Title: ***Relative trapping efficiencies of different types of attraction traps for three insect orders in an agricultural field***

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Abstract

Insect monitoring is an important step for adequate and sustainable management of crops. Attraction traps, which capture insects using colours and shapes, are one of the most popular methods for insect monitoring. Despite such popularity, there are surprisingly few studies that quantitatively compare relative trapping efficiencies for a wide range of insect taxa among different types of attraction traps in crop fields. Here, we compared trapping efficiency among seven attraction traps (three colours each of the pan and sticky traps and a yellow funnel trap) for Hymenoptera, Diptera, and Coleoptera in crop fields of two cucurbitaceous species (*Cucurbita maxima* and *Momordica charantia*). We found wider usability of the traps than previously thought. Funnel traps that have been developed to capture Lepidoptera exclusively gathered Apidae (Hymenoptera), especially *Bombus diversus diversus* Smith, more than any other traps. Sticky traps, which are often applied to Diptera and Hemiptera, efficiently sampled many families of Hymenoptera and Coleoptera, as well as Diptera. Furthermore, across-trap comparison of the three colours clarified that colour effects on some insect taxa can vary depending on trap types. Our study demonstrated wider usability of the traps than previously known and directed effective trapping methods for future studies.

Introduction

Insects provide essential ecosystem services for crop production, including pollination services by flower-visiting insects and plant bodyguards by predatory or parasitoid insects (Hooper et al. 2005; Klein et al. 2007), while some insects harm crops as agricultural pests. Conversely, crop production can enhance or destroy insect diversity depending on selected agricultural practices (Calvo-Agudo et al. 2020; Fuller et al. 2005; Pywell et al. 2015). Therefore, monitoring the local entomofauna in crop fields is a critical step for effective and sustainable agricultural crop management (Kiritani 2000; McGrady et al. 2019).

One of the popular monitoring methods for entomofauna is the use of trapping devices. In particular, traps which capture insects using colours, odour and shapes (e.g., pan, sticky, and funnel traps) are called as attraction traps, in contrast to traps which capture insects by interception (e.g., flight intercept, malaise, and pitfall trap) (Missa et al. 2009). For example, pan traps, which are one of the most common insect traps, are often used to sample agricultural pests and flower visitors, such as flying Hymenoptera, Coleoptera, Diptera, and Hemiptera (Lebuhn et al. 2016; Leong and Thorp 1999; Morandin and Winston 2005; Scriven et al. 2013; Toler et al. 2005; Vrdoljak and Samways 2012). Sticky traps are less common than pan traps, and often used to monitor the abundance of pest insects, including Hemiptera, Diptera and Thysanoptera, in agricultural fields and houses (Kuwazawa 2002; Shimoda and Honda 2013; Tsujino et al. 2006). Funnel traps (i.e., plastic cups having a funnel-structure) are intensively utilised to capture arboreal Coleoptera (Hanula et al. 2011; Hayes et al. 2009; Miller and

Duerr 2015) and Lepidoptera (Kehat et al. 1981; Kehat and Greenberg 1978; Malo et al. 2006).

Colour is an important factor determining the sampling efficiency of attraction traps. The attractiveness of each colour often depends on insect taxa and ecological functions. For example, yellow attracts a relatively diverse number of phytophagous insects and their parasitoids, such as leafhoppers, parasitoid wasps, flies, and bees (Abrahamczyk et al. 2010; Prokopy and Owens 1983; Shimoda and Honda 2013; Vrdoljak and Samways 2012), whereas blue is mainly preferred by flower-visiting insects, such as Thripidae (Chen et al. 2004) and Hymenoptera (Campbell and Hanula 2007; Cane et al. 2000; Giurfa et al. 1995; Kimoto et al. 2012; Leong and Thorp 1999). It should be noted that the attractiveness of colours to insects could vary depending on the circumstances, such as shapes and the background component of traps (Liburd et al. 2009; Mainali and Lim 2010; Prokopy and Owens 1983). Considering the context-dependency of colour effects on insect vision, differences in traits of the pan and sticky traps, such as angles (horizontal or vertical), texture, or height, may also alter the effects of colours on each insect.

Because no trapping method can accurately reflect the community structure of all local species, information regarding the taxonomic bias of individual trap types is necessary to effectively apply traps (Hoback et al. 1999). Nevertheless, we know little about non-biased information regarding relative trapping efficiencies of different types of attraction traps for different orders, since attraction traps tend to have been applied to collect a specific order or functional groups. There are few studies reporting that some types of attraction traps gather insects which are taxonomically distinct from targeted insects. For example, in a cranberry garden, sticky traps for leafhoppers captured lady beetles, hoverflies, parasitoid wasps, and honeybees (Rodriguez-Saona et al. 2012). Information regarding relative trapping efficiencies of attraction traps for a wide range of insects would be helpful to determine optimal trapping methods for insects that have been difficult to trap. Moreover, it will meet the increasing requirement for accurate monitoring for diversity of insects in crop fields (Blaauw and Isaacs 2015; Duelli et al. 1999; Landis et al. 2000; Scherr and McNeely 2008).

The objective of this study is to evaluate trapping efficiencies of multiple types of attraction traps for a wide range of insects, considering the consistency of colour effects among different trap types. Specifically, we examined the trapping efficiency of three insect attraction traps (pan, sticky, and funnel) in Hymenoptera, Diptera, and Coleoptera in an experimental garden growing two Cucurbitaceae species (*Cucurbita maxima* Duchesne and *Momordica charantia* L.). These plants are ideal for our study because they produce abundant food for insects, such as nectar and pollen, as well as foliage, and thus, attract various insect species (Phillips and Gardiner 2016; Quinn et al. 2017). In this study, we evaluated trapping efficiency using three community indices: cumulative abundance, relative abundance, and family richness. Cumulative abundance informs us of the advantages and disadvantages of each trap under these experimental conditions. Relative abundance, which is a standardised cumulative abundance, provides us more general response patterns for the three insect orders (Nakamura et al. 2006; Waltz and Whitham 1997; Whitham et al. 1994). Family richness suggests which traps could collect diverse families of insects.

Materials and Methods

Study site

The field experiment was conducted during summer (from late June to August) 2018 when *C. maxima* and *M. charantia* were in full bloom at the experimental garden of the Tsukuba-Plant Innovation Research Center (36°07′, 140°05′), Ibaraki Prefecture, Japan. We used two areas (2.64 a each), both of which comprised two rows of *C. maxima* and two rows of *M. charantia*. In individual rows, 20 plants were grown with 1 m spacing, and each row was spaced 3 m apart. The distance between the two areas was 150 m.

Description of traps

We used three colours (white, yellow, and blue) of pan and sticky traps, and yellow funnel traps. The pan and sticky traps were made by ourselves out of commercially available materials, and the funnel traps were purchased (details are described in the next paragraphs). Preliminarily, we confirmed that the traps with the same categorized colours had an almost similar peak range of light reflectance spectra from 300 to 800 nm, although the peak hight is somewhat different among trap types (Fig. S1). Sizes of pan and sticky traps fall within the range of typical values of previous studies (Atakan and Pehlivan 2015; Campbell and Hanula 2007; Hoback et al. 1999; Kitching et al. 2001; Rodriguez-Saona et al. 2012; Toler et al. 2005).

