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Ecological and socio-economic impacts of the red import fire ant, *Solenopsis invicta* (Hymenoptera: Formicidae), on urban agricultural ecosystems

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Abstract

The agricultural impacts of the Red Imported Fire Ant, *Solenopsis invicta* Buren 1972, have been well studied in North America, but have received less emphasis in Asia where the species was first detected in the early 2000's. Simultaneously, with urbanization rapidly expanding in Asia, *S. invicta* impacts on the socio-economic benefits of urban farming are to this point unknown. Our study focuses on establishing a baseline on the geographic distribution of the *S. invicta* spread in Hong Kong urban agroecosystems and its potential impacts on native ant communities and farmers through a series of field surveys and interviews. Our results show that in 15 years, *S. invicta* has invaded half of the Hong Kong urban agroecosystems, with infestation levels slightly varying in farming practices (organic vs. traditional) but greatly among the different types of cultures. Ecologically, the presence of *S. invicta* and its increased abundance were associated with a decrease in ant community species richness and evenness. Economically, the farmers' perception indicated that *S. invicta* could have impacts on crops production ranging from 10% to 80%, as well as important public health issues associated to indirect economic costs due to the aggressive stinging and consequences on other educational activities. Finally, all control methods used were mainly inefficient and maladjusted to these environments. With dense infested farm locations and current management, *S. invicta* prevalence and its cost are expected to expand. This prospective situation requests the development of professional guidance and management plans to impede *S. invicta* spread and rising impacts.

Keywords Biological invasions · Hong Kong · Socio-economic costs · *Solenopsis invicta* · Urban farming

Introduction

Biological invasions have become one of the most serious threats to biodiversity and economy as a consequence of rising international trading and transportation (Early et al. 2016; Dawson et al. 2017). Insect invasions are particularly damageable to local biodiversity and economy through various ways, including ecosystem alteration, attack to human and livestock and damage to the crops production, with an annual estimated cost exceeding 70 billion US$ globally (Bradshaw et al. 2016). Invasive ants especially are considered one of the most widespread and damaging species for local communities, economies and public health (Lowe et al. 2000; Holway et al. 2002; Lach and Hooper-Bùi 2010; Rabitsch 2011).

The Red Imported Fire Ant (RIFA), *Solenopsis invicta* Buren 1972, is a major invasive species causing important damages to natural and anthropogenic ecosystems (Gotelli and Arnett 2000; Stiles and Jones 1998; Stuble et al. 2009) including within agricultural ecosystems (Adams 1986; Zhang et al. 2007). For instance in the USA, *S. invicta* is responsible for a decline in production through direct predation on different plant parts (e.g. roots, fruits, flowers, stems), with reduction estimated to 15 to 33% in soybean, 20 to 35% in potato crops, or 50% in eggplant (Adams 1986). Moreover, this species also causes indirect damage to crop production through their mutualism with sap-sucking insects, such as aphids and mealybugs, and limits the efficiency of biological control programs through the predation of auxiliary insect predators or parasitoids (Eubanks 2001; Hill and Hoy 2003; Parys and Johnson 2012). As a result, the presence of *S. invicta* generates important costs for agriculture estimated

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to 200 million US$ per year for its control in the USA (Pimentel et al. 2005) with losses estimated to 6 billion US$ annually (Drees and Lard 2006). Finally, fire ants impact public health directly, through their aggressive stinging behavior characterized by the injection of venoms; resulting into multiple medical problems such as white pustules, pain, nausea and most severely anaphylaxis, which ultimately affects working continuity of farmers (Kemp et al. 2011).

Asia, a major reservoir of global biodiversity, is particularly exposed to a high risk of biological invasions due to the rapid development of international trade (Early et al. 2016), with *S. invicta* one of its current main invaders (Wang et al. 2013). Hong Kong, a central trading hub connecting Asian regions to the global market, has been colonized by *S. invicta* since at least 2005 (Wang et al. 2013); with the New Territories, the northern part of Hong Kong where agricultural activities are mostly concentrated, heavily infested by the spread of this species (unpublished data). While the agricultural industry of Hong Kong is relatively small in size and production, occupying 698 ha of land and generating a total 44.7 million US$ in 2017 of crop production, farms are geographically scattered at the periphery of urban areas (Agricultural, Fisheries and Conservation Department [GovHK] 2017) with growing popularity in urban farming. In Hong Kong, urban farming is usually surrounded by villages and housing development (Fig. 1) and is characterized by polycultures (including vegetables, flowers and fruits) and small, irregular farming area (average size per farm of 0.29 ha). This type of urban farming helps securing urban food supply, supporting low-income families' living and protecting urban biodiversity (Food and Agricultural Organization of the United Nations 2011). Its educational role in connecting metropolitans to the food production process and ecology also represents an important societal benefit. With the expansion of urbanization in Asia, small-sized urban farming can be expected to become increasingly popular and play a major role within the urban matrix.

However, preliminary exchanges with local farmers have revealed a series of potential problems caused by *S. invicta* related to health, farming practice and productivity, as well as educational activities, ultimately leading to economic issues and the sustainability of these farms. Moreover, the current prevalence of the RIFA infestation and local control methods efficiency within Hong Kong agricultural land use have not been investigated. This lack of data has limited the studies to control the invasion and to assess potential socio-economic costs and spread of this species. Hence, in this study we aimed to (1) evaluate the prevalence and area of *S. invicta* infestation in Hong Kong urban agricultural system, (2) investigate the occurrence and abundance within both traditional and organic farms, which are distinct through their use or not of chemical pesticides, (3) explore the impact of *S. invicta* on biodiversity under different agricultural practices, and (4) evaluate the farmers' perceptions on the spread and impacts associated with the fire ants through survey method while identifying the potential main problems associated with the presence of this species, as well as the methods currently used for its control.

