

Pollen Collection, Honey Production, and Pollination Services: Managing Honey Bees in an Agricultural Setting

Shelley E. Hoover¹ and Lynae P. Ovinge

Alberta Agriculture and Forestry, Lethbridge Research Centre, 5401-1 Avenue South, Lethbridge, AB T1J 4V6, Canada and

¹Corresponding author, e-mail: shelley.hoover@gov.ab.ca

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Abstract

Hybrid canola seed production is an important pollination market in Canada; typically both honey bees (*Apis mellifera* L. (Hymenoptera: Apidae)) and Alfalfa Leafcutting bees (*Megachile rotundata* Fab. (Hymenoptera: Megachilidae)) are concurrently managed to ensure pollination in this high-value crop. Beekeepers are paid to provide pollination services, and the colonies also produce a honey crop from the canola. Pollen availability from male-fertile plants is carefully managed in this crop to provide an abundance of pollen to fertilize male-sterile ('female') plants. This abundance of pollen represents an underutilized resource for beekeepers, and an opportunity to diversify the hive-products produced for market in this management system. We used a commercial-style pollen trap to collect pollen from colonies twice weekly for the duration of canola pollination, and compared the honey production and amount of sealed brood in colonies with pollen traps to those without pollen traps. We found that while pollen trapping reduced honey production, there was no negative impact on brood production, and at current market prices, the per-hive revenue was higher in colonies from which pollen was trapped. Pollen trapping honey bee colonies in the context of hybrid canola pollination, therefore, offers beekeepers an opportunity to diversify their products and increase their revenue.

Key words: pollen trapping, pollen collection, honey production, honey bee management, pollination

In addition to water, honey bees gather two foods; nectar is converted to honey and acts as a source of carbohydrates, while pollen satisfies the need of the colony for protein, minerals, and fats (Winston 1987). Nutritionally, pollen is important not only for the production of brood food, but is also critical for newly emerged workers to fully develop tissues such as the hypopharyngeal gland and fat body (Haydak 1970, Fluri and Bogdanov 1987, Hrassnigg and Crailsheim 1998, Keller 2005a) required for brood-rearing and overwintering. In adult workers, pollen consumption is dependent on the age and behavioral tasks performed by workers, with nurse bees that are actively engaged in brood-rearing and feeding the queen consuming relatively large amounts of pollen (Hrassnigg and Crailsheim 1998).

Honey bee colonies do not maintain a large amount of stored pollen, rather they actively regulate the amount of pollen in the colony according to their current need. Fewell and Winston (1992, 1996) demonstrated that in contrast to nectar foraging, which is largely controlled by availability, pollen foraging behavior in honey bees is very sensitive to colony state, in particular, the amount of uncapped brood (eggs and larvae) relative to pollen stores. The presence of eggs and larvae stimulate pollen foraging (Free 1967), in particular, the presence of older larvae is highly stimulatory to pollen collection (Hellmich and Rothenbuhler 1986).

Colonies manipulated by experimenters or beekeepers to have low pollen stores respond primarily by increasing the foraging effort

of individual workers (intensity and load size) (see also Eckert et al. 1994), but also secondarily by changing the choices made by foraging bees (pollen vs. nectar or water, see also Free 1967, Camazine 1993, Dreller et al. 1999, Pernal and Currie 2001) and the recruitment of previously inactive foragers (Fewell and Bertram 1999, Anderson 2001). Fewell and Winston (1992) suggest that there is a 'set point' around which honey bee colonies regulate pollen levels; too little incoming pollen would limit the colony's ability to rear brood, too much is unnecessary expenditure of foraging energy. Ultimately, the ability of the colony to rear adequate amounts of brood determines the population of adult bees and probability of colony survival; therefore, any restriction to the amount of pollen brought into a colony can have dramatic consequences on colony survival, particularly overwintering success in temperate climates.

In commercially managed honey bee hives, pollen can be easily collected from returning foragers through the use of pollen 'traps'. These traps are placed either in front of or underneath the hive entrance, and returning foragers are required to walk through a metal or plastic mesh to enter the hive. The mesh is specifically sized such that the foragers can get through it, but large corbicular pollen loads are scraped off the bees' legs and into a collection tray (e.g., GOA 1985, BC Ministry of Agriculture & Lands 2006). These traps are used by beekeepers when there is an abundance of

pollen to collect pollen either for sale or to feed their bees during periods of pollen dearth, or more recently to sell to the managed bumble bee industry to feed commercial bumble bee colonies. They are not typically used by beekeepers who are being paid to pollinate crops in Alberta. While a large amount of pollen can be collected this way, some pollen still enters the colony as traps are typically only 3–43% efficient at trapping incoming pollen (Duff and Furgala 1986b, Keller et al. 2005b). The efficiency of a trap depends on trap style and manufacture, bee size, pollen load size, and hive equipment. Small corbicular loads may not be scraped off the forager's legs, and any holes in the equipment may allow the bees another (non-trapped) entry to the comb. In addition, reducing the pollen income of a colony results in increased foraging effort (Camazine 1993). This allows some pollen to enter the hive, ensuring continued brood-rearing. However, depending on the type of trap, hive equipment, pollen supply, and the duration of trapping, reducing the colony pollen income via trapping can have unintended negative consequences on the ability of the colony to rear brood, and ultimately to survive.

