**Title:** Influence of pollinator species identity and priority effects upon fruit quality in two mass-flowering berry crops

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**Abstract**

1. Animal pollination is mediated by both floral morphological structures and animal pollen vector traits, with important implications for persistence of natural plant populations and economically, mass-flowering crops.
2. Compositional differences in pollination services may be mediated not only by trait matching (i.e. the concordance between plant and animal functional traits) in floral visitation sequences but also preferential interactions of certain species, such as through priority effects, here the influence of the initial visit.
3. We measured floral visitation sequences (1-20 visits) of either single-species (*Apis mellifera* or *Tetragonula carbonaria*) or mixed-compositional visits and resultant fruit weight in two mass-flowering crops, blueberry (*Vaccinium corymbosum*) and raspberry (*Rubus idealis*).
4. We used linear-mixed models to relate the length and composition of floral visitation sequences to fruit quality. Further, we examined the influence of priority effecst using the species identity and visit duration of initial visits on fruit weight.
5. Blueberry and raspberry demonstrate crop-specific relationships between floral visitation and fruit weight. Increased visitation by honeybees resulted in greater fruit weight for blueberry, whereas mixed and stingless bee visits resulted in greater fruit weight in raspberry.
6. Species identity of the initial visit in mixed-compositional visits was more important in examining patterns of fruit weight in blueberry, where stingless bee visited initially, there was significantly greater fruit weight. In raspberry, the duration of the initial visit, irrepsecitvef of species, had an additive effect along with visitation rate on fruit weight.
7. Pollination and plant reproductive success represent the cumulative influence of a pollinator community interacting with a given plant species. Crop-specific trends, as well as the presence of priority effects in floral visitation sequences, highlight the benefits of increased biodiversity for multiple crops grown in the same environment.

**Introduction**

Animal-mediated pollination services typically represent an animal communities’ cumulative floral visitation patterns, with individual pollinator species differing in their efficiency and ability to pollinate plants, depending on their functional traits and those of each plant species. As such, understanding how pollinator species interact with flowers individually and collectively, will lead to better understanding and management of both natural and agricultural ecosystems. Trait matching, whereby pollinator functional traits (e.g., body size, tongue length and behaviour) are well-adapted to floral morphological structures has been demonstrated to better-predict pollination rates (i.e. fruit set) in crop systems than trait diversity (i.e. a larger number of species with different functional traits) (Garibaldi et al. 2015). As such, many plant species are pollinated by a few common species (WHATS THE REF), although globally, species richness has also been linked to greater provision of pollination services and crop yields (Dainese et al. 2019).

Pollinator species frequently interact with flowers collectively, (i.e. more than one species will visit a given flower across duration of flowering, termed a `visitation sequence`), for better (e.g. BUMBLE + APIS PAPERS, Garratt) or worse (e.g., Dedej & Delaplane 2004). However, despite the knowledge of the cumulative influences of mixed-species assemblages on pollination, mechanistically much remains unexplained. One way, in which, that collective insect visitation may structure the effect of pollination is through `priority effects`. Typically, priority effects have been examined in explaining the compositional trajectory of ecology communities and how this is strongly influenced by the order of species arrival to those communities (REF). Priority effects often determine how species interact and compete with each other within communities, and can drive divergent successional trajectories among sites, and in pollination, differences in gene flow and dispersal within plant populations. For example, Homquist, RANDY & Karron (2012) demonstrated that recipient plants of *Mimulus,* as a result of pollen grooming by bumblebees,receive donor pollen from the three most recently visited individuals. Further, studies detailing priority effects in floral bacteria communities have shown that floral bacterium can reduce pollination success by reducing pollinator foraging and nectar consumption (Vanette et al. 2013; Good et al. 2014).Importantly, pollination-related priority effects are likely mediated by floral morphology (e.g., the presence and location of floral resources and rewards), given the influence of trait matching in explaining patterns in pollination services.