Methods

Study period

Hong Kong is located within the Indomalayan realm and is characterized by a subtropical climate. The study was performed during the wet season and early part of the dry season with field surveys conducted from July to November 2017. Temperature averaged 28.2 °C during the period surveyed (minimum = 19 °C; maximum = 36.6 °C). Fieldwork starting time for each sampling session was dependent to the farmers' availability but mostly started after 10:00 AM, which consequently limited the impact of cooler temperatures on the later part of the season. The study was separated into two distinct parts: 1) a field ant survey to assess the presence of *S. invicta* and other ant species at each site, and 2) farmer interviews to collect information about the perceived impacts of *S. invicta* on agricultural, economical and health aspects.

Fig. 1 Fig. 1 Example of urban farming in Hong Kong sitting between housing development (Left) or villages (Right) with a variety of crops grown over small and irregular areas

Study sites

Ant surveys were conducted on 50 farms for a total of 53 study sites located within the New Territories region where most agricultural areas are located and one more site on south Lantau Island (Fig. 2). Accesses to the farms were all confirmed with prior authorization by email or acquaintance's referral before conducting the study. No preference on the practice type (traditional, organic, integrated pest management) or *S. invicta* infestation level in an area had been set prior to the survey.

Ant sampling

The sampling aimed to establish the overall distribution of *S. invicta* within Hong Kong agricultural systems, with measurements of its occurrence and abundance within various crops.

At each study site, depending of the farm size, one to four study plots with 30 × 30 m grid configuration were set. Baiting stations, made of 5 × 5 cm white laminated paper, were installed along the grid with each bait separated by 5 m from each other for a total of 49 stations maximum per grid. However, due to the relatively small and irregular size of the local farms, adjustments have been made to accommodate these constraints. As a result, the mean stations number per plot was 20.4 (SD ± 9.7; min = 5; max = 47). A spoon of 2.5 mL of tuna and honey mixed bait (50% *v*/v) were placed on each baiting station for a period of one hour. Ant abundance at each station was recorded under a ranking system ranging from 0 to 6 (0 = no ants; 1 = 1 ant; 2 = 2–5 ants; 3 = 6–20 ants; 4 = 21–50 ants; 5 = 51–100 ants; 6 = >100 ants) adjusted from previous studies (Andersen 1997; Parr 2008). This method allows to minimize the distortion of ant abundance measurements that are affected by the distance between baiting stations and the ant active foraging area (Andersen 1997). Furthermore, under tropical climates, the one hour time period was sufficient for the bait to be discovered and exploited by behaviorally dominant species (Hahn and Wheeler 2002), with *S. invicta* particularly efficient for discovering, exploiting and monopolizing food source (Calcaterra et al. 2008). Crop types near each baiting stations were recorded in common name with reference to the farmer. As the farmer did not specify the crops to species level, crop types would then be identified and classified to the plant family level to avoid any misunderstanding or inaccuracy (Online resource 1). Meanwhile, the baiting station at the field overgrown with weed or with no plantation along the grid would be noted as "overgrown field" and "fallow field". Ant vouchers were collected at each bait and preserved in 75% ethanol with information on location and date, for later use in species identification. Identification was completed to species level or when not possible to morphospecies (Online resource 1).

Survey of farmers

Although 50 farms were surveyed for ant sampling, a total of 53 farmers had been contacted as 3 farmers were only willing to be interviewed but not to provide farm access. But meanwhile, two farmers declined to respond the questionnaire (but provided access to their farm), only 51 interview questionnaires were collected. The interview aimed to obtain farm's primary information (e.g. size, exploitation duration, type of cultivation and crops type), farmers' perception and control

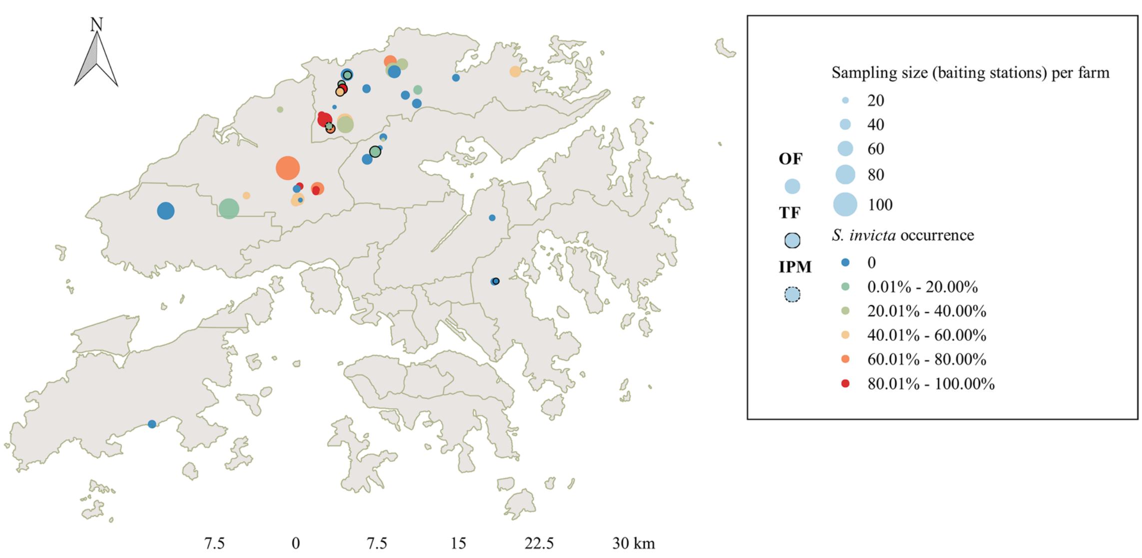


Fig. 2 Map of Hong Kong presenting the distribution of the different sampling sites, the sampling effort size (radius) and the percentage of occurrence of *S. invicta* by 20% scaling. (Notes: OF: Organic Farm [circle with no outline]; TF: Traditional Farm [circle with solid outline]; IPM: Integrated Pest Management farm [circle with dashed outline])

