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Temperature and humidity conditions in underground burrows of the lesser Japanese mole, *Mogera imaizumii* (Talpidae)

Masahiro A. Iwasa* & Riho Abe

ABSTRACT. In burrowing mammals, the temperature and humidity in burrows are important microenvironmental factors for the metabolism. To characterize the temperature and relative humidity inside the burrows of the lesser Japanese mole, *Mogera imaizumii*, digital loggers were set to record these microenvironmental characteristics in underground burrows and the aboveground air as a control. The current temperature and relative humidity were more stable in underground than in aboveground considering that smaller daily differences in both temperature and relative humidity were recognized only in the burrows. The inside temperatures showed up to 26.1 ± 1.2°C irrespective of over 30°C in the aboveground and the mean inside relative humidity showed constantly values over 100% irrespective of the range from 42.8 ± 11.7% to 84.2 ± 9.0% in aboveground through a year. To avoid a restraint of radiation of body heat by evaporation in higher temperature and humidity, lower temperature as possible above 23°C as considered to be the lower limit of the thermoneutral zone seems to be more appropriate condition for the mole. The current results showing the temperatures around the limit (25.1 ± 0.6–26.1 ± 1.2°C) with over 100% relative humidity seem to fit to the more appropriate environment, at least in summer. The current findings means that the high humidity with lower temperature saves energy expended by increasing the metabolic rate in *M. imaizumii* and probably also in other burrowing mammals.

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KEY WORDS: *Mogera imaizumii*, inside burrow, temperature, relative humidity.

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Температурно-влажностный режим в подземных норах малого японского крота, *Mogera imaizumii* (Talpidae)

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РЕЗЮМЕ. Температура и влажность в норах роющих млекопитающих являются важными факторами, влияющими на обмен веществ. Для исследования температуры и относительной влажности внутри нор малого японского крота *Mogera imaizumii*, были установлены цифровые датчики для регистрации этих характеристик микросреды в подземных норах и надземном воздухе в качестве контроля. Текущая температура и относительная влажность были более стабильными в подземных условиях, чем в надземных, учитывая, что меньшие ежедневные различия как в температуре, так и в относительной влажности наблюдались только в норах. Внутренние температуры составляли до 26.1 ± 1.2°C независимо от температуры над землей более 30°C, а средняя внутренняя относительная влажность постоянно превышала 100% независимо от диапазона от 42.8 ± 11.7% до 84.2 ± 9.0% над землей в течение года. Чтобы избежать ограничения охлаждения тела за счет испарения при высокой температуре и влажности, более подходящим условием для крота кажется относительно температура, около 23°C, которая считается нижним пределом термонейтральной зоны. Полученные результаты, свидетельствуют, что температуры, близкие к предельному значению (25.1 ± 0.6–26.1 ± 1.2°C) с относительной влажностью более 100%, похоже, соответствуют более подходящей среде, по крайней мере, летом. Полученные данные означают, что высокая влажность при более низкой температуре позволяет экономить затрачиваемую энергию за счет увеличения скорости метаболизма у *M. imaizumii* и, вероятно, также у других роющих млекопитающих.

КЛЮЧЕВЫЕ СЛОВА: *Mogera imaizumii*, норы, температура, относительная влажность.

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Introduction

Underground burrow systems are considered to be spaces where small mammals are safe from terrestrial predators and temperature extremes (Nevo, 1979, 1999; Gano & States, 1982; Nevo & Reig, 1990; Kinlaw, 1999; Martin, 2017). On the other hand, it is expected that food resources are scattered and more restricted in the underground ecotope than aboveground.

To date, the physiological adaptations of subterranean mammals have been studied with metabolism and thermoregulation. It has been pointed out that underground burrow temperatures above the upper limit or below the lower limit of thermoneutral zone showing that metabolic rate is minimal are physiologically stressful for burrowing mammals (Vleck, 1979; Lovegrove & Knight-Eloff, 1988; Burda *et al.*, 2007). Generally, temperatures are more stable in underground than in aboveground, and those in the nest areas are below the thermoneutral zone of each species (McNab, 1966, 1979; Bennett *et al.*, 1988, 1994; Contreras & McNab, 1990; Marhold & Nagel, 1995; Burda *et al.*, 2007; Luna & Antinuchi, 2007; Zelová *et al.*, 2007; Iwasa & Tabata, 2016). In addition, humidity is considered to be the most stable factor in underground burrows and is kept at a higher level irrespective of any condition of aboveground air (Kay & Whitford, 1978; Moore & Roper, 2003). In such higher humidity showing a highly water-saturated condition in underground ecotope, cooling by respiratory evaporation can be restrained to save water balance (Burda *et al.*, 2007; Okrouhlík *et al.*, 2015). Furthermore, humidity is closely related to thermal condition and it is expected that higher ambient temperature lead to suppress evaporation cooling and heat loss. Most studies about relationship between underground microenvironments and physiological adaptations for mammals have been performed in subterrestrial rodents, mainly mole rats (McNab, 1966; Vleck, 1979; Lovegrove, 1989; Bennett *et al.*, 1994; Marhold & Nagel, 1995; Burda *et al.*, 2007; Luna & Antinuchi, 2007; Zelová *et al.*, 2007; Okrouhlík *et al.*, 2015). As other subterranean mammals, it is well known that talpid moles, of the fossorial species taxa, inhabit underground ecotopes and use burrow networks (Gorman & Stone, 1990). However, such physiological study about burrowing talpids has been scarce contrary to burrowing rodents.