To assess the trapping efficiency of the pan, sticky, and funnel traps for insects, we prepared each treatment in the following manner. For setting of pan traps, each eight of polystyrene hexagone pans (16 cm diameter × 3 cm height, MISUMI Group Inc., Tokyo, Japan) were painted with yellow or blue water-soluble acrylic resin spray paints (Asahipen Corporation, Tokyo, Japan), and the other eight pans were not painted as white colour treatment. These pans were filled with propylene glycol (Wako Pure Chemical Industries, Ltd., Osaka, Japan), and placed on a white plastic case (26 cm width × 35 cm length × 8 cm height). We prepared sticky traps as follows. First, yellow, blue, or white coloured plastic corrugated board (Fukuoka Kosan Co., Ltd., Saga, Japan) was adjusted to a 30 cm × 10 cm size using box cutters. Second, clear sticky seals (No. 448T, Daikyo Giken Kogyo Co., Ltd., Kanagawa, Japan) were pasted on both sides of the boards using double-sided tape. Finally, these sticky boards were suspended from the gardening poles at a height of 75 cm for the sticky trap treatment (i.e., the top edge of a sticky board is 75 cm height from the ground).

We used funnel traps (Sankei Chemical Co., Ltd., Kagoshima), which were developed to capture moths. This trap consists of a clear plastic cup (16.5 cm diameter × 8 cm height), a yellow plastic cap in a funnel shape (16.5 cm diameter × 8 cm height), and a green circular roof (16 cm diameter) (Fig. 1). Funnel traps were suspended from arched gardening poles at a height of 55 cm. Although this trap is often used with pheromone attractants, we did not use any attractants because our target was not a specific species. As an insecticide, we used a 5 cm^2 Vapona plate containing dichlorvos as the active ingredient (Earth Corporation, Tokyo, Japan) inside the plastic cups. Because the efficacy of Vapona plates persists for 3 months, we used them continuously during the experiments (3 weeks).

We placed a set of pan and sticky traps together in the middle of each row (two sets × two plant species × two areas), and funnel traps were placed among the rows on the edge of the gardens (Fig. S2) (one trap × two plant species × two areas). Captured insects were collected a week later after the setting. We repeated this setting and collection three times each for *C. maxima* and *M. charantia* (*C. maxima*: 9, 17, and 23 July; *M. charantia*: 26 July, 1 and 7 August). When we collected the sticky traps, we covered the surfaces of the boards with cellophane wrap such that they did not adhere to each other. Because of strong winds, some captured insects were lost from a white pan trap, a yellow sticky trap, and two blue sticky traps. Therefore, we analysed 152 trap samples, which were placed in eight rows or on four edges of rows. All samples collected by the funnel, pan, and sticky traps were stored in freezers before identification.

Captured insects were identified morphologically to the family level using microscopes, whereas some Hymenoptera were identified to the superfamily level because of difficulty in identification. In particular, for identification of insects on sticky traps, we carefully stripped the insects from the sticky boards and cellophane wrap using a pair of tweezers, after soaking individual sticky boards in 100% limonene (Tokyo Chemical Industry Co., LTD, Tokyo, Japan) liquid in glass cases for 30 min. After identification, all specimens from this study were stored in 95% ethanol and deposited at the Laboratory of Conservation Ecology, University of Tsukuba, Japan.

Statistical analyses

To evaluate the trapping efficiency of the seven traps, we calculated cumulative abundance, relative abundance, and family richness of the three insect orders. Cumulative abundance was the sum of the captured insects. Although the cumulative abundance provided the actual number of insects in each trap, it may reflect responses of dominant families, which swamp the responses of minor families. Therefore, to obtain general response patterns for the three insect orders, following the method described by Whitham *et al*. (1994), we calculated the relative abundance, the sum of the standardised log (n + 1) values for each family (having a standard deviation of 1 and a mean of 0.5). Finally, to evaluate which traps can capture a diversity of families of insects, family richness of the three orders were calculated as the sum of the number of families for each trap.

To examine whether the three indices of the three insect orders were influenced by the seven trap types and whether the effects of trap type were altered by plant species, we performed generalised linear mixed models (GLMMs). The explanatory variables were traps (funnel, blue pan, white pan, yellow pan, blue sticky, white sticky, and yellow sticky), plant species (*C. maxima* and *M. charantia*), and their interaction with a negative binomial distribution of the error (a log-link).

The second analysis was performed to evaluate whether the effects of trap colours on insects were consistent among pan and sticky traps, considering the effects of plant species near the traps. Explanatory variables were the trap type (pan or sticky), colour (blue, yellow, white), plant species, and their interactions.

In all models, the number of trials was included as an offset term, and the identity of areas was included as a random effect. To facilitate interpretation, least-square means, which were adjusted for the effects of components other than the focused effects, and their standard errors were presented. We compared least-square means using the Tukey–Kramer multiple post-hoc comparisons to assess differences between the number of captured insects in each of the traps. Analyses were performed using the GLIMMIX procedure of SAS/STAT software 15.1 (SAS Institute 2018).

To visually evaluate how the characteristics of traps affected the community composition of captured insects, we performed principal component analysis (PCA). For this, the cumulative number of each insect per device per trial was log (n + 1) transformed. Confidence intervals of the same trap groups were estimated based on the Chi-square distribution with 2 d.f. Additionally, to shed light on responses of minor families, PCA based on correlation matrixes was performed. These analyses were conducted using the package 'vegan' in R.3.5.1 (R Core Team 2018).

Results

In total, we obtained 818 individuals from 20 hymenopteran families and ~~2~~ two super families, 811 individuals from 24 dipteran families, and 401 individuals from 18 coleopteran families in the traps (Table 1).

Trapping efficiency of the seven traps for the three orders

The cumulative abundance, relative abundance, and family richness per device per trial for the three insect orders were significantly influenced by trap types (Table 2). There were no significant interactions between plants and traps for most indices of the three insect orders, indicating that the effects of trap type on these indices were not influenced by plant species. As an exception, interactions between trap type and plant species were significant for the relative abundance of Hymenoptera (Table 2). Specifically, the relative abundances of Hymenoptera in yellow sticky traps were significantly greater than those in white sticky traps in the *C. maxima* field, whereas there was no significant difference between white and yellow sticky traps in the *M. charantia* field (Fig. S3). Trends for other traps were similar between the two plant species (Fig. S3).

The cumulative abundance of Hymenoptera in funnel traps per trial was much higher than that in any other trap (Fig. 2a). Comparing within traps, except for funnel traps, the cumulative abundance of Hymenoptera in blue and yellow traps tended to be greater than in white traps (Fig. 2a). In fact, according to the second analysis assessing colour effects on different trap types, cumulative abundances of the pan and sticky traps were influenced by colour irrespective of trap type (Table 3). In contrast, the colour effects on relative abundance and family richness of Hymenoptera were altered by trap type (Table 3). In particular, although yellow significantly increased the relative abundance and family richness of Hymenoptera more than the white did within sticky traps (relative abundance: $t = 3.30$, adjusted $P = 0.025$; family richness: $t = 3.30$, adjusted $P = 0.025$), there was no significant difference between white and yellow traps within pan traps ($t = 3.30$, adjusted $P = 0.025$). Consequently, in the case of the relative abundance and family richness of Hymenoptera, yellow sticky traps had the largest effect among the seven traps (Fig. 2b, c).

Regarding Diptera, all indices of the funnel traps were the least effective among the seven traps (Fig. 2d-f). The cumulative abundances of the three colours of sticky traps were significantly higher than those of pan traps, except for the yellow ones, which had the greatest number among the seven traps (Fig. 2d). The second analysis indicated that colour effects on the cumulative abundance significantly differed between the pan and sticky traps (Table 3). In contrast, the relative abundance and the family richness for yellow pan traps tended to be equal to those other pan and sticky traps (Fig. 2e, f), and the colour effects on relative abundance and family richness of Diptera were independent of trap type (Table 3). Overall, sticky traps tended to have higher relative abundance and family richness than pan traps, and yellow tended to be more effective than white.