method towards *S. invicta*, as well as the history of spread. The farming practices of the study sites were also identified by the farmers with the following definition: 1) Traditional farming: broad-use of chemical pesticide. 2) Organic farming: complete ban of using chemical pesticide. 3) Integrated Pest Management: adopt multiple pest-targeted methods while open to the limited use of chemical pesticide. It should be noted that around half (45%) of organic farming sites were not officially-credited. Interviews were conducted in Cantonese to reflect the language commonly spoken by local farmers. The questionnaire is presented in the Online Resource 2. To compare the farmers' perception on several issues (e.g. effect of *S. invicta* stung, work disturbance from *S. invicta* and efficiency of control methods), scaling systems were applied to those questions to obtain quantitative data.

Analysis

To understand how the local agricultural practices and crops may affect *S. invicta* spread, two indicators were calculated. 1) The occurrence of *S. invicta* at farms indicates the incidence of *S. invicta* present at each farm, and was calculated as the fraction of baiting stations with *S. invicta* presence over the total number of baiting stations at each farm. 2) The occurrence of *S. invicta* at crops indicated the incidence of *S. invicta* to be present on particular crop family, and was calculated as the fraction of baiting stations with *S. invicta* present over the total number of baiting stations for a particular crop family. The occurrence of *S. invicta* at "overgrown field" and "fallow field" were also treated the same as occurrence at crops.

To investigate the relationship between *S. invicta* and ant diversity, two indicators were used: species richness and species evenness with the use of the Simpson's index of diversity ($D = 1 - \sum P_i^2$ [Morris et al. 2014]). The relative occupancy of *S. invicta* at each farm, which indicated the proportion of *S. invicta* in the ant community was calculated as the number of baiting stations occupied by *S. invicta* out of the total number of baiting station with ant present.

Python 3 (Python software foundation 2017) was used to calculate the indicators of each farm and visualize the graphics. R 3.4.2 (R core team 2017) was then used in this study for statistical test. Moran's I index was calculated by the function "Moran.I" in R's library *ape* (R documentation 2018) to test for spatial-autocorrelation effects in this study. The study sites with corresponding *S. invicta* occurrence and sampling size were mapped (Fig. 2) using QGIS 2.18.14 (QGIS development team 2017). A Mann-Whitney-Wilcoxon test (Wilcoxon 1945; Mann and Whitney 1947) was applied to compare 2 groups of nonparametric data of indicators between organic and traditional farms. To investigate differences in the nonparametric occurrence and abundance levels of *S. invicta* among the different crops (> 10 plant families), crop families with a sampling size >20 were selected for visualization and Kruskal-Wallis test by ranks (Kruskal and Wallis 1952) with post-hoc Dunn test (Dunn 1964) was applied for multiple comparisons using these nonparametric data. "Overgrown field" and "fallow field" were also included in the same analysis for crops differences. The effect size was also calculated: for Mann-Whitney-Wilcoxon test in $R = \frac{Z}{\sqrt{N}}$ (Fritz et al. 2012) and for General Linear Regression(GLM) in Pearson Correlation Coefficient *r*.

Results

Sampling results

86 plots were set for a total of 1758 baiting stations across 53 study sites; 44 sites (total 1526 baiting stations) performed on organic practice farm (OF), 8 sites (209 baiting stations) performed on traditional practice farms (TF) and only 1 site (23 baiting stations) performed at an Integrated Pest Management practice farm (IPMF). A total of 36 ant species (20 genera) were collected with 36 species retrieved on OF, 9 species on TF and 5 species on IPMF (Online Resource 1). Species evenness, calculated from the Simpson's index (D) has an overall value of 0.492 (SD ± 0.308), an average value of 0.478 (SD ± 0.311) at OF, 0.558 (SD ± 0.322) at TF and 0.574 at IPMF. Overall, *S. invicta* was present in 66% (35 out of 53) of the sites sampled, 27 in OF, 7 in TF and was also present on the only IPMF. A significant and positive spatial autocorrelation was detected indicating geographic clustering (observed Moran's I = 0.1936, SD ± 0.070, $P = 0.002$).

Solenopsis invicta occurrence and abundance at different farm practices

When present, *S. invicta* occupied 35.2% (618 out of 1753) of the overall baiting stations installed, 34.0% (71 out of 209) in TF; 35.8% (544 out of 1521) in OF; 13.0% (3 out of 23) in IMPF. Meanwhile, sample size of each sites showed small effect to the occurrence ($r^2 = 0.071$). No significant difference between OF and TF was detected (Mann-Whitney- Wilcox test, $n_{OF} = 44$, $Median_{OF} = 20.7$; $n_{TF} = 8$, $Median_{TF} = 18.8$; $U = 162.5$, $P = 0.737$;). However, abundance of *S. invicta* on baits was significantly higher in OF than in TF ($n_{OF} = 544$, $Median_{OF} = 3$, $SD_{OF} \pm 1.14$; $n_{TF} = 71$, $Median_{TF} = 3$, $SD_{TF} \pm 0.69$; Mann-Whitney- Wilcox test, $U = 15{,}916$, $P = 0.011$, $R = 0.102$).