In the Japanese Islands, five species of subterranean moles of the genus *Mogera* occur (Ohdachi *et al.*, 2015). In the main areas of distribution of Japanese moles in the Japanese Islands, hot and humid summers with heavy rains are often recorded (Japan Meteorological Agency, 2023). Therefore, it is expected that such harsh conditions, particularly high temperature causing heat stress, would have certain stressful influences on the physiology (Mohyuddin *et al.*, 2022). Kashimura *et al.* (2010) measured soil temperatures at several depths to evaluate burrowing depth preferences in *M. imaizumii*. However, temperature and humidity conditions inside underground burrows have never been researched in Japanese talpids, and the temperature and humidity conditions of the underground talpid's burrows are unknown. In this study, we studied both parameters to assess the physiological effects of the underground ecotope in the Japanese talpid's burrows.

Materials and methods

Vinyl chloride pipes with two inner diameters, Ø 50 mm and Ø 25 mm, were set up to record burrow temperature and humidity (relative humidity) using a data logger. A narrower pipe that fit the digital data logger was attached at a right angle to a wider pipe that fit the burrow. The attachment point of these pipes can be ventilated by the hole through a metal mesh. A digital logger (LASCAR Electronics, EL-USB-2+) was put into the narrower pipe, and, to protect the logger from high moisture or the flow of rain, the outer hole of the pipe was completely closed using a silicon plug (Fig. 1a).

The current research area mainly consists of soil exposed with sparce short-grasses (height several centimeters) on the floor, and the underground also consists of a blackish soil above a loam layer of volcanic ash accumulated during the late Quaternary (Naruse, 1963; Oka *et al.*, 1979; Iwasa & Takahashi, 2021). We set loggers using the present recording system (Fig. 1a) to four points (#A, #B, #C, and #D) of underground burrows (depth 180 mm in #A, 170 mm in #B, 240 mm in #C, and 140 mm in #D) of the lesser Japanese mole, *M. imaizumii*, on the campus of Nihon University, Fujisawa, Kanagawa Prefecture, central Honshu, Japan (35.38°N, 139.4669°E, alt. 40 m). These burrow points were previously confirmed to be regular burrows of the mole (Iwasa & Takahashi, 2021). In addition, to record the ambient temperature and relative humidity, we also set the same logger (without the vinyl pipe system) on the surface aboveground (height 100 mm) under a shady cover near point #A (Fig. 1b). The temperature and relative humidity were recorded four times per hour at 15 min intervals (:00, :15, :30, and :45) during a week (actually eight days; Table 1) late in the month from October 2016 to September 2017. The current measurement values of monthly mean ± SD were compared between aboveground and underground by the *t*-test.

Results

Unfortunately, an electrical failure occurred at logger #B in September and at logger #D in April, August, and September, and no data were obtained during these periods. However, for the other periods, all of the logger data were obtained throughout the current research (Table 1, Fig. 2). Considering the large lack of data of #D, the #D results were not included in the current analyses.

At the aboveground point, 4.6 ± 3.4°C and 27.8 ± 2.5°C were recorded as the minimum temperature in January and the maximum temperature in August, respectively (Table 1, Fig. 2). On the other hand, at the underground

