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蚁巢表层土壤温湿度对不同发育阶段红火蚁数量的影响（英文）

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摘要：红火蚁一种攻击性非常强的外来入侵蚂蚁，可对入侵地的农业生产、生态系统、人体健康和公共安全等产生负面影响，温度和湿度是影响其生长和发育的重要环境因子。本研究评估了红火蚁蚁巢表层土壤温、湿度对红火蚁幼虫、有翅蚁蛹和有翅蚁成虫数量的影响。结果表明，随着土壤温度的升高，幼虫、有翅蚁蛹和有翅蚁成虫的数量都呈先升高后下降的趋势。当温度为26～30℃时，幼虫数量达到最大值，而当温度为20～25℃时，有翅蚁蛹和有翅蚁成虫数量达到最大值。当温度＜20℃时，有翅蚁成虫和幼虫的数量均与土壤相对湿度呈负相关，但是有翅蚁雌雄蛹的数量都与相对湿度呈正相关。当温度＜20℃时，在相对湿度为41%～50%时，雄性有翅蚁的数量达到最大值，在相对湿度为71%～80%时，有翅蚁蛹的数量达到最大值。本研究将对防治这种危险的入侵害虫提供理论依据。

关键词：发育阶段；环境因子；数量变化；红火蚁
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Effect of soil temperature and relative humidity on the quantity of different developmental stages of *Solenopsis invicta* Buren in the surface layer of its nest

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Abstract：*Solenopsis invicta* is an aggressive invasive species which can cause serious negative impact in agriculture，ecology，human health，and public safety in its introduced regions. Temperature and humidity are important environmental factors affecting survival，growth，and development of *S. invicta*. In this study，the effects of soil temperature and soil relative humidity（RH）were evaluated on the quantity of larvae，alate pupae and alates of *S. invicta* in the 10-cm deep surface layer of their nests. The results found that the numbers of immature stages initially increased and then decreased with increasing soil temperature. The maximum of larvae in the 10-cm deep surface layer occurred in the 26～30°C range，

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while those of alates and pupae of alates occurred in the range of 20 ~ 25℃. The numbers of alates and larvae were all negatively correlated with soil RH when the soil temperature was < 20℃, whereas the numbers of pupae of male and female alates were positively correlated with soil RH. Meanwhile, when the temperature was below 20℃, the maximum of male alates and larvae occurred in the range of 41% ~50% soil RH, and the numbers of pupae of alates were largest in the range of 71% ~ 80% soil RH. Our findings may contribute to the control of the pest.

Key words: Developmental stages; environmental factors; changes in number; *Solenopsis invicta*

The red imported fire ant, *Solenopsis invicta* Buren (Hymenoptera: Formicidae), is an abnormally dangerous invasive species with great ability of range expansion and adaptation to local conditions (James *et al.*, 2002; Quarles *et al.*, 2005). It was native to South America and occurred naturally in areas like Parana River Basin Paraguay (Taber, 2000), Western Brazil and Argentina (Buren *et al.*, 1974; Allen *et al.*, 1995; Vinson, 1997). *S. invicta* has attracted considerable attention from Chinese researchers since it was detected in September, 2004 in Wuchuan, Guangdong (Zeng *et al.*, 2005; Wang *et al.*, 2012). It has been found in more than 390 counties of 15 provinces in China, and may spread further north potentially, both by human transportation and self-dispersal (Lu *et al.*, 2019; Wang *et al.*, 2020).

The relationship between environmental factors (such as weather and season) and development of *S. invicta* has been widely documented (Porter & Tschinkel, 1987; Cokendolpher & Phillips, 1990; Tschinkel, 2004). Temperature and rainfall determined the geographical distribution and expansion of *S. invicta* (Morrison *et al.*, 2004). Xu *et al.* (2009) reported that climate had a great effect on the colony dynamics of *S. invicta*. Its aggressive activity was affected by temperature, humidity, mound size, colony structure, habitat, disturbance degree, and pesticides (Gao, 2007). The colony quantity was greater in spring and autumn, while obviously reduced in winter (Zhou *et al.*, 2011).