Biodiversity and *S. invicta* relationship under different farm practices

The relationship between *S. invicta* and ant diversity and composition under different farming practices (OT and TF) was studied using occupancy (the proportion of *S. invicta* within the ant community), species richness and Simpson's index. No differences in biodiversity indices were found between farming practices ($n_{OF} = 44$, $n_{TF} = 8$; *S. invicta* occupancy: $W = 153$, $P = 0.561$; species richness: $W = 214.5$, $P = 0.331$; Simpson's index: $W = 147$, $P = 0.469$) indicating that the farm practices did not contribute to affect the proportion of *S. invicta* within the local ant community, nor the number of species or species evenness.

However, *S. invicta* community occupancy was significantly, negatively and linearly-correlated with species richness (GLM: $r_{OF} = -0.559$, $RSE = 2.285$, $F = 19.06$, $df = 42$, $P < 0.001$) and species evenness (D) (GLM: $r_{OF} = -0.708$, $RSE = 0.222$, $F = 42.31$, $df = 42$, $P < 0.001$) in OF indicating that increased presence of *S. invicta* was associated with lower ant species richness and evenness. Instead, in TF the occupancy was insignificantly correlated in TF for species richness (GLM: $r_{TF} = -0.533$, $RSE = 2.284$ $F = 2.376$, $df = 6$, $P = 0.174$) and species evenness (D) (GLM: $r_{TF} = -0.538$, $RSE = 0.293$, $F = 2.444$, $df = 6$, $P = 0.169$) (Fig. 3).

S. invicta occurrence and abundance within different crops

A total of 95 different crop types were recorded at the proximity of baiting stations representing a total of 36 plant families. Among these, 16 plant families were encountered near at least 20 baiting stations (total: 1121 baiting stations), with fallow and overgrown field (293 and 47 baiting stations respectively) also included in the following analyses. *Solenopsis invicta* occurrence ranged from 64.0% (Amaryllidaceae) to 12.9% (Asteraceae) (Fig. 4a). Significant difference in abundance levels of *S. invicta* were observed between crops families (Median = 3; Kruskal-Wallis test, $\chi^2 = 46.07$, $df = 17$, $P < 0.001$) for the Caricaceae crops in which *S. invicta* abundance were significantly higher than the Amaryllidaceae ($P = 0.003$), Basellaceae ($P = 0.010$), Convolvulaceae ($P = 0.007$), Cucurbitaceae ($P = 0.022$), Malvaceae ($P = 0.013$), Marantaceae ($P = 0.002$), Moraceae ($P = 0.002$), overgrown field ($P = 0.002$), Poaceae ($P = 0.006$), Rutaceae ($P = 0.008$), Solanaceae ($P = 0.005$); and abundance of *S. invicta* at Fabaceae crops were also significantly higher than fallow field ($P = 0.005$) in post-hoc Dunn's test (Fig. 4b). Insignificant differences were detected among the rest of the comparisons between crops families in the post-hoc dunn's test ($P > 0.05$).

Farmers interview summary

Farms' information

Farm size varied widely from 74 to 50,000 m^2 and with an average size of 4581 m^2 and median size of 2667 m^2. It should be noted that a majority of farms presented a modest area: 17% with area < 0.1 ha, 53% with area of 0.1 to 0.5 ha, 24% with area of 0.5 to 1 ha and only 6% with area > 1 ha. Similarly, age of the farms vaired widely from 1 to 75 years of cultivation with 32% cultivated for less than 5 years, 34% cultivated for 5 to 15 years, and 34% cultivated for over 15 years.

Solenopsis invicta observations

A majority of farmers (78%) reported to have observed *S. invicta* on their farm, with 83% indicating the first appearance of *S. invicta* within the last 15 years while the rest reported the first appearance from 20 to 60 years. 50% of the subset (appearance<15 years) also noted increased spread of the species in the past 5 years while other 25% reported decreasing. The rest of the farmers indicated observing neither a decrease or increase in the spread. The presence of *S. invicta* was confirmed through sampling in 84% of these farms.

Interviewee responses on *Solenopsis invicta* impacts on farmers and farming activities

Stinging frequency by *S. invicta* is presented on Fig. 5. If 10% of the farmers stung did not report any health reactions, others reported various single/ multiple reactions. 66% of the interviewee with reaction(s) reported blister, 40% skin swelling, 23% itchiness, and 3% allergies, dizziness and other extreme cases, such as breathing difficulties and anaphylaxis. It should

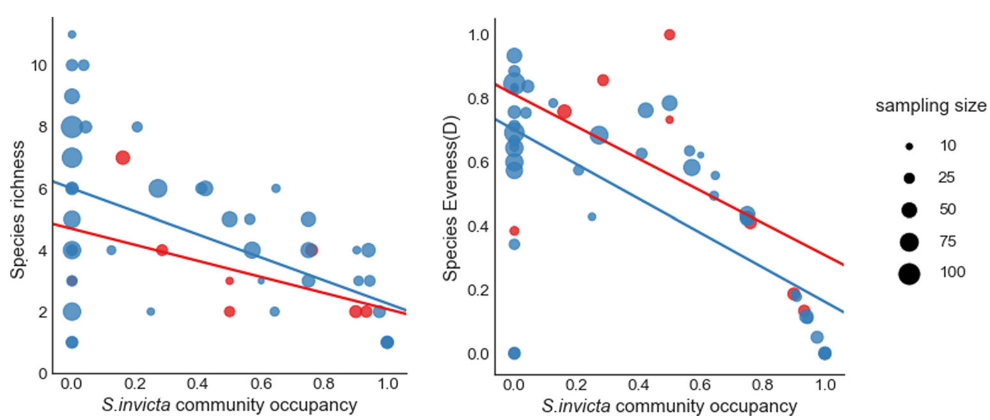


Fig. 3 Relationship between *S. invicta* occupancy and ant species richness (**a** [LEFT]); and species evenness (D) (**b** [RIGHT]). Note that the regression lines for TF (red) are shown here but insignificant in contrary to the regression lines of OF (blue) (Blue dots: Organic farms; Red dots: Traditional farms)