Regarding Coleoptera, cumulative abundance, relative abundance, and family richness of funnel traps were the least among the seven traps (Fig. 2g-i), like those of Diptera. The cumulative abundance of Coleoptera in sticky traps was greater than that the funnel and pan traps, regardless of the colours (Fig. 2g, Table 3). In contrast, the relative abundance of Coleoptera in sticky traps varied by the trap colour (Table 3). Although the relative abundances in yellow and blue sticky traps were still higher than in funnel and all pan traps (Fig. 2h), the relative abundance in white sticky traps was not significantly different from that in the funnel and pan traps. The colour-dependent effects of traps on relative abundance were supported statistically (Table 3). Comparing within family richness for the sticky traps, differences between white and other colours were relatively smaller than those of relative abundance (Fig. 2i), and only the main effects of traps were statistically significant (Table 3).

Composition of the families of insects in each trap

PCA visually illustrated that the composition of families varied among traps (Fig. 3). In Hymenoptera, the 95% confident intervals tended to separate into funnel traps, which were located on the negative side of PC1 and other traps which were located on the positive side of PC1 (Fig. 3a). The centroid of the blue colour traps had a positive PC2 value, and other traps had negative or almost zero PC2 values. Apidae was strongly negatively correlated to PC1, and Hymenoptera in funnel traps mainly consisted of Apidae. Tiphiidae tended to be captured by traps other than funnel traps. Scoliidae, Sphecidae, Formicidae, and Halictidae that were positively correlated to PC2 tended to be captured by blue traps, and Braconidae tended to be captured by pan or sticky traps slightly more than by blue traps.

In Diptera, the 95% confidence intervals for all colours of sticky traps were located on the negative side of PC1 and near one another (Fig. 3b). In contrast, yellow pan traps, which had a centroid located on the positive side of PC2, were separated from blue and white pan traps with negative PC2 values. Additionally, the 95% confident interval of funnel traps overlapped with that of the white pan, blue pan, yellow sticky, and blue sticky traps. Most of the families positively correlated with PC2 had centroids in the yellow pan and the three colours of sticky traps, except for Sarcophagidae. Dolichopodidae, which had a strong positive relationship with PC1, tended to be captured by yellow pans, and Sciaridae and Sarcophagidae, which had positive relationships with PC1, also tended to be captured by yellow or white pan traps.

In Coleoptera, community composition was separated into groups of white and yellow sticky traps, which were positioned with positive PC1 values and groups of funnel and all pan traps, which were positioned with negative PC1 values (Fig. 3c). Blue sticky traps were positioned between the two groups. Most of the families were positively correlated with the PC1 axis where sticky traps were located, particularly Coccinellidae and Chrysomelidae which tended to be captured by yellow sticky traps.

A more detailed composition of all families in the three orders is shown in the Supporting Data, which was visualised using PCA based on correlation matrices (Fig. S4).

Discussion

Wider usability of the traps than previously known

By applying multiple types and colours of traps to the three orders of insects, this study clearly demonstrated the wider usability of the traps than previously known. For example, our study showed that funnel traps, which usually target Lepidoptera, also captured Hymenoptera (Fig. 2a), in particular Apidae efficiently (Fig. 3a). Specifically, Apidae captured in this study comprised *Bombus diversus diversus* Smith (98%), *Apis mellifera* Lin~~n~~naeus (1.7%), and *Apis cerana japnonica* Radoszkowski (0.3%), and all Apidae in funnel traps were *B. d. diversus*~~*Bombus diversus diversus*~~. So far, Hymenoptera has usually been sampled using pan traps, and bumblebees have rarely been captured (Leong and Thorp 1999; Roulston et al. 2007; Toler et al. 2005). Therefore, requirement for more effective methods to monitor bees are increasing (Portman et al. 2020). Although a few studies targeting Coleoptera or Lepidoptera reported that traps having funnel structures with a pheromone lure captured bumblebees (*B. bimaculatus* Cresson, *B. fraternus* (Smith), *B, impatiens* Cresson, and *B. pensylvanicus* (De Geer)) in crop fields accidentally (Meagher 2001; Meagher and Mitchell 1999), active application of funnel traps for Hymenoptera has not existed. Taken together with the previous study and our results, funnel traps may be usable to capture bumblebees. Recently, as an alternative collecting device for bumblebees, vane traps began to been paid much attention mainly in the United States (Geroff et al. 2014; Joshi et al. 2015; Kimoto et al. 2012; Stephen and Rao 2007; Weber et al. 2009). Considering a common feature of funnel and vane traps, bumblebees may be attracted by tubular structure. Unfortunately, vane traps are hard to be obtained in countries other than the U.S. In this context, since the funnel traps which are used in this study are sold worldwide as a universal moth trap, it will be more readily available and practical in most countries.

Traditionally, sticky traps have been mainly used for monitoring or controlling agricultural and house pests (e.g., flies and thrips) rather than a wide range of insects (Shimoda and Honda 2013). On the other hand, we found that sticky traps can be a better monitoring device for Diptera and Coleoptera than funnel and pan traps, in terms of cumulative abundance, relative abundance, and family richness (Fig. 2d-i). Because of the lack of necessity of liquids or any attractants, active use of coloured sticky traps would help save costs and labour for insect sampling. In addition, although we take off all insects in this study to identify, this procedure is not necessary when the researcher can identify the insects on sticky boards. Application of sticky traps for Coleoptera would be effective because Coleoptera-captures have often required huge funnel traps with pheromone attractants (e.g., Lindegren multi-funnel traps).

Pan traps are a popular method for insect sampling. Nevertheless, the scores of the three indices for pan traps, which we examined here were not greater than those of the funnel or sticky traps (Fig. 2), except for cumulative abundance of Diptera on yellow-coloured pan traps (Fig. 2e). Such a disadvantage of trapping efficiency of pan traps in comparison to that of sticky traps is probably because the former traps cannot capture insects in the absence of active visits of insects to the traps; in contrast, the latter trap captures insects occasionally by disturbing their flight. However, as an exception, yellow pan traps were excellent devices to substantially capture Dolichopodidae (Table 1, Fig. 3b). Previous studies targeting Dolichopodidae reported that this family tended to prefer yellow pan traps to bluish green and white pan traps (Pollet and Grootaert 1994), or yellow sticky traps to blue sticky traps (Hoback et al. 1999). This is the first report of a combination of colour and trap type being crucial for trapping Dolichopodidae rather than just colour.

Effective sampling methods for monitoring diverse insects

Reactions of insects to colours are generated by their visual systems (Briscoe and Chittka 2001; Giurfa et al. 1995) and their ecological characteristics, such as habitats and foods (Pollet and Grootaert 1987, 1994; Prokopy and Owens 1983). For example, it has been known that phytophagous insects and their predators/parasitoids are often attracted by yellow, probably because yellow constitutes a supernormal foliage type stimulus for foliage seeking insects (Prokopy and Owens 1983). Supporting this, the PCA results revealed that composition of parasitoids (e.g., Braconidae and Diapriidae), predators (Coccinellidae and Dollichopodidae), and phytophagous insects (Chrysomelidae and Tenthredinidae) increased with yellow colour sticky and/or pan traps (Fig. 3 and Fig. S4). Also, we found that flower visiting Hymenoptera, Halictidae, Scoliidae, and Formicidae tended to be captured by blue traps (Fig. 3a), agreeing with the previous findings that flower visiting Hymenoptera tends to prefer blue traps (Campbell and Hanula 2007; Cane et al. 2000; Kimoto et al. 2012; Leong and Thorp 1999). Yet, there is a controversial debate whether colours of their host flowers interfere with colour effects of the traps on Hymenoptera (Cane et al. 2000; Leong and Thorp 1999; Toler et al. 2005). Our results suggest that flower colours may be neutral for colour effects of traps, because the cumulative abundance for yellow traps, which is the same colour as that of Cucurbit flowers, was intermediate between that of the blue and white traps (Fig. 2a). However, it should be noted that the relative abundance in yellow sticky traps was more than that of in the white sticky ones when the traps were set nearby *C. maxima* (Fig. S3). According to the previous studies of *C. maxima* (Ashworth and Galetto 2002) and *M. charantia* (Oronje et al. 2012), the sugar concentration of *C. maxima* flowers is about 10% higher than *M. charantia* flowers, in addition to that the storage capacity of nectar volume of *C. maxima* is much larger than *M. charnatia* due to their larger corolla size. Therefore, the amount of floral reward may influence the attraction of the same colour traps, though further examination is needed to confirm this.

