An assessment of artificial nests for cavity-nesting bees (Hymenoptera: Megachilidae) in lowbush blueberry (Ericaceae)

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Abstract—Fluctuating bee (Hymenoptera: Apoidea) populations jeopardise pollination services. Nesting habitat for solitary bees is potentially limited in many agroecosystems, but the provision of artificial nests could augment bee communities and the pollination services they provide. We investigated whether cavity-nesting bees (Hymenoptera: Megachilidae) in lowbush blueberry (*Vaccinium angustifolium* Aiton (Ericaceae)) fields would use artificial trap nests. Different nest designs were compared, as was nesting occupancy between fruit-bearing and vegetative fields. Milk carton nests had significantly more uptake by and emergence of *Osmia* Panzer and *Megachile* Latreille than wooden nests. Only 3% of wooden nests had at least one occupied nesting tube versus 73% of milk carton nests, with a total of 34% nesting tubes occupied. Bee emergence was significantly higher in nesting tubes from fruit-bearing fields than vegetative fields. *Osmia* and *Megachile* emergence was low from milk carton nests, with bees emerging from less than 10% of occupied nesting tubes, in large part due to parasitism. Overturned clay lids were tested as potential nesting sites for *Osmia inermis* Zetterstedt, but only 3% of lids had nesting evidence. Our results suggest that certain artificial nests have potential for encouraging communities of cavity-nesting bees, but further study on nest design and handling protocols is needed.

Introduction

Lowbush blueberry (*Vaccinium angustifolium* Aiton (Ericaceae)), an important crop in eastern Canada and the state of Maine in the United States of America, relies heavily on bees (Hymenoptera: Apoidea) for cross-pollination and fruit set (Aras *et al*. 1996; Eaton and Nams 2012). The crop is typically managed on a two-year cycle of an initial year of vegetative growth ("sprout year") followed by a second year of fruit development and harvest ("crop year") (Yarborough 2012). Managed honey bees (*Apis mellifera* Linnaeus (Hymenoptera: Apidae)) are often used for blueberry pollination (Yarborough 1997; Eaton and Nams 2012), but blueberry growers are interested in using and promoting non-*Apis* Linnaeus bees to pollinate their crop. Numerous species of wild bees are effective pollinators of blueberry (Javorek *et al*. 2002; Cutler *et al*. 2015) but their abundance can vary, and blueberry growers are usually unable to rely entirely on wild populations

for adequate pollination (Eaton and Murray 1997). Various tactics to boost wild bee populations have been shown to improve pollination of several crops (Vaughan and Black 2008; Wratten *et al*. 2012; Blaauw and Isaacs 2014), and such techniques could be adapted to lowbush blueberry.

Osmia Panzer and *Megachile* Latreille (Hymenoptera: Megachilidae) collect lowbush blueberry pollen (Drummond and Stubbs 1997; Sheffield *et al*. 2003; Hicks 2009) but may not be as abundant in lowbush blueberry agroecosystems as other wild bees (Bushmann and Drummond 2015; Cutler *et al*. 2015). *Osmia* and *Megachile* species nest in a variety of natural habitats including plant stems and abandoned tunnels in wood from previous insect inhabitants, as well as under rocks, but will also nest in artificial structures made of wood or other materials that mimic their natural nesting substrates (Torchio 1987; Cane *et al*. 2007; Packer *et al*. 2007; Hicks 2009; Guisse and Miller 2011; Sheffield *et al*. 2013,

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2014). In Nova Scotia, Canada, wax-cardboard milk cartons containing paper tubes were used as artificial nests for solitary bees in apple (*Malus* Miller (Rosaceae)) pollination, and provided suitable and effective nesting habitat for *Osmia tersula* Cockerell and other species (Sheffield *et al*. 2008). Certain *Osmia* species prefer to nest under rocks, and although these populations can be difficult to manage (Cane *et al*. 2007), 10% of overturned clay lids placed in lowbush blueberry fields in Newfoundland, Canada, were used by *Osmia inermis* Zetterstedt as an artificial nesting substrate (Sheffield *et al*. 2014). Despite the potential of artificial nests to support *Osmia* and *Megachile* populations in lowbush blueberry (Stubbs *et al*. 1997), little research has been published testing nest design and dispersal in lowbush blueberry fields.

Artificial nests were placed in lowbush blueberry fields in Nova Scotia to examine if Megachilidae would nest in these substrates. Nesting occupancy in three different nest designs (milk carton, wooden, and clay lid) was tested. Nesting occupancy was compared between fruit-bearing and vegetative fields for milk cartons and clay lids, and was also compared between field edge and within field for clay lids. Although *Osmia* and *Megachile* bees may not be abundant in lowbush blueberry fields (Bushmann and Drummond 2015; Cutler *et al*. 2015), we predicted there would be moderate occupancy of nests in this experiment. Nest occupancy (number of capped nesting tubes) and emergence (bees or parasitoids) were evaluated. Nesting occupancy was expected to be higher along the field edge near natural habitat compared to within field, and we predicted that nesting occupancy would be higher in fruit-bearing fields than vegetative fields due to the pollen provided by blueberry flowers. Parasitism was also expected based on previous studies (Drummond and Stubbs 1997; Stubbs *et al*. 1997; Sheffield *et al*. 2008; MacIvor and Packer 2015), and we quantified occurrence of parasites.

