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EVALUATION OF HEATING EFFICIENCY OF WATER-SATURATED PEAT SUBSTRATE WITH INFRARED HEATERS*

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A b s t r a c t. The aim of this study was to analyse the applicability of infrared (IR) heaters (400 W, HTS/1 Elstein) to increase peat temperature of water-saturated peat. The experiment was carried out within two schemes. In VARIANT I the heaters were installed perpendicular to the heated surface at a height of 2.3 m, while in VARIANT II the heaters were mounted at a height of 2 m at the edges of the heated surface so that radiation reached the heated surface at an angle of approximately 40-50°. Based on the analyses of night-time means (from 3:00 to 6:00 a.m.) of peat temperatures recorded on manipulated plots under the heaters and the reference temperature, it was found that the application of HTS/1 heaters caused an increase of the mean peat temperature by 1.1°C and 0.5°C for VARIANT I and VARIANT II, respectively. The air temperature 5 cm above the heated surfaces was increased by 0.7°C and by 0.5°C at VARIANT I and II, respectively.

K e y w o r d s: infrared heaters, temperature manipulation, peat

INTRODUCTION

The International Panel for Climate Change (IPCC) report published in 2013 forecasts an increase in global mean temperature of 0.3°C within the next decade and by 3 to 4°C by the end of the 21st century. Such an increase in temperature will result in changes in the natural environment, in ecosystem function and in human economic activity (Walther *et al.* 2002). Early diagnosis of the consequences of this phenomenon

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is crucial for the determination of adaptability of various natural elements. This may be facilitated by climate manipulation experiments conducted *in situ*, in which, through modification of environmental factors that influence ecosystem function (e.g., temperature, precipitation), one may assess the negative or positive effects of climate change.

Many climate manipulation experiments are conducted under controlled conditions and aim to determine, e.g., the effect of an increase in CO_2 concentration or temperature on plant physiology, development and gas exchange (Harte *et al.* 1995, Nijs *et al.* 1996). However, conditions in such experiments are far from natural and a relatively reliable recreation of field conditions remains an open issue (Kimball *et al.* 2009).

Various passive and active methods of soil heating exist, and their applicability for the study of the effect of heating on ecosystem functioning is well documented in literature. For example, Hiller *et al.* (1994) and Ineson *et al.* (1998) used heating cables or heating pipes arranged in the soil to increase soil temperature. Such a soil temperature manipulation system may be used only in ecosystems with very low vegetation. However, the application of such a solution leads to disturbance of soil structure and may affect soil microorganisms and root system structure. Another method of temperature manipulation is connected with the use of infrared (IR) reflective curtain covers in order to reflect long-wave radiation emitted by the Earth's surface towards the ground (Aronson and McNulty 2009, Johnson *et al.* 2013). This passive method makes it possible to slow down the decrease in temperature during the night time; however, it does not ensure maintenance of higher temperatures around the clock. An increase in the temperature of the manipulated surface may also be obtained using Open Top Chambers (OTCs), although their application is considered controversial due to the significant change in environmental conditions within OTC (Johnson *et al.* 2013).

An alternative to passive methods is the use of long-wave radiation heaters which, due to the emission of IR radiation; give the effect of heating similar to that which occurs naturally (Kimball 2011). Electric ceramic heaters are the most commonly used in this type of experiment (Aronson and McNulty 2009). This is because of the extensive range of available heater models and their properties, such as long service life, easy replacement in case of damage, as well as precise positioning ability and the amount of energy that they can supply (Kimball and Conley 2009).

Although the performance and energy cost associated with infrared heater arrays for warming field plots is well known (Kimball and Conley 2009, Kimball *et al.* 2012) and although many heating experiments exist all over the world at different ecosystem types, i.e. meadow in Eastern Finnmark, NE Norway (Silvennoinen *et al.* 2016), cropland in Arizona in the USA (Ottman *et al*. 2012), forbs and grasses on the Tibetan Plateau (Luo *et al*. 2010) or tallgrass prairie in Oklahoma in the USA (Wan *et al*. 2002), there is no knowledge about heater performance when they are used for the warming of water saturated peat soils. Hence, the aim of this study was to analyse the applicability of IR heaters (HTS/1, Elstein) as sources of energy used to heat water-saturated peat soil. We tested two different positions and ways of heater installation in order to assess the effect of heating and to evaluate the distribution of temperatures over the manipulated surface. We assumed that for a rectangular heater shape, the footprint of such a heater will be elliptic (Kimball 2005) and at the assumed installation height, the heated area will be large enough to obtain uniform distribution of the temperature field over the entire manipulated surface.

