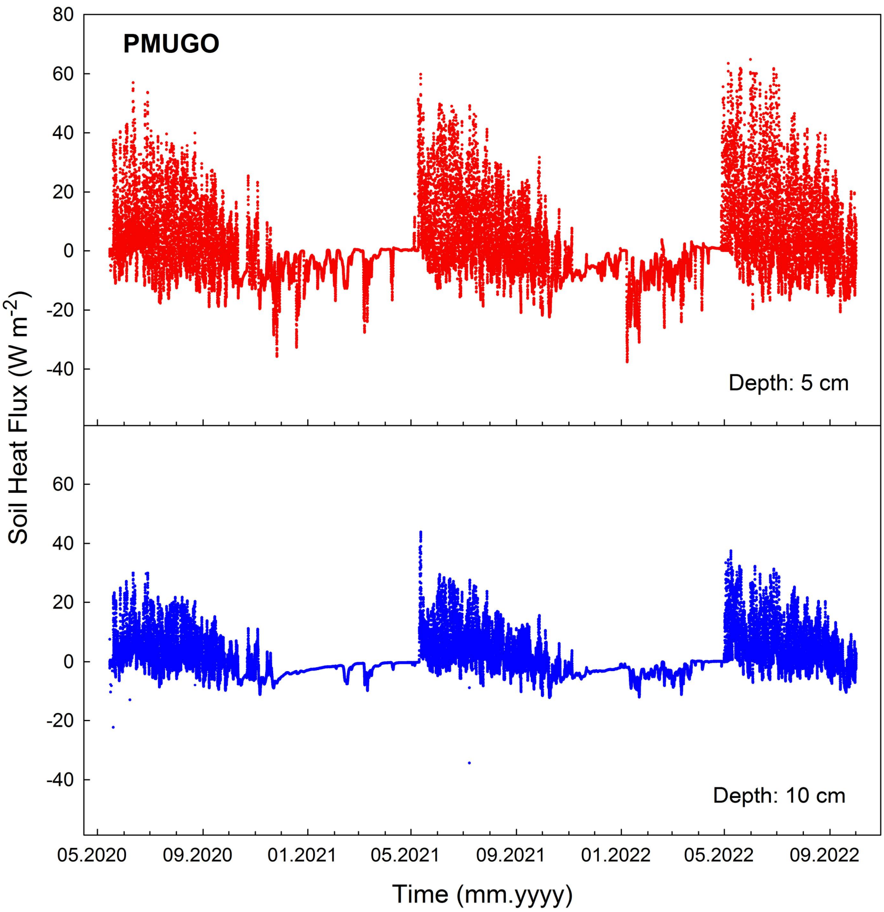

Fig. 3. Yearly courses of Soil Heat Flux (G) at the alpine tundra grassland plot in the neigbourhood of dwarf line (*Pinus mugo*) stand (*abbr*. PMUGO). The G values are presented for the soil depth of 5 (red) and 10 cm (blue).

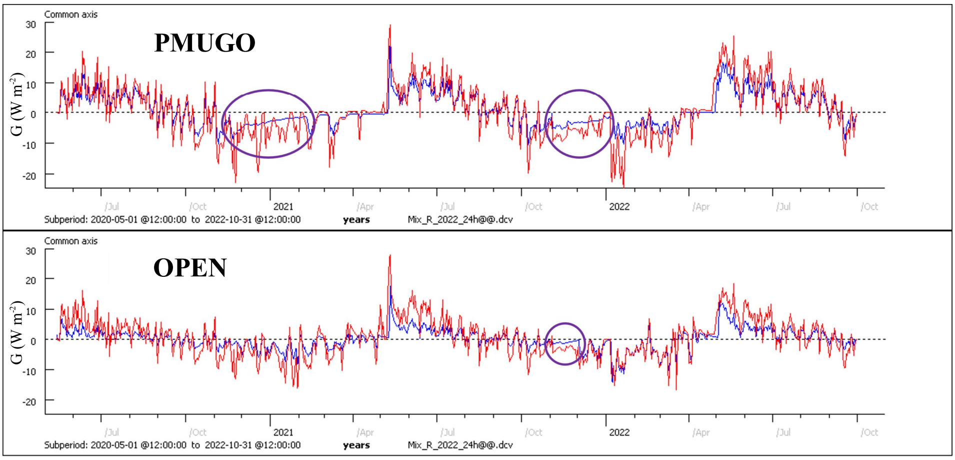

Fig. 4. Time courses of the daily means of G for the depth of 5 cm (red line) and 10 cm (blue line) evaluated for grass-dominated alpine tundra without (OPEN site) and with the proximity of a *Pinus mugo* stand (PMUGO site).

