Bee Population Returns and Cherry Yields in an Orchard Pollinated with *Osmia lignaria* (Hymenoptera: Megachilidae)

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ABSTRACT During 1998–2003, we used populations of the solitary bee *Osmia lignaria* Say to pollinate a commercial sweet cherry orchard in northern Utah. Bee densities released each year ranged from 1290 to 1857 females/ha, with approximately twice as many males. Female progeny produced each year were greater than parental populations released, except in 2003, when nesting was poor due to bird predation. Despite poor weather during bloom, and in contrast to most other local producers, the study orchard produced harvestable crops in 1999 (2,964 kg/ha) and 2001 (3,154 kg/ha). In 1998 and 2000, record yields were obtained (10,625 and 12,096 kg/ha, respectively). Including only those years with harvestable crops, average production was 2.2 times higher in 1998–2003 (when *O. lignaria* populations were used) compared with 1992–1997 (when 10 *Apis mellifera* hives were used). This is the first study reporting multiyear cherry yields in an orchard pollinated with *O. lignaria* in North America.

KEY WORDS cherry pollination, *Osmia lignaria*, *Apis mellifera*, *Prunus avium*

Osmia lignaria Say is a North American, univoltine, spring-flying solitary bee that nests in preestablished cavities. It shows a strong preference to collect pollen and nectar on fruit tree flowers, which it pollinates very effectively. Management methods to use this bee as an orchard pollinator have been developed (Torchio 1976, 1981a, 1984; Bosch et al. 2000; Bosch and Kemp 2001), and commercial-scale populations are currently available in the United States and Canada. Wintered *O. lignaria* populations are released in orchards within nesting shelters provided with nesting materials (basically a matrix of wood or some other material with 15-cm-long, 7.5-mm-diameter cavities). After emergence and mating, females begin nesting activities, which involve the collection of pollen and nectar as food for their larvae, and the collection of mud to delimit cells within the nest and to seal completed nests. A pollen-nectar provision is deposited per cell, and one egg is laid on each provision. Individual females are active for 20–25 d on average (Bosch and Kemp 2001). At the end of the blooming period, nesting materials can be removed and stored at temperatures suitable for development (Bosch and Kemp 2000, 2001). After consuming the pollen–nectar provision, the fifth instar spins a cocoon where it undergoes a dormant stage (prepupa), then pupates, and finally reaches adulthood in late summer or early autumn (Torchio 1989). Adults remain inside their cocoons, and require a period of cold temperatures (wintering) to emerge the following spring (Bosch and Kemp 2001, 2003).

Sweet cherries, *Prunus avium* L., are considered difficult to pollinate because most cultivars are self-incompatible, requiring adequate pollen transfer between cultivars usually planted in different rows, and because they bloom in early spring, when inclement weather often hinders insect pollinator activity and pollen tube growth (Thompson 1996). In addition, sweet cherries bloom profusely and have the capacity to reach fruit set levels (percentage of flowers producing fruit) as high as 20–50% (McGregor 1976). Pollination in cherry orchards is traditionally supplemented with colonies of the honey bee, *Apis mellifera* L., at a rate of three to five hives per hectare (Thompson 1996).

In 1998, we used an *O. lignaria* population consisting of 2,600 females and 3,900 males for pollination in a commercial cherry orchard (henceforth Kendell orchard) in northern Utah (Bosch and Kemp 1999). The cherry yield obtained was 2.05 times greater than the best yield obtained in the orchard in the previous 21 yr, when honey bees were used for pollination. After deducting parasitism and developmental mortality, the *O. lignaria* progeny obtained at the Kendell orchard in 1998 represented a 5.4-fold female increase and a 3.7-fold male increase over the population initially released (Bosch and Kemp 1999). In this study, we present cherry yield and bee population return data (difference between population obtained and population released) for five more years (1999–2003), in which *O. lignaria* was the only managed pollinator in the Kendell orchard. We compare the 1998–2003

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yields with yields obtained in the Kendell orchard in 1992–1997, when *A. mellifera* was used for pollination. We also compare weather records for both periods. This is the first report of a multiyear study using *O. lignaria* for commercial cherry pollination in North America.