Despite the importance of trait matching worldwide, trait diversity may influence pollination in cumulative visitation sequences, due to the distinct, sequential floral visitation of multiple species. Further, different species may deplete floral resources, leading to reduced effectiveness of subsequent visitation events, irrespective of the pollinator species. In both cases, priority effects are not only likely to be driven by pollinator functional traits, but also differences in floral structure and mating systems among plant species, such as those plants which either facultatiely or obligately require buzz-pollination for reproductive success (i.e. plant families Ericaceae and Solanaceae) as well as those with pollen incompatibility systems that require allogamous (cross) pollination for increased plant reproductive success.

Here, we examine firstly, how two common generalist bee species, *Apis mellifera,* and *Tetragonula carbonaria*, influence fruit weight for two crop species (blueberry: *Vaccinium* *corymbosum* and raspberry: *Rubus idaeus*), in either single-species visitation sequences or mixed-species sequences, and secondly, whether species’ or behavioural priority effects influence pollination in mixed-species visitation sequences. Then, test whether floral visitation sequence priority effects are diluted as the floral visitation rate increases. Finally, we test if priority effects are mediated by differences in floral structure among plant species.

**Materials and Methods**

**Study site**

We conducted this study on the North Coast, New South Wales, Australia on a large-scale 350ha-1 commercial berry farm (29.990232°S, 153.143171°E) across two flowering seasons for blueberry (May 2017 and 2018) and one flowering season for raspberry (February-March 2017).

**Plant species and floral structure**

We focussed on one blueberry species: ‘Southern Highbush’ (SH) (*Vaccinium corymbosum,* cultivar Snowchaser) and one raspberry species: *Rubus idaeus,* cultivar: Driscoll Cardinal. Both blueberry and raspberry flowers are hermaphroditic but differ considerably in shape and display. Blueberry flowers are urceolate, and in open flowers, the anthers remain enclosed within the corolla whereas a single stigma protrudes slightly above the corolla aperture. In contrast, raspberry flowers are dish-shaped, with an open floral display, with ~100 stigmas encircled by ~100 anthers (Driscoll Cardinal Patent).

A figure of each would be nice here I think.

**Floral visitation**

For both blueberry and raspberry, we placed organza bags (mesh size < 0.01mm) over developing shoots and tagged developing flowers before opening. We un-bagged flowers upon opening and observed visits from the two dominant pollinator species (European honeybees, *Apis mellifera* and native stingless bees, *Tetragonula carbonaria*). This resulted in sequential visits from honeybees (number of visits range: x-x), stingless bees (number of visits range: x-x) or a mixture of honeybees and stingless bees (number of visits range: x-x). For each pollinator visit, we ~~recorded the foraging behaviour of the individual (i.e., either pollen or nectar foraging) based on the presence or absence of corbiculae (i.e. pollen baskets, comprised of collected pollen, on the hind legs) and~~ recorded visit duration in seconds. Once the flowers had been visited for the target number of visits, each flower was re-bagged for the duration of its flowering to prevent further visitation from pollinators. We picked the fruit upon ripening and measured fruit weight (grams) in both species using an analytical balance (accuracy: 0.00 g) on the same day.

**Data analysis**

**Does a mixture of floral visits from different pollinator species result in greater fruit set and/or heavier fruits than visits from a single species?**

To test whether visits from multiple pollinator species result in greater fruit weight compared with visits from single species we used a LMM with berry weight as the response variable and species visit composition (honeybee, stingless bee, or a mixture of both; categorical) in interaction with the number of visits (continuous) as fixed effects. For the blueberry model, we included the random terms of block crossed with year because visitation data were collected from different plant individuals in different cropping blocks across two growing years. For the raspberry model, we included a random effect term of block because visitation data were collected from different cropping blocks, in one growing season. Finally, we tested whether slopes for fruit weight with an increasing number of pollinator visits were significantly different from zero for each pollinator species using “emmeans” (V.X.X.X, REF et al. XXXX).

