

Dynamic changes in home-ranges of the subterranean rodent: a case study on *Myospalax baileyi*

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Research

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Abstract

Background

Subterranean rodents, as ecosystem engineers, excavate and inhabit burrow systems. Their underground space-use mobility is poorly recorded. There is conflicting evidence regarding that burrow system of subterranean rodents, once established, are relatively stable because of high-energy costs of digging. For monitoring data at different stages of a year's life cycle. We predict that mating and habitat characteristics might influence home-range size and locomotion.

Methods

The present study implemented successive radio-tracking in order to quantify the locomotion and overlap of the plateau zokor (*Myospalax baileyi*) home-range throughout the year. Home-ranges were calculated according to the 100% minimum convex polygon (MCP) methods. We also examined the relationships of home-range sizes with body mass, vegetation biomass, and soil compaction, respectively.

Results

We found that sizes of home-ranges varied monthly for both male and female, except for the long winter (from November to March of the following year) challenging to excavate with activity ranges of all individuals concentrated on their own nests. During the mating season, the average size of males' home-ranges is 3.4 times larger than females' home-ranges. Males likely expanded the burrows to overlap with multiple females and to enhance their chances of mating. However, there was no overlap between estrus females or males, perhaps by reducing encounters and unnecessary fights. Home-ranges between males and females showed similar in size after courtship ends one month, and interestingly, single zokor's home-range overlapped with the home-ranges of several neighbors. Most individuals remained territorial and excluded intraspecific from their home-ranges. Besides, the position of the females was stable throughout the year, while half of the males shifted nests and established completely new home-ranges in the non-breeding season, mainly in October.

Conclusions

We conclude that space use of *M. baileyi* is flexible in response to meet physical contact and food resource. Regarding locomotion of home-range, subterranean plateau zokors to affirm that their home-ranges are dynamics and males shift in space with one breeding cycle.

Background

Basic theoretical studies on the use of animal space are all based on the concept of home-range, which was initially defined as an area where animals to meet its daily needs [1]. But more recently, the home range has been defined as an area that an animal repeatedly traversed [2, 3]. Most resident mammals limit their movements into a fairly well-defined area, rather than just wandering randomly. The original range has been explored in a variety of ways, including empirical and theoretical. The fact is that the home-range of animals is dynamic in size and position in the spatiotemporal sequences has been overlooked in most studies [4]. Only in the last 20 years, researchers realized that the dynamics of home-range have essential effects on population dynamics and other aspects of animal ecology [5]. Moreover, studies of these home-range dynamics have been restricted to relatively few subterranean rodent groups [6]. Most studies have focused on factors that influence the size of the home-range at a given point in time.

Subterranean rodents are convergent ecological groups [7, 8]. Compared with ground-dwelling species, its scope of activity and dispersal are greatly restricted by the underground environment. Most of their activities take place in underground burrow systems that are occupied by solitary and society individuals. Subterranean rodents mainly rely on plants' underground storage organs for food. They must constantly extend burrow systems to ensure adequate food resources. Begall et al. proposed burrow systems of subterranean rodents must be continuously transformed by excavating new tunnels while part of the older tunnels will be abandoned [9]. In addition, some subterranean rodents maintain an optimal size of burrow systems through backfilled tunnels

with soil [6]. If the home-range size of animals is too large, it will disadvantage other competitors. But this can be even more detrimental to the domain's occupant because the cost of defending the territory increases dramatically as the home-range expands [10]. The food resource and soil characteristics can directly influence the home range sizes and burrow systems dynamic of subterranean rodents in different habitat types [11, 12]. Home range size is usually linked to the animal body size, where larger animals require larger areas to encounter potential mates or recruiting. Cutrera et al. observed the intraspecific variation of home-range size between two different sites in the South American Talas tuco-tuco (*Ctenomys talarum*) [13]. Home range size influenced by body size and soil characteristics (mainly soil hardness and soil humidity) between the study sites [14]. For those small mammals inhabiting the underground environment, live trapping and radio-tracking become a valid tool to collect data systematically on their characteristics of movement and space use. At present, a few species of *Bathyergus* and *Ctenomys*, and *Spalax* studies on home range size have been carried out by radio-tracking [15–19]. Surprisingly, there are few studies on the long-term space utilization of subterranean rodents. Although there have been studies of seasonal changes in home-range dynamics [20, 21], these studies were conducted in different populations of the same species at different seasons. Nevo indicated that all underground mammals' home-ranges [22], once established and use for one breeding season, which is essentially permanent for life. However, in solitary subterranean rodents, blind mole rat (*Spalax ehrenbergi*) constantly shifting home ranges were described (but not quantified) [23]. Šklíba et al. kept tracking silvery mole-rat (*Heliophobius argenteocinereus*) for three months in non-breeding season and found their home ranges were dynamic and continuous change in space [6]. Based on all the facts as mentioned above, we assume the home range is dynamic, patterns of animal space use, resulting from life-history strategies or interactions between individuals and the external environment.

In this study, we analyzed the use of space and stability of home range in the plateau zokor *Myospalax baileyi* (Rodentia: Myospalacinae), a widely distributed solitary subterranean rodent from the Qinghai – Tibet Plateau [24]. Adult females of plateau zokors give birth once a year between April to July. The gestation period and lactation period last about 50 days, respectively [25]. *Myospalax baileyi* occurs various habitats with different food supply and soil properties in an environment with an alternate change of cold and warm season, and it exemplifies a successful adaptation to an extreme subterranean environment [8]. We investigated individual home-range using a radio-telemetry. We tracked *M. baileyi* from June 2016 to May 2017, because it contains different physiological changes of plateau zokor during the year, as well as changes in food supply and soil characteristics. Here, it occupies various habitats with varying characteristics of soil and food supply in a seasonal environment with regular inter-change of the dry and rainy season. The main objectives were: (i) to quantify home-range dynamics, overlap degree between individual home ranges, the quantity of new mounds bulldozing, movements of single individual home-range position, and changes of the nest; (ii) to assess how these animals explore the underground environment in a full year.

Material And Methods

The study was conducted in the eastern part of the Qinghai-Tibet Plateau in the Gansu province (Fig. 1), at the Tianzhu alpine grassland system station of Gansu agricultural university (37°18'34" N, 102°36'22" E, elevation 2892 m). The vegetation types in the study area are alpine meadows. The vegetation consists of a mosaic of grass (mainly *Elymus nutans*), sedge (mainly *Kobresia humilis*), and forbs. The climate in Tianzhu is characterized by a warm season (May.-Sep.), and a cold season (Oct.-Dec./Jan.- Apr.). Precipitation mainly concentrated in June to September of each year. The rainfall from June to September in 2016 was 372.2 mm, accounting for 73.4% of the total rainfall in a research year (Fig. 1). From November 2016 to March 2017, the average temperature and the soil temperature of 15 cm underground were both below zero degrees Celsius (Fig. 1). The meteorological data are from the China Meteorological Administration (Available at <http://www.cma.gov.cn/>).

