University of California, Santa Cruz

# Using solitary bees for pollination in agricultural settings

A Senior Thesis submitted in partial satisfaction
of the requirements for the degree of

BACHELOR OF ARTS
in
ENVIRONMENTAL STUDIES
by

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June 2018

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ABSTRACT: The loss of habitat due to agriculture and urban development influences the availability of flower and nesting resources for bees, compromising their populations and subsequently the delivery of pollination services. With the rapid decline of the European honeybee, more research must be done on alternative pollinators, such as solitary bee populations. Domestication of solitary bee species for utilization in agriculture has become of more interest in recent years as European honey bee populations continue to rapidly decline. The use of artificial nests also known as "bee hotels" is a habitat restoration method that is becoming increasingly popular. As further research is conducted, the large potential of using solitary bees in agriculture is becoming more evident and seems to be an effective method of diversifying our pollinators in agricultural settings. Understanding the habitat preferences for these bee species, such as Mason bees, is essential for understanding how we can best replicate their natural habitats. My senior thesis project examines the colonization rates of native bees in bee hotels placed in Santa Cruz County. By building six bee hotels and studying three primary variables, I am able to determine the preferred habitat of cavity nesting bees in Santa Cruz. The study focuses on three primary variables (location, wood type and cavity size) and how they influence the rate of establishment within the bee hotels.

KEYWORDS: Santa Cruz, solitary bee, native bee, honey bee, *Osmia lignaria*, bee hotel, habitat restoration, artificial nest, nest material, urban agriculture, agroforestry.



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Student Signature Date

## Literature Review

Many plant species rely on animals for pollination. Pollination is an essential part of the plant reproductive cycle, and also contributes to essential natural processes. Pollination of plant species promotes plant reproduction and healthy plant populations, which play a role in carbon sequestration and can improve water and soil quality by preventing erosion and buffering the quantities of harmful toxins in the soil (United States Department of Agriculture, n.d.). Pollination is a vital ecosystem service provided to humans. Globally, 35% of food crops rely on animal pollination (Klein et al., 2007). Of these animal pollinators, a large majority are insects such as flies, butterflies, wasps and bees. While all of these insects are present in natural and agricultural settings, bees are the pollinator group most commonly manipulated by humans for pollination services, as they are cheap, effective and versatile (Klein et al., 2007).

The European honey bee (*Apis mellifera*) was domesticated by humans nearly 10,000 years ago, 2,000 years after humans largely changed from foraging to farming (Barker, 2009). The early domestication of honey bees was largely oriented around the production of honey, a substance important for food, religious ceremonies and medicinal uses. As agriculture continued to expand, and as natural habitat declined, the importance of honey bees switched from honey production to pollination services (Weber, 2013). The honey bee is now the most commonly used pollinator in agricultural systems. As of 2014, the estimated annual value of pollination services provided by honey bees was $11-15 billion in the United States alone (Dennis & Kemp, 2016). Humans have domesticated and utilized this bee species so extensively that the species now faces several problems, termed collectively as “colony collapse disorder” or CCD. The cause of CCD seems to be multifaceted, but is likely influenced by monoculture use of honey bees, along with pesticides, land-use change and pathogens. These factors have caused honey bee populations to rapidly decline (Goulson et al., 2015). In 2006 and 2007 alone, 29% of beekeepers reported a 75% loss of their honey bee populations (Winfree et al., 2007). While the European honey bee remains a very important species for both honey production and pollination services, it is clear that we need a focus on alternative pollinators. As CCD has led to honey bee population decline, domestication of solitary bee species for agricultural use has become of more interest.