Materials and methods

Artificial nest designs

This study was conducted over two years in Nova Scotia, Canada, with $n = 4$ fields in 2014, and $n = 12$ fields in 2015. In 2014, one milk carton

nest design was tested along with eight different wooden nest designs (Supplementary Table S1), while in 2015, only milk carton nests were tested. Nests were placed in lowbush blueberry agro-ecosystems before bloom began, and were monitored throughout the summer. Lowbush blueberry bloom typically begins in mid to late May, until mid to late June. Habitats surrounding all blueberry field sites were generally mixed forests of softwood and hardwood trees, including maple (*Acer* Linnaeus (Sapindaceae)), fir (*Abies* Miller (Pinaceae)), and spruce (*Picea* Dietrich (Pinaceae)), with no other agricultural or developed (urban/industrial) areas within 1000 m of our test plots.

The wooden nests tested in 2014 (9.5 cm deep × 5 cm wide × 18.5 cm tall) were constructed from spruce wood (*Picea*) and each contained twelve 8-cm-long drilled holes, either all 0.7 or 0.9 cm in diameter, and approximately 1.5 cm apart (Fig. 1). Two different nesting tube diameters were used as this can be an important factor in nesting occupancy (Westerfelt *et al*. 2015) and preference varies among bees (Fye 1965; MacIvor 2016). The two diameters selected were previously used in trap-nest studies in lowbush blueberry (Drummond and Stubbs 1997; Stubbs *et al*. 1997). Some wooden nests had exteriors and roofs that were charred by lightly burning the wood with a propane torch until the wood exterior turned black. Roofs consisted of a 14.5 cm long × 5 cm wide × 2.5 cm thick piece of wood nailed to the top of the nest, providing an overhang at the front of the nest. These two features were tested as roofs may provide protection from rain and sun (Taki *et al*. 2004), and because some blueberry growers have suggested that darker or charred surfaced are attractive to trap-nesting bees.

Milk carton nests in 2014 were made by inserting paper nesting tubes into washed 2-L milk cartons that were painted white (Beauti-Tone interior/exterior latex paint, Home Hardware, St. Jacobs, Ontario, Canada) (Fig. 1). Nesting tubes were made by rolling together a sheet of newsprint over a sheet of white multiuse paper (21 × 10 cm) (Staples, Richmond Hill, Ontario, Canada). A wooden dowel (0.7 or 0.9 cm diameter) was used to roll the paper into tubes, with the newsprint on the outer surface of the nesting tube. There were six 0.7 cm and six 0.9 cm

Fig. 1. Artificial nests for Megachilidae bees in Nova Scotia lowbush blueberry fields: **A**, a wooden nest with a roof; **B**, milk carton nest (notice-capped nesting tubes); **C**, terra cotta lids in a blueberry field (photographs by N.L. McLean and R.S. McCallum).
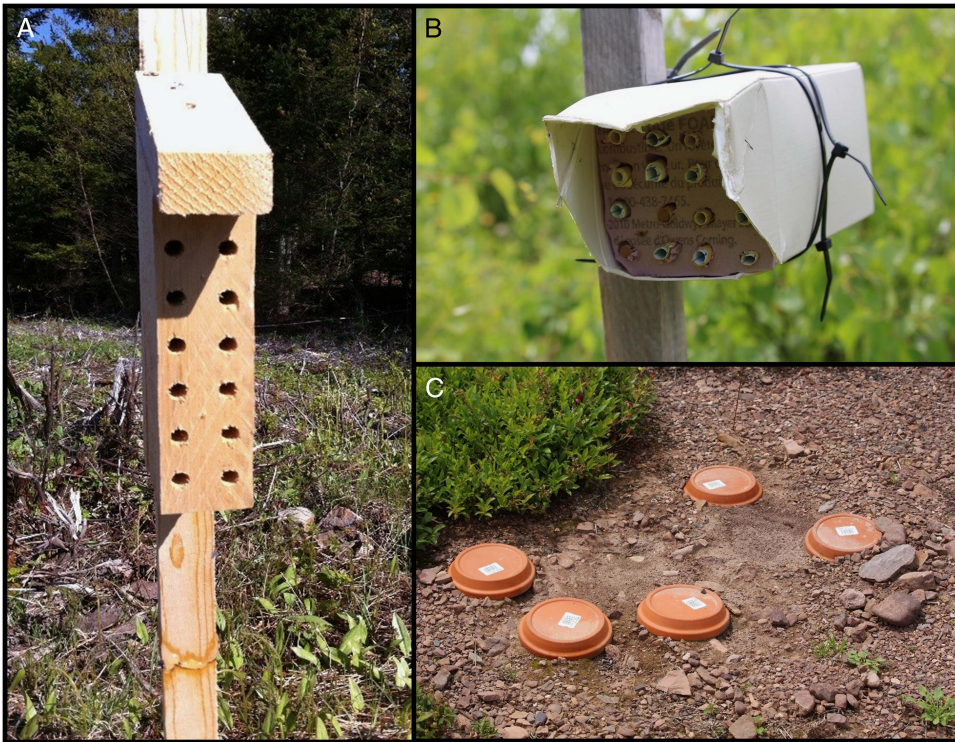
diameter nesting tubes per milk carton. All nesting tubes were trimmed to 15 cm long and placed through a square (9.5 × 9.5 cm) piece of pink polystyrene. Spray foam insulation (Great Stuff, Home Hardware, St. Jacobs, Ontario, Canada) was applied around the nesting tubes and the polystyrene, and the nesting tube structure was then inserted into the milk carton such that it was held in place when the spray foam dried, with the polystyrene block containing the nesting tube openings fitted snuggly into the front opening of the milk carton (Taki *et al.* 2004; Sheffield *et al.* 2008). The milk carton design was modified slightly in 2015 to include 16 nesting tubes instead of 12, all of which were 0.7 cm in diameter. Wooden nests were nailed to wooden stakes while milk carton nests were secured to wooden stakes using nylon cable ties, both at a height of 1 m. Tanglefoot (Home Hardware, St. Jacobs, Ontario, Canada) was applied around each stake at the base to deter ants and other arthropods

(Sheffield *et al.* 2008). Clay lids (also known as "nesting saucers" or "terra cotta lids") (14 cm diameter) (Canadian Tire Corporation, Toronto, Ontario, Canada) were tested as potential nesting substrates for *O. inermis* (Sheffield *et al.* 2014) in 2015. Overturned clay lids were placed directly on the soil surface of blueberry fields with a small opening made in the soil underneath to facilitate bee access (Sheffield *et al.* 2014) (Fig. 1).