In previous study, we revealed the effect of soil temperature and relative humidity (RH) on the dynamic changes of quantity of worker ants at the surface of the ant nests (Li *et al.*, 2014). Yamamoto *et al.* (2008) reported that the activity of ants was correlated with temperature and humidity. In order to evaluate the effects of environmental factors on the quantity of *S. invicta*, we analyzed changes in the numbers of larvae, alate pupae and alates of *S. invicta* at the surface of the ant nests at different temperature and humidity.

1 Material and Methods

1.1 Investigation sites

Solenopsis invicta was collected from Guangzhou Higher Education Mega Center (N 22.94°, E 113.38°), Nancun Town (N 23.01°, E 113.32°), Yushan Road West (N 22.95°, E 113.31°), Nanjiao Park (N 22.93°, E 113.35°), and Guangzhou Asian Games City (N 22.96°, E 113.50°), respectively. The habitat types included park, sidewalk of highways, and wastelands. The average length of the nests is 40 cm, the width is 28 cm, and the height is 12 cm.

1.2 Investigation methods

Live nests of *S. invicta*, which were undisturbed, were selected and sampled under different temperature and humidity on sunny days from February to August, 2013. The temperature and humidity of each nest in the 10-cm deep surface layer (10 cm deep from the top of the nest) were measured three times by a portable humidity and temperature indicator (HMI41SET, Vaisala, Finland). For each nest, a top 10 cm^3 × 10 cm^3 × 10 cm^3 of soil was taken by a shovel and placed into a cleanwrap plastic bag. Absolute ether was placed in the cleanwrap bags to prevent the fire ants from escaping. In order to clarify differences in the numbers of larvae, alate pupae and alates at different temperature and RH, the samples were separated according to different temperature ranges (< 20℃, 20 ~ 25℃, 26 ~ 30℃, 31 ~ 35℃, 36 ~ 40℃, 41 ~ 45℃) and RH ranges (31% ~ 40%, 41% ~ 50%, 51% ~ 60%, 61% ~ 70%, 71% ~ 80%, 81% ~ 90%) in the lab. Thirty nests of *S. invicta* were chosen in each temperature and humidity range. Then, ants in each sample were picked out from the soil with tweezers and placed in a petri dish. The numbers of larvae, pupae and alates of *S. invicta* in different temperature and humidity ranges were determined (Li *et al.*, 2014).

1.3 Statistical analysis

Statistical analyses were conducted in SPSS 16.0 (SPSS Inc., Chicago, Illinois, USA). Differences in the numbers of larvae, alate pupae and alates were analyzed by one-way analysis of variance (ANOVA). The means were separated by Tukey′s test at $P \leqslant 0.05$. Correlations between the numbers of ants in different development stages and temperature as well as RH were analyzed by Pearson′s Correlation.

2 Results

2.1 Numbers of larvae, alate pupae and alates of *S. invicta* in the nest surface layer in different soil temperature range

The numbers of adult and immature antsin the 10 cm deep surface layer of nests were significantly different in different temperature ranges (male alates: $F = 10.58$, df = 179, $P < 0.001$; female alates: $F = 11.07$, df = 179, $P < 0.001$; larvae: $F = 14.833$, df = 179, $P < 0.001$; pupae of male alates: $F = 5.62$, df = 179, $P < 0.001$; pupae of female alates: $F = 2.53$, df = 179, $P < 0.05$) (Table 1). With increasing soil temperature in the 10-cm deep surface layers of nests, the numbers of adult and immature ants increased initially and then decreased (Table 1). The maximum of larvae (87.81) occurred in the temperature range of 26 ~ 30℃. However, the numbers of larvae sharply decreased in the 36 ~ 40℃ (2.72) and 41 ~ 45℃ ranges (4.07). The numbers of alates and alate pupae reached maxima in the range of 20 ~ 25℃, but decreased when the soil temperature rose above 26℃ (Table 1).