Long-term pollen trapping can have negative consequences on honey and wax production (Moriya 1966, Lavie 1967, Katsanov and Petkova 1975, Duff and Furgala 1986b), brood-rearing, adult population (Moeller 1977, Webster et al. 1985, Duff and Furgala 1986a), and in some cases, disease levels and colony survival (McLellan 1974, Moeller 1977). Even short-term pollen dearth, when severe, can lead to cannibalism of young larvae and a shortening of larval development time (Schmickl and Crailsheim 2001), and the effects of pollen limitation on brood development can be measured for multiple generations (Dustmann and Ohe 1988). However, these effects are not always observed, particularly when traps are placed for a short period of time, or used intermittently (Rybhakov 1961, Lavie and Fresnaye 1963, Lavie 1967, Barker 1971, van Laere and Martens 1971, Goodman 1974, Katsanov and Petkova 1975, Duff and Furgala 1986a, Nelson et al 1987).

The Prairie Provinces of Alberta, Manitoba, and Saskatchewan are the largest honey producers in Canada. Production far exceeds consumption, and beekeepers in the region primarily sell their honey in bulk, to packers in Alberta and other regions of Canada as well as to export markets, notably the United States and Japan. Beekeepers in Alberta sell an estimated 94% of their honey through bulk sales (Laate 2017) as opposed to direct to consumer sales or retail packages. The price of bulk honey fluctuates with international production, and from 2007 to 2017 ranged between \$0.98 and 2.25 CDN per lb (\$2.16–4.95 per kg; Laate 2017). Alberta accounts for 42–45% of honey production in Canada and 43% of national production is exported rather than being consumed domestically (Statistics Canada 2016).

Annually, 55,000–75,000 honey bee colonies are rented to pollinate hybrid canola seed production fields in southern Alberta (Figs. 1 and 2). These fields are carefully managed to produce an abundance of pollen to ensure adequate seed set of this high-value crop. As seed canola pollination takes place primarily in mid-summer (end of June to the beginning of August), these colonies are typically very large, double brood chamber colonies that produce a honey crop while in pollination, despite a high stocking rate (1–1.5 hives per acre). In addition to quantity, the quality of pollen in this crop is also high. Canola pollen is high in fat, has sufficient protein and the required amino acids for successful brood rearing, and is highly attractive to honey bees (Somerville 2002). As a result, the abundance of quality pollen is a boon to the colonies, which typically grow their populations while on this crop.

This abundance of pollen is also a potential resource for beekeepers, who can collect it for resale or to feed their colonies during subsequent periods of pollen dearth. While some previous research

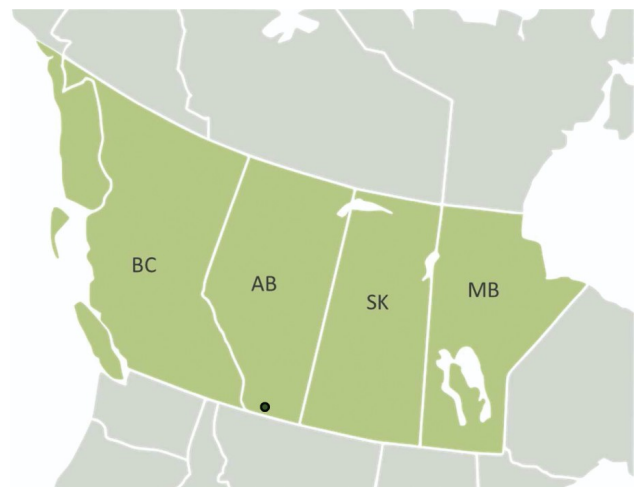


Fig. 1. The dot indicates the location of the study sites, three hybrid canola seed production fields near Lethbridge, Alberta, Canada (Nearctic-Ecozone Western Canada by CarolSpears is licensed under CC by-SA 3.0).

has demonstrated negative effects of prolonged pollen trapping on brood production, we predicted no negative effect of short-term trapping during canola pollination. Here we investigate whether beekeepers paid to provide pollination services in seed canola production systems could increase their revenue by collecting pollen, without detrimental effects on their colonies.