Radio-tracking

Radio-tracking was carried out in June 2016 to May 2017. We captured 14 adults *M. baileyi* (7 females and 7 males) in 2016 and 12 (five females and seven males) adults in 2017, respectively (Table 1). In addition, we captured a sub-adult (ID: M981) in 2017, which was not included in the statistical analysis. Animals were captured using a living trap for subterranean rodents [26]. In order to ensure the integrity of the tunnel, we did not re-capture individuals, so we did not obtain weight data for other months of 2016. After capture animals were anesthetized (1% pentobarbital, 0.5 mg/100 g body mass), weighted, sex, fitted with a radio-collar (Ag 357, Biotrack Ltd., Wareham, Dorset, U.K. Battery life is about 9 months). The animals were released only when fully recovered

from the effects of the anesthetic and released at their respective trapping locations. We used radio collars that weighed 4.75 g (< 4% of the body weight of the smallest zokor used in this study) [27]. Experimental procedures involving capture, handling, and use of radio-collars in this study was approved by the Institutional Animal Care and Use Committee of the Grassland Science College of Gansu Agricultural University (GSC- IACUC-2018-0011). We used a Sika radio-tracking receiver (Biotrack Ltd., Wareham, Dorset, U.K.) and two-element Yagi antennas (Sirtrack Ltd., Havelock North, New Zealand) to locate zokors. In 2016, radio fixes were taken in 24-h sessions for 10 days each month (the 15th to 25th of each month). To ensure the independence of data collection, there was a 2-h time interval between fixes [19]. In 2017, radio-tracking began 36–48 h after animal release. All individuals continued to be tracked until May 25. Radio fixes were taken in 12-h sessions (8:00–20:00) and 2-h time interval between fixes. 13 zokors (7 females and 6males) from June to August and 11 zokors (5 females and 6 males) in September and October of 2016, and 12 (5 females and 7 males) in April and May of 2017 were successfully radio-tracked. The radio collars of two zokors (ID: F533, F663) fell off in September 2016, and we were not able to recapture them, so we did not obtain any more data after that. Another radio-collared male (ID: M425) was not radio-tracked, because it left its burrow system after two days of release and spreading out from aboveground to the outside of the study area and created new caves in June 2016. The data from individuals with missing or incomplete transmission were not used in analyses (see Supplementary Data1). In March 2017, the battery power of the radio-collars by most individuals was exhausted, so we re-captured the individuals wearing the collar and replaced them with a new one in April. Recapture zokors and recycle radio-collars for studies in other areas (or purposes of other studies).

Individual home-range size was calculated using 100% minimum convex polygon (MCP) methods. This method is commonly used to evaluate the home range size of subterranean rodents [3]. In order to accurately record the current position of zokors, we set up a geo-referenced grid (5 m × 5 m cell size) above all burrow systems before radio-tracking. By measuring the vertical distance between the fixes and the nearest tunnel, we estimated the accuracy of radio-tracking points at < 1 m. In the process of radio-tracking, we found that some individuals' home range did overlap. Therefore, the degree of the home range overlapped is calculated by dividing the area of one individual overlap with other intraspecific individuals by the total area of the zokor. We also calculated the MCP using all tracking points from each individual for purposes of comparison with other studies. MCP 100% and overlap calculations were performed using the Ranges 8 version 2.1.6 (Anatrack Ltd., Wareham, U.K.).

Environmental Factors Measurement

To evaluate the soil and vegetation characteristics, we considered every individual nest as a central point. At each of the central points, plant biomass and soil compaction were sampled in the three sampling units situated a distance of 3 meters in the three cardinal directions. To estimate plant biomass and soil hardness, we referred to the method of Galiano et al. [28]. In brief, the vegetation present in a 0.25 m² × 0.3 m sample was collected and separated in aboveground and subterranean portions, dried for 24 h at 80°C and weighted to the nearest 0.1 g. Soil samples were produced from near the capture points. Soil compaction measured 12.5 cm, 15 cm, and 17.5 cm (soil depth) use SC-900 Soil Compaction Meter (Spectrum, USA), we calculated the mean of three depths as the compaction (unit: kg·cm⁻²) of one sampling point, because the tunnel depth at the capture points of the zokor is between 10–20 cm [29]. For analysis of soil compaction and vegetation variables, we computed the mean of the three sampling units and then the mean in the analysis.

Statistical analysis

We applied Student's t-tests or Mann-Whitney U tests (in the case where the assumptions of the t-test were not fulfilled) to compare the differences in home-range size and overlap between sex in same months. We also used the same analysis methods to compare the differences between male and female body mass in two years. The comparisons of overlap area of the same individual's home-range between June and October, and the percentage of the overlap ratio in two months were examined using a Student's t-test or a Mann–Whitney U test. A comparison of all variables was implemented in GraphPad Prism version 8.0.1 (GraphPad Software, San Diego, CA).

For multiple comparative analyses, we used one-way analysis of variance (ANOVA) to deal with the repeated measured data (home-range sizes, number of new mounds, soil compaction, and plant biomass) of different months. The ANOVA analyses were performed with STATISTICA StatSoft Inc. (version 17.0) for Windows. The influences of each row represent matched data (soil compaction and biomass of aboveground or underground) on the mean home-range of females, males and individuals were test

using a linear aggressive analysis, as implemented in GraphPad Prism. In all cases, the critical significance level was set at $P < 0.05$. Results are shown as mean \pm SEM.

Results

Space use in the breeding season.— The sizes of home-ranges of females and males changed dynamically throughout the breeding season. Based on 100% MCP methods, home-range sizes of males ($n = 7$, average $289.90 \pm 73.76 \text{ m}^2$) were significantly larger than home-ranges of females ($n = 5$, average $66.93 \pm 12.70 \text{ m}^2$) in courtship and mating stages (April–May, 2017), (Mann-Whitney $U = 0$, $P = 0.0025$; Fig. 2). During pregnancy and lactation period (June–July, 2016), home ranges of males ($n = 7$) averaged $280.30 \pm 40.92 \text{ m}^2$ versus $184.10 \pm 42.69 \text{ m}^2$ for home ranges of females ($n = 6$) in June and $77.42 \pm 22.14 \text{ m}^2$ versus $93.25 \pm 33.92 \text{ m}^2$ in July; these difference in size was not significant (Student's t -test: June, $t = 1.609$, d.f. = 11, $P = 0.136$; July, $t = 0.344$, d.f. = 11, $P = 0.744$; Fig. 2). During the mating period, females' home-ranges overlapped those of males by $3.52 \pm 1.08\%$ ($n = 5$, female-male pairs), whereas home-ranges of male overlapped females' home-ranges by $23.52 \pm 11.02\%$ ($n = 8$, male-female pairs; Fig. 3F). No overlapping was found between the home-ranges of females. We observed M697 spread over the aboveground from captured area a to area b (after 72 hours of radio-tracking), and after staying at point b for two days, it spread over the aboveground to area c and built a new home-range. There was no overlap between home-ranges of other adult males. Only one sub-adult had a small overlap with M198 (Fig. 3F). In addition, we found that the female's nest was within the overlap of the male's and female's home-ranges, and we detected the radio-collars signals of the males that overlapped with the female's nest at the same time.