MATERIALS AND METHODS

Experiment design

The experiment was conducted over a box filled with water-saturated peat in order to simulate conditions found in a wetland ecosystem. The wooden box, 250 cm by 90 cm and 15 cm deep, was sealed with PCV foil and filled with garden peat substrate (pH 3.5-4.5) mixed with water, resulting in a water-saturated layer. 27 temperature probes (T-107, Campbell Sci., USA) were installed in the substrate at a depth of 1 cm below the surface (Fig. 1). Additionally, 15 thermocouples covered with aluminium foil were installed 5 cm above the plot surface in order to measure air temperature (Fig. 1). Peat thermometers were placed in three lines, with nine sensors in each line (grid size 25 cm × 25 cm), while the thermocouples were installed in three lines (not placed directly over the peat thermometers), with five sensors in each (grid size 35 cm × 50 cm).

In this paper the peat thermometers are denoted as $S_{i,j}$, while $A_{i,j}$ are the thermocouples applied for air temperature measurements; *i* refers to the line number, while *j* denotes the successive thermometer.

The reference surface (no heating applied) was prepared as a separate box (1 m^2; 15 cm depth), filled with the same material as in the heated box. In this reference box, three temperature probes (T-107, Campbell Sci., USA) were installed in the substrate at a depth of 1 cm along with three thermocouples at a height of 5 cm above the surface.

Two heating variants were applied (VARIANT I and VARIANT II) in this study. The first variant of the experiment was carried out from 26th March to 13th April 2014. During that period, two ceramic long-wave heaters were installed on a horizontally oriented common boom at a height of 230 cm over the tested surface, at a distance of 120 cm between heaters and 65 cm from the edge of the plot (Fig. 1).

On the 14th of April, the location of heaters was changed and they were installed parallel to the shorter side of the box. The head of each heater was tilted to such a position that the emitted radiation reached the surface at an angle from around 40° to 50°. Both heaters were placed at a height of 200 cm, at a distance of 280 cm from each other (Fig. 1). This setup was tested until the 22nd of April (VARIANT II).

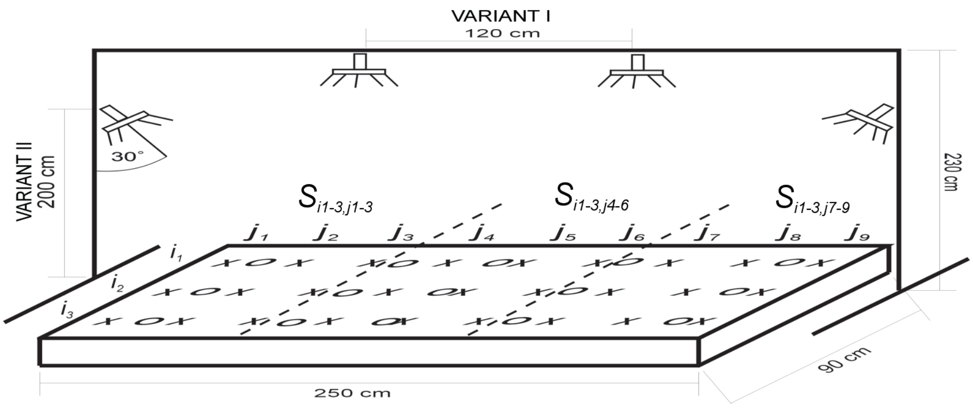

Fig. 1. Sensors (x = thermometers, o = thermocouples) location and IR heaters position in both variants of experiment (VARIANT I, VARIANT II) at the plot

For both variants of the experiment, HTS/1 IR radiation heaters by ELSTEIN (24.5 × 6 cm, 400 W) were used, emitting radiation within the wavelength range from 2 to 10 µm. Considering the small dimensions (24.5 cm × 6 cm) and the shape of the heaters, under VARIANT I the radiation intensity is inversely proportional to the square of distance and here we assume that the distribution of radiation from each heater is circular. Under VARIANT II, the situation is much more complicated, since the heaters are installed over the edge of the heated surface and their heating surfaces are tilted at 30°. Thus, the amount of radiation that reaches each fragment of the heated surface depends not only on the distance from the radiator but also on the angle at which the radiation reaches the heated surface. For this reason, in this study we assessed changes in the temperature of the heated surface and did not focus on the distribution of heat and heat amount reaching the surface.