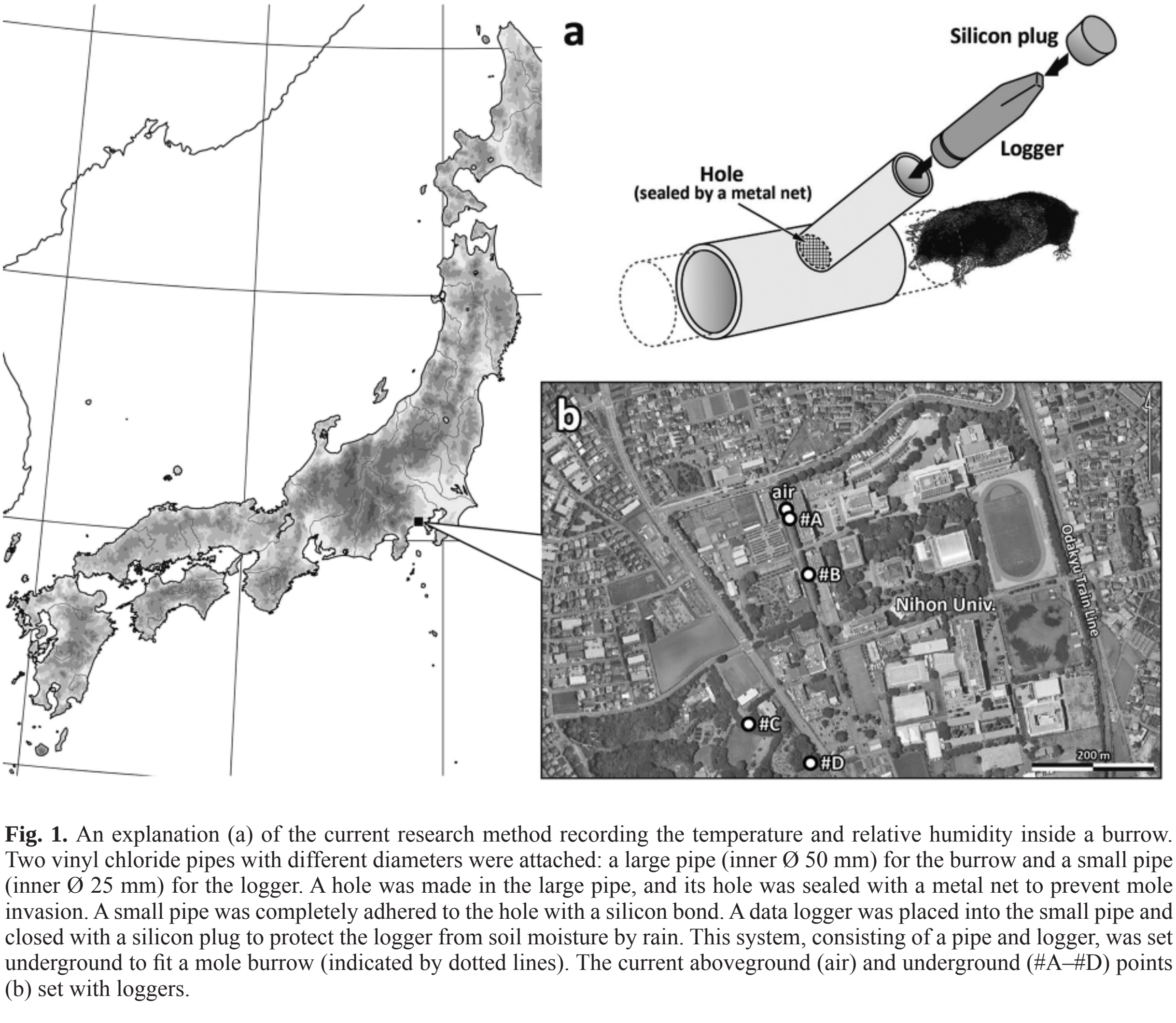

Fig. 1. An explanation (a) of the current research method recording the temperature and relative humidity inside a burrow. Two vinyl chloride pipes with different diameters were attached: a large pipe (inner Ø 50 mm) for the burrow and a small pipe (inner Ø 25 mm) for the logger. A hole was made in the large pipe, and its hole was sealed with a metal net to prevent mole invasion. A small pipe was completely adhered to the hole with a silicon bond. A data logger was placed into the small pipe and closed with a silicon plug to protect the logger from soil moisture by rain. This system, consisting of a pipe and logger, was set underground to fit a mole burrow (indicated by dotted lines). The current aboveground (air) and underground (#A–#D) points (b) set with loggers.

points, 5.2 ± 0.9°C (January at #C) and 26.1 ± 1.2°C (August at #B) were recorded as the minimum temperature in January and the maximum temperature in August, respectively (Table 1, Fig. 2). The temperature of the underground points fundamentally tended to be different from that aboveground with except for October at #A, December, February, and March at #B, and December and April at #C and the aboveground logger sometimes recorded over 30°C in July and August (Fig. 2), while the underground temperatures never reached 30°C (Tabs. 1, 2, Fig. 2).

At the aboveground point, 42.8 ± 11.7% and 84.2 ± 9.0% were recorded as the minimum relative humidity in January and the maximum relative humidity in June, respectively (Table 1, Fig. 2). On the other hand, at the underground points, 99.6 ± 3.1% (March at #B) and 107.2 ± 0.4% (August at #C) were recorded as the minimum relative humidity and the maximum relative humidity, respectively (Table 1, Fig. 2). The relative humidities were stably higher at the underground points than at the aboveground points with significance ($p < 0.01$, ranges from –18.0 ± 5.0% to –59.8 ± 9.6%) throughout all months (Table 2). In January, the lowest relative humidity was recognized at the aboveground point, and the monthly differences in relative humidity between above and undergrounds were highest (Table 2). Namely, it was revealed that the relative humidities of the underground points were stably kept near 100% or over 100% throughout all seasons, which is contrary to the variable relative humidities aboveground (Tabs. 1, 2, Fig. 2).

The differences during a day between the daily maximum and minimum temperatures ranged from 4.7 ± 1.1°C (July) to 10.9 ± 1.6°C (January) in the aboveground and 0.6 ± 0.4°C (July and August at #A) to 3.3 ± 2.1°C (December at #C) underground (Table 1). In addition, the differences between the daily maximum and minimum relative humidities ranged from 17.1 ± 4.7% (July) to 41.4 ± 11.6% (February) in the aboveground and 0.6 ± 0.4% (July at #C) to 3.6 ± 5.0% (May at #C) underground (Table 1). The differences during a day of both temperature and relative humidity at the undergrounds were significantly differed from those of the aboveground ($p < 0.01$) throughout all

Table 1. Mean ± SD in temperature and relative humidity in each month at the aboveground (air) and the underground burrow points (#A–#D).