Native, solitary bees are of great interest to farmers because of their excellent ability to pollinate crops. Of the 16,000 species of bees described worldwide, the majority are solitary species. Solitary bees live and function individually. About 70% of solitary bee species are ground-nesting, and live in burrows in the soil; others are cavity-nesting and readily nest inside aboveground cavities in wood or reeds (Gardner, n.d.). North America alone is home to over 4,000 of these species, only a small percentage of which have been domesticated and utilized as pollinators. As further research is conducted, the potential of using solitary bees in agriculture is becoming more evident and it seems that these species may provide an effective method of diversifying our pollinators in agricultural settings (Kremen et al., 2002). In agriculture, a large majority of the bees pollinating are honey bees; however, native, wild bees are often present and providing pollination services as well (Dainese et al., 2018). Many solitary bee species are more efficient pollinators compared to honey bees because of their varied foraging behaviors and thermal and temporal flexibility. Some native bee genera, such as bumble bees (*Bombus)* and mason bees (*Osmia)*, can fly in cooler and wetter conditions. A number of species are active for longer or more variable times of the day or times of the year, making them more versatile and therefore more effective pollinators. For example, it takes a mere 250-300 blue orchard bees (*Osmia lignaria)* to pollinate an acre of orchard trees, whereas it takes 15,000-20,000 honey bees (*Apis mellifera*) to pollinate the same area of orchard (Vaughan et al., 2008). Furthermore, increasing bee diversity on a farm results in optimal pollination services, in part, because the activity of different bee species is highly variability with time (Kremen et al., 2002). Solitary bees belonging to the family Megachilidae, which includes primarily mason bees (*Osmia)* and leafcutter bees (*Megachile),* carry pollen and nectar on the underside of their abdomen, opposed to on their legs, which increases the chances of spreading pollen from flower to flower (Vaughan et al., 2008). Leafcutter bees are generally considered beneficial insects in agriculture, due to their ability to pollinate crops such as blueberries, onions, carrots; as well as legumes such as alfalfa, which can be difficult for many insects to pollinate due to complex flower morphology. Leafcutter bees are becoming more popular to farmers to be used as domesticated pollinators, however, they can also be considered pests, due to their leaf cutting behavior. Leafcutter bees trim circular pieces off of plant foliage in order to build cell caps within their nesting cavity. Although this rarely damages the plant In any significant way, it can harm the aesthetics of ornamental flowers (Seranno, 2005). Another example of a bee used by farmers is the alkali bee (*Nomia*), a species of bee native to western and southwestern United States. This species of bee is ground nesting and is also particularly useful for alfalfa growers because of their ability to easily pollinate the complex alfalfa flower, a task honey bees have a hard time executing (Moisset & Wojcik, n.d.).

Cavity-nesting bees, such as those belonging to the family Megachilidae, have a relatively simple life cycle, making them a particularly manageable group of bees. The blue orchard bee (*Osmia lignaria)* is native to Northern California and is easy to domesticate and handle, and exhibits excellent pollinating abilities (Gardner, n.d.). This species of bee has a small, black, metallic appearance and nests inside preexisting holes or cavities. Once the female bee has chosen a nest, she will mark it with a scent which will allow her to return the same hole.

Males and females mate, the male dying shortly after, leaving the female to lay eggs and collect pollen for the larvae. The female bee lays her eggs starting in the back of the cavity. Adjacent to the egg is a small ball of nectar and pollen that acts as a food source for the growing larvae. Using mud from an external source, the female bee then builds a protective wall of mud, known as a mud cap. She will continue to repeat this process until she meets the end of the hole. The female bee controls which of the larvae are male or female by fertilization. Fertilized eggs will become females, whereas unfertilized eggs will become males. Mason bees strategically fertilize the eggs deepest in the holes and leave the eggs closest to the exterior unfertilized. This protects females from outside forces and also assures that males hatch first and are ready to mate when the females hatch (Estep et al., 2015).

Despite the utility of solitary bees in farms, agricultural intensification and land-use change both largely contribute to declining populations of solitary bees. Large-scale conventional agriculture often uses monocrop systems that eliminate the essential floral biodiversity that is present in most natural systems. The use of monocrops limits the floral resources for native bees by shortening the flowering period. In a natural habitat plants have different flowering periods, which increases and broadens the availability of flowers to bees. Along with disturbing floral resources, land-use change fragments and degrades the natural living habitats for bees leading to a decline in abundance and diversity. In a quantitative synthetic analysis that looked at a number of studies conducted at agricultural sites around the world, Ricketts et al. (2008) determined that habitat alteration directly influences the quantity and diversity of wild bee populations. Both pollinator diversity and visitation rates were cut in half every 1.5 km traveled away from areas of natural habitat. With the rapid development of the globe, habitat restoration is becoming increasingly vital. One method that is being explored is the use of artificial bee homes in agricultural settings.