**Do interspecific pollinator priority effects mediate fruit weight in different plant species with distinct floral structures?**

To identify pollinator priority effects in blueberry and raspberry, we subsetted each data set to only include fruit weights produced as a result of mixed pollinator visits (minimum two visits to flowers from both honeybees and stingless bees). We then categorised each fruit as a being produced from a flower initially visited by either a honeybee or a stingless bee. With this data structure, we specified linear mixed effect models (LMMs) to estimate fruit weight as a function of the initial floral visitor (honeybee or stingless bee; categorical) in a three-way interaction with the total number of floral visits (continuous) and ratio of honeybee to stingless bee visits (continuous). In the blueberry model, we included two crossed random effect terms (block and year; categorical) because visitation data were collected in the same orchard block across two growing years. In the raspberry model, we included one random effect term (block; categorical) as data were collected across multiple orchard blocks within the same growing year. We then conducted model selection on these models using the *MuMIn* package (v.X.X.X, Ref et al. XXXX) and found that, in both blueberry and raspberry, the best model for predicting fruit weight included the initial floral visitor, number of floral visits and their interaction. Accordingly, we present model-estimates and slope contrasts for these reduced models. To calculate slope contrasts (i.e., whether there was a significant difference in model-estimated slopes for fruit weight according to the identity of the initial visitor) we used emmeans (v.X.X.X, Ref et al. XXXX). Thus, evidence of a pollinator priority effect is indicated by a significant difference in the model-estimated slope for fruit weight as a function of the number of pollinator visits between the two initial visitor categories (i.e., honeybee or stingless bee) or a signficant relationship with the initial visit duration.

We specified all LMMs using the *glmmTMB* package (v.0.2.3, Brooks et al., 2017). For both intra- and interspecific priority effects analyses, we modelled fruit weight with a Gaussian distribution. We assessed model residuals using the *DHARMa* package (v.0.2.2, Hartig 2019). All analyses were conducted in *R* v3.5.1 (R Core Team, 2018).

*~~Intraspecific priority effects~~*

~~We first subsetted our data to single-species compositional visits (categorical; honeybees or stingless bees). We then estimated fruit set or fruit weight as a function of the first floral visitor’s behaviour (categorical; pollen or nectar foraging) in interaction with the proportion of pollen forager visits (continuous) and total number of floral visits (continuous). Again, in blueberry, we included one random terms:~~ *~~year,~~* ~~as visitation data were collected in the block across two years,~~~~and in raspberry, one random term:~~ *~~block,~~* ~~as data were collected across multiple blocks.~~

**Results**

**Does a mixture of floral visits from different pollinator species result in heavier fruits than visits from a single species?**

For blueberry, we found that fruit weight increased with an increasing number of visits from honeybees (slope = 0.136 ± 0.049, *z* = 2.759, *P* = 0.003; Figure 3) and weakly for stingless bees combined with honeybees (slope = 0.022 ± 0.016, *z* = 1.318, *P* = 0.095) but not for stingless bees only (slope = 0.018 ± 0.078, *z* = 0.237, *P* = 0.407). Overall, fresh weight from flowers visited by both honeybees and stingless bees were significantly greater than those visited by honeybees alone (contrast: 0.114 ± 0.0519, *t* = 2.199, *P* = 0.044).



**Figure 3.** Weight of blueberry fruit from flowers visited by only honeybees or stingless bees or a mixture of honeybees and stingless bees. Solid lines are the model-estimated fruit weights with an increasing number of pollinator visits and shaded ribbons are the model-estimated confidence intervals. Hollow circles are the actual data.

In contrast, for raspberry, we found that fruit weight increased with an increasing number of visits from stingless bees (slope = 0.178 ± 0.069, *z* = 2.559, *P* = 0.006; Figure 4) and stingless bees combined with honeybees (slope = 0.043 ± 0.016, *z* = 2.657, *P* = 0.0042) but not from honeybees only (slope = 0.026 ± 0.029, *z* = 0.886, *P* = 0.1883).



**Figure 4.** Weight of raspberry fruit from flowers visited by only honeybees or stingless bees or a mixture of honeybees and stingless bees. Solid lines are the model-estimated fruit weights with an increasing number of pollinator visits and shaded ribbons are the model-estimated confidence intervals. Hollow circles are the actual data.

