

PASSIVELY CROWDSOURCING ONLINE IMAGES FOR MEASURING BROAD-SCALE FLY (DIPTERA) FLORAL INTERACTIONS AND BIODIVERSITY

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Abstract—Flies (Diptera) represent one of the largest and most important groups of pollinators on the planet; however, little is known about the interactions between flies and flowers compared to well-known pollinators, such as bees. Understanding pollinator assemblages is key to conserving biodiversity and ecosystem services, but monitoring Diptera is time and cost intensive. Using photographs of blooming flowers taken by photographers worldwide and uploaded on internet repositories, we built a dataset of 1,275 images of fly-flower visitations and extracted fly and flower taxonomic information, flower characteristics (shape and color), and fly activity (pollen carrying and foraging). The resulting dataset shows taxonomic and other biases but can still provide an initial overview of factors that affect pollination by Diptera. We identified 22 families of flies, with blow flies (Family Calliphoridae) most represented (29%) and 63 families of flowers, with Asteraceae (42%) and Apiaceae (21%) as the most common. Using logistic regression, we found that the likelihood of flies carrying pollen was determined by the interaction between flower color and shape: pollen-carrying was more likely when elongate cluster flowers were *green-yellow*. Fly foraging on flowers was determined by flower color: flies were more likely to feed on *green-yellow* and *white* flowers. Overall, Syrphidae flies were less likely to forage for nectar than non-Syrphidae, but were more likely to carry pollen. While biases exist in crowdsourced data, we show that data from photographs collected through citizen science offers potentially valuable information for monitoring pollinator-flower interactions and augment our understanding of pollinator ecology in an era of global insect declines.

Keywords— Data mining, photos, fly pollinator, myophily, species richness

INTRODUCTION

The severity of documented insect declines worldwide (Wagner et al. 2021) challenges modern research methods to keep up with monitoring ongoing shifts in insect assemblages. Loss of insect diversity and abundance results in a cascading effect on ecosystem functioning (Hallmann et al. 2017; Forister et al. 2019); in particular, declines of pollinating insects poses a major threat to global food security and human health, as plant reproduction parallels the existence of pollinators

(Biesmeijer et al. 2006; Potts et al. 2010; Powney et al. 2019). Despite the large-scale implications of pollinator declines, no large-scale monitoring is in place to assess distributions of all pollinating insects (Powney et al. 2019); existing monitoring efforts focus on native bees and butterflies in the US (Woodard et al. 2020) and Europe (Bumblebee Monitoring Scheme n.d.; Bumblebee Conservation Trust n.d.; UK Butterfly Monitoring Scheme n.d.).

The most important pollinator taxa are Hymenoptera, Lepidoptera, Coleoptera, and Diptera (Vanbergen et al. 2013), yet current

conservation efforts place emphasis on well-known and charismatic pollinators, such as bees and hover flies (Family Syrphidae) (Orford et al. 2015). Little is known about the role of less charismatic pollinators, such as flesh flies (Family Sarcophagidae) or mosquitoes (Family Culicidae) (but see, e.g., van der Niet et al. 2011; Peach & Gries 2020); the shortcomings of traditional monitoring methods (traps, field studies) contribute to the lack of knowledge regarding flower visitation and pollination potential of thousands of species. Advances in communication technology, social media platforms, online biodiversity databases and repositories, and accessible camera technologies have the potential to contribute much to our understanding of biodiversity and pollinator ecology (Fink et al. 2014; Sauermann & Franzoni 2015; Silvertown 2009). The mass production and distribution of user-generated online content has become readily available; this 'collective intelligence' has produced many open access databases of geographic and taxonomic information that can be appropriated in scientific studies, particularly in relation to biodiversity (e.g., iNaturalist, Pl@ntNet (Jacobs 2016; Nguyen et al. 2018; Torney et al. 2019)). The emergence of online photo sharing platforms (i.e. Flickr, Instagram, agefotostock, etc.) is providing opportunities to evaluate biodiversity at broad spatial scales as well as powerful tools and data for biodiversity research (Joly et al. 2016; Van Horn et al. 2017; Terry et al. 2020). The exploitation of ecological information provided by the public has become increasingly popular in the scientific community as *citizen science* (Cohn 2008; Pocock et al. 2015; Johnston et al. 2018; Trouille et al. 2019).

Citizen science is a rapidly evolving field for large-scale information collection (Eitzel et al. 2017; Heigl et al. 2019). It has become a valuable tool for researchers, for example for studies of climate change, water quality monitoring, ecological restoration, and conservation biology (Silvertown 2009; Cooper et al. 2014). Citizen science includes passive observations, such as photographs of organisms uploaded to various repositories on the Internet. As such, data resulted from photo uploads by members of the public can vary dramatically in quality based on equipment used, photography skill and intent, and individual interests, leading to potential data biases in terms of taxonomic, geographic and seasonal coverage of

data (Bahlai & Landis 2016). Nonetheless, in the absence of systematic surveys, passively sourced photographs can be a valuable tool for informing conservation actions, such as identifying pollinator-friendly plant mixes used in habitat restoration (e.g., Bahlai & Landis 2016). In particular, as declines in pollinator species increases research interest on plant-pollinator interactions, crowdsourcing citizen science has the potential to add valuable information on the pollinator and plant diversity and to aid monitoring of pollinator assemblages around the world.

