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Significant yield benefits from honeybee pollination of faba bean (*Vicia faba*) assessed at field scale

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ABSTRACT

There is growing evidence globally that improved pollination practices can help support higher yield and reduced variability for a wide range of insect pollinated crops. Managed honeybees are provided to pollinate some orchard crops, but they are less commonly used for field crops, in part because of uncertainty as to whether the potential benefits are justified by the costs. This uncertainty comes from a lack of studies conducted at the appropriate scale. In this study we examine the yield benefits from managed honeybees applied to *Vicia faba* in field scale trials. We provided honeybee hives to 17 fields in South Australia, and observed that bee activity and fruits per stem decreased with increasing distance from hives. We examined the spatial pattern of yield using yield map data collected at harvest and found there was an effect of distance from hives on mean yield (declining with distance) and spatial variability of yield (increasing with distance). The presence of a distance gradient was consistent across all fields, across two years, two *V. faba* varieties and two different bee-hive management methods. The average benefit is estimated to be an additional 17% yield, 90% of which is attained within 767 m of hives. Our economic analysis indicates that provision of hives is profitable for a wide range of realistic values for crop value (dollars per tonne) and pollination cost (dollars per hive).

1. Introduction

Seventy five percent of the 115 most important crops globally are at least partly dependent on insect pollination to maximise yield (Klein et al., 2007). The range of yield benefits is great, and many of the crops with the highest potential yield benefits are orchard crops (Klein et al., 2007). Nevertheless, the provision of pollinators has only become standard management for a small number of crops where reliance is highest (e.g. almonds), and many of the other crops that could benefit from pollinator management are often grown without deliberate pollinator management strategies (pers. obs.). It has been suggested that variability in pollination management is the reason that, compared with other crops, pollination dependent crops have shown lower yield growth and greater annual and spatial variation in yield over the past four decades (Garibaldi et al., 2011). Conversely, better pollination could be a significant part of improved practice to increase and stabilise yield, including strategies to increase pollination by wild insects and use of managed honeybees (Garibaldi et al., 2013). Field crops offer particular challenges for pollination because they are usually grown at a large scale (compared to orchards) requiring many hives be spread over large areas, and because potential yield benefits are not as great as for the most pollination-dependent orchard crops. As a consequence the potential economic benefits of pollination for field crops are poorly understood and managed pollinators are not usually applied. To understand the potential for pollination benefits to these crops it is important to examine outcomes at large scale, and to consider the cost of pollination relative the possible benefits. The goal of this study was to use this approach to examine the effect of managed honeybees in faba bean (*Vicia faba*).

Many studies have tried to assess benefits to *V. faba* from insect pollination (Free, 1993), but it is difficult to draw a clear conclusion from the mixed results. Kendall and Smith (1975) noted great variation among studies done to that point, but recorded a pollination benefit from bee visits in their own research. Free and Williams (1976) showed that *V. faba* plants were pollen limited when further from the edge, probably because pollinators were less likely to penetrate there. Studies comparing plants caged with bees to those without have shown 25% (Somerville, 1999) and 49% (Musallam et al., 2004) yield benefits. In contrast, cage experiments by Hebblethwaite et al. (1984) suggest no yield benefit from honeybees, and Suso et al. (1996) conclude that resources rather than pollen availability limited yield across 12 different genotypes in their study. Given these variable results it is perhaps not surprising that in the region of this study most fields of *V. faba* are grown

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without managed pollinators, but some growers make the choice to pay for pollination services.

Some of this variation in results is likely to be due to differences in climate and the pollinator community. For example, Stoddard (1991) argues that honeybees can be more important in Australia than in places with colder climates, because flowering occurs in late winter and early spring when feral honeybees are in search of pollen. *Bombus*, which are active at lower temperatures than honeybees, are absent from mainland Australia. A number of different studies suggest that honeybees are less effective pollinators of *V. faba* than various other bee species including *Anthophora plumipes* (Bond and Kirby, 1999) and *Eucera pulveracea* (Aouar-Sadli et al., 2008). Additional variation is likely to be due to varietal differences in levels of self-compatibility and other reproductive traits. It is important to recognise, however, that pollinators can contribute to higher yield even for crops that are considered self-pollinating (e.g. Bommarco et al., 2012). Finally there are almost certainly artefacts arising from different experimental approaches. In particular, caged pollinator experiments can create unrealistic pollinator densities and unusual pollinator behaviour because they restrict the movement of insects that normally forage over much larger areas, and can also cause unintended effects on plant growth (Blanche et al., 2006). Studies conducted only at the flower or stem level can fail to detect important resource-mediated effects that are best understood at plot scale and above.