Many species of solitary bees are easily domesticated, relatively benign and take little time or effort to manage. Artificial homes, often termed “bee hotels” or “bee boxes”, can be used to recreate the natural habitat of cavity dwelling species such as Mason bees. Domestication of solitary species is becoming increasingly attractive to farmers as CCD continues to negatively impact honey bee populations (Fortel et al., 2016). An experiment conducted by a research team (Campbell & Horth) in Virginia, USA, examined the effectiveness of *Osmia lignaria* as a pollinator for strawberries. They studied the activity of *O. lignaria* with regards to strawberry pollination, and how using this pollinator may enhance the growth of strawberry fruit size, an important trait related to the economic value of the crop. The experiment also looked at the use of artificial nesting boxes, specifically how different nest substrates influence the establishment rates of *O. lignaria.* Results showed that *O. lignaria* are exceptional pollinators and have the potential to aid or even replace honey bees (*Apis mellifera)* in certain agricultural systems. Their study showed that wild pollinators, such as *O. lignaria,* were able to double the fruit set in a wide variety of crops. This experiment, along with others of similar nature, have showed *O. lignaria* to be a generalist species, meaning that upon emergence from pupal stage, the female adult bee is readily available to pollinate a wide variety of species, both woody and herbaceous. This species is also of particular interest due to their emergence time, which allows them to pollinate early spring crops, such as strawberries. Although strawberries are capable of self-pollination, outcrossing by animal pollinators increases the weight of the fruit, yielding optimal fruit (Horth & Campbell, 2018). Campbell and Horth (2018) also found that bamboo as a nest material resulted in the highest rate of colonization. They argue this may be due to its antimicrobial properties and its ability to provide good insulation (Campbell & Horth, 2018).

There are also arguments that the creation of artificial homes for solitary bees can have negative effects on bee populations as well. A study conducted in Toronto looked at the activity and establishment rates of native and introduced bees using nearly 600 bee boxes (MacIvor & Packer, 2015). The results of this particular study were rather problematic, as they showed bee hotels to have a negative effect on the native bee populations. The boxes led to unusually high establishment rates of parasitic wasps, which parasitized the native populations of bees more than the introduced populations. The bee boxes also increased the spread of pathogens interspecifically between bee species living in the same box, as bee boxes encourage unnaturally high densities of bees to live in one vicinity (MacIvor & Packer, 2015).

Although a number of studies have shown certain solitary bee species to have high potential as domesticated agricultural pollinators, there is limited research that goes into detail regarding biotic and abiotic factors that influence nesting site selection. Certain methods such as providing bee boxes for cavity nesting species or leaving sun-rich, barren ground open for ground nesting, will likely increase solitary bees richness and abundance. Increasing the floral resource abundance and diversity can also promote pollinator populations (Fortel et al., 2016). For cavity-nesting solitary bees, installing boxes facing south to south-east ensures maximum morning sunlight, allowing bees to optimize their activity (Golick & Weissling, 2015).

Solitary bees are largely understudied, given the potential that they have as agricultural pollinators. While we understand their life cycles and their effectiveness as pollinators, we know little about which species have potential as manageable pollinators (Fortel et al., 2016 & Bosch & Kemp, 2002). The lack of research revolving around alternative pollinators largely stems from the absence of organized monitoring programs (Potts et al., 2010). The Toronto study conducted by MacIvor & Packer makes it clear that more extensive research must be conducted in order to figure out how to optimize bee hotels for the wanted species. More research must be conducted regarding nesting preferences of specific bee species; more specifically the influence of nest medium, cavity dimensions, location, as well as more extensive research exploring which species have the most potential as pollinators (Dennis & Kemp, 2016).

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**Testing Bee Hotel Construction Methods as a Means of Pollinator Habitat Restoration**

Project Documentation

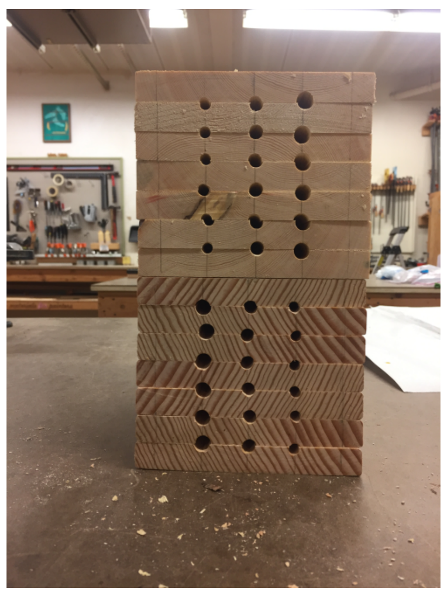
## Introduction (project summary)

The loss of habitat due to agriculture and urban development impacts the availability of flower and nesting resources for bees, compromising their populations and subsequently the delivery of pollination services. With the rapid decline of the European honey bee, more research is needed regarding alternative pollinators, such as solitary bees. Solitary bees such as mason bees and leafcutter bees, have proven to be useful as agricultural pollinators (Rios-Velasco et al., 2014). For my senior internship, I examined the colonization rates of native bees in solitary bee hotels placed in Santa Cruz County. I built six bee hotels and installed them at six different agricultural sites in Santa Cruz. To determine which nest types native bees prefer, I manipulated three variables: nest substrate, cavity size, and nest location. The use of six different agricultural sites helps determine the influence of location on establishment rates; specifically, how colonization rates differ between an agroforestry setting (Chadwick Garden, Kresge Garden), an urban-agricultural setting (Trescony Garden, Homeless Garden Project, The Grange) and a larger, tractor-scale setting (Center for Agroecology and Sustainable Food Systems). Understanding the habitat preferences for these bee species, such as mason bees, is essential for understanding how we can best replicate their natural habitats in an urban garden.