		2016			2017								
		19th–26th	19th–26th	19th–26th	19th–26th	19th–26th	19th–26th	19th–26th	19th–26th	20th–27th	21st–28th	19th–26th	20th–27th
		Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Temperature (°C)													
DR*	Air	18.1 ± 3.3	10.0 ± 4.9	11.1 ± 4.4	4.6 ± 3.4	8.9 ± 3.8	9.4 ± 3.0	14.9 ± 2.4	21.1 ± 2.1	23.0 ± 1.6	27.1 ± 1.6	**27.8 ± 2.5**	22.6 ± 2.4
	#A	18.1 ± 1.4	11.3 ± 2.6	10.6 ± 2.1	5.6 ± 0.8	8.4 ± 1.1	8.7 ± 1.0	13.5 ± 0.6	18.5 ± 0.6	21.3 ± 0.4	25.1 ± 0.4	25.6 ± 0.7	21.8 ± 0.6
	#B	18.6 ± 1.3	12.6 ± 2.0	11.4 ± 1.5	6.7 ± 0.6	9.1 ± 0.7	9.4 ± 0.5	13.9 ± 0.5	18.5 ± 0.6	21.2 ± 0.4	25.1 ± 0.6	**26.1 ± 1.2**	*nd*
	#C	18.5 ± 1.6	12.1 ± 2.0	10.8 ± 2.4	5.2 ± 0.9	8.4 ± 1.0	9.6 ± 0.9	14.8 ± 0.7	19.1 ± 0.6	21.4 ± 0.5	25.1 ± 0.5	24.8 ± 0.9	22.2 ± 0.6
	#D	16.5 ± 1.9	10.2 ± 3.1	10.4 ± 1.7	4.7 ± 0.8	7.3 ± 1.7	8.1 ± 1.1	*nd*	18.0 ± 0.8	20.3 ± 0.4	*nd*	*nd*	*nd*
max DR*	Air	23.4 ± 3.0	16.7 ± 4.3	17.3 ± 2.6	11.6 ± 2.1	15.5 ± 3.0	14.5 ± 1.9	19.0 ± 2.5	25.1 ± 0.7	26.4 ± 0.7	30.4 ± 1.2	**32.1 ± 2.1**	27.1 ± 1.9
	#A	18.7 ± 1.5	12.4 ± 2.6	12.7 ± 2.9	6.2 ± 0.6	9.6 ± 1.0	9.4 ± 0.9	14.3 ± 1.0	18.9 ± 0.2	21.7 ± 0.5	25.5 ± 0.3	26.0 ± 0.7	22.1 ± 0.4
	#B	19.1 ± 1.4	13.2 ± 2.1	12.7 ± 1.9	7.1 ± 0.4	9.6 ± 0.6	9.8 ± 0.6	14.3 ± 1.0	19.0 ± 0.3	21.6 ± 0.3	25.8 ± 0.5	**28.0 ± 0.9**	*nd*
	#C	19.7 ± 1.7	12.9 ± 2.1	12.5 ± 3.0	6.1 ± 0.8	9.5 ± 0.8	10.9 ± 0.4	15.7 ± 0.9	19.9 ± 0.2	22.1 ± 0.4	25.5 ± 0.6	25.6 ± 0.5	22.6 ± 0.9
	#D	18.1 ± 2.0	11.6 ± 2.9	11.9 ± 2.1	5.5 ± 0.8	9.3 ± 1.5	9.4 ± 0.69	*nd*	19.3 ± 0.9	20.7 ± 0.6	*nd*	*nd*	*nd*
min DR*	Air	15.1 ± 2.4	7.3 ± 4.9	7.6 ± 4.2	0.7 ± 1.8	4.9 ± 2.1	6.1 ± 1.6	12.4 ± 1.9	18.5 ± 1.2	20.9 ± 0.9	**25.6 ± 0.9**	25.4 ± 1.6	19.8 ± 1.1
	#A	17.4 ± 1.4	10.1 ± 3.1	9.6 ± 1.4	4.9 ± 0.6	7.4 ± 0.7	8.0 ± 0.9	13.0 ± 0.6	18.1 ± 0.7	20.9 ± 0.6	24.9 ± 0.5	**25.4 ± 0.9**	21.4 ± 0.5
	#B	18.0 ± 1.4	11.9 ± 2.1	10.6 ± 1.0	6.2 ± 0.7	8.5 ± 0.6	9.0 ± 0.4	13.6 ± 0.4	18.1 ± 0.7	20.9 ± 0.6	24.8 ± 0.6	**25.4 ± 0.9**	*nd*
	#C	17.5 ± 1.2	11.4 ± 2.2	9.2 ± 1.1	4.4 ± 0.8	7.3 ± 0.8	8.6 ± 0.7	14.1 ± 0.4	18.6 ± 0.6	21.0 ± 0.5	24.8 ± 0.6	24.4 ± 1.1	21.8 ± 0.3
	#D	15.3 ± 1.8	8.7 ± 3.7	9.5 ± 1.2	3.9 ± 0.8	5.8 ± 1.2	6.9 ± 0.8	*nd*	17.3 ± 0.6	20.0 ± 0.5	*nd*	*nd*	*nd*
DD*	Air	8.4 ± 1.6	9.4 ± 1.2	9.6 ± 3.6	**10.9 ± 1.6**	10.6 ± 2.5	8.4 ± 0.8	6.6 ± 3.6	6.6 ± 1.5	5.5 ± 1.2	4.7 ± 1.1	6.7 ± 1.4	7.4 ± 1.1
	#A	1.4 ± 0.6	2.2 ± 1.9	3.1 ± 2.3	1.3 ± 0.3	2.2 ± 0.6	1.4 ± 0.4	1.3 ± 1.1	0.8 ± 0.6	0.9 ± 0.6	0.6 ± 0.4	0.6 ± 0.4	0.7 ± 0.4
	#B	1.1 ± 0.4	1.3 ± 1.4	2.1 ± 1.4	0.9 ± 0.4	1.1 ± 0.4	0.8 ± 0.3	0.7 ± 0.9	0.9 ± 0.8	0.7 ± 0.4	1.0 ± 0.4	2.6 ± 0.7	*nd*
	#C	2.2 ± 0.9	1.6 ± 0.9	**3.3 ± 2.1**	1.6 ± 0.5	2.2 ± 0.4	2.4 ± 0.6	1.6 ± 0.9	1.3 ± 0.6	1.1 ± 0.3	0.7 ± 0.5	1.3 ± 1.2	0.9 ± 0.6
	#D	2.8 ± 1.3	2.9 ± 1.9	2.4 ± 1.5	1.5 ± 0.4	3.5 ± 0.6	2.4 ± 0.7	*nd*	2.0 ± 1.7	0.8 ± 0.3	*nd*	*nd*	*nd*