Despite these trends, for both raspberry and blueberry we found no differences between slopes (association between fruit weight and the number of pollinator visits) for fruits produced from stingless bee versus honeybee visits. Similarly, there were no differences between slopes for fruits produced from a mixture of stingless bee and honeybee visits versus visits from either one of these taxa (Table SX).

**Do interspecific pollinator priority effects mediate fruit weight in different plant species with distinct floral structures?**

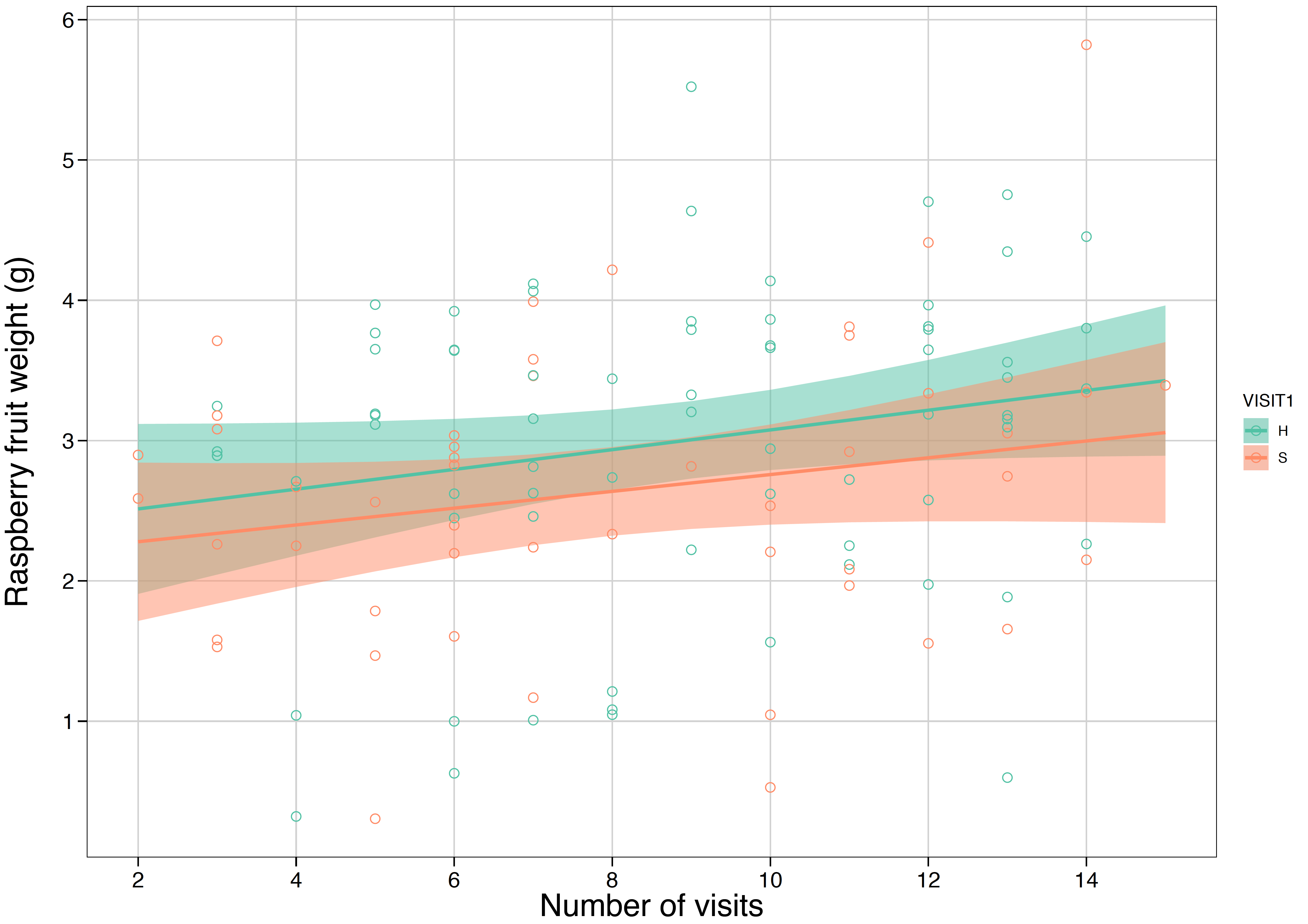
We detected a strong priority effect in blueberry, whereby fruit produced from flowers that received their first visit from a stingless bee were initially 79% heavier than those that had a honeybee visit first (*t =* 2.601 , *P* = 0.009, stingless bee : visit number interaction, *t* = -2.284 *P =* 0.02240) and exhibited significantly different slopes (honeybee – stingless bee slope contrast = 0.071 ± 0.031, *t* = 2.283, *P* = 0.0273; Figure 1). With an increasing number of visits, weight of fruit produced from flowers those that received first received honeybee visits increased significantly (b = 0.051 ± 0.017, t = 2.9, *P* = 0.006), whereas weight of fruit from flowers that first received a stingless bee visit did not increase (b = -0.02 ± 0.026, t = -0.787, *P* = 0.436).