Methods and Materials

We identified 40 queenright double brood-chamber colonies (colonies with a mated, laying queen, each with two boxes containing brood and two additional boxes of comb for honey collection as per industry standards on this crop) in each of three hybrid canola seed production fields (total $n = 120$ colonies) near Burdett, AB ($49^{\circ}49'44.4''N$ $111^{\circ}31'03.9''W$) on 4–7 July. Each field was stocked with a total of 160 honey bee colonies, and approximately two gallons of Alfalfa Leafcutting bees per acre (3.1 liters per hectare). All fields were irrigated and approximately 49 hectares (120 acres) in size.

Each hive was marked with a unique numbered tag, and an initial assessment of brood population was conducted 4–7 July 2016, within a week of the hives being moved to the crop. For this initial assessment, the total amount of sealed brood in each colony was assessed by taking a photo of each side of each frame containing brood, and subsequently analyzed with HoneyBee Complete (WSC Regexperts, version 4.2) software. The brood population for all colonies was assessed when the colonies were first brought into pollination (4–7 July 2016), then again shortly before they were removed from the field (25–28 July 2016). Between these two assessment periods, we placed pollen traps on 20 double brood chamber hives per field (total $n = 60$ trapped colonies), dispersed amongst the untrapped hives. We placed the pollen traps on all four hives on each of five pallets, in an alternating manner with pallets of untrapped hives. We used bottom mounting 'OAC' (Ontario Agricultural College)-style pollen traps (BC Ministry of Agriculture and Lands 2006), with a front entrance, and an absorbent liner in the collection tray to reduce the amount of moisture in the collected pollen samples.

We collected the pollen twice weekly throughout the period (approximately 3 wk) the colonies were on the field. We then dried and weighed all the pollen collected. We dried the pollen by placing them in organza wedding-favor bags with color-changing silica gel



Fig. 2. Photograph of a typical layout of a canola seed production field, showing honey bee colonies on the field edge, and leafcutting bee shelters (orange and green tents) within the crop. Visible are the wide bays containing male-sterile (female) plants, and the narrower, pollen-bearing male bays. Both male and female plants offer nectar as a floral reward, whereas only the male plants offer pollen. Male bays may be mowed to induce re-flowering.

beads. We repeatedly changed the beads until they no longer changed color, indicating that the pollen was dry. We also recorded the honey production for each of the 120 colonies over the same time period by recording the weight of each honey super (box containing comb used to store honey) at both the initial and final hive assessments, and subtracting the initial weight of each super from its weight at the end of the study.

Statistical Analyses

All statistical analyses were performed using JMP 13 (JMP, Version 13 SAS Institute Inc., Cary, NC, 1989–2007). Separate factorial ANOVAs were conducted to compare the main effects of site and pollen trapping, and their interaction on honey production and change in sealed brood population (final–initial measurement), with Tukey’s HSD post-hoc analyses ($\alpha = 0.05$) where appropriate. A paired *t*-test was used to compare the sealed brood population of the colonies at the two different time points. ANOVA was also used to compare the initial brood population across sites, with Tukey’s HSD post-hoc analyses ($\alpha = 0.05$). The relationship between sealed brood and honey production was examined with linear regression, as were the relationships between initial brood and honey production, and pollen production and honey production. Finally, differences in pollen production across sites were examined using ANOVA with Tukey’s HSD post-hoc analyses ($\alpha = 0.05$).

Results

Colonies that became queenless over the duration of the experiment (four trapped and two untrapped) were excluded from subsequent analyses.

Sealed Brood

Despite previous reports of negative impacts on brood production associated with prolonged pollen trapping, short-term trapping during an abundant pollen flow had no impact on brood production,

whereas apiary did (factorial ANOVA with factors: trap, apiary site, and trap*apiary site on change in sealed brood from initial to final measurement; $F_{\text{TRAP } 1,114} = 0.23, P = 0.64$; $F_{\text{site } 2,114} = 4.80, P < 0.01$; $F_{\text{TRAP*site } 12,114} = 0.03, P = 0.97$). Colonies at site ‘92’ increased in sealed brood area less than colonies at the other two sites (apiary ‘92’ $\bar{x} = 1,946 \pm 825$ cell increase [mean \pm 1 SE], apiary ‘84’ $\bar{x} = 4,917 \pm 533$ cell increase, apiary ‘83’ $\bar{x} = 2,853 \pm 689$ cell increase). Both trapped and un-trapped colonies increased the amount of sealed brood per colony (paired *t*-test between time points, $T_{1,114} = 7.930, P < 0.0001$) (Fig. 3).