Measures of pollination efficiency focus primarily on pollen transfer efficiency and visitation frequency; therefore, pollinators with high abundance and high floral visitation are considered proficient pollinators (Rader et al. 2009). Diptera represent one of the most diverse orders of insects on the planet, with over 124,000 recorded species (Skevington and Dang 2002; Rhodes 2018), and their diverse distribution throughout all landscapes contributes to their success as pollinators (Raguso 2020). An estimated 555 of the more than 240,000 described species of angiosperms have regular visitation by anthophilous flies, including upwards of about 100 cultivated crops, such as cacao, tea, mango, onion, cashew, and oil seed rape (Kearns 2001). As such, the strength of Diptera as pollinators stems from the wide geographic distribution and their extremely high abundance (Orford et al. 2015; Toivonen et al. 2022). While many pollinator species within Hymenoptera and Lepidoptera are specialists (i.e., restricting their floral visitation to a particular flower family or species), flies tend to be generalist visitors (i.e., visiting numerous flower species), which may increase pollination effectiveness (Motten et al. 1981; Kearns and Inouye 1994; Rhodes 2018). Therefore, healthy populations of generalist pollinators may act an insurance policy for pollination services given the widespread declines in some species, particularly specialist pollinators (Kearns 1992; Rader et al. 2016). Like all pollinators, flies visit flowers primarily in search of carbohydrates (nectar) and protein (pollen) (Brodie et al. 2015; Doyle et al. 2020).

In this study, we used images posted on social media platforms to investigate the potential of flies

as pollinators. Specifically, we investigated three main questions: (Q1) what flower characteristics predict pollen carrying by flies? (Q2) what flower characteristics predict foraging by flies? Finally, (Q3) are there differences among fly families in their visitation and attraction to floral resources in pictures taken by the citizen scientists? For questions 1 and 2, we used inflorescence type and colour to evaluate flower attributes that are related to visitation, feeding and pollen carrying. For question 3, we hypothesized that there will be differences between Syrphidae flies (hover flies) and non-Syrphidae flies with respect to the types of flowers visited and pollen carrying based on dependency on flowers. Adult Syrphidae are dependent on pollen and nectar to complete their life cycle (Gilbert, 1981; Hickman et al. 1995) and 97 families of non-Syrphidae Diptera are flower visitors and likely facultative foragers (D. Inouye, personal communication, November 24, 2022). We also evaluated the diversity of fly pollinators and their floral resources, and the potential role citizen science has as a large-scale biodiversity monitoring tool. An additional goal for our passive crowdsourcing fly pollinator study is to help spearhead other initiatives that take advantage of the massive amount of biodiversity information available on social media and content sharing platforms to advance biodiversity studies, particularly for species that are widespread, non-charismatic and difficult to study at broad spatial scales.

MATERIALS AND METHODS

Internet searches were performed between August 2016 through August 2020 using the Google Chrome v. 33.x web browser. Search engines evaluated were [Google Images](#), with resulting external links, and three major social media platforms [Flickr](#), [Instagram](#), and [agefotostock](#). We explored platforms with general search terms, such as “fly flower” and, as fly families appeared in queue, targeted searches with Latin Family names and common names of flies combined with “flower”, e.g., “house fly flower” and “Muscidae flower” (Appendix. 1). Additionally, we targeted lesser flies and flower flies (Family Syrphidae) by using search terms including “Culicidae flower” and “mosquito flower” or “flower fly flower” and “Syrphidae flower”, for example. Resulting images containing

a true fly (e.g., not a bee or other non-target insect) together with a flower shown in bloom, and with sufficient image quality such that taxa could be reliably identified (e.g., the image was not blurry, key identifying features of fly and inflorescence was clearly visible), were examined sequentially in the order they appeared in search results. Images from the same photographer were only used once for the same fly family, unless photographed on a different day or location. Although iNaturalist is becoming increasingly popular for biodiversity-related research, we did not use this database because it has limited functionality for labelling and searching interspecific interactions. However, we did use iNaturalist to verify taxonomic information (e.g., family, genus, and species) alongside [Twitter](#), [BugGuide](#), experts in the field, and field guides (Niering & Olmstead 1979; Skevington, 2019).

For each image, taxonomic information was recorded for the fly, including suborders Nematocera and Brachycera (*Higher/Lesser*), Family (when possible; including *Syrphidae/non-Syrphidae*), and Genus and species (when possible); and flower, including Family, and Genus and species (when possible). Flies were further characterized by sex (determined based on morphology), feeding status (visible proboscis extension into the flower), and pollen presence or absence (visible pollen particles on body). Flowers were further sorted by their petal colour (grouped according to visible spectrum wavelength): purple to blue (ranging from 380-520 nm), green to yellow (ranging from 520-590 nm), orange to red (ranging from 590-740 nm), or white; and also by shape: elongate cluster, round cluster, composite shaped, or simple shaped (Fig. 1). Additionally, for each photo, a web link, geographic location, and date, were also recorded. To ensure thorough data, we reached out to photographers to request missing information when necessary. With exception of Family, Genus and species (fly and flower), and sex, all above information was required for photos to be included in the data set and analysis.

STATISTICAL ANALYSIS

We used logistic regression to predict the probability of flies carrying pollen (yes = 1 / no = 0) or feeding from flower with proboscis extended (yes = 1 / no = 0) as a function of four categorical variables: flower *Shape*, and flower *Colour*,



A. Round Cluster B. Elongate Cluster C. Simple Shaped D. Composite

Figure 1. Illustration of inflorescence/flower shape categories. (A) Round Cluster: flat-topped or round-topped inflorescence, (B) Elongate cluster: inflorescence with flower clusters arranged along pedicel, (C) Simple Shaped: single flower with an uncomplicated structure, including fused, partially fused petals, and free petals, and (D) Composite: inflorescence with numerous thin ray petals in dense flower head.

