A preliminary study on the ecological consequences of *Solenopsis invicta* invasion

Zhi-xing LU[a,†], Xiang ZHANG[a], Shu-tong GAO[a], Qiao LI[b], You-qing CHEN[a]

([a]) Research Institute of Resources Insects, Chinese Academy of Forestry, Kunming, China; †*luzhixing@caf.ac.cn*
([b]) Southwest Forestry University, Kunming, China

Introduction

- Red fire ant (*Solenopsis invicta* Buren) is native to South America and has expanded to 24 countries and regions in Central America, North America, Australia, and Asia over the past 80 years(Inoue and Goka, 2009. Red fire ant is a global high-risk invasive species first reported in China in 2004 and has occurred successively in many places in recent years (280 Counties within 13 Provinces and 38 Counties in Yunnan Province).


- Red fire ant has high fecundity, high aggressiveness, and strong adaptive capacity that they can colonize rapidly(Haines et al.,2017), which leads to the local biodiversity loss and negative consequences of agroforestry ecosystems, such as harming human health(Tschinkel, 1993), reducing yields in agriculture and forestry(Adams et al., 1988; Jetter et al., 2002), and hazardous to public facilities(Zhao et al, 2008; Tang, 2017). Red fire ant also poses a significant threat to the local ant communities through direct or indirect impacts(Mann, 1994; Gotelli and Arnett, 2000; Allen et al., 2004), such as replacing native ant by interference competition and greatly reducing the diversity of native ants in invaded areas(Porter and Savignano, 1990; Pennisi, 2000). In heavily invaded habitats, the abundance of native ants was drastically reduced, while the red fire ants accounted for almost 90% of the total number of ants(Porter and Savignano, 1990). Huang et al. (2010) showed that red fire ant invasion led to a 65.3% reduction in arthropod species richness in corn farms in Guangdong Province, 88.9%, 71.4%, and 68.8% reduced in Hemiptera, Lepidoptera, and Arachnids, respectively, while Hymenoptera species richness decreased from 58.6% to 31.0%, and there was a negative correlation between the red fire ant density and local arthropod species richness. The effects of red fire ants on arthropods differed in spatial distribution, with milder effects on arthropod communities in the canopy arthropod communities and significant negative effects on the ground-dwelling arthropod communities(Wang et al, 2017).
- Successfully invading exotic species must have their unique intrinsic advantages(Hufbauer and Torchin, 2008), and have evolved to acquire more variation so that they can survive in a broader range of environmental conditions, exploit more resources, and gain an advantage in the competition ultimately(Hoffmann et al., 1999). The tolerance of invasive ants to adverse environments is another essential factor for their successful invasion(MacMillan and Sinclair, 2011; Chen et al., 2014), mainly in terms of abiotic stresses such as cold tolerance, heat tolerance, water tolerance and chemical resistance(Xu et al, 2009; Chen et al, 2014). Red fire ants have a high tolerance to low temperatures(Quarles, 2007; Xu et al, 2014), better than most native ants in the invasion site. Red fire ants are also water-tolerant, able to survive in water for a long time(Zhou et al, 2011; Yu et al, 2013). Red fire ants also show a high resistance to some pesticides(Huang et al, 2007; Gao et al, 2011; Qiu et al, 2016).
- The most critical invasion mechanism of invasive ants is to replace other ants through competition(Davidson, 1998), which mainly includes exploitative competition and interference competition. Exploitative competition refers to the ability of species to find and use resources prioritize over other species(Cerdá et al., 2012). In contrast, interference competition refers to the ability of a species to prevent other species from using resources (or to drive them out of the resource) through direct invasion or monopolization. The correlation between interference or exploitative competition actually promotes the coexistence of native ants(Adler et al., 2007), forms a balance of resources finding and control(Lebrun and Feener, 2007; Parr and Gibb, 2012). The red fire ant is a typical aggressive ant that mainly controls resources by interference competition. Lei's study (2016) showed that red fire ants outperformed native ants in both physical and chemical attacks. Especially in habitats with shortage food resources, the interference competition among red fire ants and native ants is often a nest-level activity(Parr and Gibb, 2012), and large populations of red fire ants greatly enhance their competition ability(Human and Gordon, 1996).
- After understanding the effects of red fire ant invasion, it becomes more critical to analyze the mechanisms of how red fire ants successfully invade. Numerous studies have explained the invasion mechanism in terms of population expansion rate, tolerance, and competitive interspecific relationships, but fewer studies have compared the tolerance of red fire ants with other ants(Chen et al., 2014). Soaking in high concentrations of ethanol can lead to losing enzyme activity due to protein denaturation and disruption of cell membranes, resulting in the inability to walk and disorientation, and can even affect reproductive ability(King and Porter, 2004). Comparing the tolerance of red fire ants and other ants in ethyl ethanol can visualize the difference in tolerance. Therefore, in this study, we analyzed the effects of red fire ant invasion on ant community diversity, community structure and functional diversity in different habitats, compared the tolerance difference between red fire ants and other ants in ethyl ethanol and the effect of red fire ant invasion on the competitive balance between native ant species, and explored the effects of red fire ants on local ants and some of their invasion mechanisms after entering Yunnan. It will provide a theoretical basis for in-depth research and control of red fire ants. This study will provide a theoretical basis for further research and control of red fire ants.

