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INSULATING AGAINST THE EFFECTS OF FROST ON SOILS: AN ORIGINAL EXPERIMENT ON THE ROOF OF THE "SOIL HOUSE" OF THE BOTANICAL GARDEN OF NEUCHÂTEL

BLAISE MULHAUSER[1] & BAPTISTE BOVAY[2]

Abstract

Following the 2020 prize awarded by the Swiss Society of Pedology to the Botanical Garden of Neuchâtel, an experiment on the possibility of creating floodable peat soils on green roofs as cool islands started in April 2021. This article presents the results of the effects of frost on three types of soil reproduced 5 times in different microclimatic situations: an anthropogenic lithosol 5 cm in depth (named C5) and two peat soils, or histosols, one 5 cm in depth (named T5) and the other 15 cm (T15) in depth. Thermal sensors measured temperatures lower than those of the ambient air in the C5 soils (min >-9.5°C). However, they revealed a buffering effect close to 0°C during periods of frost under the peat soils, with a better insulating effect in the T15 soils than in the T5 soils. Thus, it can be concluded that peat, even when flooded, provides good insulation during periods of frost, revealing good potential for the creation of wetlands on roofs; the additional objective being that of a substitute environment for the threatened flora of peatbogs.

Keywords: anthropic soil, green roof, coolness island, peat.

Résumé

Suite au prix 2020 décerné par la Société suisse de pédologie au Jardin botanique de Neuchâtel, une expérience sur la possibilité de créer des sols tourbeux inondables en toiture végétalisée comme îlot de fraîcheur a débuté en avril 2021. Cet article présente les résultats de l'effet du gel sur trois types de sol reproduits 5 fois dans des situations microclimatiques différentes : un lithosol anthropique de 5 cm de profondeur (nommé C5) et deux sols tourbeux, ou histosols, l'un de 5 cm de profondeur (nommé T5) et l'autre de 15 cm (T15). Les capteurs thermiques ont mesuré des températures plus basses que celles de l'air ambiant dans les sols C5 (min >-9.5°C). Ils ont en revanche révélé un effet tampon proche du 0°C lors des périodes de gel sous les sols tourbeux, avec un meilleur effet isolant dans les sols T15 que dans les sols T5. On peut ainsi conclure que la tourbe, même inondée, crée une bonne isolation en période de gel, ce qui révèle un bon potentiel pour la création de zones humides sur toiture ; l'objectif complémentaire étant celui de milieu de substitution pour la flore menacée des marais tourbeux.

Mots clés : sol anthropique, toiture végétalisée, îlot de fraîcheur, tourbe.

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Zusammenfassung
Im Anschluss an den von der Schweizerischen Bodenkundlichen Gesellschaft verliehenen Preis 2020 startete der Botanische Garten Neuenburg im April 2021 eine Untersuchung des Potenzials von überflutbaren Torfböden in Dachbegrünungen als Frischeinseln. In diesem Artikel werden die Ergebnisse der Frosteinwirkung auf drei Bodenarten in fünf verschiedenen Mikroklimata vorgestellt: ein anthropogener Lithosol mit einer Tiefe von 5 cm (genannt C5) und zwei Torfböden oder Histosole, einer mit einer Tiefe von 5 cm (genannt T5) und der andere mit einer Tiefe von 15 cm (T15). Die Temperatur in den C5-Böden war niedriger als jene der Umgebungsluft (min >-9.5°C). In Frostperioden zeigte sich eine Pufferwirkung und die Temperatur unter torfigen Böden blieb bei nahezu 0°. Diese isolierende Wirkung war in T15-Böden besser als in T5-Böden. Zusammengefasst konnte gezeigt werden, dass in Frostperioden eine Dachbegrünung mit Torf eine gute Isolation bewirken kann, selbst wenn der Torf überflutet ist. Dachbegrünungen mit Torf könnten ausserdem ein Ersatzlebensraum für die bedrohte Flora der Torfmoore sein.

Stichwörter: Anthropogener Boden, Dachbegrünung, Frischeinseln, Torf.