Higher/Lesser flies and Syrphidae/non-Syrphidae flies (see above). We implemented simple (one-variable) models and additive models with or without an interaction term (shape \times colour) for each of the two main questions (pollen carrying and feeding) for three subsets of data: Syrphidae-only flies, non-Syrphidae flies, and all flies. For each question and data subset, we used a model selection information-theoretic approach and Akaike Information Criterion (AICc) to rank the models. We then calculated the odds for each variable in the top model to evaluate differences in selected flower colour and shape. We evaluated the fit of the top model using a Hosmer-Lemeshow goodness-of-fit test using package *performance* (Ludecke et al. 2021) for program R (p-values >0.05 denote good model fit). We also evaluated model performance using the Area Under the Curve (AUC) of the Receiver Operating Characteristics (ROC). AUC values >0.7 denote good model performance (i.e., capacity to discriminate between carrying and not carrying pollen or between feeding and not feeding on flowers, given our flower and fly variables), while AUC = 0.5 denotes no performance or capacity to discriminate between our binary response variables (i.e., the Null or intercept-only model). All analyses were implemented in program R (R Core Team 2021).

RESULTS

We collected 1275 usable images of fly-flower visitations from photographs taken worldwide

and posted on the Internet. Most photographs in this data set were taken in Europe (63%) and North America (32%), and the remainder were taken in Asia (1.5%), Australia (1.5%), South America ($<1\%$), and Africa ($<1\%$).

INVENTORY OF MYOPHILOUS TAXONOMIC DIVERSITY

Fly biodiversity

The dataset included 22 distinct fly families, consisting of 1001 flies (17 families) of the suborder Brachycera and 273 flies (5 families) of the suborder Nematocera (Fig 2). Also, 164 flies were in family Syrphidae and 1111 flies were in non-Syrphidae families. The largest portion of our dataset consisted of the Calliphoridae (Brachycera) (27%). A total of 486 (38%) flies had pollen visible on some part of their bodies (Fig. 2) and 652 (51%) of flies were observed actively feeding on flowers. Lastly, 52% of flies were female, 26% were male, and 22% could not be identified from the photograph.

Flower biodiversity and characteristics

The best-represented flower family in our dataset was Asteraceae (42%), followed by Apiaceae (21%) (Fig. 3), and these families were major contributors to the groups of flowers classified as elongate cluster (17%) and round cluster (36%). A variety of families had flowers classified as composite (17%) and simple shaped (30%). White (37%) and green to yellow (36%) flowers were most common, while

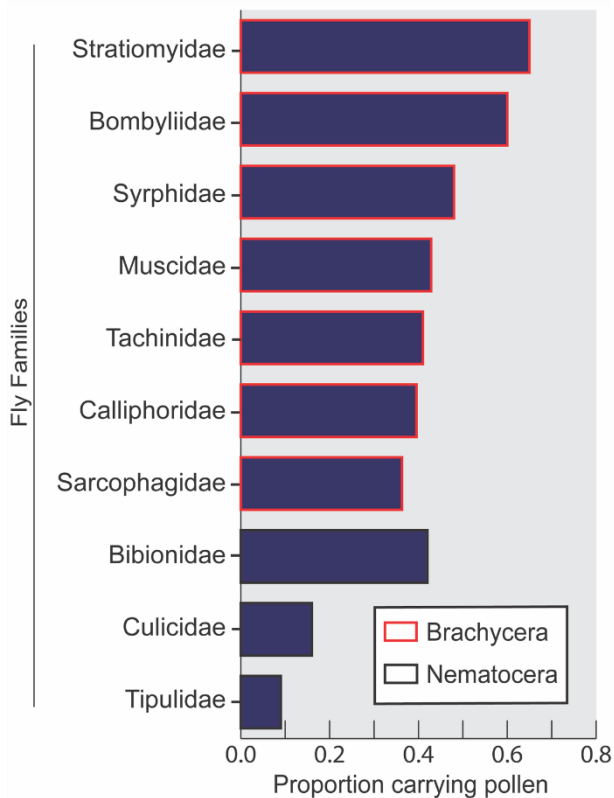


Figure 2. Proportion of flies within each family visibly carrying pollen. (Only the 10 most observed families are shown.)

purple to blue (15%) and orange to red (12%) were less well-represented in our dataset.

PREDICTING POLLEN CARRYING

When considering the all-flies dataset, we found that the best logistic regression predicting the probability of carrying pollen was the most complex model (AICc weight = 0.478), which included the interaction between flower *Colour* and *Shape*, as well as fly attributes (*Syrphidae* / *non-Syrphidae* and *Higher* / *Lesser* fly; Appendix II). The model had good fit (Hosmer-Lemeshow goodness-of-fit-test $\chi^2_5 = 7.026$, $P = 0.219$) and the AUC ROC value was 0.672. Overall, *Lesser* flies were less likely to be carrying pollen than *Higher* flies (OR = 0.313, 95% CI = 0.221 - 0.437) and *Syrphidae* flies carried pollen more often than *non-Syrphidae* flies (OR = 1.345, 95% CI = 0.942 - 1.923), (Fig. 4A). The interaction between flower *Colour* and *Shape* was largely driven by variation in the effect of flower colour on pollen-carrying for flies visiting *elongate cluster* flowers: pollen-carrying was less likely when flowers of this shape were *orange-red* or *white* and more likely when they were *green-yellow* (Fig. 4).