2014 nest study

Wooden and milk carton nests were installed at four fruit-bearing lowbush blueberry fields in Nova Scotia in 2014 (Supplementary Tables S1–S2). A randomised complete block design was used with each site (field) serving as a block. Sites were separated by at least 2 km and were considered to be independent, given the limited foraging distances of solitary bees (Gathmann and Tscharntke 2002; Zurbuchen *et al.* 2010). Four milk carton nests and two wooden nests of each of

the eight unique designs were installed at each field (Supplementary Table S1). Nests were installed on 22 April 2014, before *Osmia* nesting occurred. Nests were randomly placed 5 m apart along the south-facing edge of each field, and were retrieved on 9 October 2014. The nests were monitored bi-weekly for the presence of capped nesting tubes. An *Osmia* or *Megachile* female caps the end of a nesting tube when she has completed provisioning her offspring in that nest (Bosch and Kemp 2000; Guisse and Miller 2011) and nesting tubes were therefore classified as occupied if a cap was observed (Fig. 1). Retrieved nests were placed in an unheated outdoor shed at the Dalhousie University Agricultural Campus in Truro, Nova Scotia, Canada, and capped nesting tubes were brought to the laboratory for dissection the following spring (2015). Bees in tubes were counted and identified. The effect of nest design on nesting occupancy was measured by the total number of capped nesting tubes per field per nest design. Model assumptions of normal distribution and constant variance of the residuals could not be met for the raw data or through transformation, and a non-parametric Kruskal–Wallis test using Proc npar1way was therefore conducted in SAS v. 9.4 (SAS Institute 2014) for this analysis.

2015 milk carton study

Based on limited nest occupancy in wooden nests in 2014, only milk carton nests were studied in 2015. Nesting occupancy was compared between fruit-bearing and vegetative blueberry fields. The progression of capped nests was monitored throughout the season to determine when nesting occurred and if nesting overlapped with blueberry bloom. Bee emergence after overwintering was examined, as well as emergence of parasitoids. A completely randomised design was used with one factor (field type: fruit-bearing or vegetative) and six replicates (fields) per factor level, for a total of 12 fields (Supplementary Table S2). There were three milk carton nests per field, placed 5 m apart along the south-facing field edge, for a total of 36 nests in the experiment. Nests were placed in fields on 5 and 6 May 2015, and monitored bi-weekly as in 2014. All nests were collected from fields on 20 October 2015 and placed in an unheated shed (as in 2014) until

4 March 2016. The nests were then placed in an environmental chamber to observe emergence of bees and parasitoids. Each capped nesting tube was removed, labelled, and placed in its own inflated plastic bag in the environmental chamber according to a method used by J.H. Cane (J.H. Cane, United States Department of Agriculture, personal communication). The temperature was initially set at 8 °C and then warmed with daily increments of 4 °C up to 25 °C. After 10 days at 25 °C, the environmental chamber temperature was increased to 30 °C for an additional three days. Relative humidity was maintained at 60% throughout the experiment (MacIvor and Packer 2015). Bee and parasitoid emergence were recorded daily. Nesting occupancy, measured as number of capped nests from all possible nesting tubes per nest (16), was compared between fruit-bearing and vegetative fields using one-way analysis of variance using the Mixed Procedure (SAS Institute 2014). A Kruskal–Wallis test using Proc npar1way (SAS Institute 2014) was used to test the effect of field type on bee and parasitoid emergence, as the assumptions of normal distribution and constant variance of the residuals could not be met.

2015 clay lid study

Overturned clay lids were evaluated as potential nesting substrates for *O. inermis* (Sheffield *et al.* 2014) at field edge (0 m) and 25 m from the field edge, and between fruit-bearing and vegetative fields. Parasitism of bees was also recorded. A completely randomised design was used for a 2×2 factorial experiment with field type (fruit-bearing or vegetative) and distance from the field edge (0 or 25 m) as the two factors of interest. There were three replicate fields per factor level for a total of 12 fields. These 12 fields were also used for the 2015 milk carton nest experiment (Supplementary Table S2). Within each field, 10 lids were placed either along the field edge (0 m) or 25 m from the field edge, into the blueberry field. The lids were placed in the fields on 5 and 6 May 2015 and collected on 20 October 2015. Each lid was placed overturned onto bare ground and pushed firmly into the soil, with a ~ 2-cm-wide entrance formed in the soil under the lid for bees to gain access (Sheffield *et al.* 2014). The lids were stored in a freezer upon retrieval until they could be dissected.

Insect identification

Bees were identified using characters described in Mitchell (1962) and Packer *et al.* (2007), and parasitoids were identified using descriptions from Bohart and Kimsey (1980) and McAlpine *et al.* (1987). Voucher specimens were sent to the Canadian National Collection of Insects, Arachnids, and Nematodes (Ottawa, Ontario, Canada) for identification based on morphology to the lowest possible taxonomic level (family, genus, or species). Voucher specimens were pinned and deposited at the A.D. Pickett Entomology Museum, Dalhousie University Agricultural Campus (Truro, Nova Scotia, Canada).