1. INTRODUCTION

In March 2021, the Swiss Soil Science Society awarded its prize to the Neuchâtel Botanical Garden for the creation of the permanent exhibition "The Soil House". Thanks to this recognition, it was possible to initiate research on the "cool island" effect of different types of soil on the roof of this building (MULHAUSER & RIEDER, 2021), while allowing the public to follow the evolution of the results thanks to a monitor showing the evolution of the temperatures of these soils in real time (fig. 1). The project has a twofold objective: to develop a technique for creating islands of coolness on a roof while ensuring the ex situ conservation of the threatened flora of peatbogs. In this article, we look at a specific question on the first aim: what is the insulating effect of a floor on the roof of a building during periods of frost?

For many decades, one of the main rules of building was to keep the heat inside a building by insulating the roof and facades. In the face of climate change and the higher temperatures observed in cities (YANG *et al.*, 2016), new aims are appearing. Architects and urban planners are exploring new techniques to create urban cool islands in overheated cities (KOLOKOTRONI *et al.*, 2010). In this context, soils in urban and built-up environments will play a major role in demonstrating resilience in a global environment that is difficult to predict (DE KIMP & MOREL, 2000; ALCAZAR *et al.*, 2016; JIM, 2015; POLO-LABARRIOS *et al.*, 2020).

Furthermore, we have also explored the potential effects of these "islands of coolness" during the winter, in order to quantify the insulating effects that these soils provide. Indeed, peat has interesting potential insulating properties, such as low heat conductivity and high heat capacity (ZHAO *et al.*, 2019; ZHAO & SI, 2019). In addition to acting as islands of freshness in the summer and shelters for threatened species, these peat soils may act as a great insulation layer in the roofs of buildings.

A major challenge is to increase the natural quality of urban soils while continuing to densify the habitat. Soil scientists are thus asking two key questions: 1) how can we build sustainable cities that are suitable for human well-being while preserving our natural soil capital? and 2) how can we get more ecosystem services from the same surface? (MOREL *et al.*, 2014; translation Mulhauser & Bovay). The experiment designed at the Neuchâtel Botanical Garden seeks to provide some answers to these questions. We illustrate this experiment here along with the example of the effects of frost on temperature variations in three different soil types.

2. MATERIAL AND METHODS

The experiment, which began in April 2021, was installed on a low-slope (6.2%) single-pitch roof, galvanized along its entire length, and divided by five raised strips perpendicular to the direction of the slope, so that water could temporarily stagnate in different places, while ensuring slow drainage towards the bottom of the roof with a 15 cm high overflow (fig. 2). Once the metal cover was in place, it was covered with a layer of waterproof material. Six planks placed equidistantly from each other separated each strip, resulting in 35 squares of 88 x 88 cm (fig. 3).

The building is an unheated and uninsulated wooden shed (fig. 2) located in the Neuchâtel Botanical Garden (vallon de l'Ermitage, Neuchâtel, Switzerland: 46°59'59'' N / 6°56'07'' E / alt. 531 m). It was built on the edge of a forest located to the south, and its slope was oriented along a NE - SW axis in order to promote two gradients:

- Moisture - from dry soil at the roof peak (band E) to flooded soil (band A) at the lowest point;
- Sunlight - from a shaded area at the edge of the forest (south-east; band 1) to an open area surrounded by grassland (north-east; band 7).

Figure 1. A touch-sensitive screen inside the "Soil House" presents the results of temperature measurements for three types of soil in real time.

Figure 2. General view of the Soil House from the north-west on 9 January 2022. Note the "refrigerator" effect of the frozen ground on the roof, which keeps snow in place longer than in the surrounding meadow and forest.