## Methods

January through February 2018, was spent building the six bee hotels. The hives were constructed from Douglas fir and pine, with a galvanized sheet metal roof. Each box contains thirty-six cavities that were drilled 6” deep, 1/2” from one another. Twelve cavities were drilled with a ¼” diameter, twelve with a 5/16” diameter and twelve with a 3/8” diameter. The use of different size cavities is intended to help determine the different cavity-size preferences for different bee species. In order to minimize the possibility of no bees establishing in the boxes, special attention was given to a few key factors of a bee hotel. Sufficient protection from rain was provided by the metal roofing. Preliminary research was conducted in order to find the cavity sizes best suited for the bee native to the Santa Cruz region. And lastly, the cavities were carefully sanded in order to remove splinters (this can be a strong deterrent to many cavity-nesting bees) (MacIvor, 2016). The design of the boxes (stacked 1”x6” boards) allows them to opened upon completion of the project, which will allow a more detailed analysis of the activity within the cavities. This experimental set up will help provide information regarding which nest construction material promotes bee diversity, and how land-use in cities might impact their efficacy. Upon completion of the construction phase, the six boxes were installed at six agricultural locations around Santa Cruz.

*1"x6" Douglas fir (left) and pine (right).*



*Stacked boards will allow the boxes to be opened for data collecting purposes.*

Observations will be taken for the fifteen weeks following installation. The observations will take place two times a week, for twenty minutes in order to take note of all of the activity that will take place at each nest site. Observations will be recorded into data tables, specifically, looking at the number of cell caps, adult bee activity, and pest activity. At the end of the fifteen-week period, the observations will be compiled together and the influence of the three variables will be determined.

**Observations**

Late February and into March, Santa Cruz City was experiencing very poor weather. Almost immediately after installation, the boxes were subject to heavy rain and wind. For nearly two months (February 22nd-April 15th) there was no bee activity in the hives. Within three weeks after installation (March 14th) there were pests within a few of the nests. Initially, the box at CASFS had a number of insect droppings within the holes, but it was unclear what insect the frass belonged too. Chadwick garden had a large number of spider webs, likely because large quantities of spiders were using the box to avoid being exposed to the rain. The box at Kresge Garden quickly became spotted with black mold on the exterior, however, the mold disappeared once the rainy season came to an end. It did not take long to realize that the insect frass within the cavities belonged to earwigs (*Dermaptera: Forficulidae).* For the next month (March 14th – April 14th) pest activity increased. There was no trend regarding what wood type, cavity size, or location the pests preferred; they seemed randomly distributed throughout the hives. However, it became apparent on April 13th that earwigs were much more abundant at CASFS, Chadwick Garden, and The Grange. It did not take long to figure out that all three of these boxes were nestled in the crotch of trees, whereas the other three sites had the boxes hanging by steel wire. Earwigs have a much easier time entering the boxes that were physically touching the branches of the trees, as they can easily crawl in, opposed to the hanging boxes which have little surface area touching the tree. During the following observational period, the infested boxes were uninstalled, opening and cleaned of earwigs and spiders. Upon reinstallation, The Grange box and the CASFS box were hung by wire instead of resting in on the tree. The box at Chadwick Garden remained nestled in the tree, as to not disturb the Blue Orchard Bee that had recently established in the box!