Table 1 (*ended*).

		Relative humidity (%)											
DR*	Air	67.9 ± 11.6	81.2 ± 11.2	63.6 ± 11.7	42.8 ± 11.7	52.4 ± 15.8	55.2 ± 19.4	66.1 ± 13.4	77.2 ± 8.7	**84.2 ± 9.0**	82.1 ± 5.3	82.9 ± 8.3	19.0 ± 8.6
	#A	102.2 ± 2.0	100.5 ± 2.9	100.5 ± 1.9	102.5 ± 2.0	103.2 ± 1.4	102.3 ± 3.0	101.1 ± 1.3	105.2 ± 1.3	105.2 ± 1.3	104.2 ± 1.6	106.6 ± 2.2	102.2 ± 1.3
	#B	101.1 ± 2.9	101.3 ± 1.7	100.5 ± 2.8	100.4 ± 2.4	101.6 ± 1.2	99.6 ± 3.1	101.7 ± 1.0	100.9 ± 1.0	102.1 ± 0.4	103.0 ± 0.4	103.1 ± 0.4	*nd*
	#C	100.6 ± 2.2	101.3 ± 1.8	101.3 ± 2.8	102.1 ± 2.7	106.2 ± 1.5	103.1 ± 3.8	105.6 ± 1.1	105.7 ± 1.2	106.6 ± 0.5	107.0 ± 0.3	**107.2 ± 0.4**	105.8 ± 1.6
	#D	102.3 ± 2.4	101.3 ± 1.7	101.6 ± 2.7	100.4 ± 2.4	102.1 ± 2.1	101.4 ± 3.5	*nd*	105.3 ± 1.4	106.0 ± 0.3	*nd*	*nd*	*nd*
max DR*	Air	78.2 ± 8.7	91.5 ± 4.3	74.6 ± 11.8	54.4 ± 11.0	73.4 ± 13.8	71.7 ± 19.0	77.9 ± 11.5	87.4 ± 5.6	94.4 ± 3.9	88.6 ± 2.1	**91.0 ± 1.0**	87.3 ± 5.7
	#A	102.9 ± 1.6	101.9 ± 2.8	101.7 ± 1.6	103.6 ± 1.4	104.4 ± 0.4	103.2 ± 2.0	102.2 ± 1.7	106.2 ± 0.4	106.4 ± 0.8	104.9 ± 2.0	**108.1 ± 0.8**	102.7 ± 0.9
	#B	102.1 ± 2.7	101.9 ± 1.6	101.4 ± 2.2	101.2 ± 2.0	102.3 ± 1.0	100.6 ± 2.3	101.9 ± 0.6	101.4 ± 0.4	102.4 ± 0.2	103.1 ± 0.2	103.5 ± 0.0	*nd*
	#C	101.6 ± 1.9	102.2 ± 1.6	102.6 ± 2.3	103.4 ± 2.1	107.2 ± 1.1	104.8 ± 2.4	106.4 ± 0.2	106.6 ± 0.5	107.0 ± 0.0	107.2 ± 0.3	107.4 ± 0.4	106.4 ± 2.0
	#D	103.0 ± 1.9	103.0 ± 2.1	102.5 ± 2.1	103.0 ± 2.1	103.1 ± 1.0	102.6 ± 2.5	*nd*	105.8 ± 0.3	106.0 ± 0.0	*nd*	*nd*	*nd*
min DR*	Air	50.1 ± 6.6	63.6 ± 8.5	45.4 ± 5.0	25.7 ± 5.8	31.9 ± 12.2	31.4 ± 4.5	47.9 ± 11.9	62.0 ± 2.0	67.0 ± 6.6	**71.6 ± 4.6**	68.1 ± 8.6	64.8 ± 8.1
	#A	100.7 ± 3.0	98.9 ± 2.9	98.9 ± 2.6	100.8 ± 3.1	101.7 ± 1.6	99.6 ± 6.7	99.8 ± 1.1	102.6 ± 3.5	103.6 ± 0.9	103.1 ± 0.9	105.2 ± 2.3	101.6 ± 1.9
	#B	99.5 ± 3.4	100.4 ± 2.4	98.9 ± 4.5	99.4 ± 3.4	100.9 ± 1.5	97.5 ± 6.5	100.2 ± 3.9	98.9 ± 4.8	101.7 ± 0.5	102.4 ± 0.5	102.3 ± 0.6	*nd*
	#C	98.4 ± 3.3	99.8 ± 2.3	99.1 ± 4.2	100.1 ± 3.8	104.6 ± 1.8	98.6 ± 9.6	103.2 ± 3.6	103.0 ± 5.1	105.9 ± 0.5	106.6 ± 0.3	**106.7 ± 0.4**	104.1 ± 1.0
	#D	100.9 ± 3.7	101.6 ± 3.0	99.6 ± 3.9	100.5 ± 4.1	100.1 ± 2.5	97.9 ± 7.6	*nd*	98.8 ± 10.7	105.5 ± 0.0	*nd*	*nd*	*nd*
DD*	Air	28.1 ± 4.5	27.9 ± 9.7	29.4 ± 11.2	28.6 ± 10.2	**41.4 ± 11.6**	40.3 ± 17.5	30.1 ± 9.1	25.4 ± 7.1	27.4 ± 4.4	17.1 ± 4.7	22.9 ± 7.1	22.5 ± 2.8
	#A	2.2 ± 1.6	3.0 ± 1.3	2.8 ± 2.0	2.8 ± 2.2	2.6 ± 1.4	3.6 ± 4.9	2.4 ± 2.3	3.6 ± 3.2	2.9 ± 1.4	1.9 ± 1.4	2.9 ± 2.0	1.1 ± 1.3
	#B	2.6 ± 2.1	1.5 ± 1.0	2.6 ± 2.6	1.9 ± 1.6	1.4 ± 0.5	3.1 ± 4.4	1.7 ± 3.4	2.5 ± 4.6	0.7 ± 0.5	0.8 ± 0.3	1.2 ± 0.6	*nd*
	#C	3.1 ± 2.4	2.4 ± 1.2	3.4 ± 2.3	3.3 ± 1.9	2.6 ± 0.9	6.2 ± 7.6	3.1 ± 3.5	**3.6 ± 5.0**	1.1 ± 0.5	0.6 ± 0.4	0.7 ± 0.6	2.3 ± 1.2
	#D	2.1 ± 1.9	1.4 ± 0.9	2.9 ± 2.1	2.5 ± 2.2	3.1 ± 1.3	4.8 ± 5.4	*nd*	7.0 ± 10.4	0.5 ± 0.0	*nd*	*nd*	*nd*