Syrphidae vs. *Non-Syrphidae* flies

The overall percentage of flies visibly carrying pollen was similar for *Syrphidae* (47%; $N = 163$, Fig. 2) and *non-Syrphidae* (37%; $N = 1112$, Fig. 2). Flower *Colour* was the best predictor for the probability of carrying pollen for both groups. The best model for non-*Syrphidae* flies contained flower *Shape* and *Colour* (AICc weight = 0.680, Appendix II, Fig. 4B). The model had good fit (Hosmer-Lemeshow goodness-of-fit-test $\chi^2_3 = 1.174$, $P = 0.759$) and the AUC ROC value was 0.595. *Non-Syrphidae* flies were less likely to be carrying pollen when visiting *purple-blue* flowers than *green-yellow* and *white* flowers; the likelihood of carrying pollen when on *orange-red* flowers was intermediate. *Non-Syrphidae* flies were also less likely to be carrying pollen when visiting *simple-shaped* flowers (Fig. 4B).

The best logistic regression predicting the probability of carrying pollen for *Syrphidae* flies contained *Colour* only (AICc weight = 0.595, Appendix II, Fig. 4C), but the model did not show a good fit (Hosmer-Lemeshow goodness-of-fit-test $\chi^2_3 = 0$, $P < 0.001$). Because they so rarely visited *purple-blue* flowers, this category was not included in the model. Considering the remaining flower colours, *Syrphidae* were less likely to carry pollen when visiting *orange-red* flowers than *green-yellow* and *white* flowers.

PREDICTING FLORAL FORAGING

When considering all the flies in the dataset, we found that the best logistic regression predicting the probability of active feeding on flowers was the most complex model (AICc weight = 1.000), which included the interaction between flower *Colour* and *Shape*, as well as fly attributes (*Syrphidae* / *non-Syrphidae* and *Higher* / *Lesser* fly; Appendix III). The model had good fit (Hosmer-Lemeshow goodness-of-fit-test $\chi^2_4 = 1.940$, $P = 0.747$) and the AUC ROC value was 0.729. *Non-Syrphidae* flies were much more likely to be nectar-foraging than *Syrphidae* flies, and *Higher* flies were more often foraging than *Lesser* flies (Fig. 5A). There was a main effect of colour, with flies were more likely to feed on *yellow-green* and *white* flowers than on flowers of other colours. The interaction between flower *Colour* and *Shape* was not significant, and primarily driven by flies feeding more often on yellow-green flowers than those of other colours, but not when the flowers were *elongate cluster* shaped (Fig. 5).

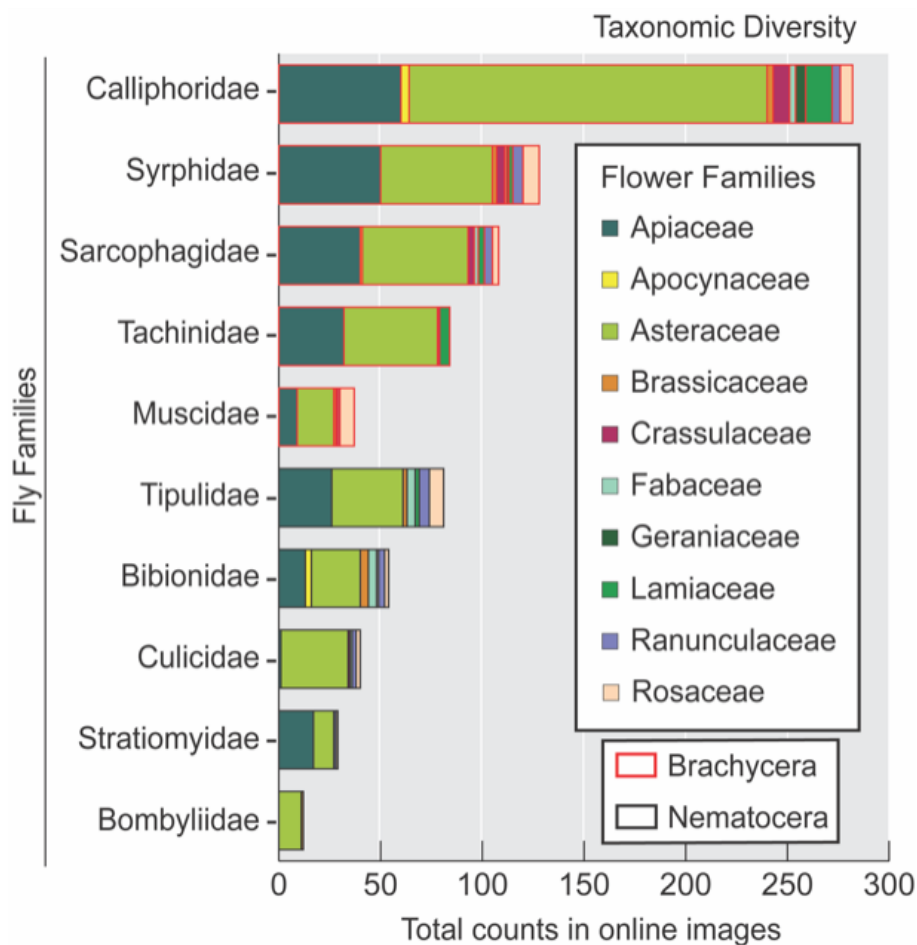


Figure 3. Fly and flower taxonomic diversity in 1,275 online photographs (only the 10 most observed families are shown). Blow flies (Family Calliphoridae) represented the largest family of fly (27%) followed by flower fly (Family Syrphidae; 13%) and flesh flies (Family Sarcophagidae; 11%). The largest representative flower families included composite flowers (Family Asteraceae; 43%) and umbel flowers (Family Apiaceae; 21%).