Results

2014 nest study

Nest design affected bee nesting, with significantly more capped nesting tubes in milk carton nests than wooden nests ($\chi^2 = 39.9$; df $= 8$; $P < 0.0001$) (Table 1). Only 3% of wooden nests – two nesting blocks in total – contained at least one capped nest compared to 71% of milk carton nests that had at least one capped nesting tube (Table 1). The two wooden nests that had capped nesting tubes were of different designs: one was burned with 0.7 cm diameter holes and a roof, and the other was not burned with 0.9 cm diameter holes and no roof. These two wooden nests had two and five capped nesting tubes, respectively, out of 12 possible nesting tubes per nesting block. Although more than 70% of milk carton nests had at least one capped nesting tube, none had more than two capped tubes, and 50% of successful

nests contained only one capped nesting tube (Table 1). Two milk carton nests, one each from Masstown and Portapique field sites, were discarded due to damage by animals. After overwintering in an unheated shed, 13 nesting tubes were dissected. Sixty-one *O. tersula* Cockerell were identified, as well as 34 *Megachile* bees, 10 fully developed sapygid wasps (*Sapyga martinii* Smith) (Hymenoptera: Sapygidae), and one tachinid fly (Diptera: Tachinidae).

2015 milk carton study

Of the 36 milk carton nests placed in 12 different blueberry fields, three nests were damaged at one site and removed from the study. Of the remaining 33 nests, 24 (73%) contained at least one capped nesting tube. A total of 176 out of 512 nesting tubes (34%) were capped and considered occupied. The first capped nesting tube was observed in a field on 25 June 2015, during late blueberry bloom, and the last capped nesting tube was observed on 30 July 2015, after blueberry bloom had finished. The majority of nest capping was completed by mid-July (Fig. 2).

Although nesting occupancy was not significantly different between the two field types, there were almost twice as many capped nesting tubes in fruit-bearing fields than vegetative fields (Table 2). In the environmental chamber, 40 *O. tersula*, two sapygid wasps, one chrysidid wasp (Hymenoptera: Chrysididae), and six tachinid flies emerged from 17 of 176 capped nesting tubes. Significantly more bees emerged from capped nesting tubes from fruit-bearing fields than from vegetative fields (Table 2). Most bees

Table 1. Mean number and percentage of nesting blocks and nesting tubes containing bees when placed in commercial fruit-bearing lowbush blueberry fields in Nova Scotia, Canada, 2014.

Nesting block type*	Number of nesting blocks (12 nesting tubes per block)	Mean number ± SD capped tubes/nesting block	Number of nesting blocks with 0 capped tubes (% total)	Number of nesting blocks with one capped tube (% total)	Number of nesting blocks with two tubes (% total)
Milk carton	14	1 ± 0.73	4 (29)	7 (50)	3 (21)
Wooden≅	64	0.1 ± 0.67	62 (97)	0	2 (3)

Notes: A Kruskal–Wallis test was used to compare the number of capped nesting tubes in milk carton versus wooden trap nests.
  *Each of four fields had four milk carton trap nests and 16 wooden trap nests. Due to damage, a total of 14 milk cartons and 64 wooden nests were tested. Each nest had 12 possible nesting tubes.
  ≅Multiple wooden trap nest designs were used but because occupancy by bees was low, data from all wooden nests were combined. The two trap nests containing capped nesting tubes were from two designs: roof, burned, small holes and no roof, not burned, and large holes.

emerged over a period of approximately one week, starting five days after placement in the environmental chamber and peaking at day 9 (Fig. 3).

Field type did not have a significant effect on emergence of wasps or flies (Table 2), although bees only emerged from one capped nesting tube from a vegetative field. After removal of nesting tubes from the environmental chamber and placement in the laboratory at room

Fig. 2. Occurrence of capped nesting tubes in milk carton nests by bees (Hymenoptera: Megachilidae) in lowbush blueberry fields (fruit bearing and vegetative) in Nova Scotia, Canada, 2015. *x*-axis is not linear in scale.
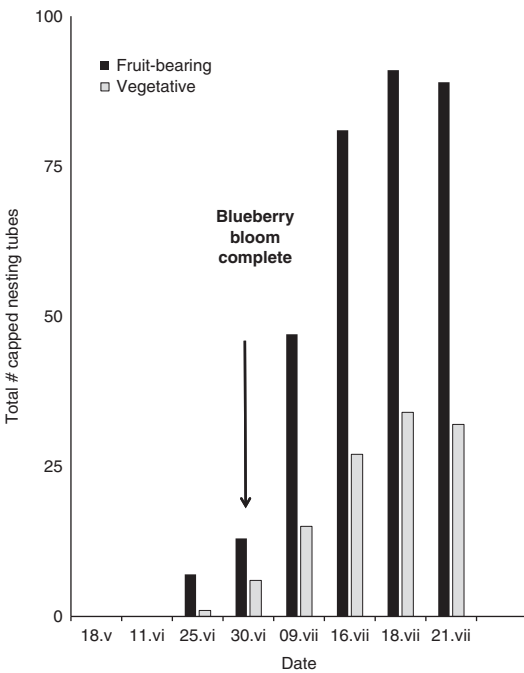

temperature, 16 leafcutter bees (*Megachile* species) emerged. No *Osmia* emerged from tubes that contained *Megachile*. Dissection of the 176 nesting tubes after emergence found 266 failed or incomplete cells that could be recognised as well as fully developed dead bees that were mouldy. It is possible more cells were present but many of the tubes were damp and mouldy, and nesting evidence was not recognisable. The number of failed cells per tube ranged from one to 16 and included *Osmia* and *Megachile* bees, and chrysid and sapygid wasps. Additionally, six Phoridae (Diptera) pupae, two satellite fly adults and 10 pupae (Diptera: Sarcophagidae: Miltogramminae), and seven Tachinidae (Diptera) in various stages of development were dissected from the nesting tubes.