*Earwig (Dermaptera) infestation within cavities.*

*Large amounts of earwig frass.*

The first sign of bee activity within the bee boxes was on April 18th, approximately fifty-five days after installation. A 3/8" pine cavity was sealed by a mud cap at the exterior of the hole, a common sign of a blue orchard bee (*Megachilidae: Osmia lignaria).* No adult blue orchard bee was seen at this time. During the next observational period (April 23rd), a wasp-like hymenopteran was seen entering a 1/4" pine cavity at the Chadwick site. This insect looked similar to a yellow jacket (*Vespidae)* but smaller. It was unclear if this was a true wasp, or a lookalike bee or fly. After doing some research, it seemed likely that it was a wasp belonging to the family *Sapygidae,* a solitary wasp that is a kleptoparasite of blue orchard bees (United States Department of Agriculture, 2017). This wasp was only observed once and was not seen after this. A week later (April 30th), another mud cap appeared at the Chadwick site, in a 1/4" pine cavity, however, there was still no sign of the adult bees. On May 8th a third cap was observed, built in a 1/4" Douglas fir cavity. During this observational period, an adult bee was seen entering one of the 1/4" cavities. This bee seemed slightly small to be a blue orchard bee, however, due to the three mud caps and high abundance of this species at the Chadwick Site, it seems likely this was the species observed.

*First mudcap built at Chadwick Garden site (Osmia lignaria).*

*Adult Osmia lignaria caught entering nesting box.*

After seeing the third mud cap and observing the adult bee enter the hive, there was no more bee activity recorded at this site. It seems likely that the reason no more bees established at this site is because of the large number of earwigs occupying the rest of the cavities. The Chadwick Box could not be uninstalled and cleaned of pests, as this would disrupt the development of the blue orchard bee larvae.

On May 15$^{th}$ three black, adult bees were observed inside of the box at CASFS. All three bees were inside ¼" Douglas fir cavities, two of which were facing forwards and one facing backward. Initially, it seemed that these bees were solely using the bee box as a place to sleep or hide, as they didn't appear to be building any mud caps and they were never seen entering or exiting during observational periods. It was difficult to identify what family these bees belonged to, as observations were restricted to what could be seen looking into the small cavities. These bees appeared to have black bodies with yellow/white hair on the head, legs, and sides of the thorax (view from the front). The backside of this species appeared to be fully black, with a yellow stripe around the ventral part of the abdomen; although it was hard to get a clear observation looking into the tiny hole. On May 21st, two bees belonging to the same species were observed at the Trescony Garden location. For the following twenty days, observations were taken twice a week in the late afternoon and the bees seemed to remain inactive in the cavities at both Trescony and CASFS. The number of adult bees fluctuated minimally, sometimes increasing in numbers and sometimes decreasing by one. By the end of May (May 29th) there were six bees hiding within the cavities at the CASFS site, primarily in the ¼th diameter cavities; and one adult bee at the Trescony site.

*Adult leafcutter bee (Megachilidae) protecting cavity entrance. Large amounts of pollen can be seen on the abdominal scopa of the female leafcutter bee.*

An important observation was made at Trescony Garden on May 29th. In five of the 5/16" pine cavities and three of the 1/4" Douglas fir cavities, there appeared to be some sort of cell wall built deep inside. The use of a new, stronger flashlight made it evident that there were indeed cell caps made of what appears to be nectar and pollen. After discussing the newly discovered cell walls with a colleague, it was determined that what was being observed was likely the cell walls of a leafcutter bee (Family: *Megachilidae,* Genus: *Megachile).* During the following observational period (June 3rd), the box at CASFS was inspected more carefully, with a better flashlight, and similar cell walls were seen inside of nearly eleven cavities. Although it was difficult to see, there were small green areas around the perimeter of the nectar/pollen cell walls, which are pieces of leaves that the leafcutter bee used to construct the wall. It also seemed likely that the reason these adult bees had seemed relatively inactive (remaining within the cavities) is due to the time of day observations had been taking place. The majority of observational periods throughout the last few weeks took place later in the afternoon, which may have been why the leafcutter bees seemed relatively inactive. On June 3rd, observations were taken early in the morning at Trescony and CASFS and the adult leafcutter bees were extremely active, exiting and entering the cavities regularly. This made it easy to capture an adult bee, by simply holding a glass vile over the entrance of a cavity. The bee was taken back to the lab and its identity as *Megachile* was confirmed.

*First captured leafcutter bee. Caught at Tresoncy Gardens.*

*Leafcutter bee (Family: Megachilidae, Genus: Megachile) under a microscope. Identification as Megachilidae is evident by the presence of two submarginal cells in the front wings, singular subantennal sutures and dense hairs on the ventral part of the abdomen.*

The boxes at the other three locations, The Grange, Kresge and Homeless Garden Project, received no bee activity. At the beginning of May, an insect with a large black abdomen was seen inside of one of the 3/8" Douglas fir cavities. The abdomen looked like that of a bee, however, was much larger than most of the native bees in Santa Cruz. During the next observational period the bee was gone; however, it returned a week later. By May 15$^{th}$, the insect was gone and did not return. There was no trace of the bee left in the cavity. Due to the large, shiny, black abdomen, it seems likely that this may have been a carpenter bee using the bee box as shelter.