Throughout the experiment, the heaters were working at full power (400 W). Measured peat and air temperatures were recorded using a Datalogger CR1000 coupled with an AM16/32 multiplexer (Campbell Sci. USA) with 10 minute time steps.

Data analysis

Thermometer intercomparison

In order to eliminate potential differences in values of measured temperature due to the thermometers systematic errors, the correlation matrix was applied. A high value of the coefficient of determination R^2 (0.98) indicates that the installed thermometers react identically and differences in the measured temperature are negligible. An identical analysis was conducted for the thermocouples and high $R^2 > 0.95$ were found too.

In order to eliminate solar radiation bias the analyses were conducted on the set of temperature data obtained during the nights between 3:00 and 6:00 a.m.

Statistical analyses

We first analysed the distribution of peat temperature during each variant of the experiment. Since the data did not pass the Lilliefors normality tests (both variants), which were adapted for large data sets (above 5000 samples), we used a nonparametric Mann-Whitney-Wilcoxon, Kruskal-Wallis rank sum test with Bonferroni approach and as a post hoc test Tukey HSD was used. All statistical tests were performed using RStudio on the Open Source License (ver. 0.98.1087) compatible with R (ver. x64 2.15.2).

RESULTS

Within VARIANT I, the maximum temporary difference in peat temperature between the heated peat substrate and the peat substrate in the reference site, during the period from 3:00 to 6:00 a.m., was 3.4°C. The mean temperature of the peat on the manipulated plot was 1.1±0.8°C higher than on the reference plot.

The peat and air temperatures for the 3-hour period (3:00-6:00 a.m.) during VARIANT I on 31st March (randomly selected as an example) are presented in Figure 2. No significant differences were found between values of peat temperatures measured for the *j*-th thermometer at individual *i*-th lines.

In the case of peat substrate, a lower temperature was found in the middle of the experimental plot ($S_{i1-i3,j4-j6}$) (Fig. 2A). Although these differences are not significant, this indicates that temperature of peat is highly dependent on the position and distance between the heaters (temperature is higher at plots being just beneath heaters).

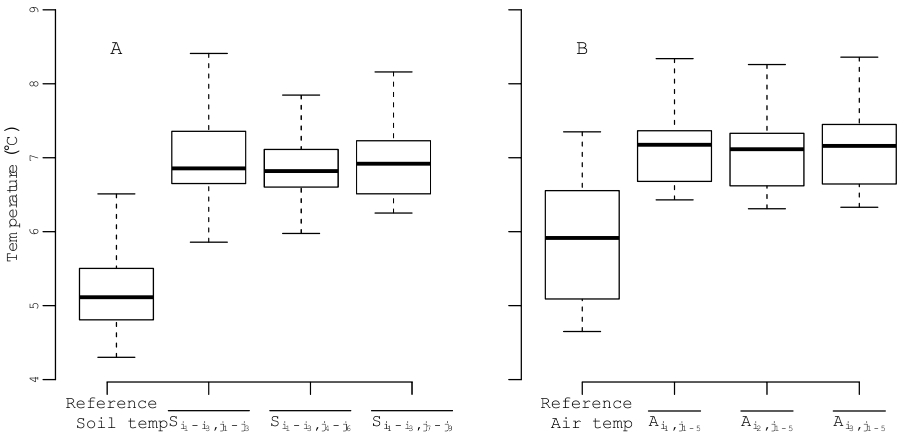

Fig. 2. Night-time (3:00-6:00 a.m.) peat substrate (A) and air (B) temperatures for VARIANT I; 5th day of experiment (31st March 2014). The thick line marks the median; the boundaries of the box are the first and third quartiles, while whiskers are extreme values

The same relationship was observed for the whole duration of VARIANT I (restricted to night-time periods from 3:00 to 6:00 am, Fig. 3). Nonetheless, if the whole experimental plot is considered, the peat and air temperatures of manipulated surface are significantly higher than on the reference non-heated plot (Fig. 2 and 3).