- **Materials and methods**
- The sample sites located in Kunming City and Mouding County, Chuxiong City, Yunnan Province. Five occurrence intensity classes ranging from mild to severe occurrence were selected to investigate ant community diversity at different sites, was determined based on the number of red fire ant mounds. Pitfall traps and bait method for competition test designed concerning to McGlynn (2000). Standard methods measured data on 12 ant traits, and ant functional diversity was calculated and compared based on ant traits. The tolerance of red fire ants to ethyl ethanol was studied using the *Solenopsis tipuna*, *Plagiolepis rothneyi* and *Camponotus confucii* as controls.


Results

(1) Effects on local ant assemblages of red fire ant invasion

The relative abundance of ant species in the three sample plots had significantly differences ($F_{(2, 33)}$= 3.361, P= 0.047), with high-density plots > low-density plots > control plots. There was no significant difference between high-density plots and low-density plots, and also had no significant difference between low-density plots and control plots, but high-density plots were significantly higher than control plots. Species richness in the three types of sample plots had no significantly differences ($F_{(2, 33)}$= 0.742, P= 0.484), with high-density plots > low-density plots > control plots. ACE values in the three types of sample sites also had no significantly differences (χ^2= 5.938, P= 0.051), with high-density sites > low-density sites > control sites.

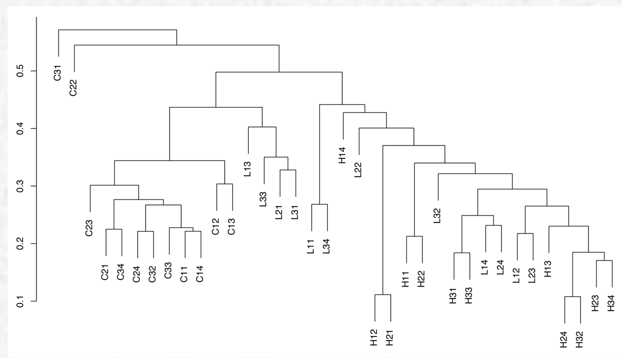
After removing the data of red fire ants, relative abundance in the three sample plots had significantly differences ($F_{(2, 33)}$ = 3.989, P= 0.028), control plots > low density plots > high density plots, control plots were significantly differences from high density plots, control plots had no significantly differences from low density plots, high density plots had no significantly differences from low density plots. There was no significant difference in species richness between the three types of sample plots ($F_{(2, 33)}$ = 0.008, ·P= 0.992), and the three sample plots were almost identical; there was also no significant difference in the ACE value between the three plots ($F_{(2, 33)}$ = 3.013, P= 0.063), with high-density plots > low-density plots > control plots. There was a significant difference in ground-dwelling ant community structure between the three plots (ANOSIM Global R= 0.562, P= 0.001).