**Figure 4.** Weight of blueberry fruit from flowers first visited by a honeybee versus those first visited by a stingless bee. Solid lines are the model-estimated fruit weights with an increasing number of pollinator visits and shaded ribbons are the model-estimated confidence intervals. Hollow circles are the actual data.

In raspberry, a strong priority effect, raspberry fruit weight were best explained by an additive relationship between the duration of the first visit and the total number of visits, irrespective of pollinator identity (scaled first visit duration, b = 0.215 ± 0.093, *t* = 2.323, *P* = 0.02; total visit number, b = 0.075 ± 0.027, *t* = 2.745, *P* = 0.006).

~~However, we found no evidence of a pollinator priority effect in raspberry, where fruit weight was similar across the visit number range regardless of first visitor’s identity (honeybee – stingless bee slope contrast = 0.024 ± 0.035,~~ *~~t~~* ~~= 0.699,~~ *~~P~~* ~~= 0.48; Figure 2).~~ The ratio of honeybee to stingless bee visits had no effect on fruit weight for both blueberry and raspberry.



**Figure 4.** Weight of raspberry fruit from flowers first visited by a honeybee versus those first visited by a stingless bee. Solid lines are the model-estimated fruit weights with an increasing number of pollinator visits and shaded ribbons are the model-estimated confidence intervals. Hollow circles are the actual data.

**Discussion**

Honeybees and stingless bees differ in their ability to pollinate both blueberries and raspberries, resulting in crop-specific trends between floral visitation patterns and fruit quality. In blueberry, only increased honeybee visitation resulted in higher fruit weight relative to stingless bee or mixed visitation sequences. In raspberry, however, a greater number of mixed or stingless bee visits increased fruit quality but not honeybee visits. Increased fruit quality has previously been associated with increased visitation by honeybees and bumblebees in Apple (Garratt), however the clear differences between the two crops indicates that each pollinator species interacts distinctively, both individually or collectively, with the floral structure of each crop species.

The degree to which these two species can pollinate a plant species relies upon both the functional traits of each pollinator (i.e. body size, tongue length) as well the plant species (i.e. nectar accessibility), an interaction called ‘trait matching’. Garibaldi et al. (2015) found that trait matching between plants and pollinators benefits pollination services more so than trait diversity, through the synergistic influence of pollinator morphology (in particular body size, and behaviour), although it is ultimately mediated by plant mating system and level of self-compatibility, and the inherent need for pollen transport between and within individuals (Minnaer et al. 2019).

Blueberry requires buzz-pollination for greater pollen transport, however, both honeybees and stingless bees are unable to buzz-pollinate. As such, both nectar- and pollen collecting honeybees deposit less pollen than buzz-pollinating species (e.g. blueberry bees (*Habropoda* sp.) and bumble bees (*Bombus* sp.), Benjamin and Winfree 2013). Yet, our results suggest that honeybees are able to overcome their inability to buzz-pollinate through increased visitation (longer sequences). as opposed to stingless bees or mixed visits which do not demonstrate a positive relationship between visitation rate and fruit quality. The presence of an opposite effect in raspberry, further suggests that the quality (e.g. pollen deposition rates) of individual floral visits as well as their order may be as important as the quantity of visits in predicting fruit quality and mediated through interspecific and behavioural priority effects.