In this study, whether trap types and colours interactively influence trapping efficiency depended on insect groups and indices. For instance, the differences in trap colours were larger within sticky traps than within pan traps in the case of relative abundance and family richness of Hymenoptera and Coleoptera (Fig. 2b-c, h-i), whereas the differences tended to be larger within pan traps than sticky traps in the case of all indices of Diptera. (Fig. 2d-f). Although further studies are needed to examine ~~how~~ what types of traps influences colour discrimination ability of the insects, our results suggest that considering the combination of types and colours of traps are practically important for monitoring the three orders of insects. For example, funnel traps and blue and yellow sticky traps would be adequate to monitor diverse families of Hymenoptera. Regarding Diptera, yellow sticky traps would be the best for the collection of diverse families of Diptera without a bias toward Dolichopodidae among the seven traps. Yet, a careful consideration is required for potential existence of groups that prefer dark ~~(e.g., blue)~~ colour (e.g., blue), such as soil dwelling or arboreal species (Pollet and Grootaert 1987, 1994). Though colour effects on Coleoptera were relatively weak (Table 3 and Fig. 2g-i), their relative abundance in yellow sticky traps tended to be higher than that in the funnel, pan traps, and white sticky traps (Fig. 2h). This tendency would be derived from several families that prefer yellow colour (Fig. 3c and Fig. S4c). Therefore, as with Diptera, yellow sticky traps would be efficient to monitor diverse families of Coleoptera. Collectively across the three orders, the combined usage of funnel traps, and blue and yellow sticky traps may be helpful to monitor the diversity of the three insect orders in crop fields.

In this study, we clearly illustrated relative trapping efficiency of attraction traps to the three orders under the same conditions. Remarkably, we showed the usability of funnel traps and sticky traps which has not previously been known. Additionally, we suggested that applications of funnel traps and blue and yellow sticky traps may be an efficient method to monitor all three insect orders in agricultural fields. To gain more robust patterns of trapping efficiency for each trap, examination at multiple sites and/or in different seasons is necessary. Even after considering such limitations, our study, which statistically assessed the trapping efficiency of attraction traps, provides valuable information for researchers who monitor insects in agricultural fields. In particular, following implications concerning the mechanisms determining trapping efficiencies are of worth to verify in the future studies; (1) bumblebees may be attracted by tubular structure, (2) disadvantage of trapping efficiency of pan traps in comparison to that of sticky traps may be due to the necessity of active visits of insects to the traps (3) colour of flowers ~~having~~ with abundant rewards may strengthen attractiveness of the same colour of traps. An accumulation of studies assessing trapping efficiencies of traps beyond the order level is essential for the development of effective monitoring systems for insects.

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Table 1 Insects captured by traps. Insect orders and families are arranged by cumulative abundances. * Not identified to the family level.

Order	Family	Funnel	Pan			Sticky			Total	%
			Blue	White	Yellow	Blue	White	Yellow		
Hymenoptera									**818**	100
	Apidae	334	1	1	0	1	3	3	**343**	42
	Halictidae	29	58	12	21	12	4	17	**153**	19
	Formicidae	16	17	10	9	29	18	24	**123**	15
	Scoliidae	0	13	6	6	58	4	6	**93**	11
	Tiphiidae	0	3	1	2	3	13	30	**52**	6
	Platygastridae	0	0	0	0	0	1	7	**8**	1
	Vespidae	0	0	1	1	3	2	0	**7**	1
	Tenthredinidae	0	0	0	0	0	4	3	**7**	1
	Sphecidae	0	1	1	1	0	0	1	**4**	>1
	Chalcididae	0	0	0	2	0	0	2	**4**	>1
	Crabronidae	0	0	2	0	0	0	2	**4**	>1
	Ichneumonidae	0	0	0	1	0	2	1	**4**	>1
	Braconidae	0	1	0	0	0	0	2	**3**	>1
	Chalcidoidea spp.*	0	0	1	2	0	0	0	**3**	>1
	Eurytomidae	0	0	0	0	1	0	1	**2**	>1
	Diapriidae	0	0	0	2	0	0	0	**2**	>1
	Megachilidae	1	0	0	0	0	0	0	**1**	>1
	Bethylidae	0	0	0	0	0	1	0	**1**	>1
	Mymaridae	0	0	0	1	0	0	0	**1**	>1
	Pteromalidae	0	0	1	0	0	0	0	**1**	>1
	Platygasteroidea sp. *	0	0	0	1	0	0	0	**1**	>1
	Pompilidae	0	0	0	0	0	0	1	**1**	>1
Diptera									**811**	100
	Anthomyiidae	7	18	3	28	79	58	22	**215**	27
	Dolichopodidae	0	5	15	184	0	0	6	**210**	26
	Muscidae	0	1	5	9	12	13	70	**110**	14
	Calliphoridae	2	2	0	2	33	48	21	**108**	13
	Sarcophagidae	11	4	4	12	1	2	6	**40**	5
	Chironomidae	0	4	1	3	6	5	10	**29**	4

	Asilidae	0	1	2	1	5	8	2	**19**	2
	Sciaridae	0	7	1	6	0	0	3	**17**	2
	Chloropidae	0	1	0	0	2	2	9	**14**	2
	Sciomyzidae	0	0	0	0	7	2	2	**11**	1
	Ephydridae	0	1	2	2	3	0	1	**9**	1
	Syrphidae	0	0	0	0	4	1	0	**5**	1
	Agromyzidae	0	0	1	3	0	0	0	**4**	>1
	Platystomatidae	1	0	0	0	1	0	2	**4**	>1
	Phoridae	0	1	0	2	0	0	0	**3**	>1
	Sepsidae	0	0	0	0	0	0	2	**2**	>1
	Tachinidae	0	0	0	0	1	1	0	**2**	>1
	Ulidiidae	0	0	0	0	0	1	1	**2**	>1
	Limoniidae	0	0	0	0	1	0	1	**2**	>1
	Pipunculidae	0	0	0	0	0	0	1	**1**	>1
	Lauxaniidae	0	0	0	0	0	1	0	**1**	>1
	Conopidae	0	0	0	0	1	0	0	**1**	>1
	Scaptopsidae	0	0	0	1	0	0	0	**1**	>1
	Neriidae	0	0	0	0	1	0	0	**1**	>1
Coleoptera									**401**	100
	Elateridae	2	9	8	11	69	129	94	**322**	80
	Coccinellidae	1	0	0	0	2	6	22	**31**	8
	Chrysomelidae	0	1	2	0	2	3	10	**18**	4
	Scarabaeidae	1	0	2	0	0	2	1	**6**	1
	Staphylinidae	0	0	2	0	2	1	0	**5**	1
	Silvanidae	0	0	0	2	1	0	0	**3**	1
	Apionidae	0	0	0	0	1	0	1	**2**	>1
	Throscidae	0	0	0	0	1	0	1	**2**	>1
	Nitidulidae	0	0	0	0	1	0	1	**2**	>1
	Mordellidae	0	0	0	0	1	0	1	**2**	>1
	Lycidae	0	0	0	0	0	0	1	**1**	>1
	Phalacridae	0	0	0	0	1	0	0	**1**	>1
	Haliplidae	0	0	0	0	1	0	0	**1**	>1
	Tenebrionidae	0	0	0	0	1	0	0	**1**	>1
	Curculionidae	0	0	0	0	0	0	1	**1**	>1
	Mycetophagidae	0	0	0	0	0	0	1	**1**	>1