Simultaneous measurements of air temperature showed similar values over the entire experimental plot. During the experiment the mean air temperature over the heated surface was 0.7±0.3°C higher (data from 3:00-6:00 a.m.) than the temperature recorded at the reference plot (Fig. 3B).

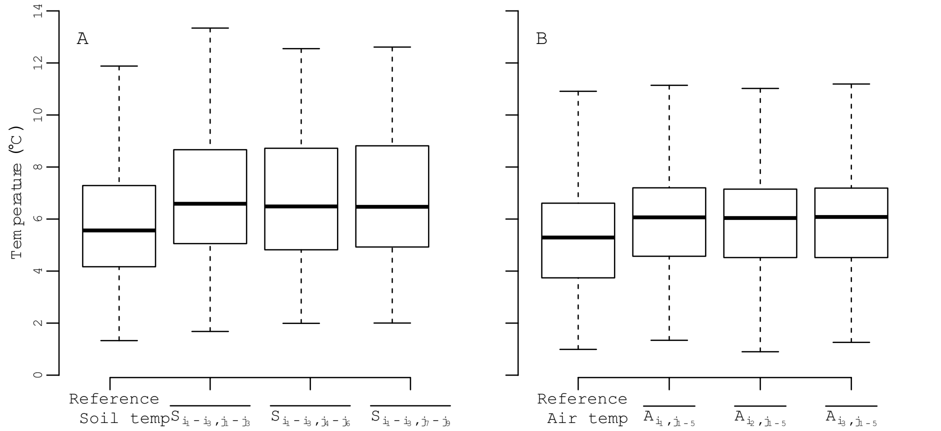

Fig. 3. Night-time (3:00-6:00 a.m.) peat substrate (A) and air (B) temperatures during the whole period from March 23 to April 12, 2014 – VARIANT I. The thick line marks the median; the boundaries of the box are the first and third quartiles, while whiskers are extreme values

In order to compare the temperatures of the heated and reference plots we used the Mann-Whitney-Wilcoxon test with a significance level of $p = 0.05$; where H_0: the peat substrate temperature at the heated site is equal to the temperature at unheated reference plot. The sample of temperature was taken from the same distribution. The obtained value of the tested statistics made it possible to estimate $p = 0.0006$. This test confirmed that temperatures at the heated and the reference plots were significantly different. The same test was used to compare heated plots ($S_{i1-i3,j1-j3}$, $S_{i1-i3,j4-j6}$ and $S_{i1-i3,j7-j9}$) with each other. High p-values indicate the lack of statistical differences in temperatures between heated plots. Kruskal-Wallis and Tukey HSD tests showed no significant differences between peat substrate temperatures (Tab. 1).

During VARIANT II (Fig. 4) the peat substrate temperature at the edge of the heated surface was characterised by smaller diurnal amplitude than during VARIANT I (Fig. 3). In the first period of the experiment (VARIANT I), mean diurnal amplitude of peat temperature at the edges of the manipulated plot was 9.8°C, while during VARIANT II it did not exceed 9.5°C. Simultaneously, mean diurnal amplitude at the reference plot was equal to 6.5 and 7.5°C during VARIANT I and VARIANT II, respectively. For the whole VARIANT II, mean peat substrate temperature was 0.5±0.4°C higher (Fig. 5) than at the reference plot. The maximum temporary difference in peat substrate temperatures between the experimental and the reference site during night time period was 1.9°C.

Table 1. Temperature comparison for individual plots – VARIANT I

Pair comparison	Kruskal-Wallis significance level (p)	Mann-Whitney-Wilcoxon significance level (p)	Tukey HSD significance level (p)
$S_{1...3,1...3} \sim S_{1...3,4...6}$		0.99	0.09
$S_{1...3,1...3} \sim S_{1...3,7...9}$	0.05	0.96	0.17
$S_{1...3,4...6} \sim S_{1...3,7...9}$		0.67	0.95