2.2 Correlation of soil RH on numbers of *S. invicta* in different developmental stages in the nest surface layer

At <20℃, the numbers of larvae ($R = -0.215$, $P < 0.05$), male alates ($R = -0.133$, $P < 0.05$), and female alates ($R = -0.223$, $P < 0.05$) in the 10-cm deep surface layer of nests were negatively correlated with soil RH, whereas the numbers of pupae of male ($R = 0.340$, $P < 0.01$) and female alates ($R = 0.260$, $P < 0.05$) were positively correlated with soil RH (Table 2). However, in other temperature ranges, the numbers of larvae, pupae and alates in the 10-cm deep surface layer of ant nests were not significantly correlated with soil RH (Table 2). At < 20℃, the maximum of male alates and larvae occurred in the range of 41% ~ 50% soil RH, and the numbers of pupae of alates were largest in the range of 71% ~ 80% soil RH (Table 3).

Table 1 Numbers of different developmental stages of *Solenopsis invicta* in 10-cm deep surface layer of nests in different temperature ranges

Developmental stages of *S. invicta*	Soil temperature in 10-cm deep surface layer of nests					
	< 20℃	20 ~ 25℃	26 ~ 30℃	31 ~ 35℃	36 ~ 40℃	41 ~ 45℃
Male alates	4.74 ± 1.47 b	10.28 ± 2.46 a	6.22 ± 1.25 b	0.66 ± 0.16 c	0.01 ± 0.01 c	0.09 ± 0.05 c
Female alates	2.44 ± 0.6 ab	3.37 ± 0.58 a	1.77 ± 0.59 b	0.32 ± 0.13 c	0.04 ± 0.03 c	0.07 ± 0.03 c
Larvae	25.2 ± 5.66 bc	33.96 ± 7.06 b	87.81 ± 15.65 a	86.13 ± 16.26 a	2.72 ± 0.98 c	4.07 ± 1.57 c
Pupae of male alates	2.99 ± 0.89 b	6.61 ± 1.83 a	2.49 ± 0.97 b	2.98 ± 0.98 b	0.08 ± 0.03 b	0.21 ± 0.16 b
Pupae of female alates	1.94 ± 0.59 ab	2.91 ± 0.67 a	1.81 ± 0.77 ab	1.93 ± 0.9 ab	0.44 ± 0.18 b	0.4 ± 0.22 b

Note: Means (± SD) in the same row followed by the same letter were not significantly different at the level of 0.05 (Turkey′s test).

Table 2 Correlation between the soil relative humidity and the numbers of different stages of *Solenopsis invicta* in 10-cm deep surface layer of nests in different temperature ranges

Soil temperature (℃)	Developmental stages of *S. invicta*				
	Male alates	Female alates	Larvae	Pupae of male alates	Pupae of female alates
< 20	-0.133*	-0.223*	-0.215*	0.340**	0.260*
20~25	-0.077	-0.139	0.072	0.020	0.143
26~30	-0.270**	0	0.184	0.062	0.046
31~35	-0.149	-0.145	0.069	-0.093	-0.135
36~40	-0.018	-0.026	-0.151	0.162	0.224*
41~45	-0.2	0.110	-0.004	0.155	0.214*

Notes: * Correlation was significant at 0.05 levels. ** Correlation was significant at 0.01 levels. R values were showed in the table.

Table 3 Numbers of different developmental stages of *Solenopsis invicta* in 10-cm deep surface layer of nests in different humidity ranges when the temperature was <20℃

Stages of *S. invicta*	Ranges of soil relative humidity					
	31%~40%	41%~50%	51%~60%	61%~70%	71%~80%	81%~90%
Male alates	0.33±0.21 b	14.22±7.34 a	5.85±2.70 ab	0 b	4.33±2.79 ab	0 b
Female alates	0 a	2.67±1.61 a	5.24±1.45 a	1.17±0.52 a	0.25±0.12 a	0.5±0.34 a
Larvae	11.83±5.71 b	83.11±46.47 a	30.82±5.56 b	22.00±12.18 b	3.50±1.99 b	14±7.10 b
Pupae of male alates	0 b	0 b	0.87±0.43 b	0 b	10.00±2.88 a	0 b
Pupae of female alates	0 b	0 b	1.36±0.77 ab	0 b	5.42±1.75 a	0 b

Note: Means (±SD) in the same row followed by the same letter were not significantly different at the level of 0.05.