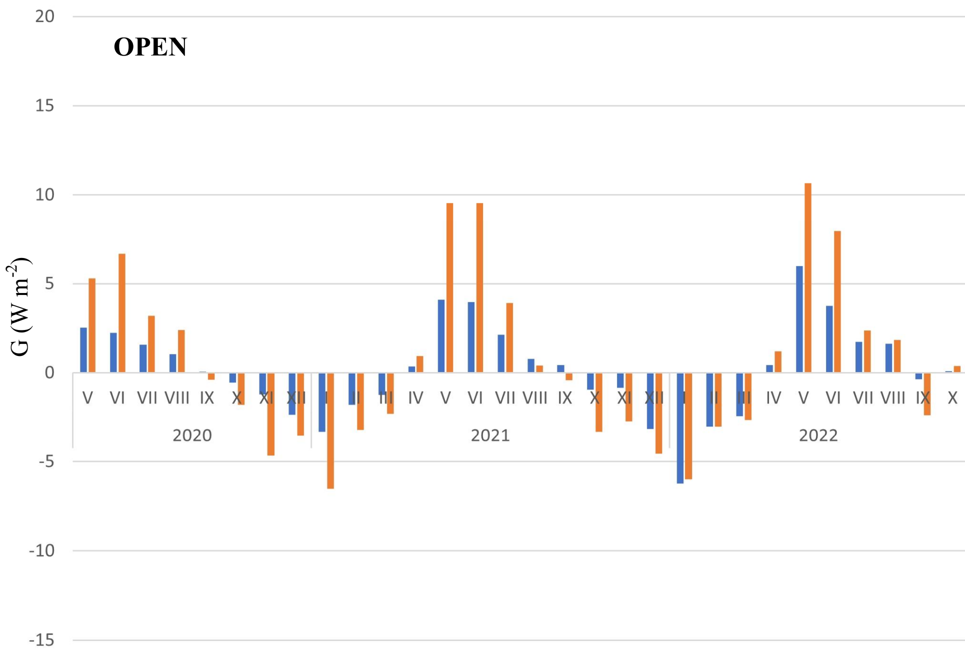

Fig. 5. Monthly means of soil heat flux (G) for the open plot (OPEN site, alpine grassland tundra), the Tabulové skály Rocks (1 445 m a.s.l., Jeseníky Mts.). G was measured by the sensors buried in the depth of 5 cm (orange columns) and 10 cm (blue columns).

Monthly means of G are presented in Figs. 5 and 6 for the OPEN and PMUGO plots, respectively. In the OPEN plot, interannual differences are apparent mainly between summer of 2021 and 2022 for the dept of 5 cm. The 2022 summer was typical by higher (May) and lower (June) G than the values of monthly means for 2021 (about 9.6 W m^{-2} for May and June). The interannual difference was more apparent for the PMUGO plot, where the mean monthly G at 5 cm was significantly higher in 2022 than in 2021 for May and June.

Experimental plot PMUGO showed slightly higher G for summer as well as for winter period as seen in Fig. 7. Mean (negative) monthly flux in soil was found highest in January on both plots. However, G values were generally higher (flux from the soil) for PMUGO than OPEN plot.