The experimental colonies had approximately 14,000 sealed brood cells at the initial assessment (initial trapped $\bar{x} = 13,955 \pm 486$ [mean \pm 1 SE] cells, initial un-trapped $\bar{x} = 13,749 \pm 579$ cells), increasing in size while used for canola pollination to approximately 17,000 sealed brood cells (final trapped $\bar{x} = 17,027 \pm 454$ cells, final un-trapped $\bar{x} = 17,137 \pm 472$ cells). This represents a growth in brood of circa 1,000 cells per week regardless of pollen collection, demonstrating that brood production was not pollen-limited in the colonies from which we collected pollen. There was a significant effect of site on the initial amount of unsealed brood in the colonies, with field site ‘92’ having more brood initially per colony ($\bar{x} = 15,896 \pm 623$ cells) than sites ‘84’ ($\bar{x} = 12,790 \pm 615$ cells) or ‘83’ ($\bar{x} = 12,885 \pm 623$ cells) ($F_{2,114} = 8.08, P = 0.0005$, Tukey’s HSD $\alpha < 0.05$). As this site difference was present at the initial colony assessment, it represents a difference among the colonies due to the source apiaries rather than the pollination sites.

Honey Production

In contrast, honey production was negatively impacted either by the physical addition of the pollen traps themselves, perhaps by slowing down foragers returning to the colony or by the removal of pollen which led to a colony-level requirement for additional pollen foraging (ANOVA on site, trap, and site*trap; $F_{\text{TRAP } 1,114} = 12.05, P = 0.0007$) (Fig. 4). There was also a significant effect of site on honey production ($F_{\text{site } 2,114} = 16.02, P < 0.0001$), with one of the

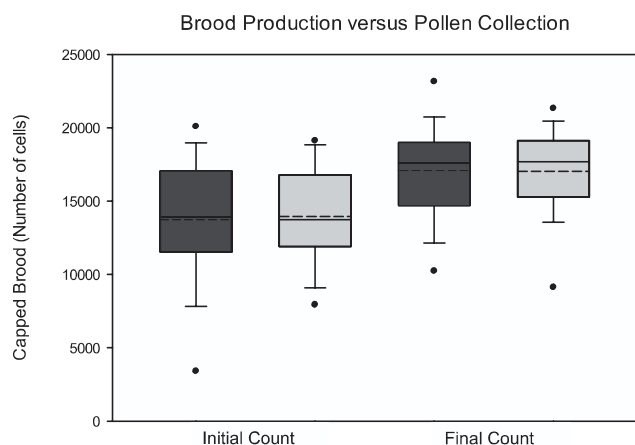


Fig. 3. There was no effect of pollen trapping on the amount of sealed brood in pollen trapped (light gray) versus untrapped (dark gray) colonies over the duration of canola seed pollination. Both trapped and untrapped colonies increased in the amount of sealed brood per colony between the initial and final assessments. For each box, the lowest part of the shaded box represents the 25th percentile, the solid line is the median, the dashed line is the mean, and the top of the shaded box is the 75th percentile. Whiskers represent 5th/95th percentile, and dots represent outliers.

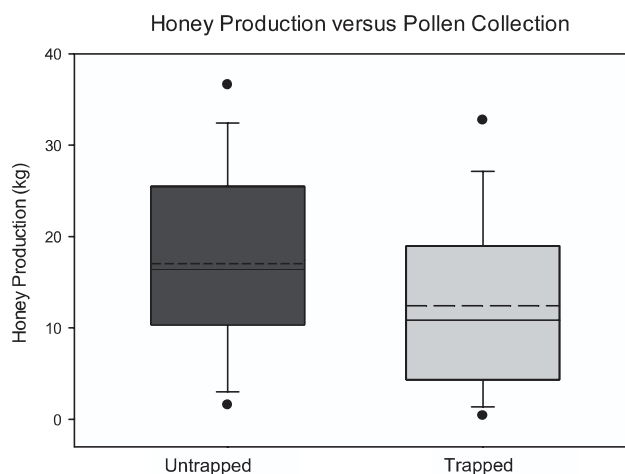


Fig. 4. The placement of pollen traps and active collection of pollen significantly reduced the honey production of trapped colonies (light gray) compared to those with no trap (dark gray). For each box, the lowest part of the shaded box represents the 25th percentile, the solid line is the median, the dashed line is the mean, and the top of the shaded box is the 75th percentile. Whiskers represent 5th/95th percentile, and dots represent outliers.

Table 1. Total revenue per hive across all hives (\$CDN) with and without pollen trapping

	Honey (kg)	Price (/kg)	Revenue	Pollen (kg)	Price (/kg)	Revenue	Total revenue per hive	% Increase in revenue
Bulk pricing								
Trap (pollen cleaned and dried)	12.41	3.04	37.73	1.80	30.86	55.55	93.28	67.68
Trap (pollen sold fresh) ^a	12.41	3.04	37.73	2.16*	18.15	39.20	76.93	38.29
No trap	18.30	3.04	55.63	—	—	—	55.63	
Direct sales								
Trap	12.41	16.50	204.77	1.80	99.21	178.58	383.35	26.96
No trap	18.30	16.50	301.95	—	—	—	301.95	

^aEstimated, as 15–25% loss in weight is typically associated with cleaning and drying pollen.

three apiaries producing significantly less honey than the other two (Tukey's HSD $\alpha < 0.05$; '83' $\bar{x} = 9.26$ kg vs. '84' $\bar{x} = 16.13$ kg and '92' $\bar{x} = 21.03$ kg). There was no interaction between site and trapping ($F_{\text{site} \times \text{trap}} = 0.45$, $P = 0.64$). Across all colonies, those with more sealed brood initially collected more honey (linear regression $R^2_{\text{initial brood}} = 0.21$, $t_{1,114} = 5.43$, $P < 0.0001$, honey = $-0.84 + 0.001 \times$ brood).