Syrphidae vs. Non-Syrphidae flies

We found that *Colour* and *Shape* were the most significant predictors of *non-Syrphidae* flies actively feeding on flowers (AICc weight = 0.688, Fig. 5B). The model had good fit (Hosmer-Lemeshow goodness-of-fit-test $\chi^2_2 = 3.140$, $P = 0.208$) and the AUC ROC value was 0.627. Flies were more likely to be foraging on *round cluster* flowers than *composite* flowers, with those of other shapes intermediate. Flies were more likely to be actively feeding on *white* flowers than *purple-blue*, *yellow-green* and *orange-red* flowers.

The best model explaining *Syrphidae* fly foraging included only *Shape* (AICc weight = 0.546, Fig. 5C; however, the model did not show a good fit (Hosmer-Lemeshow goodness-of-fit-test $\chi^2_3 = 0$, $P < 0.001$) and the next best model was the null model (AICc weight = 0.193). As with *non-Syrphidae*, *Syrphidae* flies were more likely to be observed feeding more on *round cluster* flowers than *composite* flowers, with other shapes intermediate.

DISCUSSION

This study showcases the usefulness of crowdsourcing photographs online as a valuable starting point for assessing flower-pollinator interactions and insect biodiversity in general. Applying this approach to flower-visiting flies, we obtained a dataset of both fly and flower families that reveals interesting patterns of interactions between flies and flowers. Our models suggest that (1) “higher” flies (Brachycera) and flies in family Syrphidae are more likely to be seen in photos carrying pollen on their bodies than “lower” flies (Nematocera), respectively, and that they more often carry pollen from yellow to green (medium-wavelength) and white flowers, and (2) “lower” flies (Nematocera) and non-Syrphidae flies are more likely to forage on nectar compared to “higher” flies and Syrphidae, respectively, and they more often forage on medium-wavelength and white flowers that are round-cluster shaped than flowers of other colours or shapes. To highlight the utility of this method for the global