In June, home-ranges of female overlapped those of males by $11.14 \pm 3.82\%$ ($n = 7$, female-male pairs), and home-ranges of male overlapped females' home-ranges by $9.85 \pm 3.79\%$ ($n = 6$, male-female pairs; Fig. 3F). Home ranges of 5 of the 7 females radio-tracked overlapped by a mean of $17.83 \pm 0.29\%$ (Fig. 3A), whereas home ranges of 4 of the 6 males radio-tracked overlapped by a mean of $4.49 \pm 1.02\%$. In July, there were no overlap between home-ranges of males or females. Only two pairs (M442 – F533 and M357 - F663) of all individuals had small overlaps. The mean percentage of overlap of a single zokor home-range with other individuals was $23.6 \pm 8.6\%$ in April–May and $28.3 \pm 8.3\%$ in June, respectively (Table 1); this difference in the proportion of overlapped was not significant (Mann-Whitney $U = 77$, $P = 0.978$). Although the average overlapped areas of single individual home-range ($72.0 \pm 20.8 \text{ m}^2$) in June were larger than in April–May ($9.85 \pm 3.79 \text{ m}^2$). No difference was found in two months (Mann-Whitney $U = 55$, $n = 12$, exact $P = 0.225$). In July, it was only $2.7 \pm 1.5\%$ (mean overlapped area $2.3 \pm 1.0 \text{ m}^2$, Fig. 3B and Table 1). At this stage, no individual nests were found to be occupied by other individuals, and no two individuals were wirelessly traced to the same coordinate point at the same time in the overlap region.

Space use in the non-breeding season.—The average sizes of home-ranges of males and females were small during the non-breeding season (Student's t -test: Aug., $t_{11} = 0.641$, $P = 0.535$; Sep., $t_9 = 0.069$, $P = 0.946$; Oct., $t_9 = 0.816$, $P = 0.436$; Fig. 2). No overlap was found between the home-ranges of males and females in August or September (Fig. 3C/D). In October, only two pairs (M104 – F521 and M442 – F304) of 11 individuals had overlaps (Fig. 3E). The overlap area of home-ranges between M104 and F521 was only 0.7 m^2 , accounting for 1.3% and 0.8% of their respective home-range (Table 1). However, the overlap area of home-ranges between M442 and F304 reached 14.2 m^2 , accounting for 8% and 31.2% of their home-ranges, respectively (Table 1). From November 2016 to March 2017, all individuals radio-tracked stayed in their own nests, and the home-range sizes of all individuals were less than 1 m^2 .

Table 1

The overlap area (OA) of a single individual's home-range with other individuals and the percentage of overlap (OP) in its home-range in different month.

2016											2017		
ID	June		July		August		September		October		ID	April + May	
	OA ^a	OP	OA	OP	OA	OP	OA	OP	OA	OP		OA	OP
F304	93.7	35.9	0	0	0	0	0	0	14.2	31.2	F147	11.9	11.1
F233	169.9	47.9	0	0	0	0	0	0	0	0	F533	38.4	68.0
F663	219.0	94.2	7.9	2.5	0	0	-	-	-	-	F638	30.5	100.0
F638	25.2	12.5	0	0	0	0	0	0	0	0	F521	6.7	10.9
F533	58.6	44.6	7.3	6.1	0	0	-	-	-	-	F616	17.1	21.8
F169	0	0	0	0	0	0	0	0	0	0	M370	15.4	10.4
F521	3.2	3.8	0	0	0	0	0	0	0.7	0.8	M266	31.9	16.8
M039	38.8	9.4	0	0	0	0	0	0	0	0	M697	34.1	22.0
M288	166.4	72.0	0	0	0	0	0	0	0	0	M198	36.3	5.4
M008	8.8	3.7	0	0	0	0	0	0	0	0	M455	29.7	9.7
M104	0	0	0	0	0	0	0	0	0.7	1.3	M856	0	0.0
M442	31.5	12.1	7.3	8.7	0	0	0	0	14.2	8.8	M929	29.0	7.0
M357	121.2	31.2	7.9	17.6	0	0	0	0	0	0			
Mean	72.0	28.3	2.3	2.7	0.0	0.0	0.0	0.0	2.7	3.8	Mean	23.4	23.6
SEM	20.8	8.3	1.0	1.5	0.0	0.0	0.0	0.0	1.7	2.8	SEM	3.7	8.6

^a Unit of overlap area is square meter.

Surface new mounds in different months.—The building of new mounds means that the plateau zokors are expanding the existing tunnels or establishing a new tunnel system. The production of new mounds in the plateau zokors was mainly in the breeding season, and in October of the non-breeding season (Table 2). At courtship and mating stages (2017), surface new mounds of males (average 10.1 ± 1.2) were significantly more than new mounds of females (average 4.0 ± 0.8 ; $t = 3.736$, d.f. = 10, $P = 0.004$). However, during pregnancy and lactation period, we found no significant difference between the quantities of new mounds of males (9.5 ± 1.4) and females (8.6 ± 6.1) at June ($t = 0.328$, d.f. = 11, $P = 0.749$), and new mounds of females (average 9.0 ± 1.5) were significantly more than new mounds of males at July (average 3.0 ± 0.4 ; $t = 2.385$, d.f. = 11, $P = 0.036$). During the non-breeding season, there were no new mounds in aboveground of all individuals at August, and only few new mounds at September (average: Females ($n = 5$) 2.6 ± 0.7 , males ($n = 6$) 2.5 ± 1.0 ; $t = 0.075$, d.f. = 9, $P = 0.941$). Some individuals did not even leave their own nests in August and September (Fig. 3C/D). Surface new mounds of males averaged 9.3 ± 1.2 versus females 5.0 ± 0.5 for new mounds of females at October; this differences in quantity was significant ($t = 2.996$, d.f. = 9, $P = 0.015$). From November 2016 to March 2017, there were no surface new mounds of all individuals, because the ground (15 cm away from surface) was frozen (Fig. 1). In addition, females captured in our study were less than females in body mass in 2017 (average: Females 146.6 ± 9.3 , males 257.7 ± 14.4 ; $t = 6.831$, d.f. = 10, $P < 0.0001$), and no significant difference (average: Females 179.0 ± 16.4 , males 225.8 ± 18.7 ; $t = 1.892$, d.f. = 11, $P = 0.085$) was observed for 2017 (Table 1).

Table 2

Individual ID (sex \times transmitter), capture time (CT), body mass (BM), and number of new mounds (NNM) in different months.