	Carabidae	0	0	0	0	0	0	1	**1**	>1
	Lathridiidae	0	0	0	1	0	0	0	**1**	>1

Table 2 Effects of trap (white sticky, yellow sticky, blue sticky, white pan, yellow pan, blue pan, and funnel), plant species (*Cucurbita maxima* or *Momordica charantia*) and their interactions on the cumulative abundance, relative abundance, and family richness of (a) Hymenoptera, (b) Diptera, and (c) Coleoptera on a sticky, pan, or funnel trap per trial.

*** $P < 0.0001$, ** $P < 0.01$, * $P < 0.05$.

	Cumulative abundance		**Relative abundance**		**Family richness**	
Effect	d.f.	*F*	d.f.	*F*	d.f.	*F*
(a) Hymenoptera						
Trap	6, 32.71	19.19***	6, 37	2.8*	6, 34.64	3.29*
Plant	1, 35.52	20.66***	1, 37	6.26*	1, 36.33	6.32*
Trap × Plant	6, 32.71	1.3	6, 37	2.55**	6, 34.53	1.01
(b) Diptera						
Trap	6, 37	11.14***	6, 37	5.55**	6, 29.98	4.82**
Plant	1, 37	18.56***	1, 37	3.45	1, 33.73	5.6*
Trap × Plant	6, 37	0.84	6, 37	0.57	6, 29.96	0.86
(c) Coleoptera						
Trap	6, 28.62	12.86***	6, 37	10.19***	6.59	27.35***
Plant	1, 27.75	7.74**	1, 37	0	1.53	0.49
Trap × Plant	6, 28.64	0.22	6, 37	0.44	0.46	0.02

Table 3 Effects of types (sticky or pan), colour (white, blue, and yellow), plant (*Cucurbita maxima* or *Momordica charantia*), and their interactions on the cumulative abundance, relative abundance, and family richness of (a) Hymenoptera, (b) Diptera, and (c) Coleoptera on a sticky or pan trap per trial. *** $P < 0.0001$, ** $P < 0.01$, * $P < 0.05$.

	Cumulative abundance		**Relative abundance**		**Family richness**	
Effect	d.f.	*F*	d.f.	*F*	d.f.	*F*
(a) Hymenoptera						
Trap	1, 35	7.33*	1, 35	4.38*	1, 34	2.32
Colour	2, 33	11.98***	2, 35	4.37*	2, 34	2.50
Trap × Colour	2, 33	1.53	1, 35	10.95**	2, 34	3.42*
Plant	1, 35	27.32***	2, 35	1.49	1, 35	8.04**
Trap × Plant	1, 35	0.10	1, 35	6.11*	1, 34	0.60
Colour × Plant	2, 33	0.25	2, 35	0.27	2, 34	0.75
Trap × Colour × Plant	2, 33	2.38	2, 35	2.97	2, 34	1.74
(b) Diptera						
Trap	1, 35	15.12**	1, 35	16.09**	1, 26	5.23*
Colour	2, 35	10.26**	2, 35	3.52*	2, 25	3.45*
Trap × Colour	2, 35	13.83***	2, 35	3.06	2, 25	1.30
Plant	1, 35	24.96***	1, 35	6.05*	1, 26	5.19*
Trap × Plant	1, 35	0.02	1, 35	0.06	1, 26	0.01
Colour × Plant	2, 35	0.54	2, 35	0.34	2, 25	0.52
Trap × Colour × Plant	2, 35	1.32	2, 35	0.79	2, 25	0.92
(c) Coleoptera						
Trap	1, 31	65.43***	1, 35	41.75***	1, 33	27.35***
Colour	2, 33	1.10	2, 35	2.56	2, 29	0.33
Trap × Colour	2, 33	0.09	2, 35	3.80*	2, 29	1.51
Plant	1, 33	7.58**	1, 35	0.02	1, 29	0.49
Trap × Plant	1, 33	0.10	1, 35	0.54	1, 29	0.02
Colour × Plant	2, 33	0.19	2, 35	0.47	2, 29	0.24
Trap × Colour × Plant	2, 33	0.48	2, 35	0.53	2, 29	0.88

Figure legends

Fig. 1 Installed attraction traps in the Cucurbit fields. A funnel trap (a) and traps of pan and sticky (b).

Fig. 2 Least square means ± S.E. of cumulative abundance, relative abundance, and family richness per device per trial for Hymenoptera (a-c), Diptera (d-f), and Coleoptera (g-i). W, Y, and B indicate trap colours (white, yellow, and blue, respectively). Means followed by the same letter are not significantly different (Tukey–Kramer adjustment for multiple comparisons ($P < 0.05$)).

Fig. 3 Ordination diagram of principal component analysis (PCA) of the community composition of seven types of traps for (a) Hymenoptera, (b) Diptera, and (c) Coleoptera. Dotted, solid, and dash-dotted ovals indicate 95% confidence intervals for sticky traps (white, yellow, and blue), pan traps (white, yellow, and blue), and funnel traps (yellow), respectively. Arrows indicate the direction of increasing values for the variables. Percentages of total explained variation by PCA axes are given in parentheses. In the printed version, dark grey, light grey, and white colours of circles indicate blue, yellow, and white respectively.