Fig. 3. Bee and parasitoid emergence from milk carton nests within an environmental chamber after removal from a lowbush blueberry field in Nova Scotia, Canada, 2015. The temperature was initially set at 8 °C and then warmed with daily increments of 4 °C up to 25 °C. After 10 days at 25 °C, the temperature was increased to 30 °C for an additional three days.
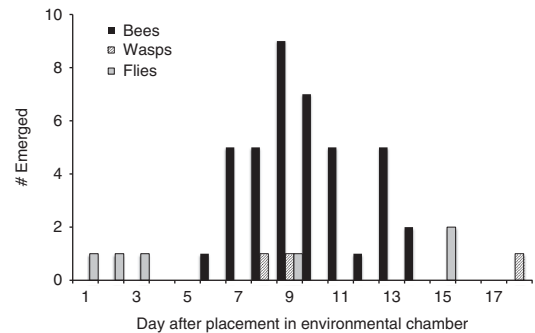

Table 2. *Osmia* nesting, emergence, and parasitism in milk carton trap nests in Nova Scotia lowbush blueberry fields in 2015.

Field type	Mean number of capped tubes/carton	Mean number of bees emerged/carton	Mean number of wasps emerged/carton	Mean number of flies emerged/carton
Fruit-bearing	6.4 (2.3–15.7)	6.5 (0–17)	0.5 (0–2)	0.2 (0–1)
Vegetative	3.5 (2.3–6.3)	0.2 (0–1)	0	1 (0–4)
Statistics	$F = 1.25$, $P = 0.29$	$\chi^2 = 46.03$, $P = 0.0030$	$\chi^2 = 23.29$, $P = 0.44$	$\chi^2 = 18.22$, $P = 0.76$

Notes: Means are presented with ranges of capped nesting tubes per field in parentheses. A mixed model was used to compare the mean number of capped nesting tubes per carton in different field types, and a Kruskal–Wallis test was used to compare bee, wasp, and fly emergence in different field types. Only milk cartons with at least one capped nesting tube were compared.

2015 clay lid study

Only 3.3% (4/120) of overturned clay lids had *O. inermis* nesting evidence. All successful lids were found in fruit-bearing fields and three of four lids were found at the field edge. The successful lids had nesting aggregations of five to 17 *O. inermis*, as determined by separating and identifying each bee the following spring. The bees ranged from pupae to adults and were mouldy, but identification was still possible. Only one of the lids showed evidence of parasitism upon dissection, with three *Chrysura* Dahlbom (Hymenoptera: Chrysididae) detected next to fully developed *O. inermis*.

Discussion

Female cavity-nesting bees and wasps carefully search their habitat and seem to prefer conspicuous, high-quality holes (Westerfelt *et al.* 2015). In our study, nest occupancy was significantly affected by nest design in 2014, with more bees nesting in tubes of milk cartons than wooden nests. The rate of occupancy in the wooden nesting blocks – a total of only two and five capped nesting tubes in two wooden nests – was lower than in other studies. For example, in Maine (United States of America) lowbush blueberry fields, 20% of wooden nesting blocks and 6% of available holes (120 nests made in 2086 holes) were occupied by *Osmia*, and the rate of uptake was similar in two subsequent years (Stubbs *et al.* 1997). In a Swedish boreal forest, more than 30% of artificial wooden nests, consisting of pine poles with predrilled holes, were occupied by bees or wasps, with *Megachile* using mostly holes that were 7 or 10 mm in diameter (Westerfelt *et al.* 2015). In our study, it is possible that the deeper nesting tubes of milk carton nests (15 cm) were more attractive to Megachilidae than shallower tubes of wooden nests (8 cm) (Stubbs *et al.* 1997; Bosch and Kemp 2002; MacIvor 2016), although *Megachile* may also readily occupy artificial holes in wood that are 8 cm or less (Westerfelt *et al.* 2015). The smoothness of the hole may be important for cavity-nesting bees. Whereas the drilled holes of our wooden nests were not modified and had a relatively coarse inner surface, the milk carton tubes had smooth paper inner surfaces and had higher occupancy. Stubbs *et al.* (1997)

inserted cellophane-coated straws into drilled holes and had greater occupancy than we did in wooden trap nests.

It is also possible that the white milk carton nests were visually more attractive than the wooden nests; in California (United States of America) almond (*Prunus dulcis* (Miller) Webb (Rosaceae)) orchards, light blue nest boxes were more attractive to cavity-nesting bees than yellow or orange nest boxes, potentially due to visual signalling, detectability, and discrimination abilities from spectral reflectance of the different colored nest boxes (Artz *et al.* 2014). In a ground-nesting solitary bee experiment, Inouye (1990) demonstrated female *Epicharis metatarsalis* Friese (Hymenoptera: Apidae) bees use visual cues to recognise nest entrances, signalling the importance of visual cues for nesting uptake and recognition for bees. In the same study, no olfactory cues were associated with female bees locating their nest entrance (Inouye 1990), suggesting olfactory factors may not be as important as visual cues for locating nest entrances.