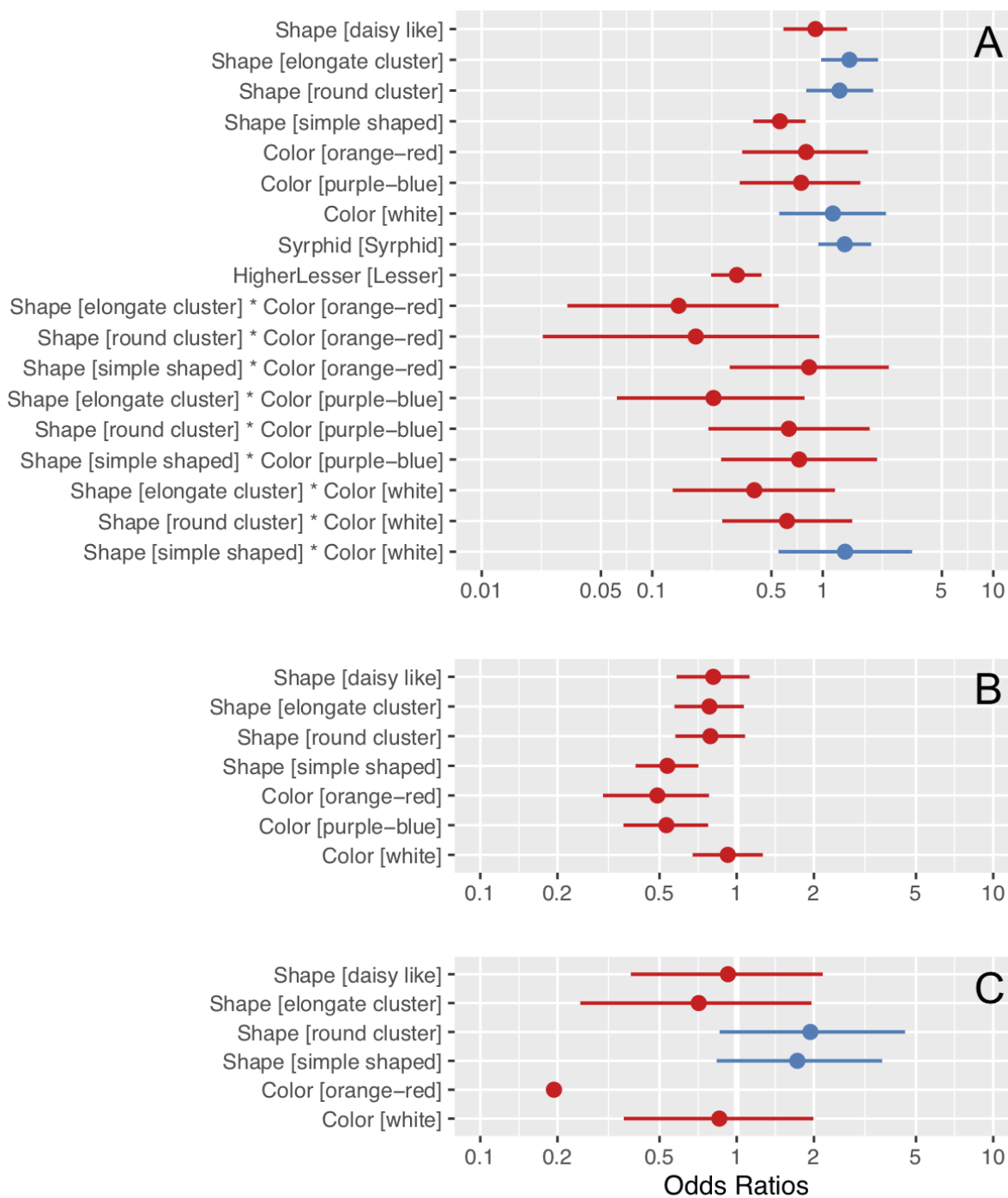


Figure 4. Odds of variables predicting the probability of flies carrying pollen. (A) All flies (B) Non-Syrphidae flies (C) Syrphidae flies. Blue dots / lines are mean odds / 95% confidence and denote a positive relationship between each variable and pollen carrying; red dot / 95% confidence intervals denote a negative relationship.

context, and to establish further the importance of flies as pollinators, we provide (3) an overall inventory of flower and fly taxonomic data, which catalogues 1,275 instances of fly-flower visitations.

Unlike most other fly families, the Syrphidae are already recognized as effective pollinators, particularly in agricultural systems, providing an

alternative to bees for managed pollination (Doyle et al. 2020). While our models indicate that the likelihood of visibly carrying pollen tends to be higher for Syrphidae than non-Syrphidae, we also found that other fly families, particularly in suborder Brachycera, were often photographed while visibly carrying pollen. Indeed, of families

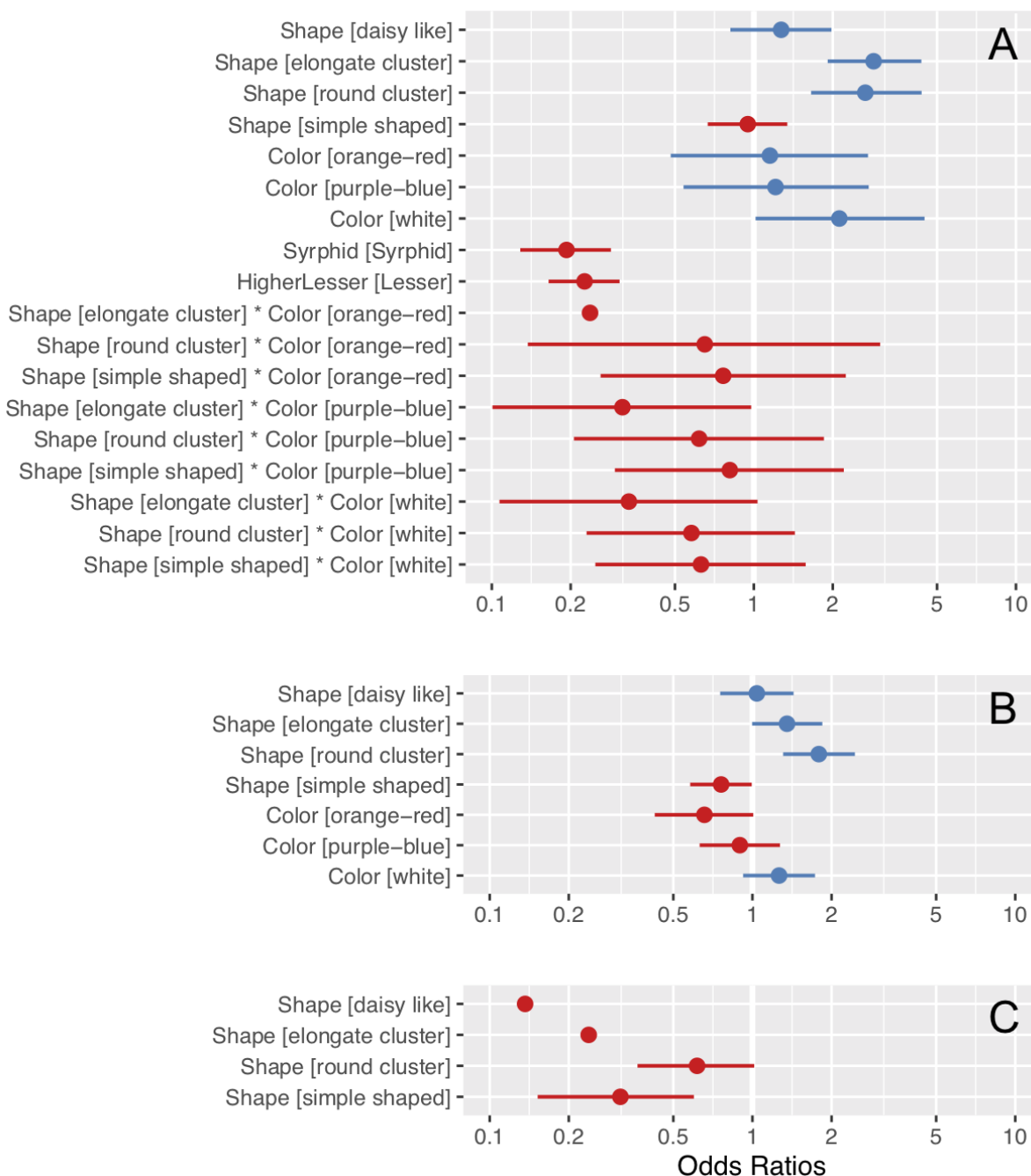


Figure 5. Odds of variables predicting the probability of floral foraging. (A) All flies; (B) Non-Syrphidae flies; (C) Syrphidae flies. Blue dots / lines are mean odds / 95% confidence and denote a positive relationship between each variable and pollen carrying; red dot / 95% confidence intervals denote a negative relationship.