Materials and Methods

The Kendell orchard is located in North Ogden, northern Utah, and has 1.4 ha of sweet cherries and 0.2 ha of peaches. From 1992 to 1997, 10 *A. mellifera* hives each year were used for pollination. In 1998–2003, only *O. lignaria* populations were used for pollination. Details concerning *O. lignaria* management (rearing and wintering, timing of emergence with bloom, and distribution of nesting materials) in 1998 are found in Bosch and Kemp (1999). We follow Westwood (1993) for cherry flower development terminology.

Weather records for April 1992–2003 were obtained from the Ogden Pioneer Weather Station, 7.3 km from the Kendell orchard. In 1998–2003, we recorded hourly data with temperature loggers installed in the *O. lignaria* nesting shelters.

Bee Populations and Rearing Methods. Each year, starting in August, a sample of ≈70 nests were periodically X-rayed (Stephen and Undurraga 1976) to monitor development.

1999. The progeny of the *O. lignaria* population used in 1998 (Bosch and Kemp 1999) was reared at 22°C throughout late spring and summer. By the end of September, all bees in the X-rayed nests had reached the adult stage. On 5 October, all nests were transferred to an unheated storage house in Logan, northern Utah, for wintering. In late March 1999, we selected 860 nests containing 1,806 females and 2,529 males.

2000. Approximately half of the 1999 progeny was reared as in 1998, with bees reaching adulthood by 24 September. These bees were cooled to 14°C on 28 September and wintered at 4°C starting on 4 October. The other half of the progeny was reared and wintered in a wooden shed in the Kendell orchard. On 24–25 March, in coincidence with a general increase in ambient temperatures, some males within the nests kept in the shed emerged. Because cherry trees were not yet close to bloom, on 26 March all nests kept in the shed were transferred to a 4°C cooler to slow emergence. Over the next several days, we selected 1,467 nests in approximately equal numbers from the progeny reared in the laboratory and the progeny reared in the shed. These nests contained a total of 2,200 females and 4,368 males.

2001. Nests from the 2000 pollination season were kept at 22°C during the developmental period, and 100% adulthood was reached by 23 August. One-half of the population was chilled to 18°C on 29 August, then to 10°C on 1 September, and finally to 4°C on 5 September. The other half was wintered in the same wooden shed as the previous year. In March 2001, we selected 1097 nests (in approximately equal numbers from each wintering treatment) containing 1,806 females and 3,258 males.

2002. In 2002, we released a population that we purchased in August of the previous year (the progeny obtained in 2001 was used in other projects). This population had been trap-nested in several forested areas in northern Utah and kept in a garage during the summer. These nests were brought to our laboratory on 20 August, when most bees were in the adult stage. On 17 September, nests were transferred to 13°C and on 21 September to 4°C. In March 2002, we selected 1,017 nests containing 2,200 females and 3,740 males.

2003. The progeny of the population used in 2002 were reared at 22°C. Bees reached adulthood by 28 August, were chilled to 14°C on 4 September, and then wintered at 4°C on 11 September. In early April 2003, we selected 1,925 nests containing 2,600 females and 6,083 males.