The influence of how species interact in floral visitation over time and the collective influence mixed pollinator visitation sequences is currently unknown. Across our mixed-compositional visits, species-level priority effects explained variation in fruit quality in blueberry. As such, this may represent that trait matching is more influential in blueberry than raspberry, in explaining compositional differences and priority effects given their floral structure (see Fig. 1). Despite neither species considered herein can buzz-pollinate, stingless bees overcome limitation by virtue of their body size (ITD: 1-2mm, Kendall et al. 2019, may as well self-cite myself hahaha), which results in within-flower visitation behaviours, as opposed to honeybees, which spent significantly less time at flowers, and primarily interact with corolla opening, using their forelegs or proboscis to collect pollen or nectar respectively. By spending more time in the flower, and directly interacting with the anthers, we suggest this may increase the likelihood of firstly, autogamous pollen (from the same flower), and secondly, geitonogamous pollen (same species, different clonal individual) of which both are beneficial means of pollination given the cultivar’s self-compatibility (REF), leading to greater fruit weight. Dedej & Delaplane (2004) demonstrated an detrimental influence of nectar-robbing Carpenter bees (Xylocopa virginica) on the pollination services provided by honeybees, altering their behaviour to become secondary thieves. In contrast, our results suggest that honeybees facultatively improve later visitation events within a sequence, whereas stingless bee priority effects diminish the influence of later visits within a given sequence, which may account for the lack of association between visitation sequence length and fruit quality in stingless bee only visitation sequences.

In raspberry, species-level differences in behaviours are less important given the open-dish shaped flowers, however initial visit duration, irrespective than species, has an additive effect in conjunction with total visit number on fruit quality. As such, this suggests that increased visit duration leads to the higher likelihood of stigmatic contact, as a function of high nectar availability in the virgin flowers, and given there are ~100 stigmas per flower, this increases the likelihood of higher proportion of stigmas being pollinated.

However, although as stingless bees exhibit longer periods in visitng blueberry, the species-level priority effect may be a result of both duration and species identity, although species in interaction with visit number better explained the variance in blueberry weight than duration and visit number.

In laboratory studies, blueberry pollen begin to react enzymatically in medium within 90 minutes *in vivo*, with maximum germination occurring within eight hours (Huang and Johnson 1996). In contrast, pollen germination rates are not known for raspberry, although germination is achieved in 20-25 hours in closely-related blackberries (*Rubus* subgen. *Rubus*) (Nybom 1985). As such, the presence of species compositional differences and priority effects in fruit quality are, hypothetically, influenced by the period of time from pollen adhesion to ovule fertilisation, and the likelihood of abiotic (wind or water) as well as subsequent floral visitors dislodging and transporting pollen between and within flowers (Minnaar et al. 2019). Future research should focus on the physiological processes that underlie these processes, to confirm the validity of priority effects, given the timeframe needed for pollen adhesion.

Management of mass-flowering crops such as blueberries and raspberries requires further information regarding the influence of floral structures, how these are exploited by different insect floral visitor species and the plant physiological processes that occur in single-species and mixed compositional floral visitation sequences. At the plant scale, flowers differ in their pollen limitation (REF, must be true), therefore the presence of both compositional differences between taxa and species-level or behavioural priority highlights an additional benefit to employing multiple pollinator species in crops and conserving biodiversity in agroecosystems. Although we demonstrated differential trends in species complexes and priority across these two species, overall, both species are beneficially influenced by the presence of multiple pollinator species, due to their differential behaviour and trait matching highlighting the need to conserve natural habitats and biodiversity in ensure continuity pollination services.

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**Author contributions**

LKK and RR conceived the study and designed the experiments. LKK and MH collected data. LKK, JS and VG undertook the data analyses. LK and JS wrote the manuscript and all authors contributed substantially to the final version.

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