2016								2017			
ID	CT	BM (g)	NNM					ID	CT	BM (g)	NNM
			Jun.	Jul.	Aug.	Sep.	Oct.				
F304	May. 31	245	4	14	0	3	5	F147	Apr. 6	128	7
F233	May. 31	116	22	9	0	4	6	F533	Apr. 17	140	4
F663	Jun. 2	182	8	9	0	-	-	F638	Apr. 17	182	3
F638	Jun. 2	193	7	6	0	4	5	F521	Apr. 18	138	2
F533	Jun. 2	189	8	5	0	-	-	F616	Apr. 21	145	4
F169	Jun. 6	130	5	3	0	2	3	M370	Apr. 6	208	13
F521	Jun. 12	198	6	3	0	0	6	M266	Apr. 6	320	12
M039	May. 30	248	7	2	0	0	9	M697	Apr. 17	319	11
M288	May. 31	175	8	2	0	2	13	M198	Apr. 18	270	9
M008	Jun. 2	179	11	5	0	5	10	M455	Apr. 18	261	7
M104	Jun. 7	205	16	3	0	0	12	M929	Apr. 25	272	14
M442	Jun. 7	265	8	3	0	6	7	M856	Apr. 27	280	5
M357	Jun. 11	283	7	3	0	2	5				
Mean		200.6	9.0	5.2	0.0	2.5	7.4	Mean		221.9	7.6
SEM		13.6	1.4	3.6	0.0	0.6	1.0	SEM		21.2	1.2
M425 ^a	Jun. 11	170						M981 ^b	Apr. 6	150	2
^a Male's radio-collar fell off after released 2 days.											
^b M981 is a sub-adult.											

Home-range movements.—All individuals' home-ranges of June had overlapped with their own home-ranges in July. Average overlaps accounted for $37.4 \pm 8.5\%$ (females $46.3 \pm 13.0\%$ and males $26.9 \pm 9.8\%$, respectively) of the home-ranges in June, whereas average overlaps accounted for $84.7 \pm 4.4\%$ (females $82.4 \pm 5.6\%$ and males $87.4 \pm 7.3\%$, respectively) of the home-ranges in July (Fig. 4). The home-ranges of 3 males (M357, M288, and M039) in July were completely contained within their own home-ranges of June (Fig. 4). No shifting of the position of home-range of all individuals at this stage.

Table 3

The overlap area of the same individual's home-range between June and October, and the percentage of the overlap ratio in each month of 2016.

ID	Overlap area (m ²)	The proportion of overlap area to the home-range size in June (%)	The proportion of overlap area to the home-range size in October (%)
F304	4.4	1.7	9.8
F233	17.1	4.8	14.5
F638	104.6	51.8	84.0
F169	13.2	57.3	41.5
F521	54.0	64.5	56.1
F663 ^a	-	-	-
F533 ^a	-	-	-
M008	87.5	36.7	100
M039	61.7	15.0	76.1
M357	119.6	30.8	95.6
M104 ^b	0	0	0
M442 ^b	0	0	0
M288 ^b	0	0	0
^a Individual's radio-collar fell off in September, and no radio-tracking data were obtained in October.			
^b Individuals abandon their original home ranges and establish new ones in October.			

Five out of the seven females, except for the two individuals (F533 and F663) of radio-collar shedding, had overlapping in June and October (Fig. 4). The average overlap area of the home-range was $38.7 \pm 18.5 \text{ m}^2$ (range 4.4-104.6 m²). The proportion of overlap area in the home-range size to June was $36.0 \pm 3.5\%$ and $41.2 \pm 13.7\%$ to October (Table 3). From June to October, the home range movements of four females (F233, F638, F521, and F169) around the respective nest. F304 appears to have been building new nest since July and almost give up its home-range of June after October. In October, the home-ranges of only three male individuals (M008) overlapped with those of June, and the position of the respective nest did not move (Fig. 4). The average overlap area was $89.6 \pm 6.8 \text{ m}^2$. The average proportion of overlap areas in a home-range was $27.5 \pm 6.5\%$ and $90.6 \pm 7.3\%$ in June and October, respectively (Table 3). Three male zokors (M104, M442, and M288) opened up new home-range and established new nests in October and the closest distance from the boundaries of the three zokor's home-range of October to June were 24.4 m, 30.0 m, and 35.6 m, respectively.

Relationships of home-range dynamics with plant biomass and soil compaction. — There was a significant effect of month on mean soil compaction (one-way ANOVA, $F_{6,98} = 4.344$, d.f. = 6, $P = 0.0006$; Fig. 5B), and there were statistically significant effect of plant biomass of aboveground and underground (one-way ANOVA: aboveground, $F_{5,81} = 24.18$, d.f. = 5, $P < 0.0001$; underground, $F_{5,81} = 24.13$, d.f. = 5, $P < 0.0001$, respectively; Fig. 5A). Home-range sizes of different months of females, males and all individuals did not exhibit significant correlations with aboveground biomass ($R^2 = 0.006-0.440$, $P = 0.151-0.885$) and underground biomass ($R^2 = 0.004-0.575$, $P = 0.081-0.901$), respectively. There was also no significant relationship between the size of the serial home-ranges with soil compaction ($R^2 = 0.085-0.180$, $P = 0.402-0.575$). Whereas, regardless of mating period, Home-range sizes of females, males and all individuals did present significant correlations with plant underground biomass ($R^2 =$

0.807–0.944, $P = 0.006–0.038$; Fig. 5C/D/E), and no significant relationships between the size of the serial home-ranges with aboveground biomass ($R^2 = 0.382–0.519$, $P = 0.170–0.267$) or soil compaction ($R^2 = 0.004–0.044$, $P = 0.852–0.924$).

Discussion

Our analysis of throughout the year variation in home range size and overlapping suggests that physical contact and environmental characteristics influence the space utilization of *M. baileyi*. Their home-range were monthly dynamic changes and constantly shifted in space. During the mating period, males occupied 3.4 times as many sizes of home-range as females in size. Both females and males occupied home-ranges of similar sizes at other stages. However, home-ranges of females increased significantly in size in June after mating, as female extend their ranges (2.6 times larger than the mating period) to overlap the home-ranges with neighboring individuals. During the non-breeding season, the most zokors' home-ranges remained within an optional size, and there were little overlaps between individuals.

In our study, exceeding 10 zokors were continuously radio-tracked for more than 10 months for the 1st time without breaking their burrow systems. The radio-collars did not appear to influence the zokors' normal activities, including mating, excavating, and building new surface mounds. The radio-collars could be precisely located the locomotor position of plateau zokor by Yagi receiver, because we used the receiver to accurately find two radio-collars that the zokors (F521 and F663) had dropped off. Although we did not dissect burrow systems of radio-tracked zokors, their home-range size in the breeding season was $123.0 \pm 50.92 \text{ m}^2$, not significantly different from the average home-range size ($122.7 \pm 53.75 \text{ m}^2$, mean \pm SEM) found by Zhou and Dou [20] radio-tracked in the same reason. Studying the secretive habits of subterranean rodents in their natural state is often challenging. Originally by dissecting the entire burrow systems for studying their home-ranges [30, 31]. This method only provides "snapshots" of the respective individuals or colonies tunnel system geometries used to estimate the size of home-range [14]. Longer period space utilization of subterranean rodents relies on registering of new surface mounds and animals' capture sites, but this method may be not appropriate for *M. baileyi*, because three females (F233, F663, and F169) of expended their home-range in August (Fig. 3C), but none of the individuals produced new mounds in this month. Although an anatomically complete tunnel can provide detailed information about the size and structure of the animal's actual tunnel system. The most effective method for long-term monitoring of home range dynamics seems to be radio telemetry for subterranean rodents in their histories [6].