Temperature and humidity can also influence nest uptake and emergence success by cavity-nesters (Bosch and Kemp 2002; Westerfelt *et al.* 2015), although these factors were not measured in our study. Relatively poor nesting occupancy overall in the 2014 experiment may have partially been due to lack of established *Osmia* populations in the fields sampled. In a study examining the wild bee community in lowbush blueberry fields in Nova Scotia, only five *Osmia* were collected from ten commercial fields over nine collection events throughout the summer (Cutler *et al.* 2015). Similarly, low captures of *Osmia* were reported from lowbush blueberry fields in Maine (Bushmann and Drummond 2015). It is possible that field history affected *Osmia* population size or fecundity; it may take multiple years of stable food supply to support increases in bee populations. In contrast, Sheffield *et al.* (2008) found an increase in the number of bees reared in trap nests each year for three years in Nova Scotia apple orchards and other habitats, even with bees removed each year.

The experiment was modified in 2015 to focus on nesting in milk carton nests and potential differences in nesting between fruit-bearing and vegetative fields, as well as parasitism. We predicted nesting occupancy would be higher in fruit-bearing fields due to the food source offered by

blueberry flowers for the provisioning females, and that early season emergence of *Osmia* would overlap with blueberry bloom (Drummond and Stubbs 1997; Sheffield *et al*. 2003). Although we found no significant difference in nest occupancy between fruit-bearing and vegetative fields, significantly more bees emerged from occupied nesting tubes collected from fruit-bearing fields. The study sites were in close proximity (within 500 m) to other blueberry fields. The industry practice of maintaining both fruit-bearing and vegetative fields in close proximity in any given year ensures that there are harvestable berries every year (Yarborough 1997). If vegetative and fruit-bearing fields are in close proximity to one another, bees that emerge near vegetative fields may be able to fly to nearby fruit-bearing fields to forage during blueberry bloom. On the other hand, we found that provisioning and capping of most nesting tubes occurred after blueberry bloom ended, suggesting that megachilid bees also collected pollen and nectar from non-crop flowering plants. Whereas the foraging period of *Osmia* is from mid-April to late June, *Megachile* have been recorded in lowbush blueberry in Nova Scotia from early June to late September (Sheffield *et al*. 2003), suggesting nesting tube capping observed in July was from *Megachile* bees rather than *Osmia*. Thus, activity of *Osmia* and *Megachile* bees may coincide with blueberry bloom (Drummond and Stubbs 1997; Sheffield *et al*. 2003), but the availability of alternative floral resources in and around fields after blueberry bloom is also important for nesting success of Megachilidae. We recovered both *Megachile* species and *O. tersula* bees from milk carton trap nests, which contained 7 and 9 mm tubes. In contrast, in Nova Scotia apple orchards, 97% of collected *O. tersula* were recovered from nesting tubes that were 3 and 5 mm diameter, while most *Megachile* occupied tube diameters ranging from 5–9 mm, depending on the species (Sheffield *et al*. 2008). If milk carton nests containing nesting tubes of variable diameters can simultaneously attract multiple *Osmia* and *Megachile* species, a more diverse pollinating force could be supported.

We detected parasitism by cleptoparasites and parasitoids (*e.g.*, Sapygidae wasps, tachinid flies), as in previous studies (Drummond and Stubbs 1997; Stubbs *et al*. 1997; Sheffield *et al*. 2008; MacIvor and Packer 2015). Of the 65 insects that emerged from tubes, nine were parasitoids. Upon

dissection of the nesting tubes, more than 200 failed cells were observed, as well as additional wasps and flies that may have caused parasitism and prevented development of bees.

Notably, this is the first record of *Sapyga martinii* east of Québec (identification confirmed by J. Huber, Canadian National Collection of Insects, Arachnids, and Nematodes). Six *Sapyga* Latreille species are known to occur in southern Canada (Goulet and Huber 1993) and this species has been recorded in Ontario and Québec (https://bugguide.net/node/view/704862), but to the best of our knowledge, no records exist for east of Québec. This species has been recorded in trap nesting studies throughout much of the United States of America and is a known parasitoid of *O. tersula* (Medler 1967; Gardner and Spivak 2014).

Field conditions may have further reduced nest occupancy and development of bees and parasitoids. Many cells with undeveloped bees were in damp nesting tubes. Nesting success of Megachilidae can be reduced by cool, damp weather conditions (Pitts-Singer and James 2008), and associated bacterial or fungal activity (Frankie *et al*. 1998). In 2015, 404.6 mm of precipitation were recorded for the study region from May to August, but this was only slightly higher than the 30-year average (1981–2010) of 397.1 mm (Government of Canada 2016). The paper nesting tubes may have also contributed to the humid conditions, and further troubleshooting of this nesting design is warranted.

Nesting by *O. inermis* in clay lids was lower than previously reported; in our study only 3.3% of lids were occupied, as compared to 10% lid occupancy reported by Sheffield *et al*. (2014), despite more extensive sampling effort. We detected parasitism by chrysid wasps in one clay lid, whereas Hicks (2009) and Sheffield *et al*. (2014) did not report any parasitism of *O. inermis* in Newfoundland. We predicted nest occupancy would be greater in fruit-bearing fields and along the field edge due to proximity of food sources (Cutler *et al*. 2015). Although more nesting in clay lids along field edge and in fruit-bearing fields was observed, the overall low number of lids occupied (four) prohibits any conclusion on the importance of these factors in *O. inermis* nesting. Blueberry bloom would provide a mass-provision of flowers for bees and could make nesting in fruit-bearing fields more efficient for

female *O. inermis*. As offspring would then emerge the following year in vegetative fields, ensuring fields are split into nearby fruit-bearing and vegetative rotations could be important to optimise pollination from wild bees. The low nesting occupancy in clay lids could have been due to poor ventilation or high humidity under lids (some mold was observed), or simply low incidence of *O. inermis* in the blueberry fields sampled. In Maine and Nova Scotia blueberry fields, relatively few *O. inermis* were collected (Bushmann and Drummond 2015; Cutler *et al.* 2015), and this was also the case for other agricultural habitats sampled in Nova Scotia (Sheffield *et al.* 2013). Our clay lid experiment suggests prospects for managing *O. inermis* in Nova Scotia blueberry fields may be limited, but further investigation into nesting already occurring in fields, for instance, in rock piles, may be of value. Alternatively, it is possible *O. inermis* could be relocated from high-abundance areas to blueberry fields for pollination.