nd, no data because of an electric failure of logger.
*DR, daily record; Max DR, maximum of daily records; Min DR, minimum of daily records; DD, difference during a day (max-min).
Bold and underlined values indicate the largest and the smallest absolute values.

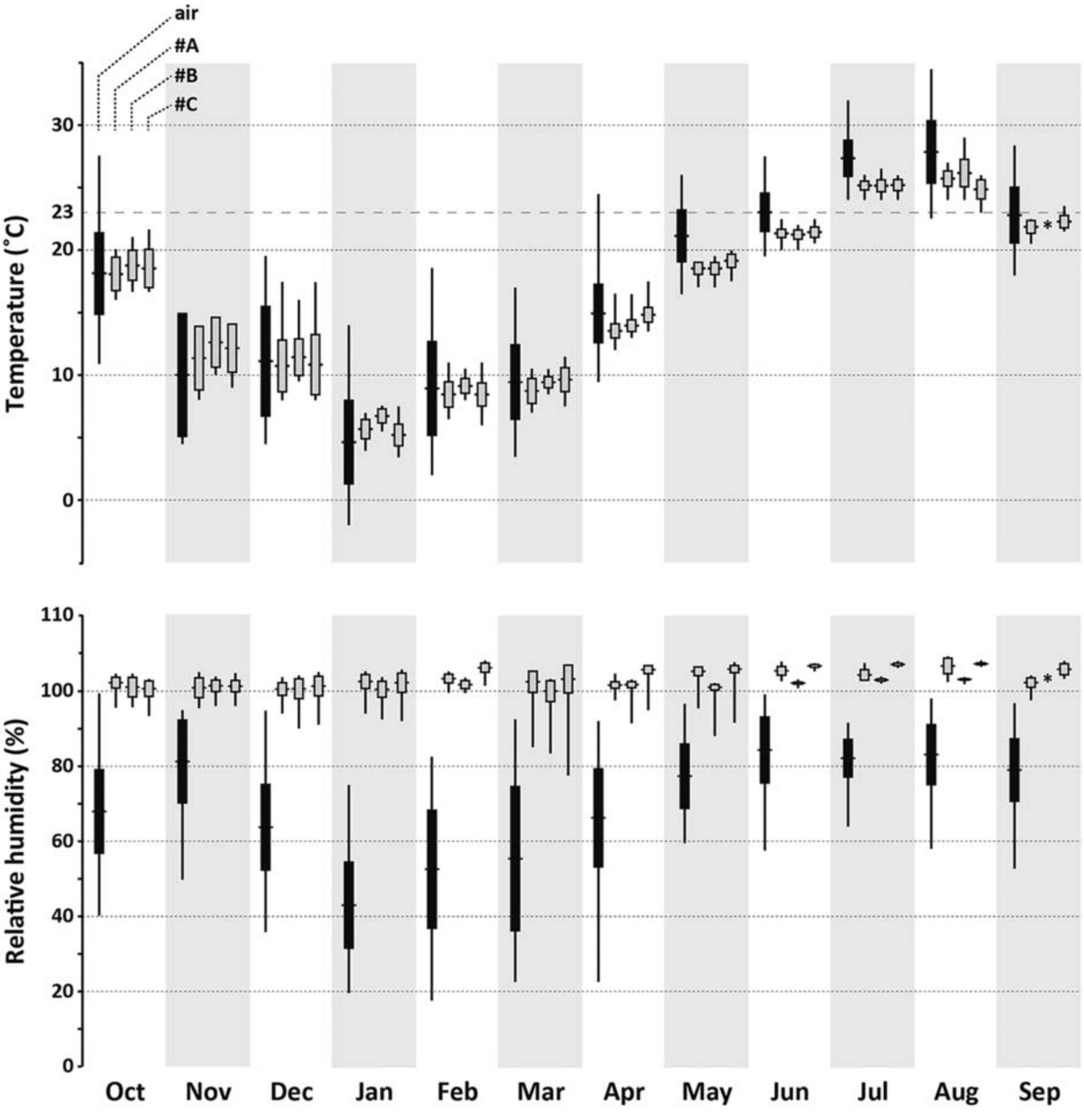

Fig. 2. Temperatures and relative humidity obtained from loggers set at an aboveground point (air) and underground points (#A–#C). Vertical bars, horizontal bars, and rectangles indicate ranges, means, and standard deviations, respectively. Asterisks indicate a lack of records due to an electrical failure of #B logger. The lower limit of the thermoneutral zone is 23°C (Kashimura *et al*., 2010).

months. These facts indicates that temperature and relative humidity seemed to be more stable at underground than at aboveground.

Discussion

The present results of the underground temperature are similar to those of the soil temperatures at a depth of 5 cm as reported by Kashimura *et al*. (2010), who investigated the spatial usage preferences in *M. imaizumii*. The temperatures of the underground points were slightly lower than the aboveground point from April to August (Tabs. 1, 2, Fig. 2). Particularly, the underground temperatures never reached 30°C in the summer irrespective of the fact that aboveground temperatures over 30°C were recorded in July and August (Fig. 2). Moreover, as found in burrows of mole rats, the temperatures of the underground points were apparently more stable throughout the day than the aboveground temperatures based on slight differences during a day (Bennett *et al*., 1988, 1994; Table 1, Fig. 2).