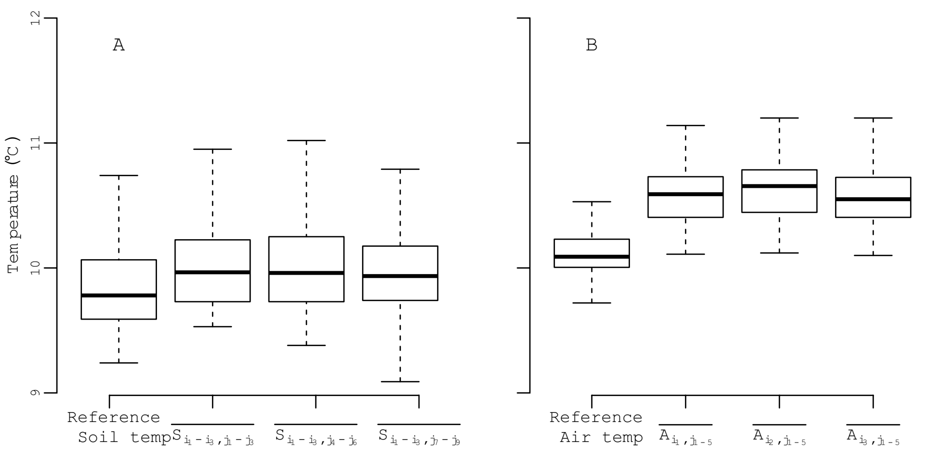

Fig. 4. Night-time (3:00-6:00 a.m.) peat substrate (A) and air (B) temperatures for VARIANT II; 30th day of experiment (22 April 2014) The thick line marks the median; the boundaries of the box are the first and third quartiles, while whiskers are extreme values

Differences between peat substrate temperatures of the heated and reference plots were much smaller during VARIANT II of the experiment (Figs 4 and 5). However, the Mann-Whitney-Wilcoxson test still showed a statistically significant difference between heated surface and reference plot ($p = 0.0001$). Assuming a significance level of $p = 0.05$ for Kruskal-Wallis and Tukey HSD tests we showed that we cannot reject the hypothesis on the uniformity of temperature distribution across the heated site (Tab. 2).

The measurement of air temperature over the heated peat surface showed that in the hours from 3:00 to 6:00 a.m. temperature was 0.5±0.3°C higher than the temperature measured at the reference plot.

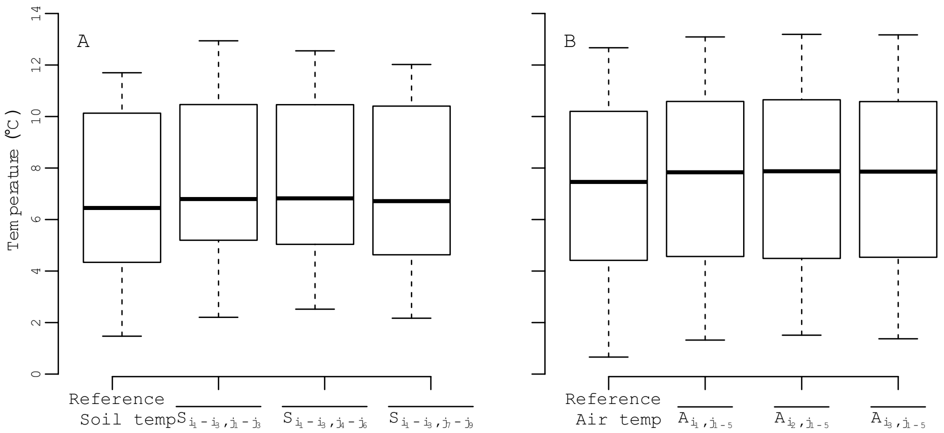

Fig. 5. Night time (3:00-6:00 a.m.) peat substrate (A) and air (B) temperatures during the whole period from 14th to 22nd of April 2014 – VARIANT II. The thick line marks the median; the boundaries of the box are the first and third quartiles, while whiskers are extreme values

Table 2. Temperature comparison for individual plots – VARIANT II

Pair comparison	Kruskal-Wallis significance level (p)	Mann-Whitney-Wilcoxon significance level (p)	Tukey HSD significance level (p)
$S_{1...3,1...3} \sim S_{1...3,4...6}$		0.94	0.53
$S_{1...3,1...3} \sim S_{1...3,7...9}$	0.075	0.35	0.71
$S_{1...3,4...6} \sim S_{1...3,7...9}$		0.98	0.15

DISCUSSION

This experiment showed that the IR heaters effectively increased the temperature of the water saturated peat layer. In the experiment, we applied two installation types of IR heaters (400 W each) and the main goal of the experiment was to determine the rate of changes of water-saturated peat substrate temperature and assess the applicability of such heaters to increase the peat temperature.