Given the efficacy of wild bees for lowbush blueberry pollination (Javorek *et al.* 2002), efforts to promote wild bees will continue to be an important complement to pollination by managed bees. Nesting occupancy in certain nest block designs was promising and could be implemented to enhance cavity-nesting bees in and around lowbush blueberry fields. The wooden and clay lid nests were not well used in our experiments, but success in previous studies (Stubbs and Drummond 1997; Sheffield *et al.* 2014; Westerfelt *et al.* 2015) suggests that further examination is warranted into the role of nest design in determining nest occupancy and emergence success of Megachilidae. The higher uptake in milk carton nests, as well as the observed failed cells, suggests Megachilidae are attracted to this nest design, but tactics to optimise emergence and reduce parasitism are needed.

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Supplementary material

To view supplementary material for this article, please visit https://doi.org/10.4039/tce.2018.45

References

Aras, P., De Oliveira, D., and Savoie, L. 1996. Effect of a honey bee (Hymenoptera: Apidae) gradient on the pollination and yield of lowbush blueberry. Journal of Economic Entomology, **89**: 1080–1083.

Artz, D.R., Allan, M.J., Wardell, G.I., and Pitts-Singer, T.L. 2014. Influence of nest box color and release sites on *Osmia lignaria* (Hymenoptera: Megachilidae) reproductive success in a commercial almond orchard. Journal of Economic Entomology, **107**: 2045–2054.

Blaauw, B.R. and Isaacs, R. 2014. Flower plantings increase wild bee abundance and the pollination services provided to a pollination-dependent crop. Journal of Applied Ecology, **51**: 890–898.

Bohart, R.M. and Kimsey, L.S. 1980. A generic synopsis of the Chrysididae of America north of Mexico (Hymenoptera). Journal of the Kansas Entomological Society, **53**: 137–148.

Bosch, J. and Kemp, W.P. 2000. Development and emergence of the orchard pollinator *Osmia lignaria* (Hymenoptera: Megachilidae). Environmental Entomology, **29**: 8–13.

Bosch, J. and Kemp, W.P. 2002. Developing and establishing bee species as crop pollinators: the example of *Osmia* spp. (Hymenoptera: Megachilidae) and fruit trees. Bulletin of Entomological Research, **92**: 3–16.

Bushmann, S.L. and Drummond, F.A. 2015. Abundance and diversity of wild bees (Hymenoptera: Apoidea) found in lowbush blueberry growing regions of Downeast Maine. Environmental Entomology, **44**: 975–989.

Cane, J.H., Griswold, T., and Parker, F.D. 2007. Substrates and materials used for nesting by North American *Osmia* bees (Hymenoptera: Apiformes: Megachilidae). Annals of the Entomological Society of America, **100**: 350–358.

Cutler, G.C., Nams, V.O., Craig, P., Sproule, J.M., and Sheffield, C.S. 2015. Wild bee pollinator communities of lowbush blueberry fields: spatial and temporal trends. Basic and Applied Ecology, **16**: 73–85.

Drummond, F.A. and Stubbs, C.S. 1997. Potential for management of the blueberry bee, *Osmia atriventris* Cresson. Acta Horticulturae, **446**: 77–85.

Eaton, L.J. and Murray, J.E. 1997. Relationships of pollinator numbers in blueberry fields to fruit development and yields. Acta Horticulturae, **446**: 181–188.

Eaton, L.J. and Nams, V.O. 2012. Honey bee stocking numbers and wild blueberry production in Nova Scotia. Canadian Journal of Plant Science, **92**: 1303–1310.

Frankie, G.W., Thorp, R.W., Newstrom-LLoyd, L.E., Rizzardi, M.A., Barthell, J.F., Griswold, T.L., *et al.* 1998. Monitoring solitary bees in modified wildland habitats: implications for bee ecology and conservation. Environmental Entomology, **27**: 1137–1148.

Fye, R.E. 1965. The biology of Apoidea taken in trap nests in northwestern Ontario (Hymenoptera). The Canadian Entomologist, **97**: 863–877.

Gardner, J.D. and Spivak, M. 2014. A survey and historical comparison of the Megachilidae (Hymenoptera: Apoidea) in Itasca State Park, Minnesota. Annals of the Entomological Society of America, **107**: 983–993.

Gathmann, A. and Tscharntke, T. 2002. Foraging ranges of solitary bees. Journal of Animal Ecology, **71**: 757–764.

Goulet, H. and Huber, J.T. 1993. Hymenoptera of the world: an identification guide to families. Research Branch, Agriculture Canada, Ottawa, Ontario, Canada.

Government of Canada. 2016. Canadian climate normals 1981–2010 station data [online]. Available from http://climate.weather.gc.ca/climate_normals/results_1981_2010_e.html?stnID=6358&autofwd=1 [accessed 21 November 2016].