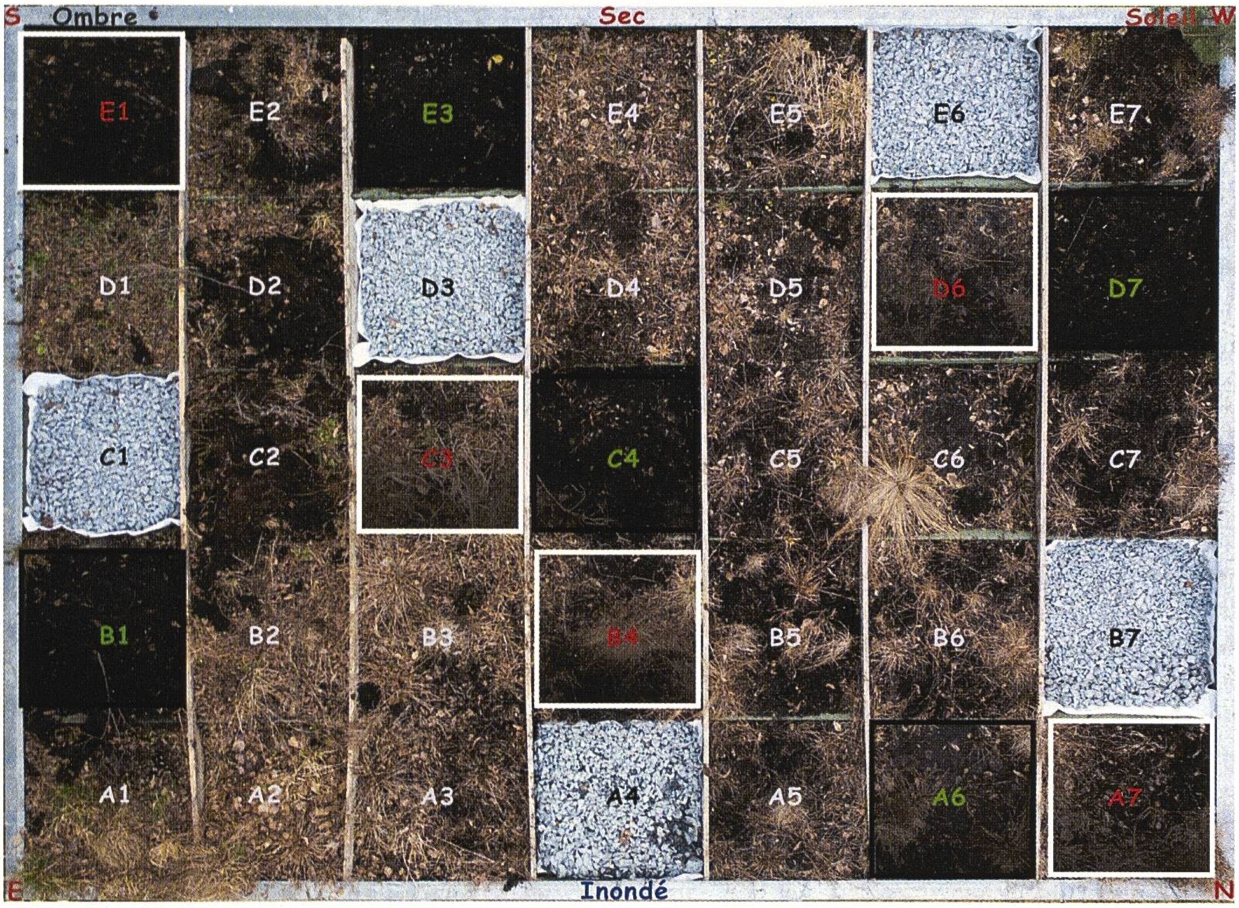

Figure 3. Drone view of the experimental setup. The thermal probes are located in the centre of the 15 study squares (5 x 3 different soils: 15 cm thick peat [red font surrounded by a white square] / 5 cm thick peat [green font surrounded by a black square] / 5 cm thick lithosol [black font on a grey background]).

Temperatures

To determine the effect of the substrate, the presence of water and vegetation on the soil temperature, 15 of the 35 roof plots are equipped with a thermal probe placed in their central point and then covered with one of the three substrates under study: **C5** (5 cm thick pebble or anthropic lithosol, GOBAT & GUENAT, 2019), **T5** (5 cm thick peat) and **T15** (15 cm thick peat or histosol, GOBAT & GUENAT, 2019). Each of these soils is replicated 5 times but distributed to account for different levels of sunlight and moisture (fig. 3). Two complementary probes measure the air temperature at the edge of the roof and the temperature in the building. These temperature measurements were taken automatically and simultaneously for all 17 probes every hour from April 2021. The measurements used for this article are from January 2022, a period marked by a prolonged period of freezing temperatures.

Hydrology

The presence of water in the soil was measured once a day in the middle of each plot, so that the height of the water column above each heat probe was ascertained. As part of the frost effect study, fifteen piezometers (pvc tube 1 cm in diameter; accuracy of measurement 0.5 mm) were installed to measure the thickness of the liquid water, ice and snow cover. The thickness of the ice was measured by hand using a ruler graduated in mm, from the area left clear by the piezometer. They were placed at the median line of the plot perpendicular to the slope against the boards of the plot to avoid disturbing the temperature sensor and to make it easier to take the measurements. All the measurements were taken between 08:30 and 09:45. The general study started in April 2021, but the more detailed frost effect measurements were taken on a daily basis throughout January 2022.