*The large black abdomen of an unknown insect hiding within a 3/8" cavity.*

**Results**

Below are the observation tables, which include: date, location, number of adult bees, number of cell caps and various notes taken each observational period.

| DATE | 3/14/2018 | # Cell Caps | # Bees | Notes |
|---|---|---|---|---|
| | CASFS | 0 | 0 | Cavities contained insect droppings of some sort, along with some insect living at the back of the cavity… not sure what type. |
| | CHADWICK | 0 | 0 | Hive intact and almost fully dry. Spider webs inside of 7/18 holes. |
| | TRESCONY | 0 | 0 | No activity. Hive intact and dry. |
| | HGP | 0 | 0 | No activity. Hive intact and dry. |
| | GRANGE | 0 | 0 | No activity. Hive intact and dry. |
| | KRESGE | 0 | 0 | Small dots of what appears to be black mold are growing on the front of the hive, which is wet. No activity. Hive is intact. |

| DATE | 4/3/2018 | # Cell Caps | # Bees | Notes |
|---|---|---|---|---|
| | CASFS | 0 | 0 | Cavities contained more earwig droppings and earwigs (6 holes). Spider webs in 4 holes. |
| | CHADWICK | 0 | 0 | Hive intact and almost fully dry. Spider webs inside of 7/18 holes. |
| | TRESCONY | 0 | 0 | No activity. Hive intact and dry. No earwigs or spiders! |
| | HGP | 0 | 0 | No activity. Hive intact and dry. Spider webs in 4 of the holes. |
| | GRANGE | 0 | 0 | No activity. Doug fir is cracking vertically. Earwig droppings in every hole. Earwigs in 7 holes, spider webs in 5 holes |
| | KRESGE | 0 | 0 | Black mold is no longer visible (less rain). Spider webs in 4 holes. |

| DATE | 4/7/2018 | # Cell Caps | # Bees | Notes |
|---|---|---|---|---|
| | CASFS | 0 | 0 | Cavities contained about the same amount of pest activity as last week. |
| | CHADWICK | 0 | 0 | Hive intact dry. Spider webs inside of 7/18 holes and some apparent earwig activity. |
| | TRESCONY | 0 | 0 | No activity. Hive intact and dry. No earwigs or spiders! |
| | HGP | 0 | 0 | No activity. Hive intact and dry. Spider webs in 4 of the holes. |
| | GRANGE | 0 | 0 | No activity. The Doug fir seems to be cracking a little more than last week. Lots of pest activity (needs to be cleaned). |
| | KRESGE | 0 | 0 | Black mold is no longer visible (less rain). Spider webs in 4 holes. |

| DATE | 4/13/2018 | # Cell Caps | # Bees | Notes |
|---|---|---|---|---|
| | CASFS | 0 | 0 | Needs to be cleared of pests. |
| | CHADWICK | 0 | 0 | Needs to be cleared of pests. |
| | TRESCONY | 0 | 0 | No activity. Hive intact and dry. No earwigs or spiders! |
| | HGP | 0 | 0 | No activity. Hive intact and dry. Spider webs in 4 of the holes. |
| | GRANGE | 0 | 0 | Uninstalled and cleaned hive! Looks good now. How long until more pests re-establish? |
| | KRESGE | 0 | 0 | Black mold is no longer visible (less rain). Spider webs in 4 holes. |

| DATE | 4/15/2018 | # Cell Caps | # Bees | Notes |
|---|---|---|---|---|
| | CASFS | 0 | 0 | Lots of earwigs, needs to be cleaned. |
| | CHADWICK | 0 | 0 | Lots of earwigs, needs to be cleaned. |
| | TRESCONY | 0 | 0 | No activity. Hive intact and dry. No earwigs or spiders! |
| | HGP | 0 | 0 | No activity. Hive intact and dry. Spider webs in 4 of the holes. |
| | GRANGE | 0 | 0 | Uninstalled and cleaned hive! Looks good now. How long until more pests re-establish? |
| | KRESGE | 0 | 0 | No activity. Hive intact and dry. Spider webs in 3 of the holes. |