Nesting Materials and Release Methods. In all 5 yr we used wooden boxes (≈80 cm in height by 100 cm in width by 20 cm in depth with one side open) as nesting shelters. Nesting shelters were individually attached, facing southeast, to cherry trees at ≈1 m above the ground (Bosch and Kemp 2001). The number of nesting shelters was increased from four in 1999 to 12–14 in 2000–2003. Inasmuch as possible, shelters were evenly distributed throughout the orchard. A small trench (≈20 cm in depth) was dug near each shelter to provide moist soil for nesting females. Each shelter was supplied with nesting units, consisting mostly of solid wood blocks (Bosch and Kemp 2001). Each wood block measured 16 by 16 by 16 cm and had 49 holes with an inserted paper straw (length, 15 cm; i.d., 7.5 mm). In 1999, some bundles of *Phragmites* reed sections also were used. These reed sections were 16–20 cm in length and 7–9 mm i.d. The numbers of nesting cavities provided per female released each year ranged from 3.6 to 4.8. Bee populations were always released as whole nests. By bloom initiation (see *Results* for dates and flowering phenology), paper straws containing natal nests were inserted in approximately equal numbers in each nesting unit. The front side of each shelter was covered with a wire screen (37-mm mesh) to prevent bird predation of emerging bees.

Frost Damage. On 10–11 April 1999, shortly after the beginning of bloom and nesting activities, night temperatures dropped to blossom freeze-kill levels. Temperatures for 10% freeze-kill in 'Bing' cherries are −2.4°C for first bloom and −2.8°C for full bloom (Proebsting and Mills 1978). Equivalent values for 50% freeze-kill are −3.2 and −3.4, respectively. To assess frost damage, we checked the pistils of a variable number of flowers on six trees of each of the two main cultivars Bing and 'Lambert') and six pollinizer trees (four 'Stella' and two 'Windsor'). Both low and high branches were selected on each sampled tree, and all flowers within a branch were checked for a total of 50–100 flowers per tree. Frost-damaged flowers show signs of necrosis on their pistils. Flowers were scored as either open-damaged, open-undamaged, closed-damaged, or closed-undamaged. In 2002, freezing tem-

Table 1. Freeze-damage in open and closed cherry flowers in the Kendell orchard (North Ogden, UT) on 19 April 1999

Cultivar	Trees *n*	Flowers *n*	% open (damaged)	% open (undamaged)	% closed (damaged)	% closed (undamaged)
Bing	6	455	36.5	33.6	8.8	21.1
Lambert	6	580	42.2	55.7	0.2	1.9
Stella	4	279	57.0	40.1	1.4	1.4
Windsor	2	151	41.7	58.3	0	0

peratures occurred during peak bloom and shortly after bloom. Bing postbloom freeze-kill temperatures are −2.7°C for 50% damage and −3.6°C for 90% damage (Proebsting and Mills 1978). We did not measure frost damage in 2002 because it was close to 100%.

Nest Analyses. Each year, nesting materials were removed from the orchard when most nesting females had died (see *Results* for dates). Nests were X-rayed in September, to quantify developmental mortality, parasitism, and live male and female *O. lignaria* progeny. Parasitism included progeny lost to three cleptoparasites (*Stelis montana*, *Tricrania stansburyi*, and *Sapyga* sp.), one parasitoid (*Monodontomerus* sp.), and a pathogenic fungus (*Ascosphaera* sp.). To assess the extent to which *O. lignaria* females foraged on cherry or other flowering plants, fecal samples of the first and last cells of each of 15 randomly selected nests were mounted on glass slides with fuchsin-stained gelatin (Beattie 1971). Each year, 100 pollen grains per sample (total 3,000 pollen grains) were identified to genus with a binocular microscope.

Results

1999. Weather forecasts in North Ogden predicted unstable conditions for late March and early April. Thus, we decided to split our *O. lignaria* release. One-half of the nests were inserted in the nesting materials at the Kendell orchard on 29 March, when apricots in the area were in full bloom. The other half of the nests were inserted on 5 April, when cherries were barely starting to bloom. Temperatures during the first week of April were low, with only 2 h above 20°C. On 8 April, night temperatures were below −2.8°C (temperature for 10% freeze-kill on Bing first bloom) for 8 and 5 h on 10 and 11 April, respectively. These temperatures slowed bee emergence, establishment, and nesting. On 19 April, with maximum temperatures reaching again 20°C, some nests at each shelter were capped (completed), and several females were observed carrying pollen, mud, or both. However, bees chewing their way out of the cocoon could still be heard at each shelter, indicating that emergence was not complete. On that same day, we assessed frost damage (Table 1). Lambert, Stella, and Windsor were close to full bloom, and Bing was at ≈70% bloom. Overall, 46.2% of the 1465 flowers sampled had pistils damaged by frost (Table 1). Weather deteriorated again on 20 April, with cold temperatures and heavy rains. From 20 April to 7 May, there were only 2 d with maximum temperatures above 20°C. Cherry bloom was completed by early May.