The knowledge gaps identified here are not particular to *V. faba*, but are general across the crop pollination literature. Extensive observations and experiences with crops and pollinating bees have been compiled in compendia of knowledge such as McGregor (1976), Free (1993) and Delaplane and Mayer (2000), but it remains the case that experiments which link field scale pollination practice to yield (rather than proxies for yield) are missing. As a consequence, recommendations for hive stocking density are usually based on experiences and assumptions rather than experiments (Free, 1993).

Our goal was to examine the effect of managed honeybee pollination on yield of a *V. faba* crop in a manner that provides clearer insights for management. The experiment was designed as a gradient analysis, where the gradient of interest is pollinator availability as a declining function of distance from managed honeybee hives placed at the edge of large fields of *V. faba*. If distance from hive proves a significant predictor of yield this suggests that pollinator availability is influencing yield. Spurious interpretations could arise if some other important environmental factor was correlated with distance from hive, but this risk is controlled by replicating the gradient over many different locations with hive placement in a diversity of environmental contexts. We also test that a pollinator gradient has indeed been created, by observing bee activity. This design has the merit of measuring the pollination benefit from managed bees at field scale under real farming conditions with free flying bees (i.e. no cages). It also allows for detection of non-linear patterns of yield in the response to the pollinator gradient. If, however, the managed pollination effect is small relative to other causes of variation in yield then this design may fail to detect any pollinator effect at all.

We examined yield benefits using yield map data, therefore measuring the response most directly aligned with real economic benefits to growers. To gain insights into mechanism we corresponded our yield results with observations on flower to fruit conversion counts at stem level. A secondary goal was to compare two different hive management approaches used by beekeepers in the region to see if they had different effects on the pollination outcome. The “single placement” strategy is the most commonly used, and does not differ appreciably from strategies used to maximise honey collection. The “in field” strategy was developed with a goal of increasing the effectiveness for crop pollination.

2. Materials and methods

2.1. Sites and hive placement

Experiments were conducted in 17 fields of *V. faba* in 2008, 2009 and 2010 (Supplementary Table 1), in an area of South Australia ranging from 34°8′ S, 138°43′ E to 34°58′ S, 137°18′ E about 160 km to the SW. The median distance between fields was 21.5 km (max = 153 km, min = 200 m) and mean field size was 68 ha (1 SE = 10) with fields usually approximately rectangular, but sometimes irregular or triangular in shape. Hives were placed when the field was at approximately 10% flowering. For the “single placement” treatment 30 hives were placed in one large cluster, outside and adjacent to the field, or just within the field boundary in an area with no crop. For the “in field” treatment bee hives were located inside the field near one edge, arranged in 2 or 3 rows, at 10 m spacing between hives and 50 m spacing between rows. Most fields received 30 hives, three larger fields (C, D, E) received more (Supplementary Table 1). The “in field” hives were all less than 300 m from the nearest edge of the field, and there was a continuous area of crop such that the far edge was more than 600 m away, allowing us to assess a distance gradient.

The different hive placements were also associated with different hive management. The “in field” hives had 4 frames of brood and 6 frames of bees, and were stripped of honey fortnightly. Pollinating hives do not need a large honey store, but crowding of the hive with honey and brood can reduce foraging (McGregor, 1976) so this management might increase the rate of foraging in compensation. The “single placement” hives were twice as large (8 frames of brood 12 frames of bees) and were not stripped of honey during the pollination period, but instead allowed to accumulate (up to 20 frames). Their honey was harvested at the end of flowering.

2.2. Bee activity

Observations on density of actively foraging bees took place at 5 sites in 2009 and 6 in 2010. We marked straight line transects through the crop with 6 or 7 points between 0 and 550 m from hives. For the “single placement” hive treatment the nearest point on the transect was 50 m from hives. At each site we made observations at all points on the transect, on a day where the weather was not too cold (<13 °C) or too windy (wind speed >25 km per h), between 10 a.m. and 2 p.m. At each location the observer counted the number of bees active in an area of 10 m^2 of crop over a 1 min period. The observations were then repeated at least once, and up to 8 times, depending on conditions (mean = 3.6). For six sites observations were made on one day, and for five sites two separate days. The total number of 1 min observations was 365.

We examined the relationship between distance from hive and bee activity using a linear mixed model. Bee visitation was log transformed ($\log_{10}$ visits + 1) to meet the assumption of normally distributed residuals. We considered distance and hive treatment as fixed effects, and site, year and variety as random effects. Hive treatment (in field vs. single placement) had no significant effect ($P = 0.127$) and so was dropped from the final model. The best random model (considering deviance and the akaike information criterion) included site but not year or variety.

2.3. Flower and fruit counts

We counted flowers and fruits on plants at points on the same transects established for bee activity observations. At each point stems were tagged and flowers were counted. Flower counts were