During VARIANT I of the experiment we observed a noticeable increase in peat temperature over practically the entire heated peat surface. Except for thermometers $S_{1,5}$ and $S_{1,7}$, (data not shown) it may be concluded that the surface was heated uniformly (high pair-wise significance level). The heating with long-wave radiation that reaches the surface at an angle close to 90° makes it possible to increase the temperature of the heated peat by 1.1°C on average. A drawback of such an arrangement of heaters may be connected with the fact that at the edges of the tested surface the temperature is lower (in this case by approximately 0.5°C) in relation to the temperatures measured under the heaters. Since two heaters are installed, their radiation was cumulative and, as a result, its spatial distribution shape is elliptical, with the focuses of the ellipse located at a point equidistant to the two heaters. Theoretically, an increase in peat temperature may be essentially uniform only within the line linking points located directly under the heaters; however, the height at which the heaters are installed and the related limited variation in radiation intensity for the heated surface suggests that the change in temperature is uniform. This method of heater installation directly over the manipulated surface is most frequently applied in climate manipulation experiments (Wan *et al.* 2002, Kimball *et al.* 2012, Johnson *et al.* 2013).

During VARIANT II we tested the feasibility of heater installation at the edges of the manipulated surfaces, such that radiation fell on the heated surface at a certain angle. Assuming a heater to be a point source of radiation it was calculated that radiation reached the heated surface at an angle ranging between 40 and 50°. This arrangement of the two heaters made it possible to increase peat temperature at the manipulated site by 0.5°C, on average. However, peat temperatures in the middle of the heated plot were smaller (although differences were not significant) than at the edge of the manipulated surface just beneath the heaters. This means that this arrangement of heaters may cause non-uniform heating of the surface.

To sum up, the use of ceramic heaters caused an increase in peat temperature by 1.1 and 0.5ºC on average during variants I and II, respectively, and an increase in air temperature at 5 cm above the heated surface by 0.7 and 0.5°C, respectively. The observed increase in air temperature was the result of convection and a consequence of greenhouse gasses absorbing thermal radiation emitted by the heaters and long-wave radiation emitted by the heated surface. In this experiment, it was not possible to separate these phenomena to determine the individual importance of these processes and their effect on air heating. However, it seems that absorption of thermal radiation by the heated surface had a greater effect on the observed increase in temperature, since the range of wavelengths of this radiation type is obviously much higher, considering the lower temperature of its surface in comparison to that of heat emitted by the heaters.

CONCLUSIONS

Application of long-wave heaters installed above the heated surface so that radiation can reach the surface at an angle of approximately 90º is recommendable from the point of view of greater homogeneity of temperature. However, under conditions whereby such an installation of heaters is not possible, heaters can be installed at the edge of the manipulated plot and need to be tilted to the surface at a certain angle. It is justified to utilise a greater number of heaters installed at the edges of the heated surface in order to provide greater uniformity in the distribution of temperatures on the manipulated surface (as suggested by Kimball and Conley 2009, Kimball *et al.* 2012). The following statements can be presented as results of our studies:

1. Ceramic IR heaters can be used in order to effectively increase the temperature of water-saturated substrates (e.g. peat).

2. The presented experiment shows that applied two IR heaters enables to increase peat temperature by 1.1°C when radiation reaching the surface is perpendicular to the surface and by 0.5°C when heaters are tilted at 30° to the surface.

3. Installation of heaters at the edge of the heated surface so that the angle at which radiation falls on the surface is approximately 40-50°, caused insufficient heating of the central part of the manipulated surface. At the same time, it enhanced non-uniformity in peat substrate temperatures. However, the temperature difference between heated areas was not statistically significant.

REFERENCES

Aronson E.L., McNulty S.G., 2009. Appropriate experimental ecosystem warming methods by ecosystem, objective, and practicality. Agric. For. Meteorol., 149, 1791-1799.

Harte J., Torn S. M., Chang F. R., Feifarek B., Kinzig P. A., Shaw R., Shen K., 1995. Global warming and soil microclimate: Results from a Meadow-warming experiment. Ecological Applications 5, 132-150.

Hiller C.C., Lowenstein A.I., Merriam R.L., 1994. Detailed water heating simulation model. ASHRAE Transactions, 100, 948-954.