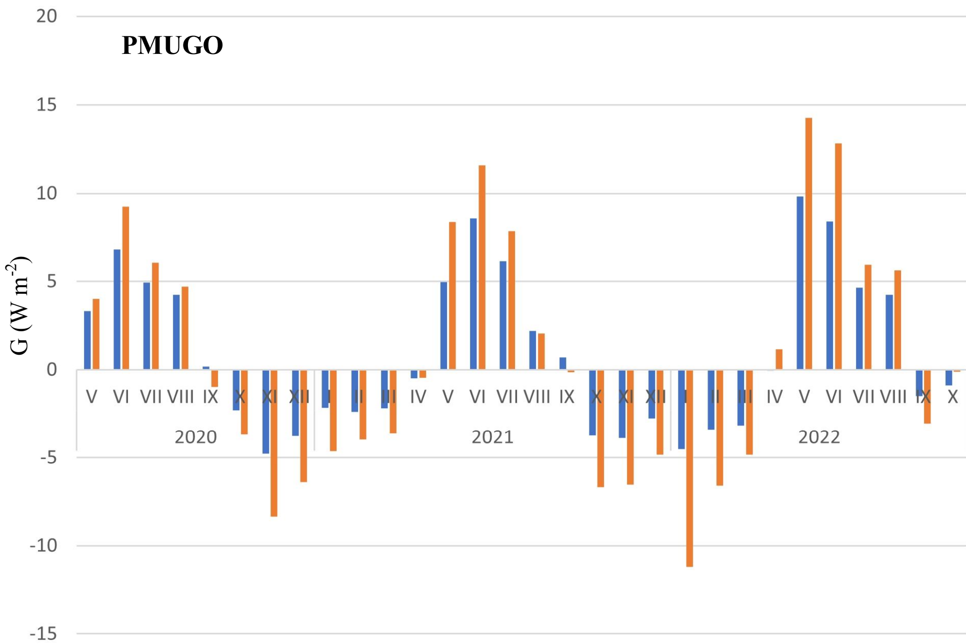

Fig. 6. Monthly means of soil heat flux (G) for the PMUGO plot with grass vegetation with neighbouring dwarf pine (*P. mugo*), the Tabulové skály Rocks (1 445 m a.s.l., Jeseníky Mts.). G was measured by the sensors buried in the depth of 5 cm (orange columns) and 10 cm (blue columns).

Time courses of the proportion of G to global radiation (R) showed that, analogically to the evidence from similar grass-dominated alpine and polar ecosystems (*see* Discussion), G represent only a small portion of R. For both experimental plots (OPEN and PMUGO), G/R reached a single peak value in the middle of May (after snow melt) followed by the values typically less than 5 % during the period of June to September (*see* Fig. 8) when leaf area of the plant community was developed and fixed. Soil heat flux (G) in both experimental plots was linearly related to incident global radiation (R) as shown for monthly means in Fig. 9. The PMUGO plot, however, showed somewhat higher values of G for the R values above 150 W m^{-2}. Therefore, a higher G was apparent for the PMUGO then the OPEN site as evident from the summer monthly means (*cf.* G in Fig. 7).

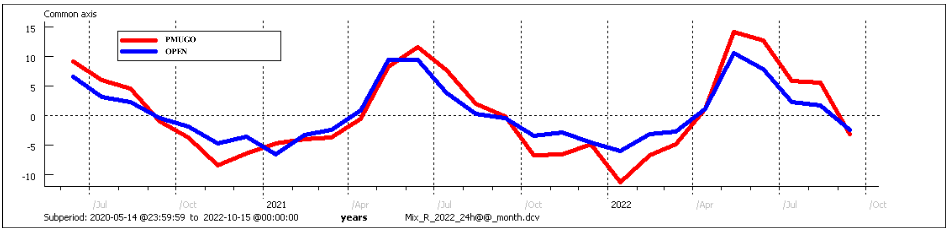

Fig. 7. Comparison of the time courses of G monthly means for the depth of 5 cm in the OPEN (blue line) and PMUGO (red line) plots.

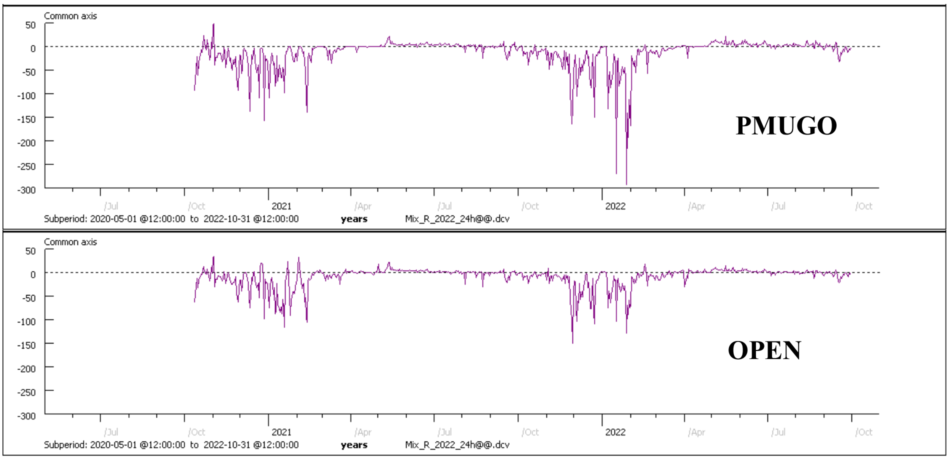

Fig. 8 Time courses of the G/R (soil heat flux / global radiation) ratio evaluated for grass-dominated alpine tundra without (OPEN site) and with the proximity of a *Pinus mugo* stand (PMUGO site).