Table 2. Mean ± SD of monthly differences of temperature and relative humidity between aboveground and underground from following formula: each value of the aboveground point — each value of each underground point.

	Month	#A		#B		#C	
Temperature (°C)	Oct	0.0 ± 1.3	ns	–0.5 ± 1.4	**	-0.3 ± 1.4	**
	Nov	–1.2 ± 2.0	**	–2.6 ± 2.7	**	-2.1 ± 2.7	**
	Dec	0.5 ± 2.0	**	–0.3 ± 2.9	ns	0.3 ± 2.9	ns
	Jan	–1.0 ± 0.9	**	–2.1 ± 1.0	**	-0.6 ± 0.9	**
	Feb	0.5 ± 1.5	**	–0.2 ± 1.9	ns	0.5 ± 1.8	**
	Mar	0.7 ± 1.0	**	0.0 ± 1.4	ns	-0.2 ± 1.4	**
	Apr	1.4 ± 0.7	**	1.0 ± 0.8	**	0.1 ± 0.7	ns
	May	**2.7 ± 0.7**	**	**2.7 ± 0.7**	**	2.1 ± 0.6	**
	Jun	1.7 ± 0.4	**	1.8 ± 0.4	**	1.6 ± 0.4	**
	Jul	1.9 ± 0.8	**	1.9 ± 0.7	**	1.9 ± 0.8	**
	Aug	2.3 ± 1.0	**	1.7 ± 0.8	**	1.8 ± 0.7	**
	Sep	0.8 ± 1.0	**	*nd*		-0.3 ± 1.1	**
Relative humidity (%)	Oct	–34.2 ± 11.4	**	–33.1 ± 12.1	**	-32.6 ± 11.4	**
	Nov	–19.4 ± 7.4	**	–20.1 ± 7.8	**	-20.2 ± 7.7	**
	Dec	–37.0 ± 8.7	**	–37.0 ± 10.3	**	-37.7 ± 10.4	**
	Jan	**–59.8 ± 9.6**	**	–57.8 ± 10.2	**	-59.5 ± 10.3	**
	Feb	–50.8 ± 11.7	**	–49.2 ± 12.0	**	-23.8 ± 12.2	**
	Mar	–47.2 ± 13.2	**	–44.5 ± 13.2	**	-48.0 ± 13.4	**
	Apr	–35.2 ± 10.1	**	–35.7 ± 9.4	**	-39.6 ± 9.5	**
	May	–28.1 ± 3.9	**	–23.8 ± 4.1	**	-28.7 ± 3.7	**
	Jun	–21.1 ± 5.2	**	–18.0 ± 5.0	**	-22.5 ± 5.0	**
	Jul	–22.1 ± 1.8	**	–20.9 ± 3.0	**	-25.0 ± 2.9	**
	Aug	–23.8 ± 6.8	**	–20.3 ± 4.9	**	-20.6 ± 2.7	**
	Sep	–23.3 ± 6.8	**	*nd*		-27.0 ± 10.1	**

nd — no data because of an electric failure of logger. *t*-test ($\alpha = 0.01$) was done between the aboveground point and each underground point throughout each month (**, significant; ns, not significant). Bold and underlined values indicate the largest and the smallest absolute values.