Cumulative honey production over the 3-wk period decreased from a mean of 18.30 ± 1.36 kg among untrapped colonies to only 12.41 ± 1.32 kg from colonies fitted with pollen traps, representing a loss of 5.89 kg per colony. This 32.19% decrease represents an economic loss to the beekeeper valued at that time at \$17.91 CDN for bulk sales ($\$3.04 \text{ CDN/kg} \times 5.89 \text{ kg} = \17.91 ; Laate 2017), \$46.47 CDN for consumer pack sales ($\$7.89 \text{ CDN/kg} \times 5.89 \text{ kg} = \46.47 ; Laate 2017), or \$97.19 CDN for direct (e.g., farmers' market) sales ($\$16.50 \text{ CDN/kg} \times 5.89 \text{ kg} = \97.19 ; Lethbridge Farmer's market, July 2016 mean price = \$16.50/kg, range \$13–20 per kg) (Table 1).

Pollen Collection and Revenue

As with honey production, there was a significant difference in the amount of pollen collected in the traps among sites, with one site producing more pollen than the other two (site '92' $\bar{x} = 2,536$ g vs. site '84' $\bar{x} = 1,546$ g and site '83' $\bar{x} = 1,339$ g) ($F_{2,54} = 9.07$, $P < 0.0004$;

Tukey's HSD $\alpha < 0.05$). Interestingly, the site ('92') that produced the most honey was also the site that produced the most pollen, likely due to the colonies at that site having had the most brood at the outset of the project; colonies with more brood at the initial assessment produced more pollen ($R^2 = 0.17$, $t_{1,54} = 3.30$, $P = 0.0018$, weight pollen = $157.62 + 0.1179 \times$ initial brood).

We found a positive correlation between honey production and pollen production ($R^2 = 0.134$, $t_{1,54} = 2.87$, $P = 0.006$; dry weight pollen = $1324.07 + 38.5 \times$ honey) (Fig. 5), a relationship likely based on colony population, with larger colonies having a larger foraging force and greater demands for feeding brood.

We collected an average of $1,802 \pm 139$ g cleaned, dried pollen per colony during the pollination period. At a market price of \$30.86 per kg bulk and \$99.21 at a local Farmer's market for clean, dried pollen, this represents \$55.61 CDN in bulk sales or \$178.78 CDN in direct pollen sales (Table 1). For bulk sales of fresh pollen to commercial pollen buyers with their own pollen cleaning lines, this would generate a revenue of \$39.20 per hive. Overall, the per hive revenue was larger from pollen-trapped colonies than untrapped colonies because of the high value of pollen relative to honey, and the large amounts of pollen collected from this crop (Tables 1 and 2). This was particularly true for bulk sales, which saw a 68% increase in revenue (38% for fresh pollen) with pollen trapping (Table 1),

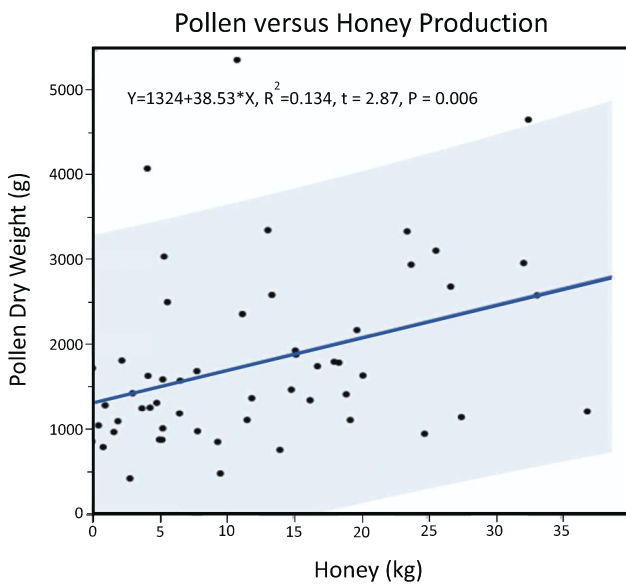


Fig. 5. Colonies that produced more honey also tended to produce more pollen. Each dot represents one colony; blue shading represents 95% confidence interval of the prediction.

versus 27% for direct sales. Beekeepers could realize even larger revenue increases if they focused on pollen collection from only high producing colonies. If we examine the potential revenue generation from the mean of the top 10 pollen producing colonies (18% of trapped colonies, Table 2), pollen trapping resulted in a 92% increase in revenue for bulk sales and a 41% increase for direct sales revenue.