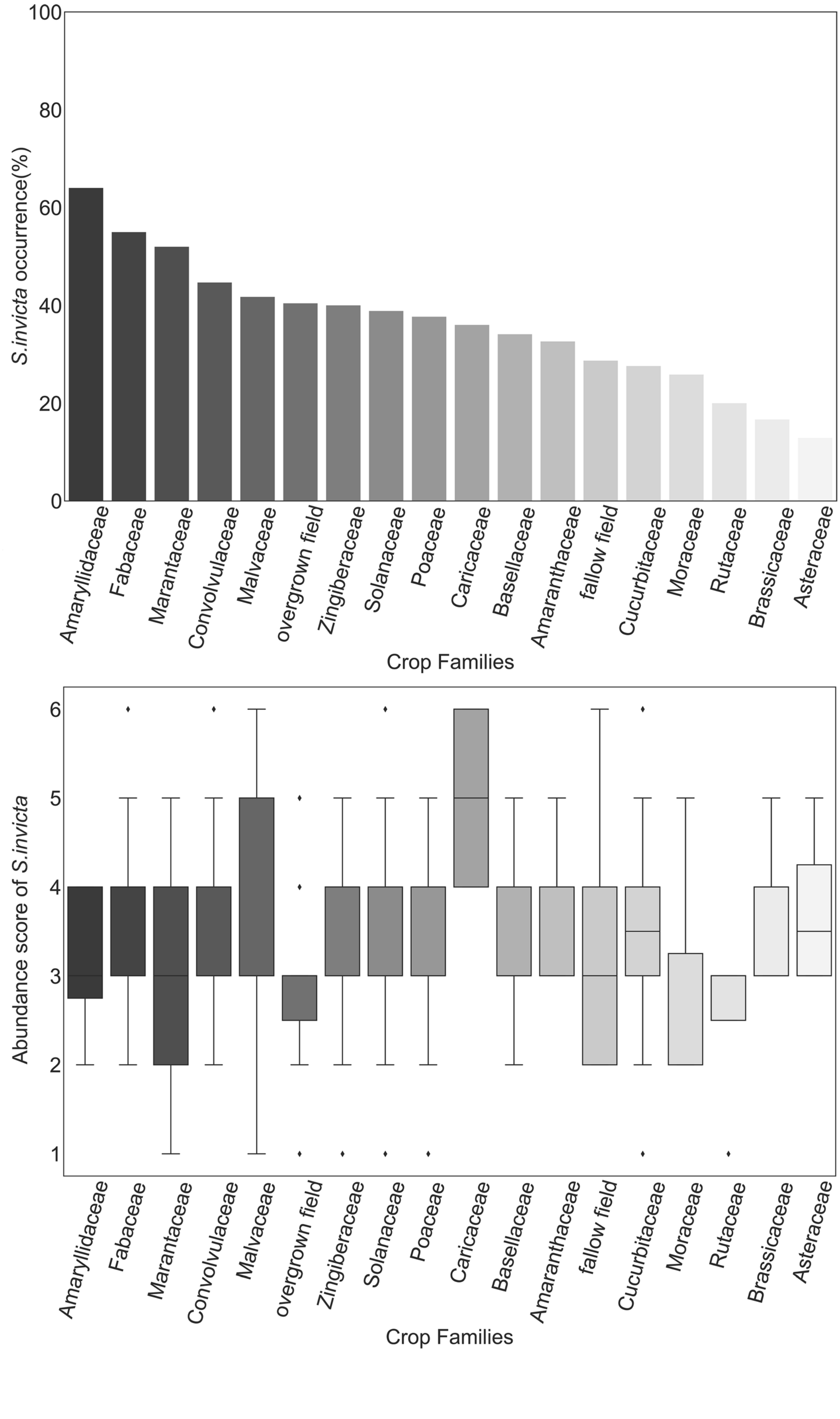


Fig. 4 Occurrence (**a** [ABOVE]) and abundance (**b** [BELOW]) of *S. invicta* at different crops family, with a minimum threshold of 20 baiting stations selected for visualization

be noted that among the reports of medical issues, half (46%) were reports of multiple reactions developing altogether, especially for blister, swollen and itchiness.

Farmers rated the work disturbance due to *S. invicta* on a scale of 0 (no disturbance) to 10 (temporary stop of activities for hours). 3% reported no disturbance (rank = 0) from the

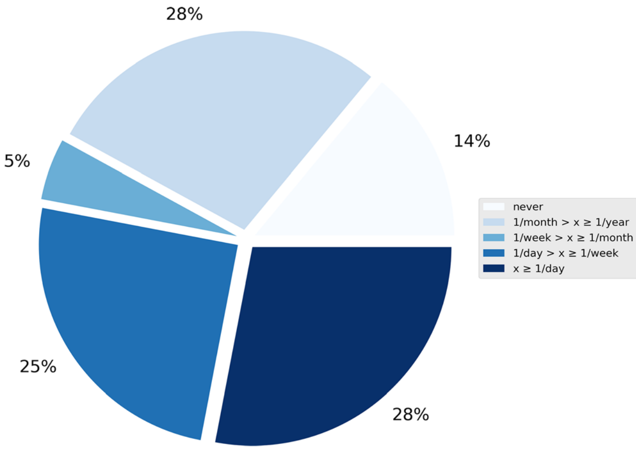


Fig. 5 Sting frequency (x) by *S. invicta* on farmers interviewed

species, 42% ranked 1–3, 38% for the rank 4–6 and 6% for the rank 7–9. 11% of the farmers reported a complete and temporary stop (rank = 10) of their farming activities due to the presence of *S. invicta* in their working zone. Although they claimed to resume work whenever the species was absent from their working area, the time period of work suspension was not precised.