Plateau zokors show dynamic changes in sizes and overlaps of home-ranges between intraspecific individuals in their natural habitat. A number of factors may explain the larger home-ranges of male *M. baileyi* during the mating period. Many solitary subterranean rodents have a polygynous mating system [32]. Males try to gain access to multiple potential estrus females by expanding their burrow systems [5], suggesting that females are a finite resource that likely affects the males' home-ranges. Although the mating system of plateau zokor is still controversial [24], we found a male zokor (M929) entering the nest of two females (F147 and F616), respectively (Fig. 3F), suggesting that *M. baileyi* has a polygynous mating system. Intersexual differences in home-range sizes of *M. baileyi* during the mating season also have been reported by Zhang et al. [33]. Our findings suggest that home-ranges of males remain relatively independent, which also avoids competing with each other for mates in the mating period. Similar findings were described by Zhou and Dou [20]. Solitary subterranean males may search for a spouse across the aboveground except for expanding underground burrows. A study reported that long distance between the home-ranges of mating partners of silvery mole-rats was found to rule out an underground looking for mates [34], revealing that males probably seek estrus females surface. In the present study, a male (M697) transformed across the aboveground to two new locations and eventually established a new home range (the area reaches 110 m^2) within 32 days (Fig. 3F). Capture-mark-recapture rates of male plateau zokors recapture lower than males over three years during the mating seasons [33], and zokor's skulls were found in vomits of many raptors [35], shows that males may be spreading out from the ground in search of opposite sexes even though they will be at a high risk of predation. This may be another factor in the changes in their home-ranges.

In the present study, one month after the mating period, home-ranges of females frequently overlap multiple home-ranges of neighbors, which were rare among solitary and aggressive subterranean rodents [36]. *M. baileyi* seems to show great tolerance for the closed neighbors. At this stage, the average size of the female's home-range was 2.6 times larger than during mating, which may be related to the large food consumption during pregnancy and lactation; the size of the male's home-range did not

significantly change compared with the mating period. However, we estimated the core area of plateau zokor using 60% cores method by Cooper et al. [32], and found that most individuals had no overlap, with only F233 and F663 overlapping 7.6 m²; their core areas remained relatively independent and exclusive. Because the core areas are the location of cache and food storage [20, 24], the defense of the cache and food resource may be a major factor in the subterranean rodents preferring to solitude. Compared with the above two stages, the home-ranges of plateau zokor were significantly reduced at the end of reproduction and the non-breeding season, and there was no overlap between the home-ranges of most individuals. The home-range at this time can even be synonymized to the territory [22]. Because maintaining and defending a large territory could pay out huge costs (e.g., predation risk and energy expenditure). In addition, approximately half of the individuals did not extend new space in August and September of the non-breeding season, which activities were mainly concentrated on their own nests, similar to what was observed by Zhou and Dou [20]. Accordingly, the decreased activity intensity of plateau zokor during this period was also reported by Ji et al. [37]. Space utilization patterns of subterranean rodents may reflect an adaption of tunnel ambient temperature [8]. This kind of narrow range may be an adaption for the avoidance of overheating during the warm season [21].

Another evidence of the dynamic of home-ranges of the plateau zokor is a relatively low overlap between a single individual's successive home ranges within five months in 2016 (Fig. 4). Females usually had a fixed nest, with the expansion of new tunnels surrounding the nest. Besides child-rearing, the home-range changes may also reflect a foraging strategy against the costs of traveling [9]. As Bandoli [38], Zuri & Terkel [23] and Smallwood & Morrison [39] proposed, burrow systems of solitary subterranean rodents must be constantly shifted by extending a new tunnel while the older tunnels while be backfilled or abandoned. Refilling the tunnels and abandoning the older burrows have made significant contribution to the dynamics of home-range in subterranean rodents. For example, Thorne and Andersen tracked the development of a single burrow system of pocket gopher (*Geomys bursarius*) for five months [40]. The pocket gopher excavated at least more than 110 m of the tunnel on top of the initial burrow system during that time, and 77 m of burrow was backfilled and 32 m of air tunnel was abandoned in the process. Silvery mole-rat (*H. argenteocinereus*), a strictly solitary subterranean rodent from Eastern Africa, continuously rebuilt their burrow systems and backfilled older tunnels, on average 64% of all tunnels with an 80-days monitoring period [6]. *M. baileyi* refilled burrows with excavated soil, which has been described (but not quantified) by Zhou and Dou [20]. Based on radio-telemetry data and new surface mounds, we suppose that male plateau zokors have a more efficient rate of digging. Compared with the home-ranges of females, the home-ranges of the males is not stable in the long-term. It would be shifting in space, especially during the non-breeding season. Three males built completely new burrows in October (non-breeding) in our study (Fig. 4). The average distance between the new home-ranges of three males and their old nests was only 30 ± 3.2 m (mean \pm SD), and there were no signs of surface movements and no opening left in the older home-ranges. This changes the location of the home range in a different way from the mating period, such as M697, which left an open cave in two abandoned sites (mating season), spreading from the aboveground more than 88 m away. Our results contradict Nevo's hypothesis that all subterranean mammals' home-ranges, once established and used for a breeding season, are essentially permanent for life [22]. With some solitary subterranean rodents, shifting home-ranges were reported for the blind mole-rat [23] and silvery mole-rat [6]. Shifting in male home-ranges may be to avoid too much inbreeding [24], or to reduce the competitive pressure for food resources and space caused by the increased number of newborns in the future. We did not capture two zokors simultaneously in the same burrow systems of females, suggesting that individuals born in the previous breeding season had built their own nests. In addition, the migration of the home-ranges in solitary subterranean rodents may be a population density self-regulation strategy [41], but Šklíba et al. thought the changes of home-ranges more likely reflect a defensive strategy [6].