Because of the positive correlation between pollen and honey production, colonies that collected relatively little pollen usually also collected relatively little honey. Of the 55 colonies we trapped pollen from, only two (3.6%) would have generated more revenue from honey production alone rather than both honey and pollen production (assuming a 32.19% decrease in honey production associated with pollen trapping). However, the absolute value of the profits generated will depend on the costs associated with pollen collection, which can vary substantially among beekeeping operations and whether the pollen is sold clean and dried or fresh and uncleaned.

Individual colonies tended to be consistent in the relative amount of pollen they produced (Fig. 6A and B), such that colonies that were top producers on the first sampling date were likely to be highly ranked on subsequent dates. Colonies that produced little pollen on the first sampling date tended to remain poor producers. Beekeepers that collect pollen as a hive product should, therefore, focus their efforts on colonies that yield high amounts of pollen, as collecting

pollen from poor yielding colonies may not be cost-effective when the reduction in honey and cost of collecting, cleaning, and drying pollen are included.

Discussion

While previous studies have found that long-term pollen trapping can have negative consequences on colony productivity, population, and even survival (Moriya 1966, Lavie 1967, Katsanov and Petkova 1975, McLellan 1974, Moeller 1977, Webster et al. 1985, Duff and Furgala 1986a), our study found no impact of short-term pollen trapping on brood production during a period of high pollen availability. This is important to establish because colonies without adequate pollen supply can maintain brood rearing for only a short time (Brodschneider and Crailsheim 2010). First, workers consume stored bee bread, then nurse bees deplete their own bodily reserves to ensure the continued protein feeding of developing brood (Haydak 1935). Finally, without incoming pollen, even short-term pollen dearth can lead to a shortening of larval development time and the cannibalism of young larvae (Schmickl and Crailsheim 2001). While cannibalized larvae can be used to supplement the protein status of the colony allowing remaining brood to be reared successfully, malnourished brood have been observed to have impairments such as malformations (Jay 1974), reduced life span, and smaller size (Eischen et al 1983, Daly et al. 1995, Brodschneider et al 2009). Finally, adult bees without access to adequate protein may also have decreased longevity (see discussion in Brodschneider and Crailsheim 2010), and decreased development of ovaries and hypopharyngeal glands (Pernal and Currie 2000, Hoover et al. 2006), thus impacting their ability to rear brood. Pollen deprivation can, therefore, have long-term impacts on colony health and survival, effects that we did not observe with our short-term trapping during a period of abundant pollen.

As we wished to examine the effects of pollen trapping on commercially managed honey bees, it is also important to identify any impacts to honey production, as that is the primary hive-product produced by beekeepers in the region. Colonies used to pollinate canola produced an average of 40.3 kg (88.9 lbs) honey per colony (2014–2016, n = 880 colonies across 22 apiaries) whereas colonies used exclusively for honey production in the same region produce an average of 24% more honey (2014–2016, n = 320 colonies across eight apiaries; Hoover and Ovinge, unpublished data). While beekeepers pollinating hybrid canola seed production fields are paid to provision each field with 120–160 hives, for a fee of \$177 per colony in 2016 (Laate 2017), the income from honey production is a substantial portion of their revenue, and factors into their decision of whether to pollinate the crop or use their colonies solely for honey production. The value of this honey crop fluctuates with market prices and availability in international markets and is primarily sold in bulk.

Table 2. Total revenue per hive for top 10 pollen-producing hives (\$CDN) with and without pollen trapping, for clean dry pollen

	Honey (kg)	Price (/kg)	Revenue	Clean dry pollen (kg)	Price (/kg)	Revenue	Total revenue per hive	% Increase in revenue
Bulk pricing								
Trap	19.83	3.04	60.28	3.57	30.86	110.17	170.45	91.75
No trap	29.24 ^a	3.04	88.89	—	—	—	88.89	
Direct sales								
Trap	19.83	16.50	327.20	3.57	99.21	354.18	681.38	41.29
No trap	29.24 ^a	16.50	482.46	—	—	—	482.26	

^aCalculated by dividing the mean weight of honey produced by the top pollen producing colonies by 32.19% decrease in production with pollen trapping = (19.83 kg) / (1 - 0.3219) = 29.24 kg, as we could not measure the honey production of these specific colonies without pollen traps.