Statistical Analyses

All the statistical analyses were performed with Rstudio (RStudio Team, 2021) and R (R Core Team, 2021). For our analysis, we have removed the data of plots D3 and E3 because these probes provided aberrant temperature data (probably due to the computer permutation of the two sensors).

We analysed our data with mixed effect models, because of the multiple samples from the same plot during this time period. This is why we introduced a random effect on the time and plots in all our models. These two random effects were also corelated, which we took into account in our models. We built our models with the functions lmer() and glmer() from the "lme4" package (Bates *et al.*, 2015). We did not test the interactions because the factors are not crossed. The formulas used in our models are the following:

M1: log(Min_T + X) ~ Line + Soil + Sun exposure + Water level + Frost + Snow + Air temperature + (1|Plot) + (0 + Day|Plot)

M2: Hour ~ Soil + Line + (1|Plot)

Min_T is the daily minimal temperature record in a plot, X is a coefficient to correct our data with a log transformation which was chosen with the function boxcox() of the "MASS" package (Venables & Ripley, 2002). Line is a factor of 5 levels which indicate the line of the roof (according to the moisture gradient). Soil is the type of soil. Sun exposure is a factor with 2 levels according to the sunlight gradient. Water level is the measure of the height (in cm) of the water table in each plot. Frost corresponds to the proportion of the thickness of the frozen soil. Snow is the thickness of the snow layer at the centre of the plots. Air temperature is a recording of the air temperature outside the shed (in °C). Plot is a variable with 15 levels according to the identity of the plot. Day is the date of the recording and Hour is the number of hours that a soil was below -0.5°C during the study period.

To check if the assumptions of the models were correct, we performed tests with the functions qqnorm() and acf() from the "stats" package, plot from the "graphics" package (R Core Team, 2021) and qqmath() from the "lattice" package (Sarkar, 2008). To interpret our models, we used the function Anova() from the "car" package (Fox & Weisberg, 2019). Post-hoc analyses were performed with the function emmeans() from the "emmeans" package (Lenth, 2022). The predictions of the models were made with the function predict() from the "stats" package (R Core Team, 2021). Finally, we also performed a PCA for the data collected during January 2022 with the "vegan" and "ggbiplot" packages (Oksanen *et al.*, 2020; Vu, 2011).

3. RESULTS

Between 2022-01-05 and 2022-01-28, the average air temperature was cold (an average of 0.11°C with a minimum of -4.25°C, fig. 4a). The soils were at least partially frozen during most of the month (fig. 4b).

Our models showing the variables which influence the temperature of the soils clearly indicate that the type of soil had a significant effect (M1: Chisq = 39.11, df = 2, P-value < 0.0001 and M2: Chisq = 28.794, df = 2, P-value < 0.0001). This effect is illustrated in figure 6a. It can be seen that below 0°C, peat soils (T5 and T15) exhibited very different behaviour from C5. The soil temperature