Nesting materials were removed from the orchard on 9 June. The number of nesting cavities with *O. lignaria* progeny was 2636 (Table 2). Compared with the population released in the orchard, the live progeny obtained (7,609 males, and 3,926 females) represented a 3.0-fold increase in males and a 2.2-fold increase in females. Overall, 74.8% of the 3,000 pollen grains analyzed were *Prunus* and 17.1% were *Salix.*

Fruit set at the Kendell orchard in 1999 was not uniform. Trees adjacent to or near the nesting shelters set heavily, whereas the trees most distant from the nesting shelters set very poorly. In general, self-compatible trees (Stella), and, among self-incompatible trees, those adjacent to pollinizer trees, set heaviest. Cherries were harvested in early July for a total of 4,150 kg (Table 3).

2000. *O. lignaria* nests were inserted in the nesting materials on 7 April, under sunny weather. Apricots were past bloom and plums were in full bloom. Peaches were starting to bloom. A few cherry blossoms were open, but most were in the open cluster stage. Males started emerging shortly after nest insertion in the nesting materials, and by 12 April, several females were already provisioning nests with pollen. The weather was conducive to bee activity throughout April. By 5 May, cherry trees were past bloom.

Nesting materials were removed from the orchard on 18 May. A total of 5,604 *O. lignaria* nests were obtained (Table 2). Compared with the population released in the orchard, the live progeny obtained

Table 2. *O. lignaria* progeny development and mortality in the Kendell cherry orchard (North Ogden, UT) in 1999–2003

Yr	Females released	Nests	Cells	Cells/nest[a]	Developmental mortality (%)	Parasitism (%)	Live ♂ progeny	Live ♀ progeny	Sex ratio (♂/♀)
1999	1,806	2,636	13,492	5.82 ± 0.18	877 (6.5)	1,080 (8.0)	7,609	3,926	1.95
2000	2,200	5,604	28,186	5.94 ± 0.13	1,599 (5.7)	683 (2.4)	16,651	9,253	1.80
2001	1,806	2,012	9,764	5.11 ± 0.04	3,879 (39.7)	257 (2.6)	3,748	1,862	2.01
2002	2,200	4,003	20,409	5.11 ± 0.03	2,311 (11.4)	336 (1.6)	12,379	5,383	2.30
2003	2,200	1,208	6,149	5.79 ± 0.05	1,251 (20.3)	84 (1.4)	3,199	1,615	1.98

[a] Mean ± SE; only capped nests.

Table 3. Cherry yields and *O. lignaria* female population increase in the Kendell orchard (North Ogden, UT) in 1992–2003

Yr	Pollinator	Cherry yield (kg)	♀ *O. lignaria* production[a]
1992[b]	*A. mellifera*	—[c]	—
1993[b]	*A. mellifera*	3,040	—
1994[b]	*A. mellifera*	5,545	—
1995[b]	*A. mellifera*	4,820	—
1996[b]	*A. mellifera*	3,695	—
1997[b]	*A. mellifera*	—[c]	—
1998[b]	*O. lignaria*	14,875	5.44
1999	*O. lignaria*	4,150	2.17
2000	*O. lignaria*	16,935	4.21
2001	*O. lignaria*	4,415	1.03
2002	*O. lignaria*	—[c]	2.45
2003	*O. lignaria*	6,680	0.62

[a] Increase or decrease factor in relation to the no. of females released.
[b] From Bosch and Kemp (1999).
[c] Most flowers or young fruits killed by frost.