Diversity comparison of ant communities in sites of different invasion intensities of red imported fire ant

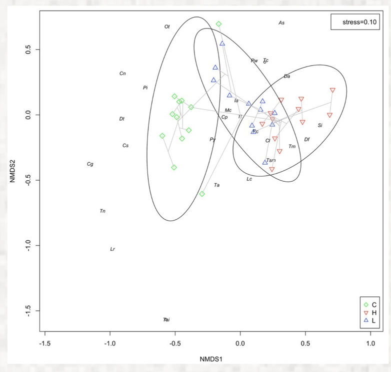
Sites	Relative abundance	Species richness	ACE
High density plot	35.42±2.19a	8.42±0.54a	11.92±0.96a
Low density plot	31.50±2.21ab	8.08±0.47a	9.57±0.49a
Control plot	26.92±2.55b	7.50±0.60a	8.53±0.64a

Diversity comparison of ant communities in sites of different invasion intensities of red imported fire ant (without fire ant)

Sites	Relative abundance	Species richness	ACE
High density plot	19.33±2.16b	7.50±0.60a	10.92±0.96a
Low density plot	26.67±1.67ab	7.42±0.45a	9.00±0.52a
Control plot	26.92±2.55a	7.50±0.60a	8.53±0.64a



Cluster analysis of ground-dwelling ant communities in sites of different invasion intensities of red imported fire ant



Similarity of ground-dwelling ant communities in sites of different invasion intensities of red imported fire ant

(2) Effects on ant functional diversity of red fire ant invasion

The functional richness FR_{ic} ($F_{(2,33)}$= 1.548, P= 0.228) of ground-dwelling ant comprehensive capacity had no significantly difference between the three plots. and also the functional evenness FE_{ve} (χ^2= 1.375, P= 0.503) of ground-dwelling ant had no significantly differences between three plots. But, the functional dispersion FD_{iv} ($F_{(2,33)}$= 4.322, P= 0.022) had significantly differences between three plots($F_{(2,33)}$= 4.322, P= 0.022), which was significantly higher in the high-density plots than the control plots, but had no significantly differences from the low-density plots, while there was no significant difference between the low-density plots and the control plots.

Comparison of functional diversity of ground-dwelling ant's general ability in different invasion intensities of red imported fire ant

Sites	FR_{ic}	FE_{ve}	FD_{iv}
High density plot	6.08±0.69a	0.69±0.01a	0.85±0.03a
Low density plot	5.76±0.81a	0.73±0.02a	0.83±0.02ab
Control plot	7.84±1.14a	0.73±0.03a	0.74±0.03b

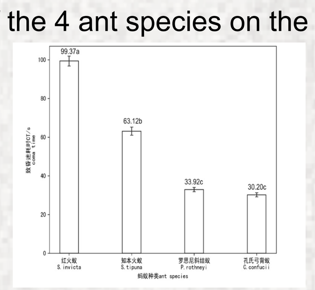
Comparison of functional diversity of ground-dwelling ant's general ability in different invasion intensities of red imported fire ant (without fire ant)

Sites	FR_{ic}	FE_{ve}	FD_{iv}
High density plot	4.20±0.66b	0.72±0.01a	0.79±0.03a
Low density plot	4.54±0.78b	0.72±0.02a	0.79±0.01a
Control plot	7.63±1.16a	0.73±0.03a	0.74±0.02a

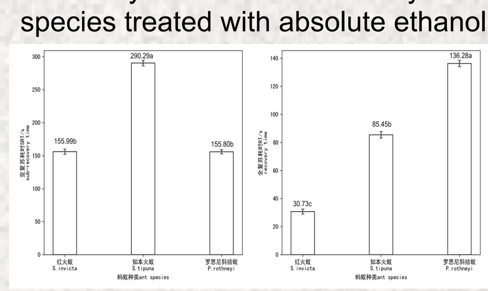
(3) Comparison of tolerance to ethyl ethanol