for which we had more than 30 observations, Stratiomyidae flies were most commonly observed carrying pollen in photographs (65%), followed by Bombyliidae (60%), Syrphidae (48%), Muscidae (43%), and Bibionidae (42%) (Fig. 2). We acknowledge that our dataset is biased by the plants and flies that people choose to photograph, such that the relative abundance of flies and plants in each family are unlikely to reflect their

availability in nature. However, it is unlikely that the presence of pollen strongly biases the decision to photograph a given fly. Consequently, our dataset can provide insight into the propensity for different kinds of flies to carry pollen and potentially act as pollinators.

Fly pollination studies tend to focus more on Syrphidae, Bombyliidae, and Muscidae, due to

their frequent association with flowers (Larson et al. 2001; Klecka et al. 2018). Of the non-bee pollinators, Syrphidae flies have gained increased attention in the literature, and their ecosystem services are valued at about \$300 billion per year owing to their frequent crop visitation (Doyle et al. 2020); however, studies have found no significant difference in pollen loads (number of pollen grains) between Syrphidae, a well-established pollinator family, and non-Syrphidae Diptera (Orford et al. 2015). Our study found a total of 387 (38.1%) flies had pollen visible on some part of their bodies (Fig. 2), including 8 families within the suborder Brachycera, and 2 families (Culicidae and Tipulidae) within suborder Nematocera, which should not be overlooked as potential pollinators (Larson et al. 2001). However, we acknowledge that the greater frequency of visible pollen grains in photographs of some families may reflect easier observation on dark body surfaces rather than greater frequency of pollen transport.

Overall, flower *shape* was not a strong predictor of pollen carrying, while flower *colour* was strongly associated with pollen carrying. The interaction between *shape* and *colour* was overall significant, but the differences between different combinations of flower *colour* and *shape* were less easy to distinguish (Fig. 4). We found that flies across all groups were more likely to be carrying pollen when photographed on green to yellow and white flowers than those of other colours (Fig. 4). These results corroborate previous studies, as several of the fly families known to have colour vision (i.e., Calliphoridae, Syrphidae, Tephritidae, Anthomoidea), innately prefer yellow stimuli (Woodcock et al. 2014; Brodie et al. 2015; Hannah et al. 2019). Rather than assessing fly behaviour based on human colour categorization, we grouped colours based on wavelengths to distinguish fly behaviour better in terms of the ability of their photoreceptors to absorb categorical wavelengths of light (Morante & Desplan 2008; Jersáková et al. 2012). Fly vision extends beyond human colour detection, and this study does not allow us to measure potential UV reflection by flowers that would be visible to the fly eye (Arnold et al. 2009). As flies have only two kinds of photoreceptor cells, their inability to perceive one colour from another (i.e., yellow from white), a possible consequence of any associated UV absorption (Woodcock et al. 2014; Inouye et al.

2015), may explain the similar rates of pollen carrying for flies visiting yellow-green and white flowers.

Both flower *colour* and *shape* were significant predictors for nectar-foraging on flowers, with *shape* having a stronger effect; the interaction term included in the best model was not significant (Fig. 5). Colour recognition is an important variable for flies in their assessment of an artificial food source (Troje 1993) and with many species of flies, their proboscis extension is innately determined based on visual stimuli (Wacht et al. 2000). For example, the hover fly *Eristalis tenax* (Family Syrphidae) has an innate proboscis reflex fixed specifically for yellow stimuli (Lunau et al. 2018). In terms of shape, the results indicate that flies most often feed on *round cluster* flowers and least often on *composite* flowers (Fig. 5), which may be attributed to foraging efficiency, foraging experience, and/or colour stimuli associated with *round cluster* flowers. Compared to angiosperms with solitary flowers, clustered flowers contain an abundance of inflorescences with a high density of flowers, which reduces the flight distance required by pollinators to attain floral rewards, and in turn increases the frequency of pollinator visitation (Klinkhamer and de Jong 1990). The majority (70%) of photographs collected in this study contained plants of the *Asteraceae* and *Apiaceae* families; the former has an uneven distribution of flower shapes including composite, elongate cluster, and round cluster, and the latter has an even distribution of flower shapes, mainly comprised of *round cluster* flowers. Although flies have been found as important pollinators of blue flowers (Kearns and Inouye, 1994), most flowers identified from photos in our study were yellow, green, and white.