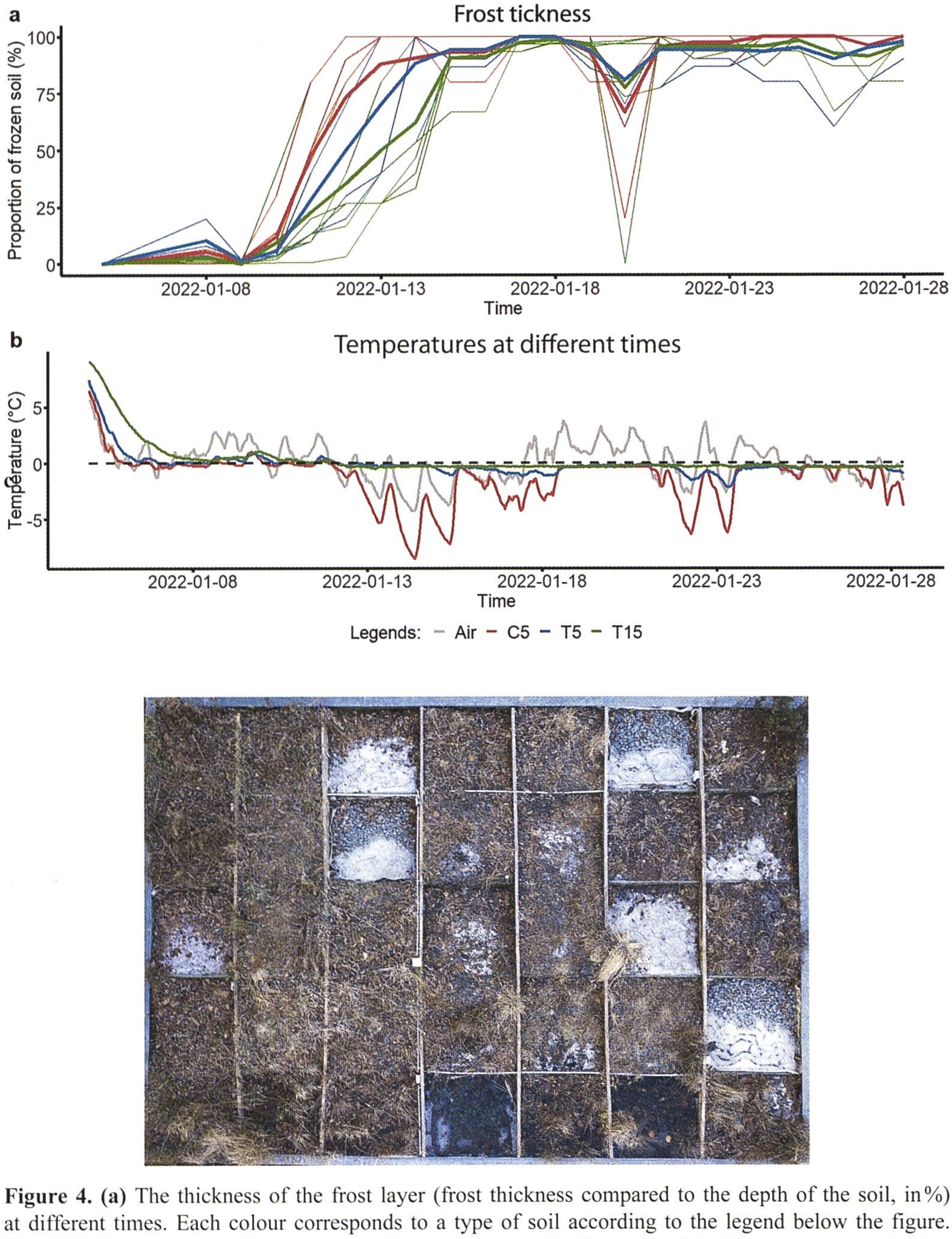

Figure 4. (a) The thickness of the frost layer (frost thickness compared to the depth of the soil, in%) at different times. Each colour corresponds to a type of soil according to the legend below the figure. The thick lines represent the mean according to the type of soil and the thin lines represent each plot. **(b)** The measured temperature of the air and under the soils at different times. The lines represent the mean temperature for each soil (the coloured legends below the figure) and the dashed line represents 0°C. **(c)** Drone view of the experimental setup on 2022.01.14 during the coldest frost.

decreases more slowly in peat soils than in pebble soils (C5) according to the decrease in temperature. For M1 (minimal daily temperature), the post-hoc analysis indicated that C5 was significantly different from the others (P-values < 0.001). However, for M2 (number of hours below -0,5°C), the post-hoc analysis indicated that T15 was significantly different from C5 and T5 (P-values < 0.01).

Frost had a significant influence on the daily minimal temperature measured in the soils (Chisq = 9.82, df = 1, P-value = 0. 0017). The frost's impact is visible in figure 4c and is shown in figure 6a, where the plots, before they went below 0°C had a period without any fluctuations. Plot B1, for example, had a flat period of more than 15 days (fig. 5b). The duration of the flat curves depends on the type of soil. In figure 5 clear differences can be seen between the different types of soils, especially between the peat soils (T15 and T5) and pebble soils (C5). These flat curves were probably caused by frost, because the temperature remained stable at around 0°C, which is the freezing point of water. Finally, these flat curves also occurred when the soils thawed, as can be seen from 2022-01-19 to 2022-01-21 in figure 5a.