A quarter of the farmers (26%) did not perceive any negative impacts of *S. invicta* on crop productivity, but a majority (74%) reported negative impacts of this species on crops - with 46% perceiving a reduction of less than 10% of production; 15% a reduction of 11–20%, 19% a reduction of 21–30%, and 10% a reduction of 61–80% of total production; with corn (−29%), okra (−29%) and eggplant (−21%) production perceived as most affected by *S. invicta*. Associations between *S. invicta* and other pest insects like aphids or coccids were noted by 26% of the farmers but the insects involved were not identified.

Two third of the farmers expressed other types of concerns. In particular, 44% of farmers reported problems for visitors' health and safety due to *S. invicta* stings which as result limit educational activities; 7% reported avoiding cultivation in areas with high population density of *S. invicta*, 7% reported increased stress at work from carefulness measures (5%) and mental pressure (2%). Finally 2% reported increased workload due to pest management and 2% reported the invasion of their house by this species.

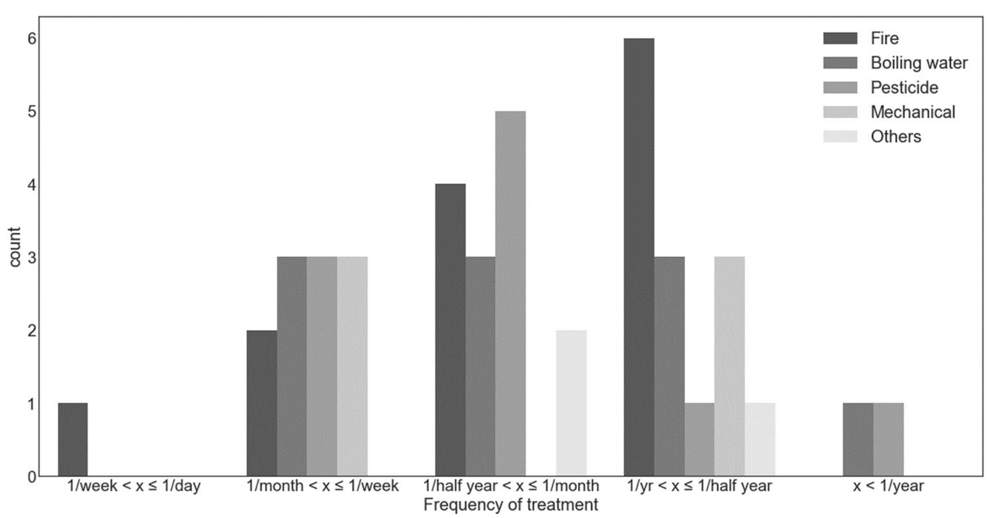
Solenopsis invicta management

Over three quarters of the interviewees declaring infestation problem (77%) used control methods to suppress *S. invicta* populations. A majority of these farmers claimed to use single type practices such as mechanical (43%) or pesticide (20%) control, while 37% used a combination of both mechanical and pesticide control methods. Control methods used are: pesticides (29%), boiling water (27%), fire (25%), mechanical (plowing, digging, weeding) (9%) and others (i.e. use of urine, lime powder, detergent, mulching and camellia seed powder) (9%). Fire ant powder (53%), agricultural pesticide (29%) and household insecticide (18%) represented the three major types of pesticides reported. The frequency of each control method is also presented in Fig. 6.

Control method effectiveness was scored by the farmers based on their personal experience with 0 (no effect) to 10 (complete destruction of *S. invicta*). The average score of perceived pesticide efficiency in controlling *S. invicta* was 6.47 ($n = 15$, SD ± 2.48); boiling water was 5.78 ($n = 14$, SD ± 2.43); fire was 5.2 (n = 15, SD ± 2.62); mechanical was 3.75 ($n = 4$, SD ± 2.08); others was 3.75 (n = 4, SD ± 0.96). Among the control methods used, complete efficiency in the destruction of *S. invicta* was cited fifth times for pesticides, twice for boiling water and once for fire. Besides active management, 33% of the farmers had reallocated or shifted the cultivation area to passively avoid *S. invicta*.

Finally, the annual cost in *S. invicta* management was estimated by farmers to be less than 1000 HK$ (<130US$) for

Fig. 6 The frequency (x) of *S. invicta* control practices (Notes: mechanical: plowing, digging, weeding; Others: use of urine, lime powder, detergent, mulching and camellia seed powder)



75% of the interviewees, while 25% estimated a cost comprised between 1000 to 5000 HK$ (=130–640 US$).

Discussion

Since its first detection in Hong Kong 15 years ago, *S. invicta* now appears widespread within urban agricultural systems with two-thirds of the farms sampled invaded. The presence of *S. invicta* is particularly important in specific regions (such as middle and northern part of the New Territories) where most of local farms are located. Potentially, the spread of *S. invicta* might be larger considering that 78% of the farmers interviewed claimed to have this species on their farms, even when 16% of them this could not be confirmed. This could be explained by the limited sampling used in this study or by the potential removal of this species before our survey was conducted. Alternatively, other native ant species can be confused with the RIFA, such as species of the genus *Carebara* (subgenus *Pheidologeton*) which present similarities with *S. invicta* in size, colour (reddish) and polymorphism and are sometimes mistaken by farmers (personal observation).