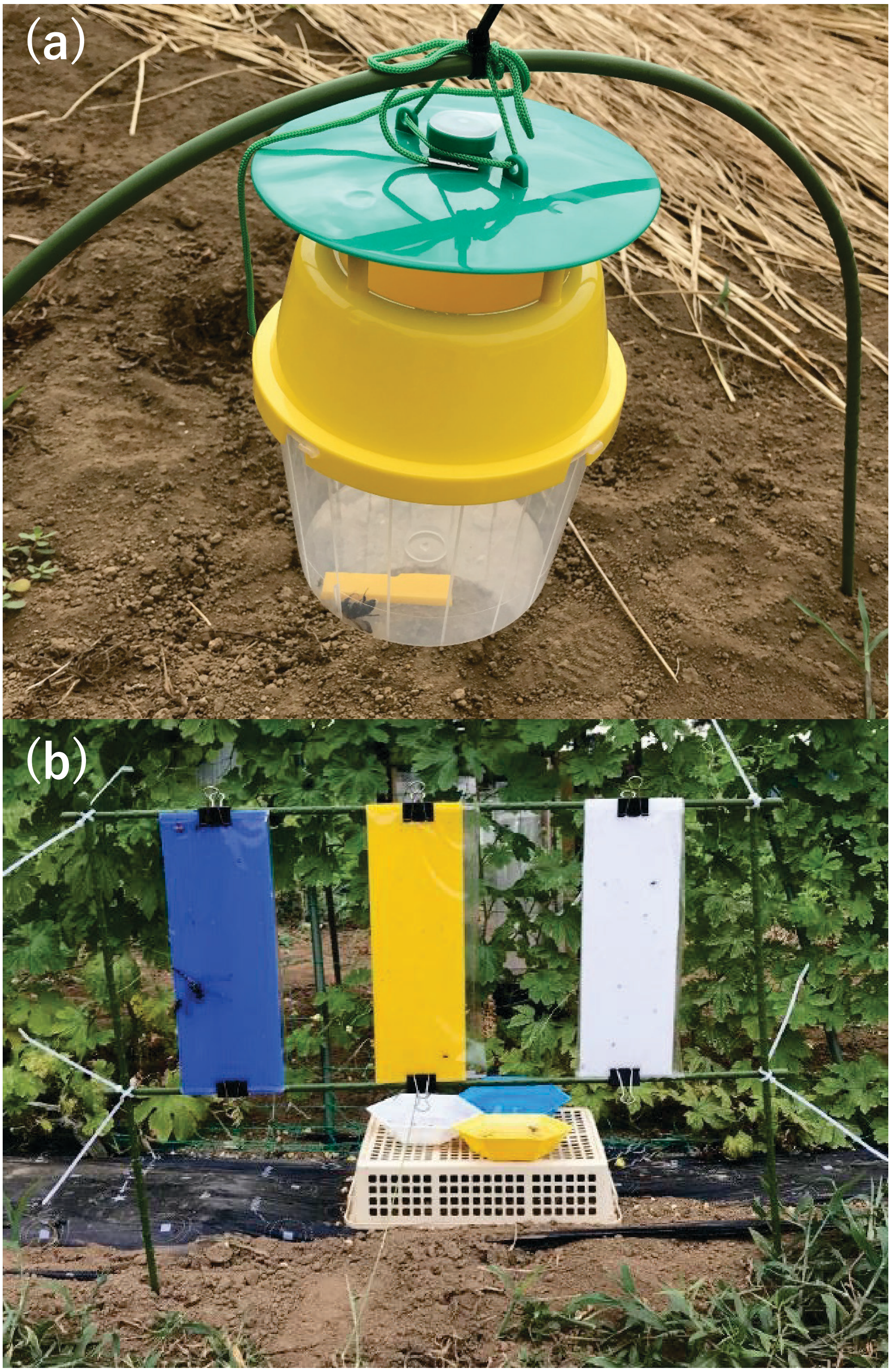
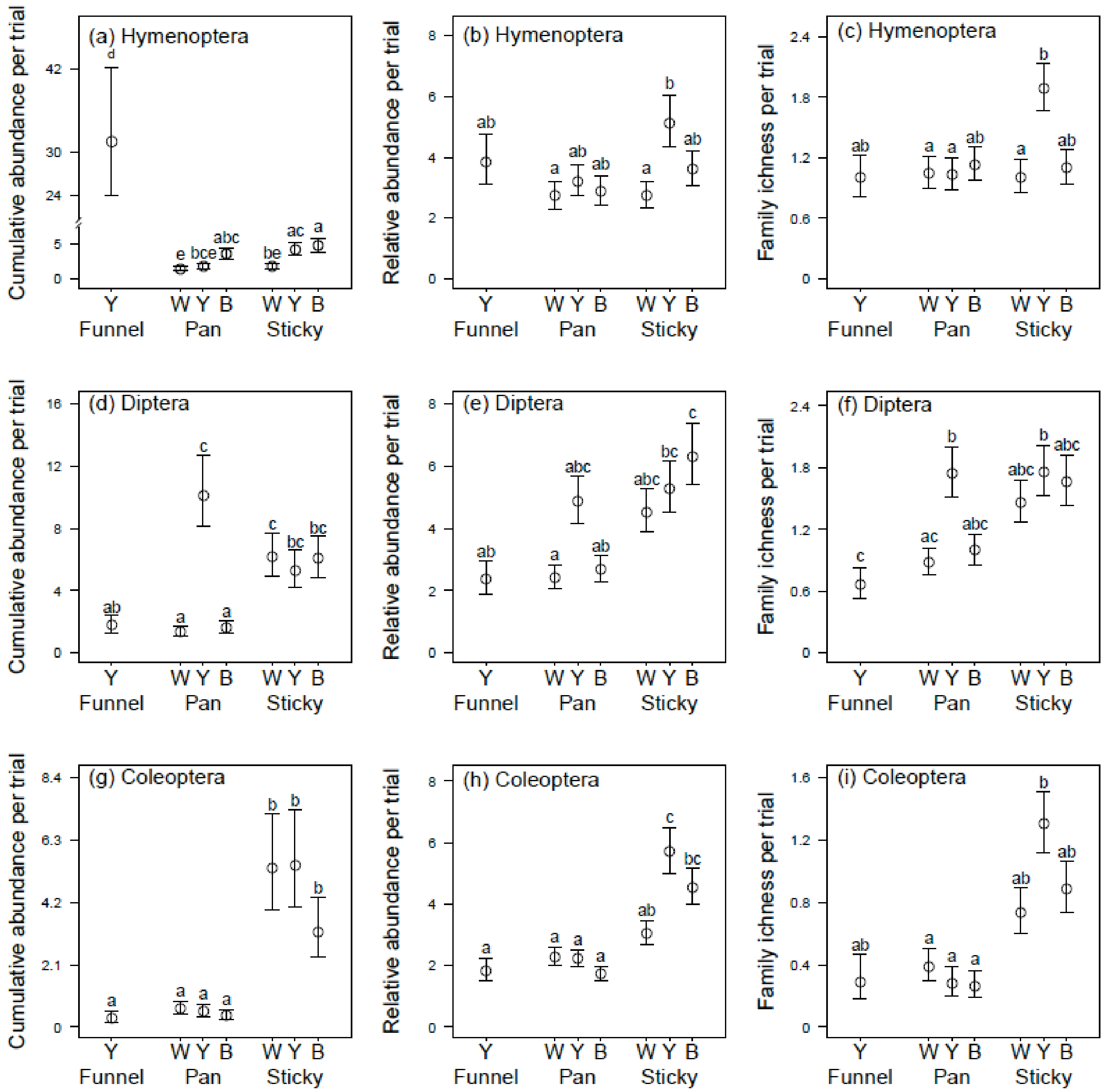
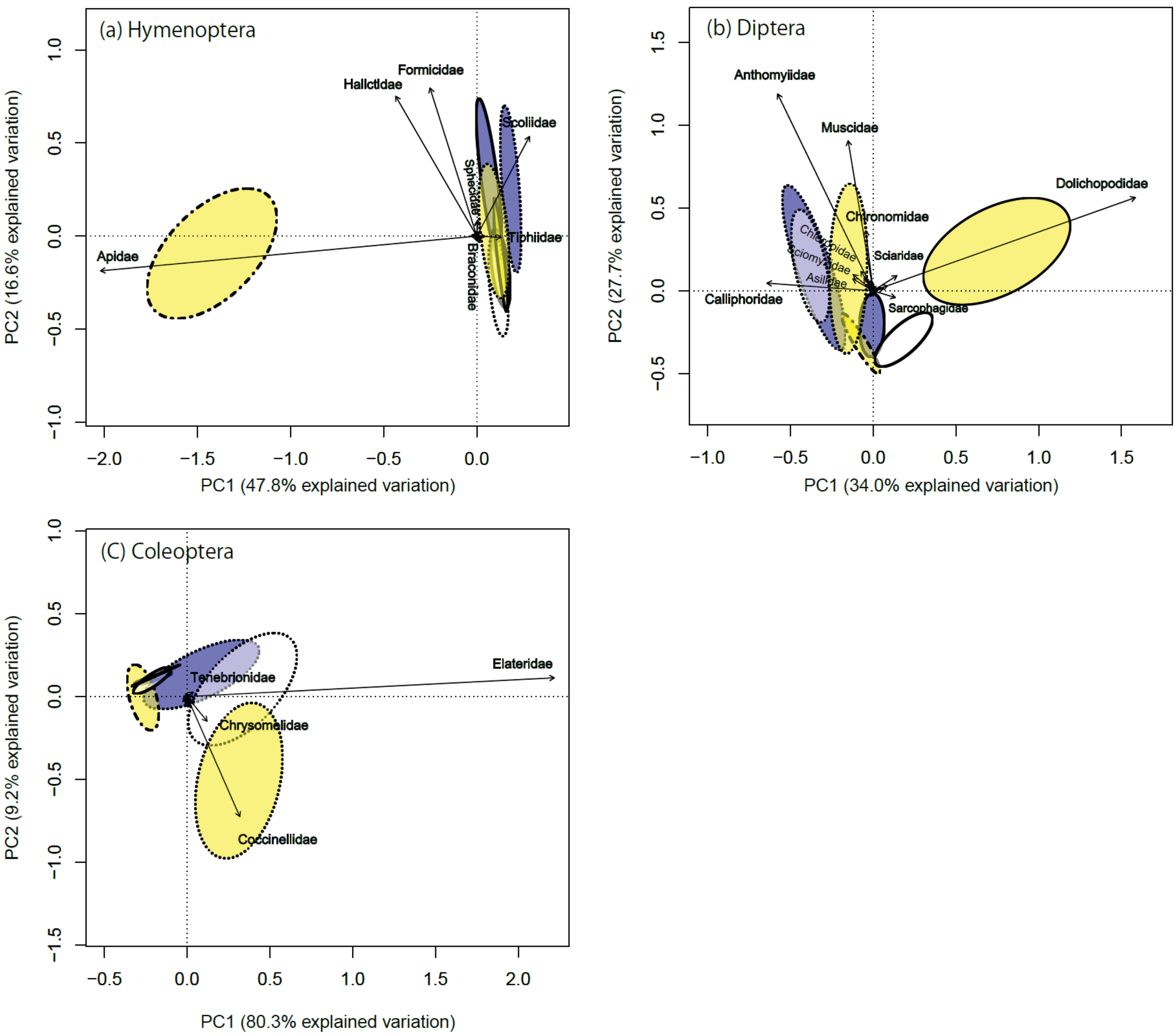