| DATE | 4/18/2018 | # Cell Caps | # Bees | Notes |
|---|---|---|---|---|
| | CASFS | 0 | 0 | Uninstalled and cleaned hive! Looks good now. Reinstalled hanging instead of sitting in the crotch of the tree. |
| | CHADWICK | 1 | 0 | One cap in the 3/8" pine. Appears to be *Osmia Lignaria*, however, I did not see any adult bees. |
| | TRESCONY | 0 | 0 | No activity. Hive intact and dry. No earwigs or spiders! |
| | HGP | 0 | 0 | No activity. Hive intact and dry. Spider webs in 4 of the holes. |
| | GRANGE | 0 | 0 | A few earwigs present. Needs to be hung instead of sitting in tree. |
| | KRESGE | 0 | 0 | No activity. Hive intact and dry. Spider webs in 3 of the holes. |

| DATE | 4/23/2018 | # Cell Caps | # Bees | Notes |
|---|---|---|---|---|
| | CASFS | 0 | 0 | Seems to be less pest activity now that the hive is hanging. No new bee activity. |
| | CHADWICK | 1 | 0 | No adult blue orchard bee seen, however, I did see a wasp-looking insect enter and leave multiple times (this could be Sapygidae) |
| | TRESCONY | 0 | 0 | No activity. Hive intact and dry. No earwigs or spiders! |
| | HGP | 0 | 0 | No activity. Hive intact and dry. Spider webs in 4 of the holes and possibly a few earwigs in Doug fir. |
| | GRANGE | 0 | 0 | no activity. |
| | KRESGE | 0 | 0 | No activity. Hive intact and dry. Spider webs in 3 of the holes. |

| DATE | 4/26/2018 | # Cell Caps | # Bees | Notes |
|---|---|---|---|---|
| | CASFS | 0 | 0 | No activity. Hive intact and dry. No earwigs or spiders! |
| | CHADWICK | 1 | 0 | Still have not seen any adult bees. Watched another hive near mine and saw them going in and out about every 5 minutes. |
| | TRESCONY | 0 | 0 | No activity. Hive intact and dry. No earwigs or spiders! |
| | HGP | 0 | 0 | No activity. Hive intact and dry. Spider webs in 4 of the holes. |
| | GRANGE | 0 | 0 | More earwigs and spider webs present. Didn’t have time to reinstall hive, but I will next visit. |
| | KRESGE | 0 | 0 | No activity. Hive intact and dry. Spider webs in 3 of the holes. |

| DATE | 4/30/2018 | # Cell Caps | # Bees | Notes |
|---|---|---|---|---|
| | CASFS | 0 | 0 | No pest activity since being hung (aside from a tiny little spider)! |
| | CHADWICK | 2 | 0 | Second mud cap in the 1/4" cavity. Still have not seen adult bees… |
| | TRESCONY | 0 | 0 | No activity. |
| | HGP | 0 | 0 | Spider webs around a few holes. Apparent mold on the bottom left. Possible bee inside? Black abdomen seen with flashlight. |
| | GRANGE | 0 | 0 | Uninstalled and cleaned hive once again. Many earwigs (~30) and three spiders. I reinstalled this hive hanging. |
| | KRESGE | 0 | 0 | No bee activity; however, there are some spiders and earwigs… should clean this hive out soon. |

| DATE | 5/1/2018 | # Cell Caps | # Bees | Notes |
|---|---|---|---|---|
| | CASFS | 0 | 0 | No activity |
| | CHADWICK | 2 | 0 | Still have not seen the adult bee yet |
| | TRESCONY | 0 | 0 | No activity |
| | HGP | 0 | 0 | Possible adult bee inside one 3/8" Doug Fir cavity... hard to tell, could be a pest |
| | GRANGE | 0 | 0 | No activity |
| | KRESGE | 0 | 0 | No activity |

| DATE | 5/4/2018 | # Cell Caps | # Bees | Notes |
|---|---|---|---|---|
| | CASFS | 0 | 0 | No activity, a few spider webs |
| | CHADWICK | 2 | 0 | Still have not seen the adult bee yet |
| | TRESCONY | 0 | 0 | No activity |
| | HGP | 0 | 0 | Previous sighting of large black abdomen insect not present? |
| | GRANGE | 0 | 0 | No activity |
| | KRESGE | 0 | 0 | No activity |

| DATE | 5/8/2018 | # Cell Caps | # Bees | Notes |
|---|---|---|---|---|
| | CASFS | 0 | 0 | No activity, a few spider webs |
| | CHADWICK | 3 | 1 | Another cap! 1 in 3/8" (pine), 2 in 1/4" (Doug fir and pine). Saw an adult bee! Looks smaller than BOB???? |
| | TRESCONY | 0 | 0 | No activity |
| | HGP | 0 | 1 | Large black abdomen in 3/8 Doug fir cavity... cannot tell what species, but looks like some bee? Size of a carpenter bee. |
| | GRANGE | 0 | 0 | No activity |
| | KRESGE | 0 | 0 | No activity |