Ineson P., Taylor K., Harrison A. F., Poskitt J., Benham D. G., Tippping E., Woof C., 1998. Effects of climate change on nitrogen dynamics in upland soils. 1. A transplant approach. Glob. Change Biol., 4, 143-152.

Intergovernmental Panel on Climate Change, 2013. Climate Change 2013: The Physical Science Basis: Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.

Johnson, C. P., Pypker, T. G., Hribljan, J. A., Chimner, R. A., 2013. Open top chambers and infrared lamps: A comparison of heating efficacy and CO_2/CH_4 dynamics in a northern Michigan peatland. Ecosystems, 16, 736-748.

Kimball B.A., 2005. Theory and performance of an infrared heater for ecosystem warming. Glob. Change Biol., 11, 2041-2056.

Kimball B.A., Conley M.M., 2009. Infrared heater arrays for warming field plots scaled up to 5-m diameter. Agric. For. Meteorol., 149, 721-724.

Kimball B., 2011. Comment on the comment by Amthor J.S., Hanson P.J., Norby R.J., Wullschleger S.D., on "Appropriate experimental ecosystem warming methods by ecosystem, objective, and practicality" by Aronson and McNulty. Agric. For. Meteorol., 151, 420-424.

Kimball B.A., Conley M.M., Lewin K.F., 2012. Performance and energy costs associated with scaling infrared heater arrays for warming field plots from 1 to 100 m. Theor. Appl. Climatol., 108, 247-265.

Luo C., Xu G., Chao Z., Wang S., Lin X., Hu Y., 2010. Effect of warming and grazing on litter mass loss and temperature sensitivity of litter and dung mass loss on the Tibetan plateau. Glob. Change Biol., 16, 1606-1617.

Nijs I., Teughels H., Blum H., Hendrey G., Impenes I., 1996. Simulation of climate change with infrared heaters reduces the productivity of *Lolium pererne* L. in summer. Environ. Exp. Bot., 36, 271-280.

Ottman M.J., Kimball B.A., White J.W., Wall G.W., 2012, Wheat Growth Response to Increased Temperature from Varied Planting Dates and supplemental Infrared Heating. Agron. J., 104, 7-16.

Silvennoinen H., Bárcena T.G., Moni Ch., Szychowski M., Rajewicz P., Höglind M., Rasse D.P., 2016. Carbon balance of a subarctic meadow under 3°C warming – unravelling respiration. Geophys. Res. Abstr., 18 EGU2016-13667 EGU.

Walther G.R., Post E., Convey P., Menzel A., Parmesan C., Beebee T.J.C., Fromentin J.M., Hoegh-Guldberg O., Bairlein F., 2002. Ecological responses to recent climate change. Nature, 416, 389-395.

Wan, S., Luo, Y., Wallace, L.L., 2002. Changes in microclimate induced by experimental warming and clipping in tallgrass prairie. Global Change Biology, 8, 754-768.

OCENA EFEKTYWNOŚCI OGRZEWANIA PODŁOŻA TORFOWEGO WYSYCONEGO WODĄ ZA POMOCĄ PROMIENNIKÓW PODCZERWIENI

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Streszczenie. Celem niniejszej pracy była ocena możliwości zastosowania promienników podczerwieni (400 W, HTS/1 Elstein) do podniesienia temperatury podłoża torfowego wysyconego wodą. Eksperyment przeprowadzono w dwóch wariantach. W wariancie I promienniki zainstalowano prostopadle do ogrzewanej powierzchni (wysokość instalacji – 230 cm), natomiast w wariancie II promieniowanie długofalowe docierało do ogrzewanej powierzchni pod kątem 40-50° z promienników zainstalowanych na brzegach ogrzewanej powierzchni (wysokość instalacji –200 cm). Bazując na analizie średnich nocnych (od 3:00 do 6:00) temperatur torfu stwierdzono, że zastosowanie promienników HTS/1 powoduje wzrost temperatury podłoża torfowego wysyconego wodą odpowiednio o 1,1°C oraz 0,5°C w przypadku wariantu I i II. Jednocześnie stwierdzono wzrost temperatury powietrza na wysokości 5 cm nad ogrzewaną powierzchnią o 0,7°C podczas wariantu I oraz o 0,5°C w przypadku wariantu II.

Słowa kluczowe: promienniki podczerwieni, manipulacja temperaturą, torf