Fig. 1



(a) Hymenoptera
(b) Hymenoptera
(c) Hymenoptera
(d) Diptera
(e) Diptera
(f) Diptera
(g) Coleoptera
(h) Coleoptera
(i) Coleoptera
Cumulative abundance per trial
Relative abundance per trial
Family ichness per trial
Y
W Y B
W Y B
Funnel
Pan
Sticky

Fig. 2



(a) Hymenoptera
Formicidae
Halictidae
Scoliidae
Sphecidae
Tiphiidae
Braconidae
Apidae
PC1 (47.8% explained variation)
PC2 (16.6% explained variation)
(b) Diptera
Anthomyiidae
Muscidae
Dolichopodidae
Chironomidae
Sciaridae
Calliphoridae
Sarcophagidae
Asilidae
PC1 (34.0% explained variation)
PC2 (27.7% explained variation)
(C) Coleoptera
Elateridae
Tenebrionidae
Chrysomelidae
Coccinellidae
PC1 (80.3% explained variation)
PC2 (9.2% explained variation)

Fig. 3

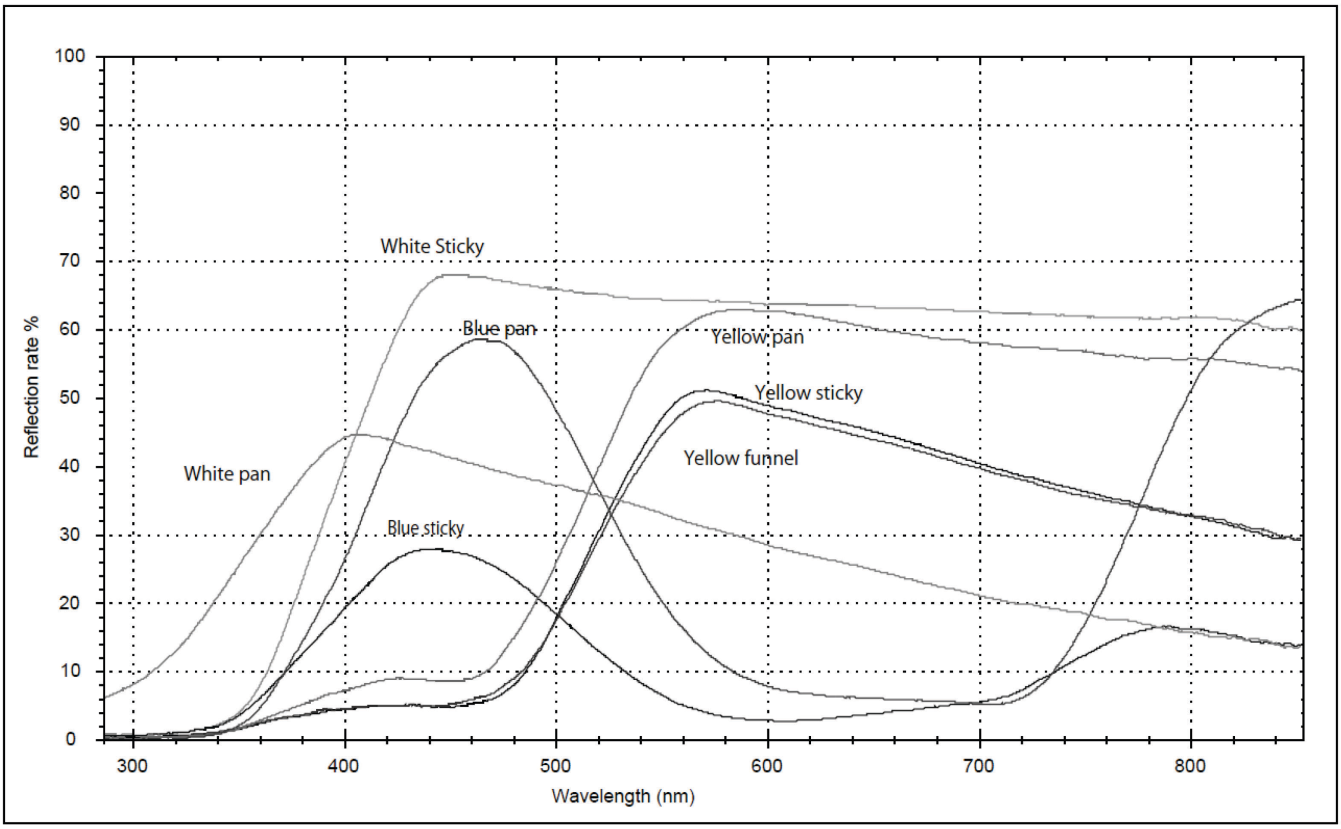


Fig. S1

Light reflection spectra of brand new samples of the traps. The light reflectance characteristics at the materials were determined by a Deuterium/Tungsten light source (BDS100: B & WTEK inc., Newark, USA) providing spectral output from 200 to >1100nm and a spectrometer (Exemplar LS: B & WTEK inc., Newark, USA). Reflection rates were calculated referring to a reflection standard (RS50: Stella Net Inc., Tokyo, Japan).