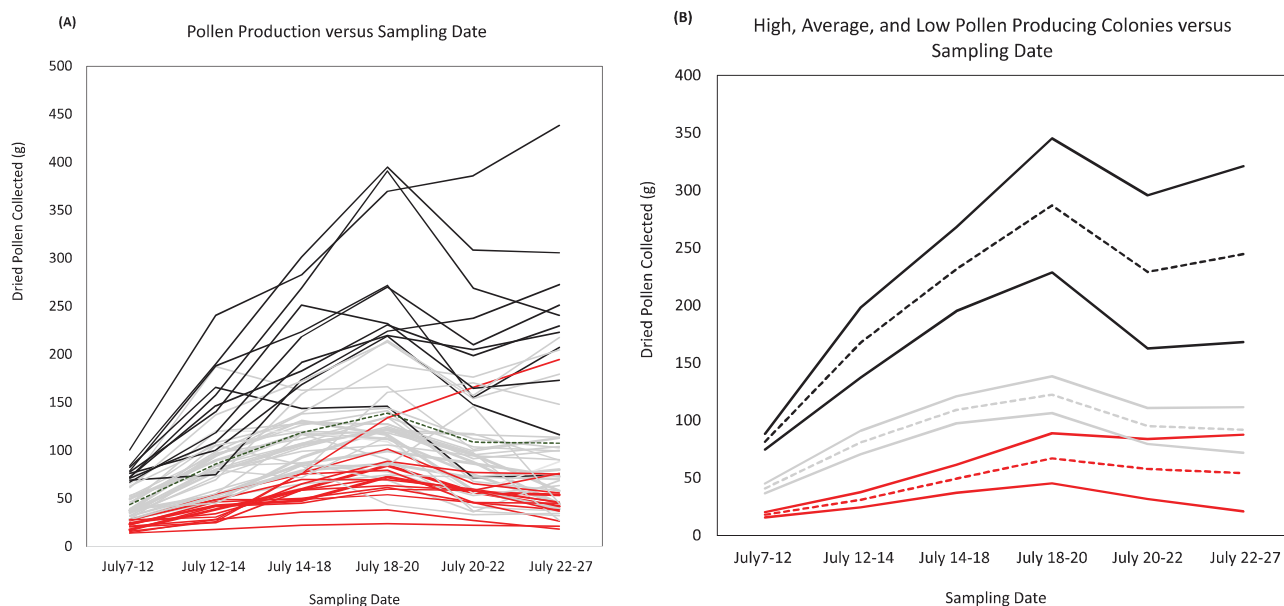


Fig. 6. (A) Colonies tend to be consistent in terms of the amount of pollen they collected per sampling date. The top 10 (black lines) and lowest 10 (red lines) pollen-producing colonies (of 58 total) as ranked on the first sampling date were reliably ranked relatively high or low on subsequent dates, with only a few exceptions. Dashed green line represents the mean weight of pollen collected per date. (B) Mean (dashed line) \pm 2 SE (solid lines) for the top (black lines, $n = 10$), middle (grey lines, $n = 38$), poorest (red lines, $n = 10$) pollen-producing colonies. Note that the \pm 2 SE of the top producers does not overlap with lower producing colonies at any date. That is, the top performing group of colonies remains the top performing at all dates.

Pollen production allows beekeepers to diversify their sources of revenue, mitigating the effects of fluctuations in honey price as an international commodity, and enabling beekeepers with direct sales to diversify their product range by selling pollen or other value-added products containing pollen. Our results (Tables 1 and 2) demonstrate that beekeepers can increase their revenue by 27–92% by collecting and selling pollen itself. The magnitude of the revenue increase depends on how the pollen is sold (bulk clean and dry [68%] vs. bulk fresh [38%], bulk clean and dry [68%] vs. direct sales clean and dry [27%]), as well as which colonies are trapped for pollen (all colonies [68%] vs. targeted high producers [92%]). In addition, value-added products such as soaps, lotions, cosmetics, and supplements could be produced with the collected pollen to further increase revenues. However, there is also a large variation in the costs associated with collecting, cleaning, and storing pollen, as well as in the production and sales of value-added products, specific to the management of individual beekeeping operations.

We found an average of 5.89 kg reduction in honey production among colonies fitted with pollen traps. This could be due to the presence of the trap itself, physically impeding foragers. Alternately, the removal of some pollen from the incoming foragers may increase the need for pollen foragers, reducing the availability of foragers to collect nectar to produce honey. If the former is true, improvements to trap design to minimize the disruption of traffic at the colony entrance could significantly reduce the impact on colony-level honey production. Indeed previous studies have varied substantially in their findings regarding the magnitude of decrease in honey production caused by pollen trapping, with some studies in some years finding no effect, and others a substantial reduction in honey. However, even within a single study, using a single trap type, substantial variation remains present. For example, in the Peace Region of Alberta, Nelson et al. (1987) found a significant reduction in honey production in only 1 year of a 3-yr pollen trapping study, with a reduction of 31.3% of honey production (79 vs. 115 kg). Despite this reduction,

however, Nelson et al. (1987) found that in all 3 yr beekeepers would receive more revenue with pollen trapping than without (21–26% increase in revenue with pollen trapping compared to honey production alone). Duff and Furgala (1986b) found that full-time pollen trapping for the entire foraging season decreased honey production more than part-time pollen production (every other week), and that both treatments caused increased moisture levels in honey compared to un-trapped controls, thus affecting honey quality. Interestingly, they also found that colonies fitted with a trap that was not engaged (and therefore did not remove pollen) also had a reduction in honey production, suggesting that in part, the traps themselves act as a physical barrier to foraging.