T5 and T15 seem to have interesting thermal properties which increased the time of the flat curve and prevented the temperatures from falling much below 0°C, while in C5 the temperature fell to -9.5°C (fig. 5a) after a flat curve of only a few days (7 days for plot B7). T15 had a minimal temperature of -0.75°C and a flat curve for almost the whole month. In figure 5, it can also be seen that line A (fig. 5a, b and c, A is the line with the highest water level) is exhibiting different behaviour from line B (fig. 5d, e and f) and the other lines. This is probably caused by the presence of water in these soils. Indeed, the quantity of frozen water was not measured but seems to have had a positive effect on the temperature of the soils, even in soil C5 (fig. 5d), which exhibited almost the same behaviour as the peat soils.

The thermal properties of the different soils are also visible on a PCA (fig. 6b). In the PCA plot (fig. 6b, 68.6% of the variance explained), it can be seen that the circles for the different soils are in the same location. However, the sizes of the circles vary a lot. T15 has a much smaller distribution than T5 and C5 has the largest distribution. It can be seen that the observations made in C5 are much more influenced by the daily minimal temperature and daily differences in temperature than T5 and T15.

4. DISCUSSION

Our findings about the peat soils' (T15 and T5) behaviour when the air temperature was below 0°C are interesting. When the air temperature was below 0°C, the daily variations in temperature were also almost 0°C and the daily minimal temperature stabilized at around 0°C for a number of days depending on the type of soil (fig. 5a). This behaviour was probably caused by the presence of water in these soils. Indeed, when water freezes, soils seem to stabilize their minimal temperature at around 0°C.

On the other hand, in peat soils, the temperature seems to remain at around 0°C even if there is a full frost layer. Clearly, the presence of hygroscopic or capillary water escapes our method of measuring free water. If this is the case, after a longer time exposed to low temperatures, the temperature of these kinds of soil should also fall far below 0°C as in pebble soils. Moreover, for a roof on a building, the water will probably take even longer to freeze completely because the heat of the building will prevent the water from freezing quickly. Consequently, peat soils could provide very efficient protection against temperatures below 0°C. Furthermore, T5 soils also have lower daily minimal temperatures than C5 soils (fig. 5a). This means that even a thin layer of peat soil may act as a good insulation layer. This thermal property could be used when constructing a building. Indeed, if the