Most subterranean rodents, including plateau zokors, inhabit seasonal environments [9]. Seasonal food availability probably influences the space use of subterranean rodents [28]. Although the underground storage organs of plants are the main source of food for subterranean rodents. Plateau zokor is known to consume aerial part of the vegetation in addition to subterranean plant organs, and even they feed on the stems and leaves of grass and sedge [42], which may affect their space utilization. Instead, the burrowing and foraging activities of plateau zokor *M. baileyi* has great influence of soil properties and plant community [43]. Some of the overgrazed areas in the alpine meadows of Qinghai–Tibetan Plateau, with the population of plateau zokor increases rapidly, which leads to increased grassland degradation [44]. In our study, we found that there was a significant positive correlation between the size of home-ranges of plateau zokors in different months and the underground biomass. Soil compaction is also considered an ecological constraint in extending burrows of subterranean rodents [45, 46]. Although we found no significant difference that soil harness was between two peaks (June and October) in the activity of the plateau, the average

size of home-ranges in June was significantly (Mann-Whitney test: $U = 20$, $P = 0.002$) larger than that in October. This may be due to the abundance of underground biomass in June. But in October, the plateau zokor is supposed to gather a great deal of food from underground (the aboveground parts of the plant are almost inedible) for the long winter. The plateau zokor did not further expand its home-ranges to obtain more food when the underground biomass was relative deprivation. They could be by digging more branching tunnels for foraging. Despite this has not been proven in our study because we did not open the tunnel for long-term monitoring. Exploration of the surrounding of permanent primary tunnels by excavating short and branched foraging tunnels is a typical feature in many subterranean rodents [6, 31, 36].

Finally, we regard as additional studies on impacting the home-range sizes, such as intraspecific seismic communication, are enhanced to illuminate further the adapting mechanism of optional space use covered by this and other studies on solitary subterranean rodents.

Conclusions

In a word, our monitoring data indicates home-range size of plateau zokor in relation to mating and food resources. Regarding locomotion of home-range, this study in natural subterranean plateau zokors to affirm that their home-ranges are dynamics and males shift in space with one breeding cycle. Subterranean rodents as ecosystem engineers, understanding their space-use and dispersal is crucial for the conservation and management of subterranean rodents. More comprehensive burrows information should be combined with subsequent dissecting and mapping burrow systems.

Abbreviations

MCP
Minimum convex polygon
CT
Capture time
BM
Body mass
NNM
Number of new mounds
OA
Overlap area
OP
Percentage of overlap

Declarations

Availability of data and materials

All data generated and analysed during this study are included in this published article [and its supplementary information files].

Ethics approval and consent to participate

Experimental procedures involving capture, handling, and use of radio-collars in this study was approved by the Institutional Animal Care and Use Committee of the Grassland Science College of Gansu Agricultural University (GSC- IACUC-2018-0011).

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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Authors' contributions

Zhou J conceived the idea, and Zhou J and Hua L designed the study, Zhou J and Chu B conducted the research and Ji C and Zhang F organised and analyzed the data. Zhou J wrote the paper with contributions from Hua L. All authors read and approved the final manuscript.

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Figures

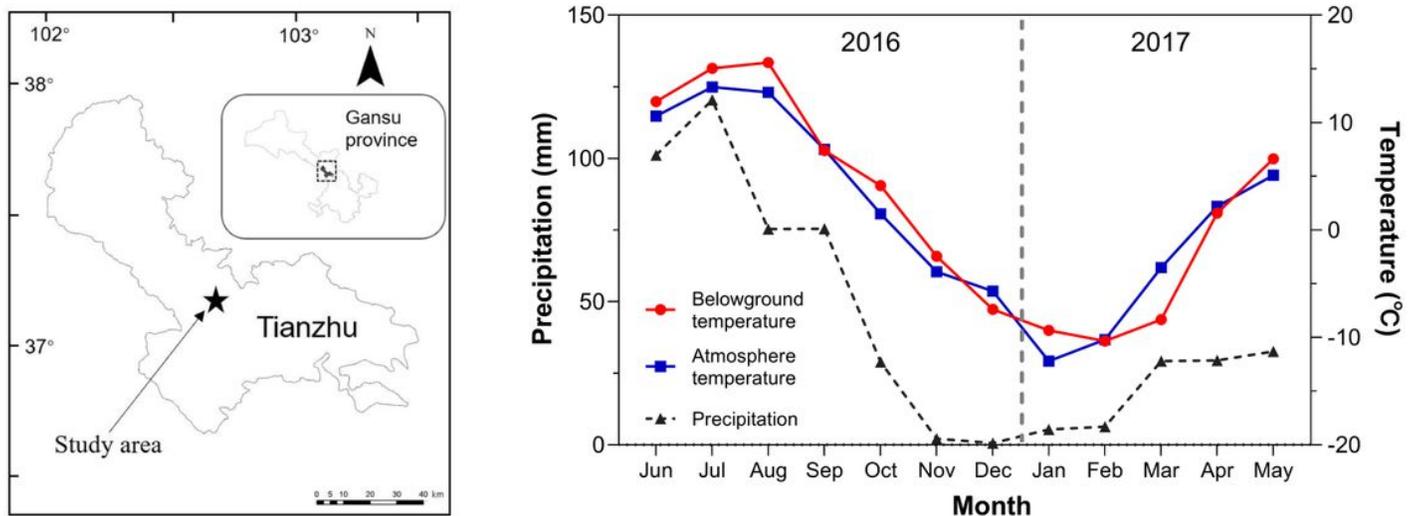


Figure 1

Left: Location of the study site. Right: Temperature (air and 15 cm underground) and precipitation changes from June 2016 to May 2017. Note: The designations employed and the presentation of the material on this map do not imply the expression of any

opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

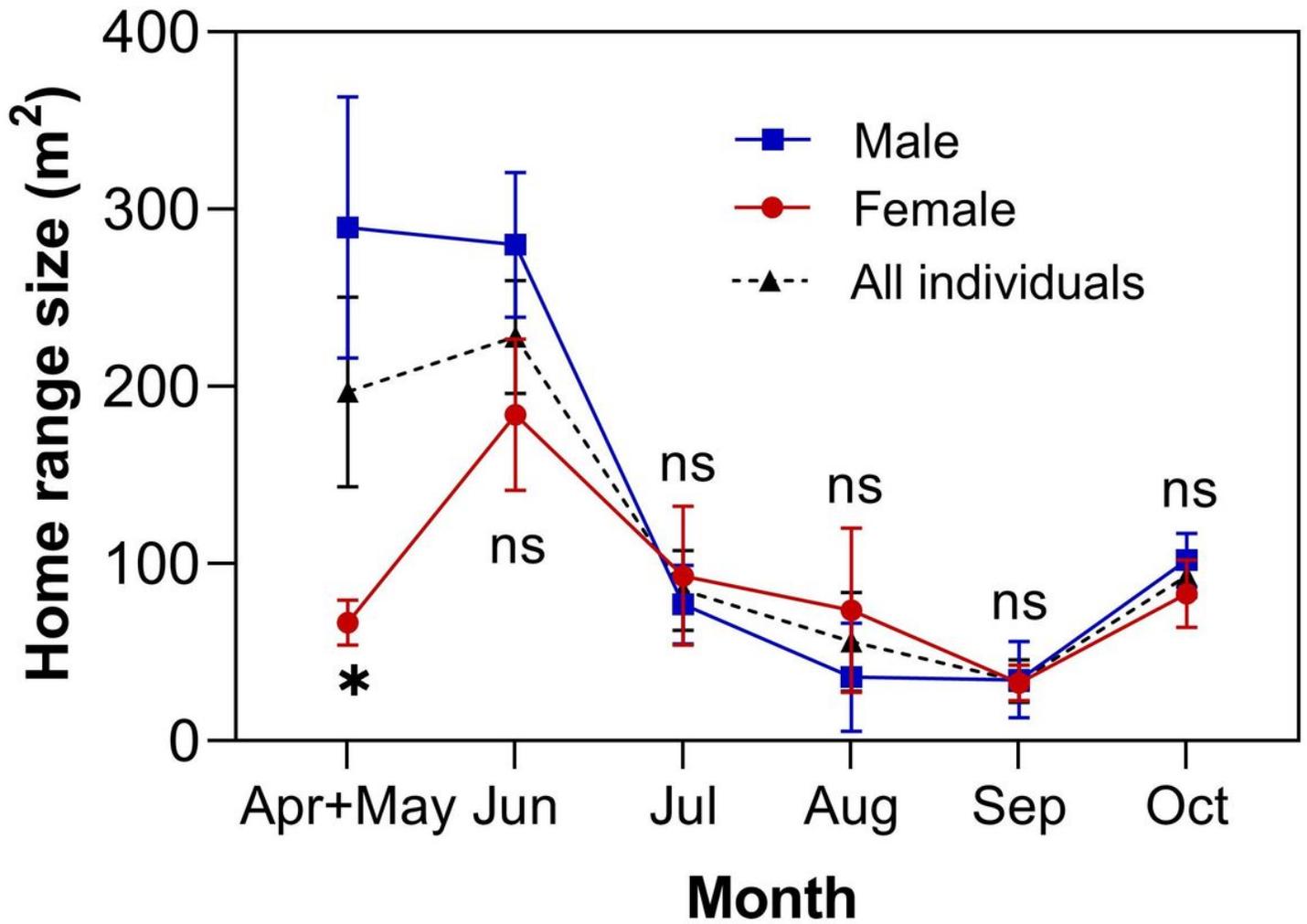


Figure 3

Comparison of the home-range sizes of males and females in different months. All individuals' average home-range sizes are represented by black dotted line. The “*/ns” reflect comparisons of home-ranges between males and females. The asterisk indicates a significant difference and “ns” means no significance. Results are showed as means \pm SEM.

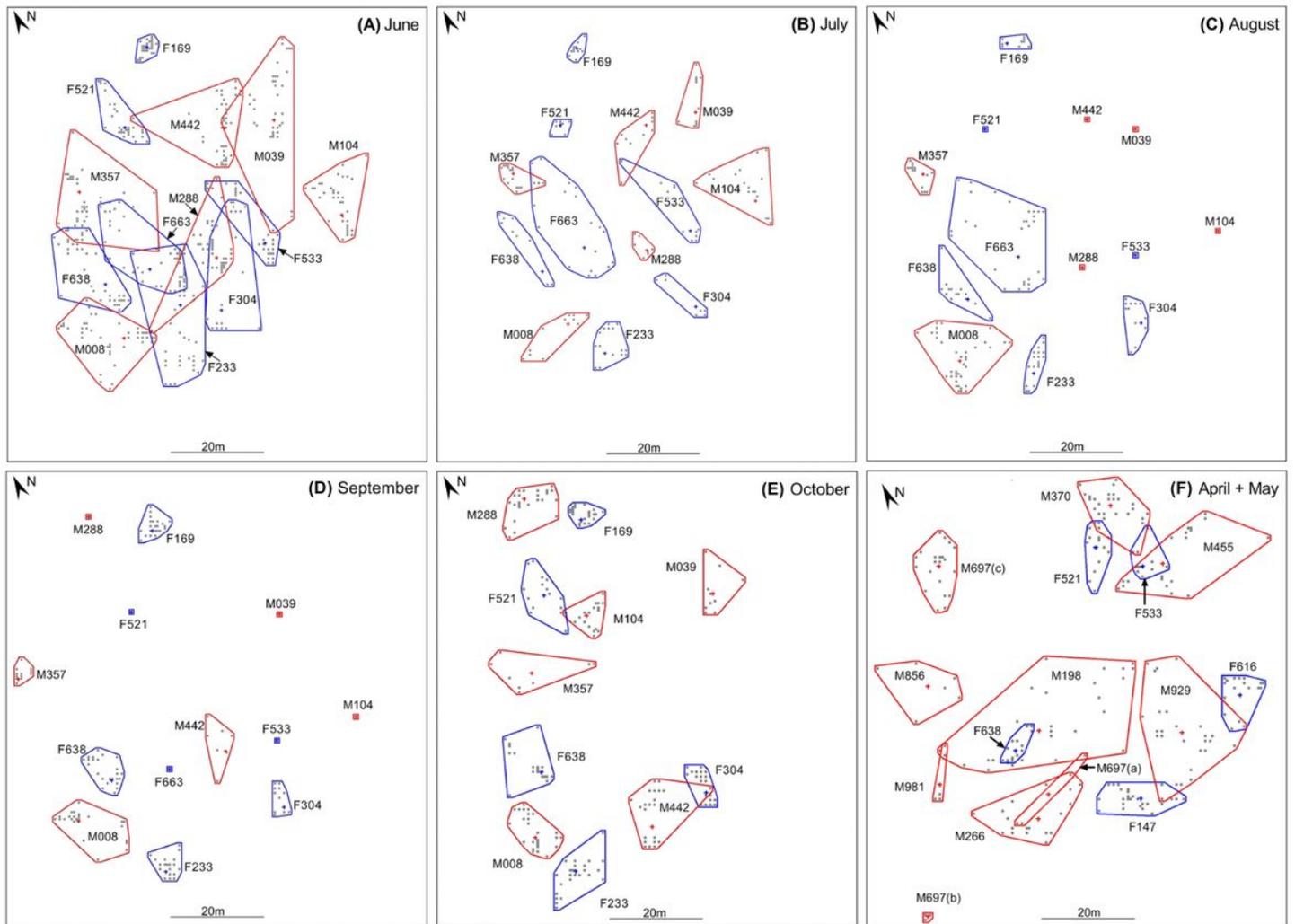


Figure 5

Representation of home range sizes estimated by 100% MCP methods for radio-tracked *Myospalax baileyi* in an alpine meadow in the eastern Qilian Mountain. Map A-E shows the continuous home-ranges in 2016 ($n = 13$). Map F represents the home-ranges of recaptured individuals in 2017 ($n = 13$). Red polygons represent male home-ranges, and blue polygons represent female home-ranges. Grey squares represent radio-tracking points.