3 Discussions

Studies on the biology and behavioral ecology of *S. invicta* may elucidate their occurrence and invasion, and lead to the identification of more reasonable and effective control measures. Previous studies showed that the range of the most suitable foraging temperature for worker ants was 22~36℃, that foraging began when the temperature rose above 10℃, and that foraging ceased below 7℃ and above 45℃ (Li *et al.*, 2014). Allen *et al.* (2001) reported that this species ceased foraging when the soil (5 cm) temperature was below 5℃ or above 49℃. Temperature and humidity can directly affect the development, survival and reproduction of pests, resulting in their different occurrence period, occurrence quantity and damage degree (Li *et al.*, 2014). Our results provided a basis for monitoring and control of *S. invicta*, and laid a foundation for further research on its prediction and evaluation of occurrence degree.

Temperature and humidity are important environmental factors, of which the survival, growth, and development of *S. invicta* were affected. Zhou *et al.* (2019) found that *Sifor* may be a key gene in *S. invicta*, responding to temperature changes with mRNA levels fluctuation. The dynamic changes of quantity of *S. invicta* at different stages in the surface layer of ant nests were observed in this study at different temperature and humidity ranges. The results showed that some developmental stages of *S. invicta* had different optimal temperature ranges. The number of larvae in the nest surface layer at 26~30℃ was greater than those in other temperature ranges, indicating that this temperature range was optimal for the development of larvae in the upper 10 cm. In the process of taking care of the larvae, workers were particularly sensitive to temperature and humidity (Cokendolpher & Francke, 1985; Porter & Tschinkel, 1993; Tschinkel, 2004). Pinson (1980) found that *S. invicta* may move up and down in the nest with daily variations in different temperature. With increasing soil temperature in the 10-cm deep surface layers of nests, the numbers of immature increased initially and then decreased. Therefore, the larvae were moved by workers to regions of the nest with the most suitable temperature. The numbers of larvae sharply decreased above the 36℃. These results indicated that high temperature, especially > 36℃, was not suitable for *S. invicta* in the surface layer. The numbers of alates and alate pupae reached maxima in the range of 20 ~ 25℃, but decreased when the soil temperature rose above 26℃. The pupae of alates appeared in colonies when the temperature rose above 20℃, and the nuptial flights of alates occurred mainly when the temperature was 24 ~ 32℃ (Vinson, 1997). This may explain why the numbers of alates decreased in the surface layer when the temperature was above 26℃.

In this study, the changes in the numbers of larvae, andalates were negatively correlated with soil RH when the soil temperature was less than 20℃. In previous study, we found that the number of workers was also negatively correlated with soil RH when the soil temperature was less than 20℃ (Li *et al.*, 2014). When humidity became higher at < 20 ℃, the numbers of larvae, alate males and females decreased, which indicated that high humidity was not suitable for the larvae and alates of *S. invicta*. Rummel (1986) found that the survival rate of insects in wet and cold environments was far less than in dry and cold environments. This also applied to *S. invicta* as a soil dwelling insect, but this ant may adapt to environmental changes by moving the brood and workers up or down in their nests (Pinson, 1980). Compared with our previous results (Li *et al.*, 2014), the current results suggested that workers might be more sensitive to humidity than other stages under lower temperature. The number of alate pupae was positively correlated with soil RH when the temperature was less than 20℃. By far the largest number of alate pupae occurred in the surface layer at 71% ~ 80% RH, which indicated that the alate pupae had more tolerance to high humidity than other stages in cold environment. These may be because of the protective integument of the pupae, which may confer a general capacity of alate pupae to tolerate harsh environments.

Our findings may contribute to the control of this dangerous invasive pest. The occurrence degree of *S. invicta* under different environmental conditions can be explored, and the spread by nuptial flight can be predicted. However, further study is needed for several issues, such as the relationship between the nests of *S. invicta* and atmospheric temperature and humidity.

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