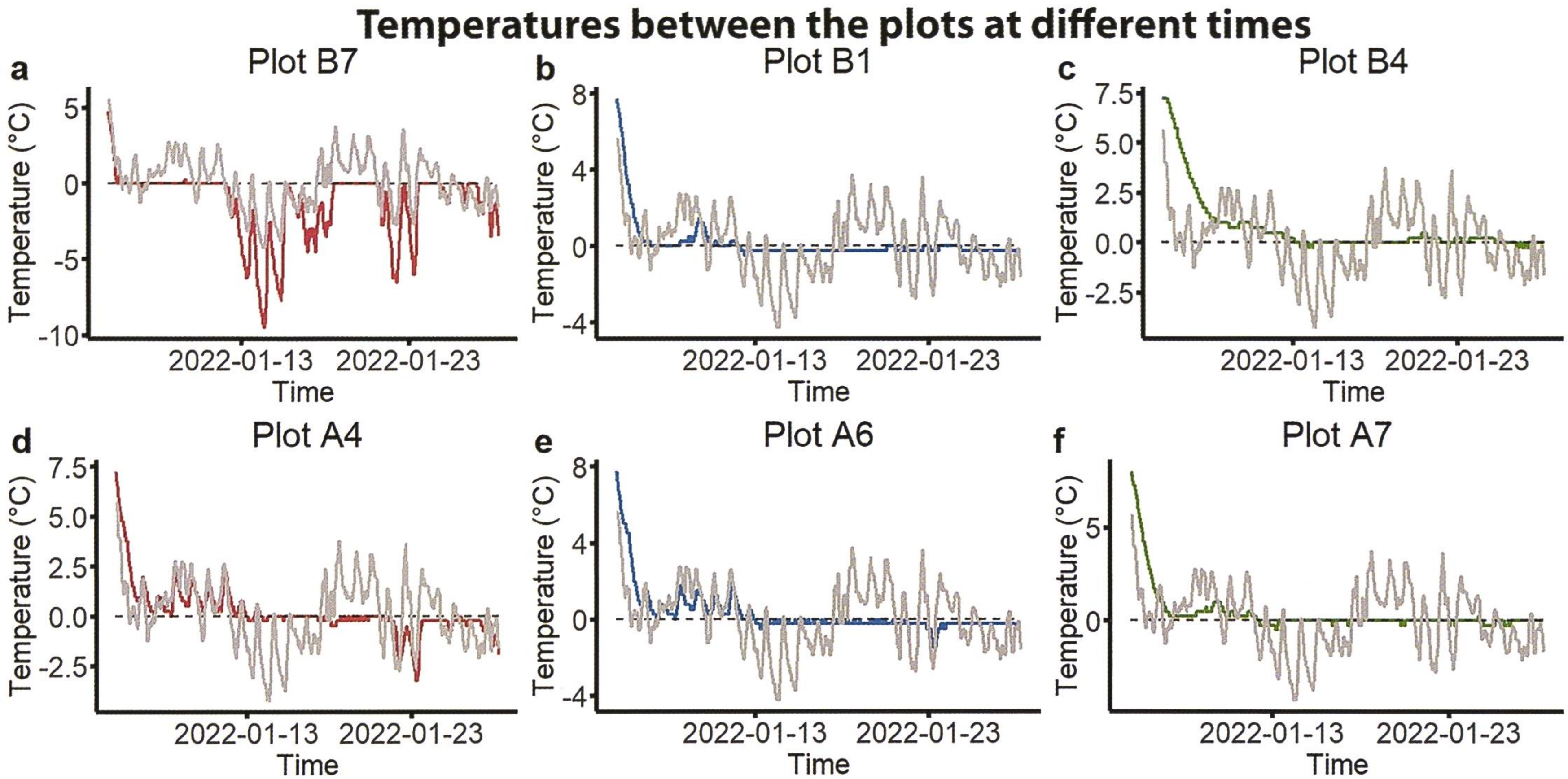

Figure 5. The temperatures of the plots at different times during January 2022. The grey line represents the air temperature, and the colours correspond to the type of soil (red for soil depth C5, blue for T5 and green for T15). Only the wettest soils are compared (lines A and B; fig. 3): plots **a**, **b** and **c** are part of line B, with a lower water table, and plots **d**, **e** and **f** are part of line A, with a higher water level. These graphics show us both the impact of the lines (which correspond to the water level) and the influence of the different types of soil.