Pollination biologists have tended to neglect myophily, primarily due to the omnivorous diet of flies, their non-cooperative brood care, lack of specialization, and indiscriminate pollination compared to valued Hymenoptera (Mitra and Banerjee 2007). In this study, we gathered 1,275 usable photographs of fly-flower visitations spanning 20 fly families and 71 flower families from around the globe. In March of 2022, we performed a Google Scholar search of papers dealing with "bee pollinators" and "fly pollinators", which returned almost 84,000 results for bees, and only half as many for flies; this great distinction in

research interest between the two groups raises the issue of pollinator value, and the criterion for such preference over another order. Compared to their bee counterparts, which depend primarily on nutrients derived from floral resources in both larval and adult stages (Vaudo et al. 2015), the fly diet extends beyond floral resources, to organic material, vertebrate blood, and insect haemolymph (Courtney et al. 2017). Where bees may exhibit more specialization, however, interactions between bee assemblages and fly assemblages may benefit flower communities (Fründ et al. 2010), particularly in areas of high elevation (Orford et al. 2015). Consequently, it may not be a question of whether flies are valued less than their bee counterparts, but rather, a question of how we can study such an indiscriminate pollinator that may not possess the same suite of traits that facilitate bee research, for example per visit pollen deposition (Kearns and Inouye 1994).

Our study has several limitations characteristic of crowdsourced data and of using photographs for ecological inference in general. One of these limitations is the geographic scope of the data. Most images used in our study come from affluent countries in North America and Western Europe. Such biases in citizen-collected ecological data are not uncommon in other taxa (e.g., Breeding Birds Survey in the US and UK, FrogWatch, Bumble Bee Watch). This bias is likely reflected in the difference between the number of families identified in our study ($N = 22$) visiting 63 different flower families, compared to the 55 fly families listed in Larson (2002) and 97 fly families listed in a 27-year online database (D. Inouye, personal communication, November 24). This discrepancy may also be due to photographer bias, as charismatic or colourful flies and flowers may be more appealing to the photographer, while very small flies or flies visiting less showy flowers may have been missed if high-performance macro lenses were not available or photographers were less interested in such species. Similarly, images with flies that are small or not easily identified as flies (e.g., bee-mimics) will not show up in search results. Although biased, crowdsourcing photographs allowed for a rapid survey of fly pollinators and their foraging resources which would have not been possible using systematic surveys, and has the potential to augment existing knowledge of fly-flower relationships as they

relate to flower characteristics, fly feeding and pollen carrying.

Using passively crowdsourced data online and the methods outlined in this study may have applications in other systems. Internet images can represent a broad sample of events and, as we have shown, provide information about biodiversity and flower-insect interactions observed in photographs (Bahlai & Landis 2016). However, when considering the crowdsourcing methodology at higher-level taxonomic categories, it is likely that not all families would be captured, especially smaller fly species and small flowers lower in the herbaceous layer. Furthermore, citizen scientists may have their own motives and interests when pursuing fly and flower photographs (Show 2015) and are more likely to document rare events and interactions (Gardiner et al. 2012). Documenting rare ecological events or interactions may lead to a biased view of flower-insect interactions, but can also provide new insights that could not be captured using systematic surveys. Therefore, a comparison of crowdsourced searches to experimental results or *in situ* observations is essential for validation and interpretation of fly-flower interactions.

In summary, while caution should be used when drawing inference from passively crowdsourced online data, such data has the potential to add valuable information on the global issue of biodiversity monitoring in the Anthropocene. As the acceleration in biodiversity loss poses a major need for efficient methods of monitoring global pollinator assemblages, citizen science offers a gateway into global biodiversity monitoring. Throughout the COVID-19 pandemic, digital technology and online repositories have aided scientists in their continued monitoring, despite physical constraints (Dwivedi 2021). Citizen platforms have always been accessible for scientists and offer an untapped resource that extends beyond the temporal and spatial capabilities of experts alone (Sánchez-Clavijo et al. 2021). This study was limited to fly-flower interactions; however, in addition to insight on taxonomic attraction, the photographs gathered offer accessible geographic, phenological, temporal activity, and sex-based behavioural data valuable for biodiversity monitoring. The information we obtained from crowdsourcing only

a small fraction of the photographs published on social media platforms harnessed a working database for running models for several fields of studies. Future work could take advantage of the >2 million photographs of flies on iNaturalist to mine this rich dataset for fly-flower interactions and gain further insights into the diversity of flies that feed on and potentially pollinate flowering plants.

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AUTHOR CONTRIBUTION

Concept and design BSB & CS, data collection AW, EB, SR, data analysis BSB, CS, & DVP, writing BSB, CS, & EB, edits and approval for publication BSB & CS.

DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

DATA AVAILABILITY STATEMENT

The full dataset of 1,275 images of flies and blooming flowers is available at Zenodo.org (Blakeman et al. 2023).

APPENDICES

Additional supporting information may be found in the online version of this article:

Appendix I. Search terms used for Google image search and number of resulting images.

Appendix II. Models predicting pollen carrying. Model results of All Flies, Non-Syrphidae, and Syrphidae models evaluating predictors (*Shape*, *Colour*, *Syrphidae / Non-Syrphidae*, *Higher / Lesser*) and predictor interactions for predicting pollen carrying. Models within 2 AICc units from the top model for each of the three model sets have similar support. (loglik – log-likelihood, AICc = Akaike's Information Criterion adjusted for small sample size; AUC ROC = Area Under the Curve of the Receiver Operating Characteristic; × denotes interaction terms).

Appendix III. Models predicting floral foraging. Model results of All Flies, Non-Syrphidae, and Syrphidae models evaluating predictors (*Shape*, *Colour*, *Syrphidae / Non-Syrphidae*, *Higher / Lesser*) and predictor interactions for

predicting floral foraging. Models within 2 AICc units from the top model for each of the three model sets have similar support. (loglik – log-likelihood, AICc = Akaike's Information Criterion adjusted for small sample size; AUC ROC = Area Under the Curve of the Receiver Operating Characteristic; × denotes interaction terms).

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