Pollen can either be fed back to bee colonies during periods of pollen dearth, such as early spring or late fall, used to rear other bee species, or sold for human consumption. Locally collected pollen is more expensive than either imported pollen or pollen substitutes for bee feed; however, the risks of introducing new pathogens or pesticides to a beekeeping operation is minimized with the use of locally collected pollen. Pollen for human consumption sells for a greater price; however, the market may become saturated more easily than the market for honey and bumble bee feed. Regardless of the intended use, pollen must be cleaned before use and dried or frozen for storage. The costs of collecting pollen, as well as those of cleaning and storing it must also be considered. Targeting collection to colonies that are high producers, using deep collection trays to minimize the frequency of collection visits (McDonald 1980), and targeting times and areas with a pollen flow are critical to the profitability of pollen collection. In addition, colony size must be optimized, with large (25,000–40,000 adult worker bees) colonies with ample open brood yielding the most pollen (Moeller 1977) and honey.

Beekeepers who are being paid to provide pollination services must also consider any effects of pollen trapping on the level of service provided. Pollination effectiveness, the percentage of flowers setting fruit, as well as the number of pollen grains deposited, is

linked to the foraging behavior of visiting bees, which could potentially be affected by pollen trapping. In general, bees that are collecting pollen are more effective pollinators than bees foraging only for nectar (e.g., Bosch and Blas 1994, Javorek et al. 2002, Monzón et al. 2004). For ‘Comice’ pears, e.g., Monzón et al. (2004) found that the rate of honey bee contact with flower stigmas (the part of the female reproductive organ where pollen germinates) was 51.8% for pollen / nectar foragers, and only 19.0% for nectar only foragers. In almonds, one visit from a pollen (or pollen and nectar) foraging honey bee produced fruit set 17–26% of the time, whereas only 0–9% of nectar forager visits produced fruit set (Bosch and Blas 1994). The increased pollination effectiveness of pollen over nectar foragers likely results both from increased body pollen, as well as increased contact with flower reproductive organs.

However, the pollination of hybrid seed crops is complicated by the need to transfer pollen from male-fertile plants to male-sterile plants. The male-sterile (or ‘female’) plants are harvested, whereas the male-fertile (‘male’) plants are only pollen donors. These distinct plant morphs are planted in rows or bays of rows, and pollinators travelling directly from male flowers deposit much higher canola pollen loads (32.19 grains) on female stigmas than pollinators travelling from female to female flowers (1.73 grains) (Waytes 2017). However, honey bees have been known to orient themselves to the rows and forage up and down rather than crossing between rows or bays (Free 1966, Thorp 1979), and the relative contribution of nectar and pollen foragers to hybrid seed pollination is unclear.

As early as 1967, it was suggested that colonies selectively bred to collect large amounts of pollen could be beneficial for commercial pollination (Free 1967). However, this practice was never widely adopted due to the logistical difficulties of selecting and maintaining pollen-hoarding lines of bees. Pollen hoarding is a genetic trait in honey bees, as is a preference for particular types of pollen (Mackensen and Nye 1966, 1969), and can be increased through selective breeding (Free 1967, Hellmich et al. 1985). Strains for bees selected for canola pollen hoarding could both increase the pollen collection (and therefore per hive revenue in this system, as well as increase the efficacy of pollination by increasing the preference for canola pollen). As pollen-trapping increases the number of pollen foragers (Webster et al. 1985), pollen-trapping could similarly be used to increase the pollination efficiency of colonies rented to provide pollination services to crops, without intensive breeding programs.

In addition to honey, pollen is a valuable hive product. In crops with ample pollen, focusing on periods of high pollen availability and high producing colonies, substantial increases in revenue can be gained by collecting pollen, even with concomitant decreases in honey production. Our results suggest that colonies with adequate pre-pollination nutrition may be trapped for a short period (3–4 wk) with no negative consequences on colony health. Pollen collection likely has no negative impact on pollination services, and may, in fact, enhance pollination as the number of pollen foragers increases. Pollen collection can, therefore, fit into a management paradigm focused on pollination service delivery and honey production, increasing the per hive revenue without negative effects on pollination services or colony health.

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