In burrowing mammals, underground burrow temperatures above the upper limit or below the lower limit of thermoneutrality cause physiological stress (Vleck, 1979; Lovegrove & Knight-Eloff, 1988; Burda *et al.*, 2007). For example, in a mole-rat taxa preferring mesic environments, thermoneutral zones are considered to be 28.0 to 32.5°C in *Cryptomys* (Bennett *et al.*, 1994); in Talpidae of Eulipotyphla, thermoneutral zones are 24.5 to 33.0°C in the star-nosed mole, *Condylura cristata* (Campbell *et al.*, 1999), and 24.9 to 32.0°C in the American shrew-mole, *Neurotrichus gibbsii* (Campbell & Hochachka, 2000). Kashimura *et al.* (2010) mentioned that the lower limit of the thermoneutral zone of *M. imaizumii* is likely to be 23.0°C because *M. imaizumii* appears at shallow layer over 23.0°C soil temperature in summer. On the other hand, Frears (1993) analyzed the metabolic rate in the European mole, *Talpa europaea*, and the minimal metabolic rate was recorded at ambient temperatures 25–26°C, although the thermoneutral zone was not confirmed. In addition, moles actually died over 35°C and the lethal body temperature seems to be 36.8–37.5°C which is lower than other mammals. Furthermore, the mean resting metabolic rate decreases during increasing up to 30°C and it is suggested that over 30°C leads to a risk of overheating (Frears, 1993). Both *Talpa* and *Mogera* are closely related Palaearctic taxa (He *et al.*, 2017) and inhabit temperate regions in Europe and Japan, respectively (Loy & Corti, 1996; Ohdachi *et al.*, 2015). Therefore, it is estimated that the thermoneutral zone of *Mogera* likely ranges from 23°C to around 30°C (Frears, 1993; Kashimura *et al.*, 2010).

In hot condition above the upper critical temperature, rising body heat sometimes become a serious problem and dissipating heat by respiratory evaporation would be performed as a themoregulation method. However, the dissipating heat would be difficult under higher humidity condition and failure of dissipating heat leads death (Feldhamer *et al.*, 2020). In addition, higher humidity make a cooling system by respiratory evaporation minimum to save water in underground ecotope (Burda *et al.*, 2007). Therefore, it is expected that higher temperature and humidity condition can cause a serious damage for the mole. Considering the current higher humidity at the underground (Table 1, Fig. 2), meaning water-saturated condition, radiation of heat by evaporation seems to be restrained, particularly in hot summer. In such situation, lower temperature as possible above 23°C (Kahimura *et* *al.*, 2010) seems to be more appropriate environment for the mole. In July and August, the underground temperatures 25.1 ± 0.6–26.1 ± 1.2°C (Table 1), corresponding to the minimal metabolic rate in *T. europaea* (Frears, 1993), at the present depths were around 23°C which is considered to be the lower limit (Table 1, Fig. 2). Therefore, in hot summer, these burrow temperature conditions would be fit for the mole as a more appropriate environment mentioned above. On the other hand, in winter, the present underground temperatures reached < 10°C (Table 1, Fig. 2), as reported by Kashimura *et al.* (2010), and the current results expected that colder stresses would expose moles to the lower extreme of thermoneutrality. According to Kashimura *et al.* (2010), deeper soil tended to have a higher temperature in February, and moles frequently used deeper burrows. It is suggested that, in order to avoid such cold stress, moles would shift to utilizing spaces at warmer depths, and/or may change their metabolic rate as other mole species do (Campbell *et al.*, 1999). Therefore, temperature and humidity conditions at more deeper burrows should be researched in winter.

According to Kay & Whitford (1978) and Moore & Roper (2003), humidity is stable in underground burrows with higher levels irrespective of any conditions of the aboveground air. As in their findings, the current underground humidities showed obvious stabilities with over 100% and smaller differences during a day; those were apparently higher than the aboveground humidity (Tabs. 1, 2, Fig. 2). Such stability is also confirmed in a case in which the humidity of the burrows of the silvery mole rat *Heliophobius* does not differ between the beginning of the dry season following rains and the middle of the hot dry season (Šumbera *et al.*, 2004). In undergrounds, higher humidity is likely to be kept throughout a year irrespective of aboveground condition and such tendency means constantly restraint of radiation of body heat through evaporation. Therefore, the current results with higher humidity with lower temperature, around 23°C, inside the burrows would give a physiological advantage in summer, to save metabolic rates in the underground life of *M. imaizumii*.

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