(16,651 males and 9,253 females) represented a 3.8-fold increase in males and a 4.2-fold increase in females. Overall, 91.6% of the 3,000 pollen grains analyzed were *Prunus.* Cherries were harvested in early July for a total of 16,935 kg (Table 3).

2001. After a period of cold weather in early April, cherries started to bloom abruptly after pronounced temperature increases, reaching 5% bloom on 16 April. Nests were inserted in the nesting materials on 17 April, and by evening of that day some trees were already at 50% bloom. Mating couples were seen on 19 April, but the weather turned rainy the next day and continued to be intermittently unstable throughout the blooming period. By 26 April the orchard was in full bloom and capped nests were seen in all shelters. Petal fall occurred in early May.

Nesting materials, containing 2,012 nests (Table 2), were brought to the laboratory on 22 May. As in previous years, we monitored development and scheduled wintering initiation shortly after reaching 100% adulthood. However, approximately one-third of the population was mistakenly wintered when the bees were still in the pupal stage. These nests had been kept in insufficiently ventilated containers during development, which caused humidity condensation and slowed development. None of the progeny in these prematurely wintered nests survived. As a result, developmental mortality was unusually high in 2001 (Table 2), and the number of live females recovered (1,862) represented only a 1.03-fold increase over the female population released (Table 2). Overall, 68.5% of the pollen identified was *Prunus.* Most other pollen grains observed were *Salix* (9.46%) and two unidentified species (22.83%). Cherries were harvested in early July for a total of 4,415 kg.

2002. Natal nests were inserted in the nesting materials on 10 April. The very first flowers were open on the earliest blooming trees, but most flower buds were in the white tip stage or younger. Plums were close to full bloom, and apricot bloom was starting to decline. Weather was conducive to *O. lignaria* activity during the first week after release and then turned cold and rainy for the following week, with temperatures between 0 and −1°C occurring on 16, 18, and 20 April. The weather then improved, but frosting temperatures (−2.3°C) reoccurred on 24 April, during peak bloom. By early May trees were mostly past bloom. On 8 May, while fruitlets were starting to develop, night temperatures were lower than −2°C for 5 h, reaching a minimum of −4.3°C (Bing postbloom freeze-kill temperature is −3.6°C for 90% damage). *O. lignaria* females continued to nest until mid-May.

Nesting materials were brought to the laboratory on 31 May. A total of 4,003 *O. lignaria* nests, containing 20,409 cells were recovered (Table 2). The number of live females recovered was 2.45 times higher than the number of females released (Table 2). Overall, 98.67% of the 3,000 pollen grains counted were *Prunus.* Frost damage prevented most fruits from developing and the orchard was not harvested in 2002.

2003. Half of the natal nests were inserted in the nesting materials on 7 April. A few cherry flowers were open on the earliest blooming trees, but most flower buds were not even showing white tips. Apricot bloom was declining and plums were in full bloom. Peach bloom was ≈10%. The other half of the nests were inserted on 9 April. By then, some of the earliest cherry trees were in 20–50% bloom, but most had not started flowering. Wire screens on the front side of the shelters were not placed until 10 April, which allowed extensive predation of emerging bees by blue jays and robins. Weather was sunny and favorable to *O. lignaria* activity until 13 April. By 14 April, emergence was nearly complete and a few capped nests could be seen in all shelters. Cherry bloom was nearing 100%. Starting on 14 April, the weather worsened and was marginal throughout the nesting period, but there were no frosts.

Nesting materials were brought to the laboratory on 16 May. The number of nests obtained was 1,208, and the number of cells 6,149 (Table 2). Developmental mortality (mostly in the egg and early larval stages) was high (Table 2). The numbers of live male and female progeny recovered were 1,615 and 3,199, respectively. Thus, female population decreased by 0.62 and male population by 0.53. Overall, 95.12% of the pollen grains counted were *Prunus.* Cherry harvest was 6,680 kg (Table 3).