The coma time of the four ant species in ethyl ethanol was significantly different (χ^2= 11.623, P< 0.001), with the longest coma time of 99.37± 2.56s for the red fire ant and the shortest time of 30.20± 1.03s for the *Camponotus confucii*. Coma time of all ants had significantly difference from each other, except for the *Camponotus confucii* and *Plagiolepis rothneyi*. The proportion of sub-recovery was significantly different among the four ant species (χ^2= 12.87, P< 0.05). The highest sub-recovery proportions were found in the red fire ant and *Plagiolepis rothneyi*, 82.89± 0.60% and 81.71± 3.13%, respectively. Majority of individuals of *Solenopsis tipuna* were unable to complete the sub-recovery stage, with only 9.23± 1.58% being able to sub-recover. All individuals of *Camponotus confucii* were unable to complete the sub-recovery stage. The percentage of full recovery was significantly different among the three ant species (excluding the *Camponotus confucii*) (χ^2= 8.11, P< 0.01), with the highest percentage of full recovery in the red fire ant (80.71± 3.34%), which was significantly higher than the other two ant species.

Coma time of the 4 ant species on the absolute ethanol

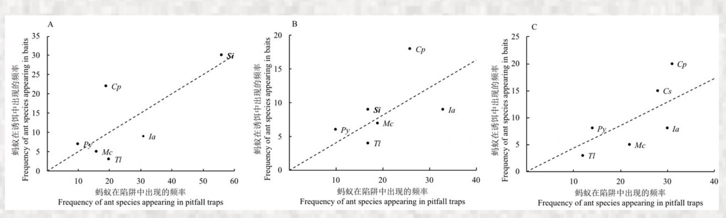


The sub-recovery time and full-recovery time of 3 ant species treated with absolute ethanol

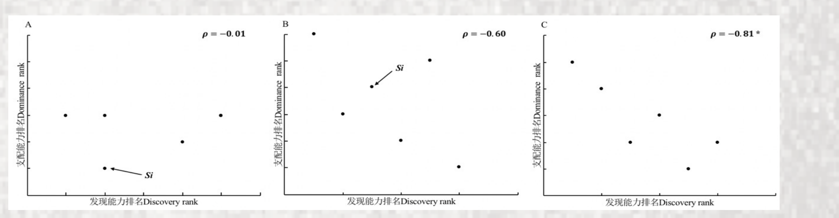


(4) Discovery-dominance trade-off

Because of the low-density red fire ant, there was a negative correlation between the relative discover ability and relative dominance ability of ant species, but it was still had no significant differences(ρ= -0.60, P= 0.21). In the red fire ant invasion area, the discovery-dominance trade-off did not exist or was not followed among ant species. However, in control plots without red fire ants, there was a significant negative correlation (ρ= -0.81, P= 0.04) between the discover ability and relative dominance ability of native ant species, following the discovery-dominance trade-off. The frequency of discovery was significantly higher in high-density plots than in low-density plots (χ^2= 17.27, P< 0.001); however, in high-density plots,there were no significantly differences from the low-density plots in the frequency of recruitment (χ^2= 1.75, P= 0.55); but there were significantly differences from the low-density plots in the frequency of dominance (χ^2= 6.25, P= 0.03).



The relative discovery ability "expected line" of among species of ant community in areas of *S. invicta* with three population density



The discovery-dominance trade-off among species of ant community in areas of the red fire ant with three invasion intensities

Conclusion

The results showed that red fire ant invasion significantly reduced the abundance of native ants at the beginning of the invasion but had no significant effect on species richness and community structure. The functional richness index of native ants was significantly reduced in the high-density areas. The red fire ant time-consuming coma was significantly longer than the other three native ants; the recovery rate and recovery time of the red fire ant were highest and shortest, significantly stronger than *S. tipuna* and *Camponotus confucii*.