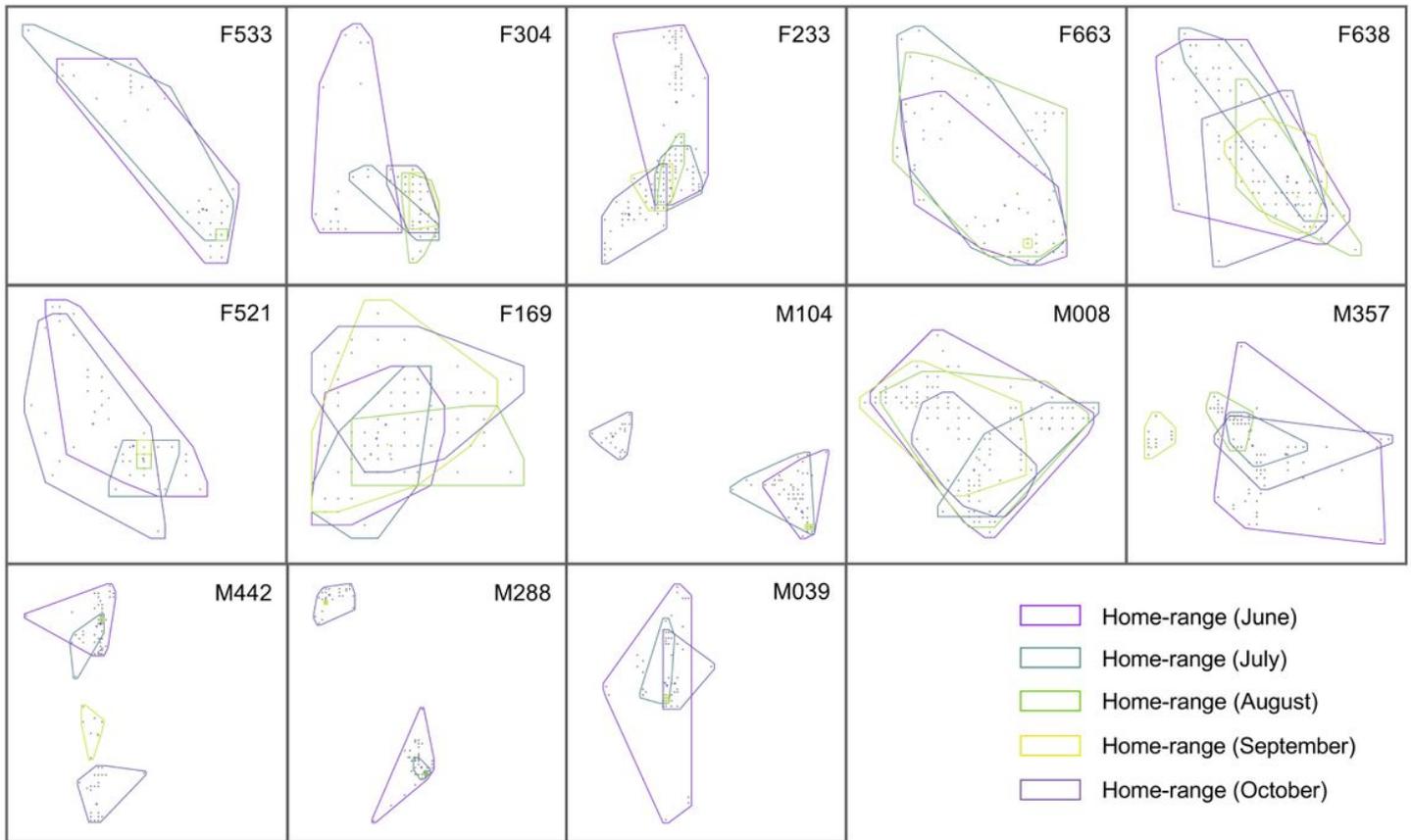


Figure 7

The monthly dynamics of each individual home-range of *M. baileyi* from June to October in 2016.

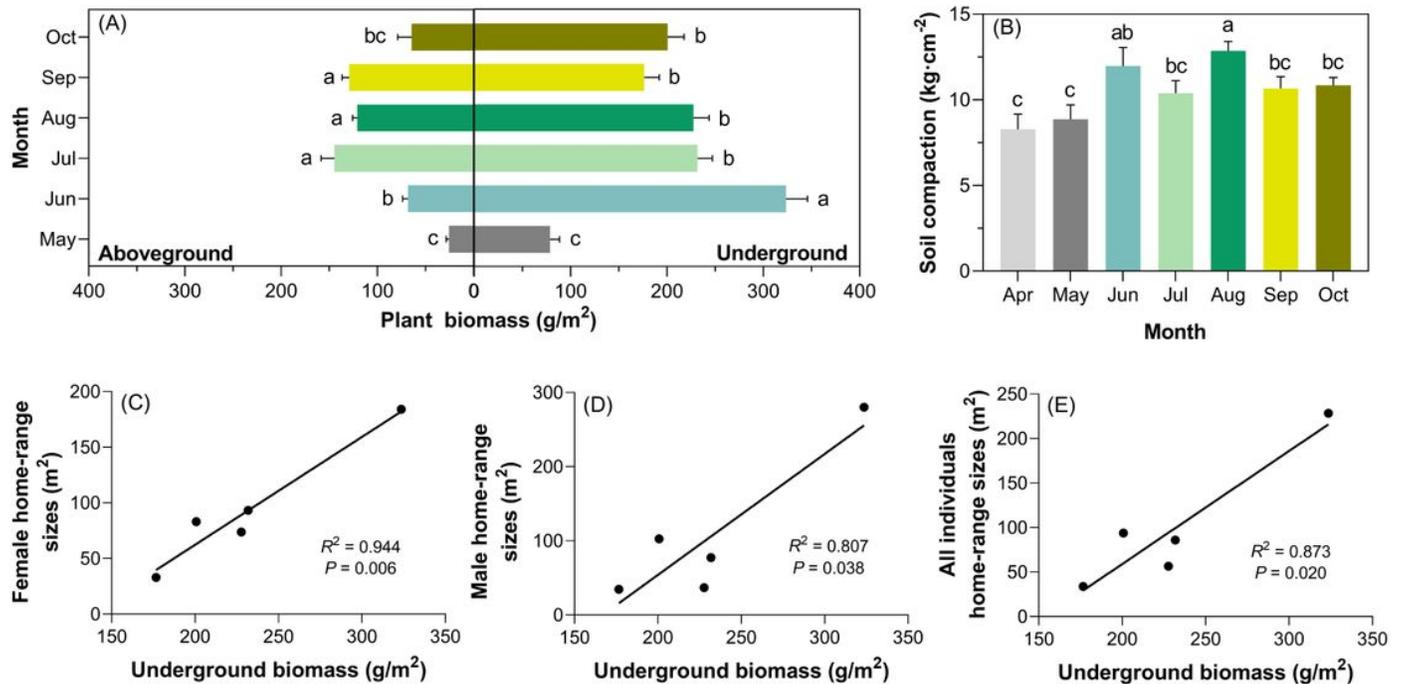


Figure 9

A): Plant biomass of aboveground and underground, respectively. The lowercase letters represent the differences between the months. B) Soil compaction changes. C/D/E) Relationships of underground biomass with average home-range sizes of female, male and all individuals in different months (from June to October) of 2016.

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