Discussion

O. lignaria population returns in the Kendell orchard were high, except in 2001 and 2003. In 2003, bird predation reduced the number of nesting females establishing at the nesting shelters (only 1,208 nests were obtained compared with 2,600 females released). In 2001, approximately one-third of the progeny was wintered too early, when bees were still in the pupal stage. Both problems can be easily avoided by placing wire screens in on time and using properly ventilated containers during development (Bosch and Kemp 2001). Overall, the Kendell orchard provided a suitable environment for *O. lignaria* propagation, as indicated by the high numbers of cells per nest and the well-balanced sex ratios obtained (Bosch and Kemp 2001). Establishment of early emerging females was possibly enhanced by the presence of a few apricot and plum trees blooming ahead of the cherries and peaches. Nests were mostly provisioned with *Prunus* pollen, but alternative floral resources were available after orchard petal fall, which allowed females to prolong nesting activities. Population increases were obtained even in years with poor weather during bloom and flower-killing frosts.

Excluding those years in which frost prevented harvestable yields, mean cherry production in the Kendell orchard was 2.2 times higher when *O. lignaria* was used as a managed pollinator ($n = 5$ yr), compared with *A. mellifera* ($n = 4$ yr). This production increase was not the result of improved weather conditions during bloom in years when *O. lignaria* was used. Including only years with harvestable crops, average daily temperatures during the last 3 wk of April (when most of the cherry bloom occurs in North Ogden) were similar in 1992–1997 (mean ± SE, 10.69 ± 0.46°C) and 1998–2003 (10.68 ± 0.43°C). Worse weather conditions in 1992–1997 compared with 1998–2003 are neither indicated by minimum temperature (4.63 ± 0.40 versus 4.57 ± 0.35°C), maximum temperature (16.76 ± 0.56 versus 16.79 ± 0.55°C) or precipitation records (1.64 ± 0.42 versus 2.10 ± 0.48 mm). Of particular interest are the 1999 and 2001 results, when, due to the unfavorable weather conditions discussed above, most local producers did not harvest. Yet, production in the Kendell orchard was comparable with 1993–1996 data (Table 3), when no freeze-kill temperatures occurred. The 1999 results also suggest that female *O. lignaria* foraging areas may be reduced in years with inclement weather and illustrate the benefit of spreading shelter distribution throughout the orchard to obtain uniform pollination in those years. *O. lignaria* populations released in the Kendell orchard in 1998–2003 were 1,806–2,600 females and twice as many males, compared with 10 honey bee colonies, each containing several thousand foragers, in 1992–1997.

Increased orchard yields can be obtained with small *O. lignaria* populations for several reasons. First, *O. lignaria* shows a strong preference to forage on fruit trees (Torchio 1976, 1981a, 1982; Bosch and Kemp 1999; Bosch et al. 2000; this study) and has a short foraging range (Bosch and Kemp 2001), so that most visits are concentrated on fruit trees within the target orchard. Second, *O. lignaria* has low temperature and light intensity thresholds for foraging (Torchio 1984, Bosch and Kemp 2001), providing many extra pollinating hours, compared with other species. Foraging activity in an apple orchard over a 5-d period spanned 33 h 40 min in *Osmia cornuta* (Latreille) (a close relative to *O. lignaria*) compared with 15 h 10 min in *A. mellifera* (Vicens and Bosch 2000). Finally, *O. lignaria* is a very effective pollinator of fruit tree flowers, contacting the reproductive organs of the flower on virtually every visit (Torchio 1981b, Kuhn and Ambrose 1984). The use of *O. lignaria* allows cherry producers to attain higher production and obtain harvestable yields in years with poor weather. At the same time, the capacity to multiply populations permits *O. lignaria* users to derive added income through the sale of surplus bees. Our study shows that it is not difficult to rear *O. lignaria* populations locally (see also Bosch and Kemp 2001) and that improved synchrony between bee emergence and cherry bloom can be achieved through monitoring flower bud development and weather forecasts.

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