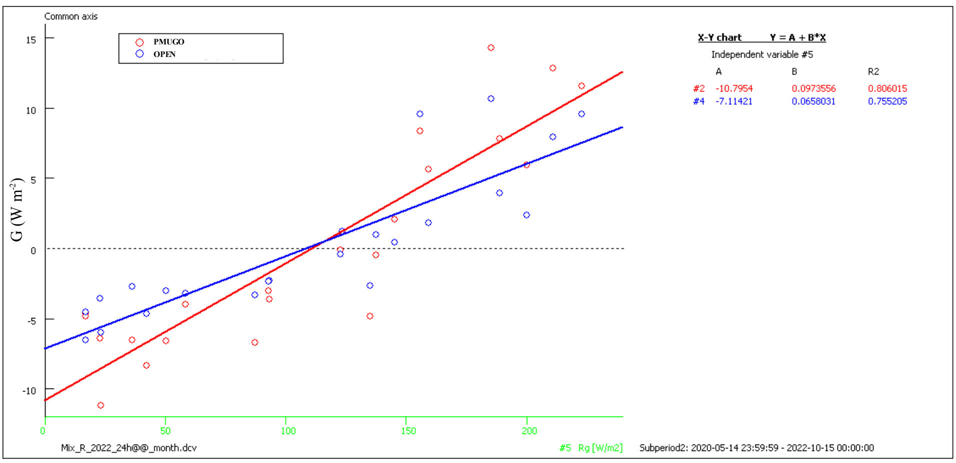

Fig. 9 Linear regression for the monthly means of soil heat flux (G) as dependent (on Global radiation flux (R) for the data recorded in grass-dominated alpine tundra (OPEN, blue line) and the site with the proximity of a *Pinus mugo* stand (PMUGO, red line).

Discussion

In polar regions, soil heat flux represents typically less then 5% of the surface energy budget since dominant component is latent heat, as shown *e.g.* for vegetation-free Antarctic deglaciated regolith sites (Ambrožová et al. 2020 for James Ross Island). For vegetation-free areas of polar regions, G is proportionaly very low to mean net radiation as shown by Ambrožová et al. (2020): mean ground heat flux was only 0.4 W m^{-2} of 102.5 W m^{-2} (mean net radiation). Latent heat was dominant component of energy balance of the site. In Antarctic terrestrial ecosystems, G/R ratio varies within particular parts of a year, Alves and Soares (2016) reported the daily ratio of G/R varying from 4.3% in December to −17.6% in March. Peak G values recorded for a mid of may in our study reached the range of 40-60 W m^{-2} in our study (*see* Figs. 2 and 3), which is well comparable to the values reported for a grassland-dominated plots in Russian Arctic (Tiksi) for the early spring season by Morris et al. (2018).

It is well established that G decreases with soil water content in tundra regions, as shown by Stiegler et al. (2016) for Abisco (Sweden) peatland sites. In the study, wet fan dominated by *Eriophorum angustifolium* with stable water near the ground surface showed much lower G (less than 2.0 W m^{-2}) than the small-area peat plateaus with sedges dominated by *Sphagnus* sp. (7.2 − 8.6 W m^{-2}). The G values are well comparable to those resulting from our study (see the monthly means in Figs. 5, 6, and 7).

The area close to the Tabulové skály rocks, where the OPEN and PMUGO experimental spots were located, was, similarly to the above-mentioned sites in Abisco, well hydrated since the area belongs to the sites with a high annual precipitation (1050 mm, annual mean of the 1981-2010 period, Czech Hydrometeorological Institute [1]). However, the upper layers of the soil may get semidry to dry during summer with limited precipitation.

For wet sedges (*E. vaginatum*), however, higher G is reported than for shrub-covered tundra (Juszak et al. 2016). In extremely moist tundra regions, such as *e.g.* the Lena river delta, G may represent up to 16 % (25 W m^{-2} for July) of net radiation input as shown by Langer et al. (2011). Moreover, G might be altered by ongoing changes in vegetation cover, in terms the changes in patchiness and proportion of vegetation componets, *i.e.* species forming distinct vegetation classes. Recent study has shown that a large difference exists in G for *e.g.* sedge-dominated (*E. angustifolium*) and dwarf shrub species-dominated (*Betula nana*) tundra (Juszak et al. 2016). Similarly, Lafleur and Humpreys (2018) reported that an increasing proportion of shrubs abundance in tundra ecosystems leads to alterations in soil-plant-atmosphere interaction including exchange of energy. Amount and distribution of precipitation is an important factor as well, affecting G during summer season (Migala et al. 2014).

Our data indicated that there was not significant difference in G monitored in the OPEN (grass-dominated alpine tundra) and the PMUGO (same vegetation cover in a neighbourhood of *Pinus mugo* stand) sites. The follow up study will address G and G/R inside the *P.mugo* stands in order to evaluate the effects of different microclimate inside the canopy of *P.mugo* stand as well as altered snow accumulation during winter and snow melt during spring season.

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