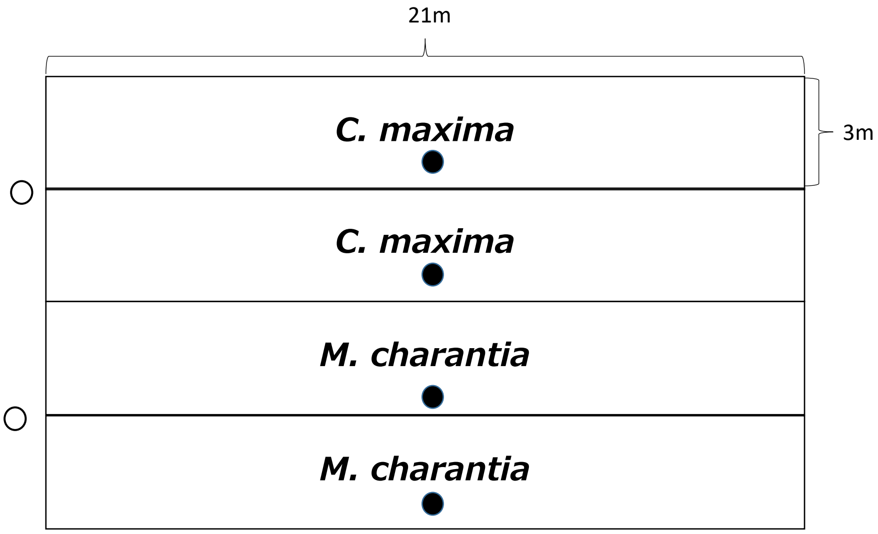


Fig. S2 Experimental setting of the traps. For rectangles shows rows of crops (*C. maxima* and *M. charantia*). Closed circles indicate the position of a set of pan and sticky traps, and open circles indicate the positions of the funnel traps.

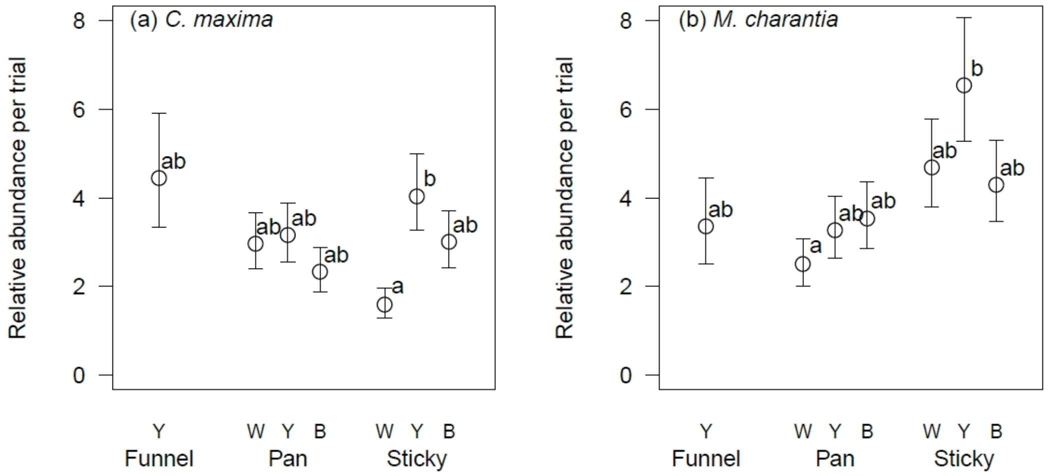


Fig. S3. Least square means (±S.E.) of the relative abundance per device per trial of Hymenoptera in *Cucurbita maxima* fields (a) and *Momordica charantia* fields (b). W, Y, and B indicate trap colours (white, yellow, and blue, respectively). Means followed by the same letter are not significantly different (Tukey–Kramer adjustment for multiple comparisons ($P < 0.05$)).

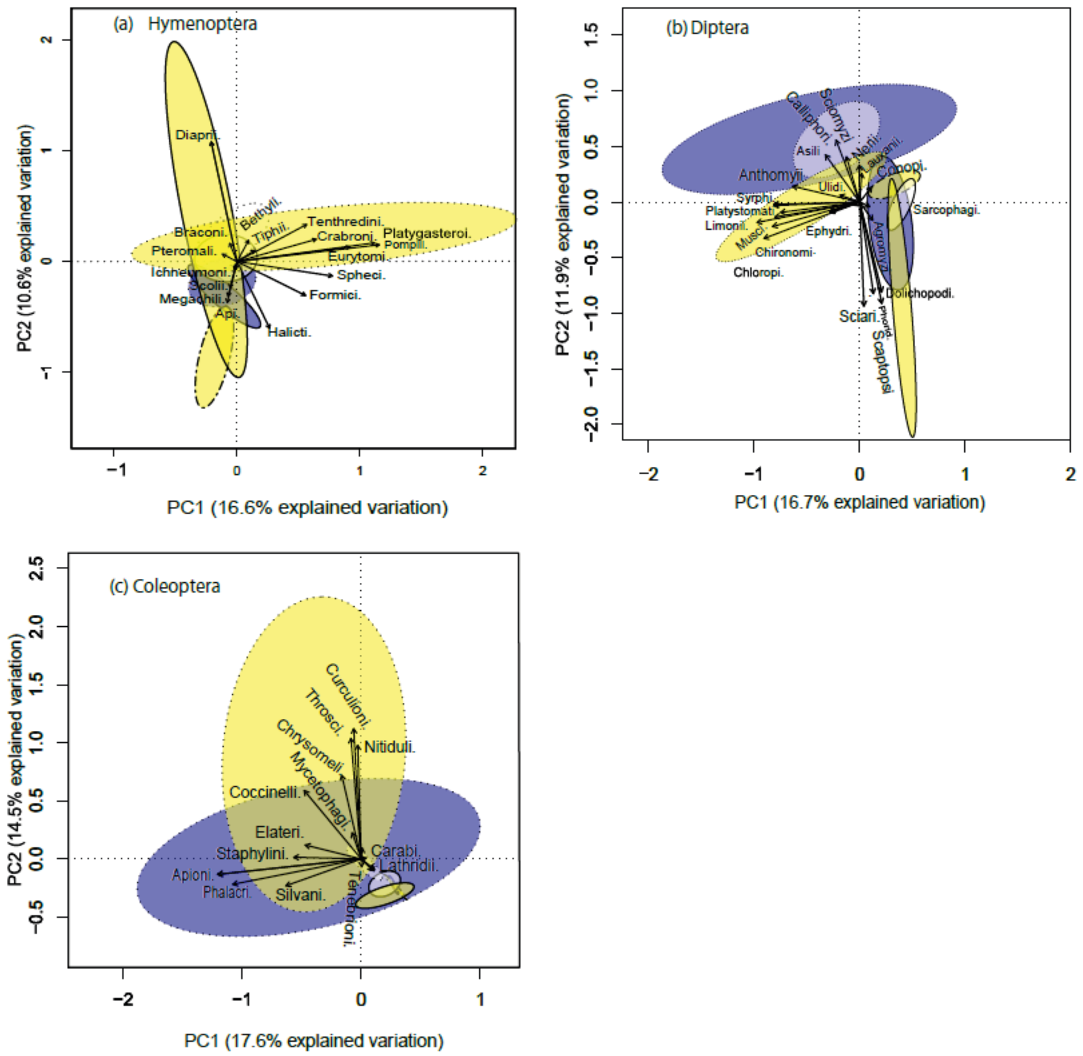


Fig. S4 Ordination diagram of principal component analysis (PCA) of the community composition of seven types of traps for Hymenoptera (a), Diptera (b), and Coleoptera (c). Dotted, solid, and dash-dotted ovals indicate 95% confidence intervals for sticky traps (white, yellow, and blue), pan traps (white, yellow, and blue), and funnel traps (yellow), respectively. The last three letters of family and super family names (i.e., “dae” or “dea”) were abbreviated. Arrows indicate the direction of increasing values for the variables. Percentages of total explained variation by PCA axes are given in parentheses.