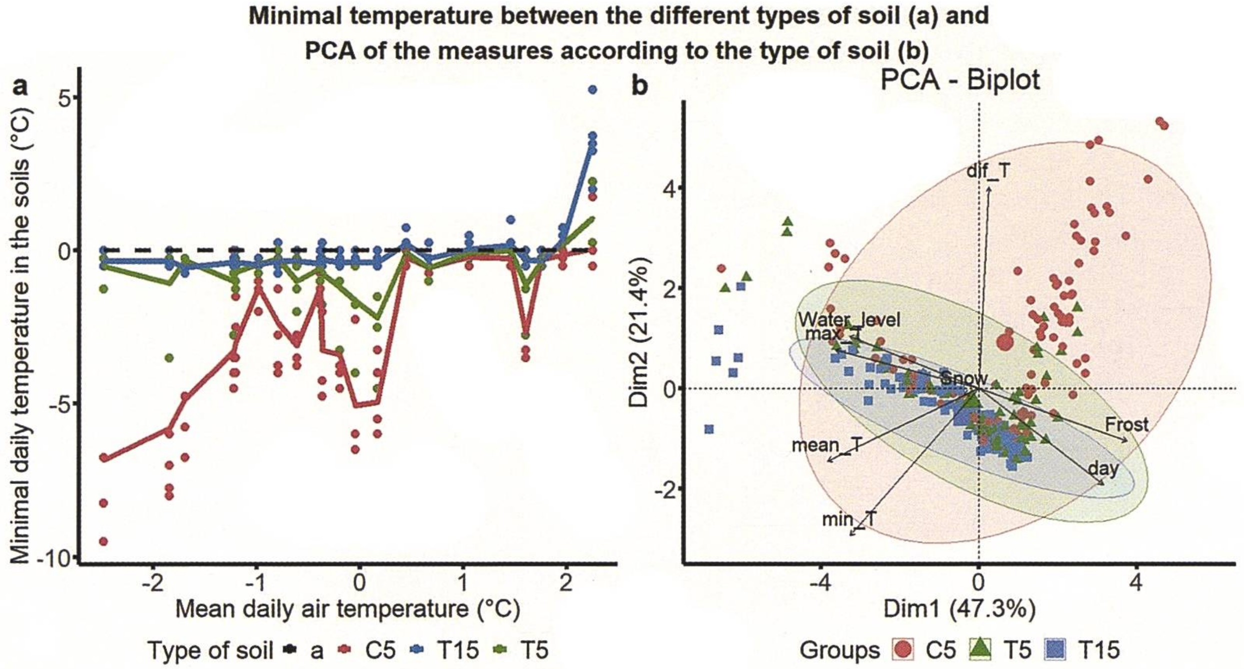

Figure 6. (a) The daily minimal temperature measured in the soils according to the air; the coloured lines represent the averages between the plots, the dots represent each plot individually and the colours indicate the type of soil (legend between fig. a and b). **(b)** PCA of the daily observations made for each plot according to the type of soil (coloured legends between fig. a and b). The arrows represent the variables tested (mean_T, min_T, max_T and dif_T = daily mean, minimal, maximal and differences in temperature in °C measured in the soils; Day = date of the measurement; Frost = thickness of the frost layer in %; Snow = thickness of the snow cover in cm; Water level = height of the water table in the soils in cm; and Tair = Air temperature in °C).

insulation layer is good enough, it could be imagined that less energy would be needed to heat a building, which in turn may reduce CO_2 emissions. Because of the low conductivity of peat, especially when dry (Zhao *et al.*, 2019), it is likely to be a very good insulation layer.

However, the fact that these soils also have a flat curve during thaw periods could be more problematic because this creates a colder area on the roof. On the other hand, the fact that these soils remain frozen even when the air temperature is above 0°C indicates that the insulation potential of these soils is good (Collins, 2016). The question that could be asked is the following: “Are the insulating benefits provided by peat soils better than cold storage when the temperature gets warmer?” In our opinion, this is not a problem because the opposite effect happens when soils begin to freeze: peat soils are warmer longer that pebble soils. This negative effect is almost completely counterbalanced by the opposite effect, while the benefits provided by good insulation are still the same.

Consequently, green peat roofs provide good insulation in the winter when the temperatures fall below 0°C. According to these thermal properties, these peat soils seem to be especially useful for places with relatively cold winters, such as Neuchâtel Canton, where this experiment took place. Having green peat roofs may save energy for heating, thus reducing CO_2 emissions in the winter. Another thing that could be imagined is that in order to reduce energy for heating, pebble roofs could be flooded when sub-zero temperatures are forecast. As in our experiment, this will significantly reduce the minimal temperatures on roofs and reduce the amount of time when the temperature is below -0.5°C. However, the main drawback to this is the weight of these flooded roofs, which must be carefully calculated whenever this strategy is applied.

Finally, these green roofs with peat soil on them will probably cost a lot of money; in order to have some buildings with this kind of roof their benefits should be clearly demonstrated. These roofs can act as insulation layers, as explained before. Moreover, the peat soil roofs will probably also act as islands of coolness during the summer and provide shelter for some threatened peatland species. Taken together, these three aspects of green peat roofs could compensate for their high cost, and may be especially suitable for large apartment buildings.

5. CONCLUSION

The preliminary results of this experiment clearly demonstrate one of the advantages that peat soils could provide on green roofs. The insulation provided by peat soil could be particularly useful for regions where the temperature falls below 0°C in the winter, like in Neuchâtel Canton, where this study was conducted. Finally, after analyzing the preliminary results, we identified four key points on the green roof of the Soils House that should be studied:

1. Making an estimation of the biodiversity on green peat roofs and determining which potentially threatened species could be introduced there (this was already underway during the first vegetation surveys in 2021, which revealed over 70 plant species in 30 m^2; MULHAUSER & RIEDER, 2021);
2. Testing the thermal properties of peat soils during heatwaves in the summer in order to assess the possibility of using these soils as islands of coolness;
3. Measuring the "best" effects of the presence of water (temporary or permanent?) on soil temperature to create beneficial islands of coolness without any technical problems (weight and inundation);
4. Measuring the effects of vegetation on the soil temperature in order to improve the quality of these green roofs.

After addressing these points, wet peat soils could be installed on roofs, especially in places where the ability of these soils to provide good insulation could be used. This is the case, for example, for large apartment buildings where these soils will provide insulation in the winter. In addition, they will also probably provide coolness in the summer and act as biodiversity shelters.

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