Interestingly, only the abundance, but not the relative occurrence, of *S. invicta* was affected by the difference in agricultural practices (OT vs. TF). Despite small statistical effect size, the actual effect of the significantly lower abundance in TF environment should be larger than the statistical expectation as the actual abundance was scaled-down in the survey. This means that the use of insecticide in TF could temporarily suppress the ground appearance level of *S. invicta* but not their overall establishment. This result contradicts the expectation that insecticide treatments would eradicate *S. invicta* population. The improper application of insecticides and incomplete identification of fire ant populations within traditional farms might contribute to the maintenance of *S. invicta*. First, the efficiency of insecticide against *S. invicta* depends on the method used and its dosage (Rust and Su 2012). The improper use of insecticide might only repel *S. invicta* (Kafle and Shih 2017) from the insecticide-treated area but not effectively eliminate the population. In addition, the infrequent treatments could also contribute to the proliferation of *S. invicta*. Empirical study found that *S. invicta* was able to reinvade from nearby environment after only 4 months following the previous insecticidal treatment that led to a 98.9% reduction of its population (Callcott and Collins 1992). With most of the infested farms concentrate in the particular regions (Fig. 2), this environment provides huge advantage for *S. invicta* to reinvade the original farm after being repelled to the neighboring farms. Thus, the frequency and scale of insecticide application is important to control *S. invicta* occurrence within Hong Kong farms, with locally adapted and coordinated control methods needed.

If the type of agricultural practices seems independent of biodiversity indices in terms of species richness and evenness, the level of *S. invicta* occupancy was negatively correlated with the species richness and species evenness of other ant species in OF (Fig. 3). This pattern is consistent with previous studies suggesting that the introduction of *S. invicta* would lead to the decline of the original community species richness and evenness (Gotelli and Arnett 2000; Morris and Steigman 1993; Porter and Savignano 1990). Surprisingly, the negative relationship of *S. invicta* with both biodiversity indicators do not apply in the TF. These indicated that several ant species could co-occur and maintain their competitiveness with the *S. invicta* (Morrison and Porter 2003; King and Tschinkel 2006), particular for those species in TF. However, it should be noted that our results did not experimentally tested the causal mechanisms of these relationships and that further work would be needed.

Solenopsis invicta occurrence and abundance at different crops

Differences in occurrence and abundance on crops indicated that *S. invicta* infestation levels might be influenced by the type of cultivation (Fig. 4). While this is beyond the scope of this study, we here briefly discuss some of the factors that could contribute to the RIFA success. First, agricultural systems are regularly disturbed (e.g. mowing, plowing) with such habitats known to be particularly suitable for this species (King and Tschinkel 2006; LeBrun et al. 2012; Atchison et al. 2018). Second, agricultural practices (e.g. irrigation and shifting cultivation) help to maintain abiotic conditions, especially soil moisture level, favorable for the establishment and growth of these colonies, with farmers' observations aligned with empirical studies supporting that increasing soil moisture level promotes fire ant occurrence (Ali et al. 1986; LeBrun et al. 2012). However it should be noted that in our study sites, habitats not currently under a particular crop regime (i.e. having multiple crop families within the same field) were similarly colonized by the RIFA. Third, some of these plantations might also host sap-sucking insects known to attract fire ants (and confirmed by farmers' observations), however with the similar result between TF and OF implying that the sap-sucking insects would not attract fire ants, the differences here might not necessarily be of prime importance. Instead, ant-plant mutualism could directly benefit the fire ants. Indeed most of plant families we sampled also possess extrafloral nectaries (EFNs) (Weber and Keeler 2012) which are capable of attracting fire ants (Blüthgen et al. 2004; Lange et al. 2017). However, after frequent human manipulation the presence or the specific information of EFNs for each crop was unknown in our study.

While it would be tempting to draw particular conclusions about the affinity of a specific type of crop with

S. invicta, a number of caveats need to be considered here. First the baiting stations here were not independent to one another and some crops could cover large continuous areas. Second, most crops observed are maintained for a short period of time (a few weeks or months) while the RIFA colonies remain for several years, thus the presence of a particular crop at a given time could be independent of *S. invicta* abundance. Third, the intensity of crops management through irrigation or farmers' activity could vary from crop to crop. Last, sampling sizes for each crop type were not standardized. As previous plantations and anthropogenic history also contribute to the fire ant colony development, thus associating the presence or abundance of *S. invicta* to a particular crop type could be hazardous.

Solenopsis invicta economic impact

A majority of farmers perceived *S. invicta* negatively for crop production, with 44% estimating impacts to exceed 10% and up to 80%; in accordance with previous studies in the USA with losses estimated between 15 to 50% of the production (Adam 1986). One extreme impact mentioned by 7% of the farmers is the abandonment of land invaded by high density of *S. invicta*. Considering the small size of the farms surveyed and the price of land in Hong Kong, this represents a major damage for local farmers; and which might become more frequent as the spread and abundance of *S. invicta* in Hong Kong increase.

Except the direct damage to the crop, several medical problems representing another source of economic damage were recorded throughout our study. Although *S. invicta* generally induces mild medical problems like blister and swollen, extreme cases including the anaphylaxis, allergic, breathing difficulty were recorded. It should also be noted that other more serious pathology like seizures, mononeuritis, and nephrotic syndrome have also been recorded in response to *S. invicta* sting (Moffitt et al. 2004). Other economic costs, not considered here like hospitalization and interruption of work, could be substantial.