Guisse, J.K. and Miller, D.G. 2011. Distribution and habitat preferences of *Osmia lignaria* (Hymenoptera: Megachilidae) and associated cavity-nesting insects in California's Sierra Nevada foothills adjacent to the Sacramento Valley. Pan-Pacific Entomologist, **87**: 188–195.

Hicks, B. 2009. Observations of the nest structure of *Osmia inermis* (Hymenoptera: Megachilidae) from Newfoundland, Canada. Journal of the Acadian Entomological Society, **5**: 12–18.

Inouye, B.D. 1990. Use of visual and olfactory cues for individual nest hole recognition by the solitary bee *Epicharis metatarsalis* (Apidae, Anthophorinae). Journal of Insect Behaviour, **13**: 231–238.

Javorek, S.K., MacKenzie, K.E., and Vander Kloet, S.P. 2002. Comparative pollination effectiveness among bees (Hymenoptera: Apoidea) on lowbush blueberry (Ericaceae: *Vaccinium angustifolium*). Annals of the Entomological Society of America, **95**: 345–351.

MacIvor, J.S. 2016. Cavity-nest boxes for solitary bees: a century of design and research. Apidologie, **48**: 1–17.

MacIvor, J.S. and Packer, L. 2015. "Bee hotels" as tools for native pollinator conservation: a premature verdict? Public Library of Science One, **10**: e0122126.

McAlpine, J.F., Peterson, B.V., Shewell, G.E., Teskey, H.J., Vockeroth, J.R., and Wood, D.M. 1987. Manual of Nearctic Diptera. Agriculture Canada, Ottawa, Ontario, Canada.

Medler, J.T. 1967. Biology of *Osmia* in trap nests in Wisconsin (Hymenoptera: Megachilidae). Annals of the Entomological Society of America, **60**: 338–344.

Mitchell, T.B. 1962. Bees of the eastern United States. II. Technical Bulletin (North Carolina Agricultural Experiment Station), 152: 1–557. Available from https://projects.ncsu.edu/cals/entomology/museum/easternBees.php [accessed 13 August 2018].

Packer, L., Genaro, J.A., and Sheffield, C.S. 2007. The bee genera of eastern Canada. Canadian Journal of Arthopod Identification, **3**: 1–32.

Pitts-Singer, T.L. and James, R.R. 2008. Do weather conditions correlate with findings in failed, provision-filled nest cells of *Megachile rotundata* (Hymenoptera: Megachilidae) in western North America? Journal of Economic Entomology, **101**: 674–685.

SAS Institute. 2014. SAS/STAT 9.4 user's guide. SAS Institute, Cary, North Carolina, United States of America.

Sheffield, C.S., Kevan, P.G., Pindar, A., and Packer, L. 2013. Bee (Hymenoptera: Apoidea) diversity within apple orchards and old fields in the Annapolis Valley, Nova Scotia, Canada. The Canadian Entomologist, **145**: 94–114.

Sheffield, C.S., Kevan, P.G., and Smith, R.F. 2003. Bee species of Nova Scotia, Canada, with new records and notes on bionomics and floral relations (Hymenoptera: Apoidea). Journal of the Kansas Entomological Society, **76**: 357–384.

Sheffield, C.S., Kevan, P.G., Westby, S.M., and Smith, R.F. 2008. Diversity of cavity-nesting bees (Hymenoptera: Apoidea) within apple orchards and wild habitats in the Annapolis Valley, Nova Scotia, Canada. The Canadian Entomologist, **140**: 235–249.

Sheffield, C.S., Wilkes, M.A., Cutler, G.C., and Hermanutz, L. 2014. An artificial nesting substrate for *Osmia* species that nest under stones, with focus on *Osmia inermis* (Hymenoptera: Megachilidae). Insect Conservation and Diversity, **8**: 189–192.

Stubbs, C.S., Drummond, F.A., and Algard, S.L. 1997. Bee conservation and increasing *Osmia* spp. in Maine lowbush blueberry fields. Northeastern Naturalist, **4**: 133–144.

Taki, H., Boone, J.W., Viana, B.F., Silva, F.O., Kevan, P.G., and Sheffield, C.S. 2004. Effect of shading on trap nest utilization by hole-nesting aculeate Hymenoptera. The Canadian Entomologist, **136**: 889–891.

Torchio, P.F. 1987. Use of non-honey bee species as pollinators of crops. Proceedings of the Entomological Society of Ontario, **118**: 111–124.

Vaughan, M. and Black, S.H. 2008. Native pollinators: how to protect and enhance habitat for native bees. Native Plants, **9**: 80–91.

Westerfelt, P., Windefalk, O, Lindelow, A., Gustafsson, L., and Weslien, J. 2015. Nesting of solitary wasps and bees in natural and artificial holes in dead wood in young boreal forest stands. Insect Conservation and Diversity, **8**: 493–504.

Wratten, S.D., Gillespie, M., Decourtye, A., Mader, E., and Desneux, N. 2012. Pollinator habitat enhancement: benefits to other ecosystem services. Agriculture, Ecosystems and Environment, **159**: 112–122.

Yarborough, D.E. 1997. Production trends in the wild blueberry industry in North America. Acta Horticulturae, **446**: 33–35.

Yarborough, D.E. 2012. Establishment and management of the cultivated lowbush blueberry (*Vaccinium angustifolium*). International Journal of Fruit Science, **12**: 14–22.

Zurbuchen, A., Landert, L., Klaiber, J., Muller, A., Hein, S., and Dorn, S. 2010. Maximum foraging ranges in solitary bees: only few individuals have the capability to cover long foraging distances. Biological Conservation, **143**: 669–676.