Other indirect economic and societal costs were also discovered. In urban regions like Hong Kong, economic activities of small farms rely on a wide range of activities besides crops production such as educational and societal activities. They rent out part of their farmland and also provide ecotour to metropolitan families. Farmers are also regularly assisted by urban citizens who help on the farm maintenance and crop production voluntarily. However, farmers depicted a decreased in these activities due to the stinging risks encountered by the visitors and their educator guides. Several interviewees even ceased public activities to prevent any possible stung to the visitors (particularly children) and claimed to be suffering from economic lost. Here again, the repeated stinging and associated health hazards due to *S. invicta* weakens this network and increase the difficulty to invite or keep new visitors and volunteers. This indirect economic lost would be expected to rise with the growing popularity of leisure faming and the continuous *S. invicta* spread. An indirect consequence, yet of importance in megalopolis region like Hong Kong (and further in Asia) is the disconnection between food production and consumption by citizens which are not exposed to farming production. The cessation of educational activities, as a consequence of the fire ant invasion, would thus increase this gap and the disconnection of urban population with natural habitats and food production process.

Solenopsis invicta management

This study has showed the major constraint for fire ant local management, and what seemed to result from a lack of professional guidance. It is unclear how much official support and guidance local farmers are receiving and using. Nonetheless, farmers mostly relied on labor-intensive, time-consuming and relatively ineffective control methods (e.g. fire, watering and mechanical method). They also often perform some inappropriate or inefficient methods (e.g. use of urine, lime powder, detergent, mulching, camellia seed powder and household pesticide) on the basis of rumors from the internet and farmers' community. The need of professional guidance for fire ant control is particularly important in Hong Kong while considering the scattered small-sized farming and the closely-connected farmers' community in local urban agriculture. While the farmers' community was not able to control the RIFA infestaion, their occasional exchange of tools/ plants/ soil might carry fire ant and boost the spread of fire ant to the scattering locations of urban farmlands in Hong Kong.

Along with the growing urbanization in Asian cities, smiliar model of urban agriculture is expected to emerge and promote the possible spread of *S. invicta* within the region soon. Thus the professional guidance of control strategies shall be the key to prevent fire ant proliferation in the local or upcoming Asian urban agriculture. Here we briefly introduce several control strategies practiced in rural farming and their suitability with regard to the constraints in urban agricultural system in Hong Kong and other Asian countries.

First, several organic pesticides extracted from plants are shown to kill or repel fire ants, such as the volatile compounds of the plants *Tephrosia vogelii* (Li et al. 2014), *Syzygium aromaticum* (Kafle and Shih 2013), *Eutrema japonicum* (Wasabi; Hashimoto et al. 2019) or the cold press-extracted orange oil (Vogt et al. 2002). Integrating the tactics by broadcasting the organic pesticide recipes and following by labor-intensive method, like hot water or drenching, to focus on remaining fire ant colonies can further eliminate *S. invicta* populations (Drees 2002). Second, controlling abiotic factors essential to fire ant, like soil moisture level and temperature, through limited irrigation and reduced soil coverage can lower the chance of fire ant prevalence (Ali et al. 1986; LeBrun et al. 2012; Dabney et al. 2001; Ramakrishna et al. 2006). Due to the attractiveness of weed-mulch to fire ant (Pullaro et al. 2006), its use by local farmers should be avoided. Third, the introduction of biological agents to management scheme, like microorganisms *Thelohania solenopsae* (Oi and Williams 2002) and strain *Beauveria bassiana* (Kafle et al. 2011), can also potentially reduce fire ant populations. Nonetheless, the application of these strategies requires caution on their non-target effect especially from the introduction of biological agents, and preliminary tests are suggested to ensure the local biodiversity stability. Farmers should also limit their exchanges of soil and plant material from one region to another to limit the spread of the fire ant, in particular in areas where no established populations have been recorded yet (e.g. south Lantau Island).

Still, the urban farming setting should also be considered before implementing new control strategies. Unlike rural agriculture where monoculture normally creates large areas of homogenized habitat with only a few actors responsible for the control strategy to implement, small urban farms present multiple crops and high spatial proximity creating a mosaic of heterogenous and fragmented habitats favoring the spill-over of fire ants from one habitat to the next. The proximity and small size of farms with the rest of the urban setting, and the use of treatments with various levels of efficiency, if any, against the fire ants, increase the risks of spill-overs. Thus, increased coordination and agreements between a variety of actors including farmers but also other stakeholders (e.g. city council, urban citizens, visitors …) is required for concerted efforts and strategies to suppress populations of *S. invicta*. This requires a region-wide strategy coordinated by officials and professionals to ensure more efficient planning of fire ant management within urban farming.

Conclusion

This study provides a baseline for a quantitative evaluation of the fire ant prevalence and impacts within Hong Kong urban agricultural ecosystems confirming the high occurrence and clustering of fire ants in the New Territories. Our results revealed the limited success of pesticide and local management strategies towards *S. invicta*. If current local management continues, the fire ant prevalence is expected to expand and the associated economic lost will increase or at best remain the same. The prospect of the fire ant situation in Hong Kong is concerning and future research should focus on the ecological and biological factors contributing to the *S. invicta* crops preference, the actual damage to agricultural production and feasibility of alternative management strategies in local application. With growing urbanization in Asia, urban farming is expected to gain more popularity but also to be increasingly exposed to biological invasions. These studies could then provide direction for management and research against the spread of *S. invicta* and response to the future trend of small-sized urban farming in Asia.

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