| DATE | 5/11/2018 | # Cell Caps | # Bees | Notes |
|---|---|---|---|---|
| | CASFS | 0 | 0 | No activity, a few spider webs |
| | CHADWICK | 3 | 0 | No sign of adult bee, still 3 caps |
| | TRESCONY | 0 | 0 | No activity |
| | HGP | 0 | 1 | Large black abdomen in cavity, closer to the entrance than prior days, but still difficult to tell what type of bee/insect. |
| | GRANGE | 0 | 0 | No activity |
| | KRESGE | 0 | 0 | No activity |

| DATE | 5/15/2018 | # Cell Caps | # Bees | Notes |
|---|---|---|---|---|
| | CASFS | 0 | 3 | 3 (maybe four) adult bees inside cavities (Doug fir). Look black with tan/brown trimming around abdomen and head. Two facing forwards, one facing back |
| | CHADWICK | 3 | 0 | No sign of adult bee, still 3 caps |
| | TRESCONY | 0 | 0 | No activity - no pests |
| | HGP | 0 | 0 | Large black abdomen in cavity is gone? So sign of anything in the whole that inset was previously in. |
| | GRANGE | 0 | 0 | No activity |
| | KRESGE | 0 | 0 | No activity - a few ears wigs and spiders |

| DATE | 5/18/2018 | # Cell Caps | # Bees | Notes |
|---|---|---|---|---|
| | CASFS | 0 | 2 | 2 adult bees inside cavities (appears to be same species as before). Facing forward |
| | CHADWICK | 3 | 0 | No sign of adult bee, still 3 mudcaps |
| | TRESCONY | 0 | 0 | No activity |
| | HGP | 0 | 0 | No new activity |
| | GRANGE | 0 | 0 | No activity aside from earwigs in 3/8" pine cavity |
| | KRESGE | 0 | 0 | No activity, nest is clean |

| DATE | 5/21/2018 | # Cell Caps | # Bees | Notes |
|---|---|---|---|---|
| | CASFS | 0 | 4 | 4 adult bees, same species, 2 facing forward, 2 facing back, all in the 5/16 and ¼ Doug fir |
| | CHADWICK | 3 | 0 | No sign of adult bee, still 3 mudcaps |
| | TRESCONY | 0 | 2 | 2 adult bees, same species, facing forward, 5/16 hole |
| | HGP | 0 | 0 | No new activity |
| | GRANGE | 0 | 0 | No new activity |
| | KRESGE | 0 | 0 | No new activity |

| DATE | 5/25/2018 | # Cell Caps | # Bees | Notes |
|---|---|---|---|---|
| | CASFS | 0 | 5 | 5 adult bees, same species, 2 facing forward, 3 facing back, all in the 5/16 and 1/4 Doug fir |
| | CHADWICK | 3 | 0 | No sign of adult bee, still 3 mudcaps, rest of holes very pest ridden… |
| | TRESCONY | 0 | 2 | 2 adult bees, same species, facing forward, 5/16 hole |
| | HGP | 0 | 0 | No new activity, lots of spider webs |
| | GRANGE | 0 | 0 | No activity aside from earwigs in 3/8" pine cavity |
| | KRESGE | 0 | 0 | No bee activity, earwig in 1 holes, a couple spider webs |

| DATE | 5/29/2018 | # Cell Caps | # Bees | Notes |
|---|---|---|---|---|
| | CASFS | 0 | 6 | 6 adult bees, same species, 2 facing forward, 4 facing back, 1 Doug fir 5/16, 4 Doug fir 1/4 and 1 3/8 Pine, Bothered by flashlight |
| | CHADWICK | 3 | 0 | No sign of adult bee, still 3 mudcaps, rest of holes very pest ridden… |
| | TRESCONY | 5 | 1 | 1 adult bee, 5 of the 5/16 pine holes have walls built half way down, appears to be a nectar/pollen cap, same inside 3 1/4 Doug fir holes, one had adult bee |
| | HGP | 0 | 0 | No new activity. Large amounts of spider webs and cobwebs |
| | GRANGE | 0 | 0 | No activity |
| | KRESGE | 0 | 0 | Earwig in 1 cavity and small amounts of spider webs in 4 holes |

| DATE | 6/3/2018 | # Cell Caps | # Bees | Notes |
|---|---|---|---|---|
| | CASFS | 11 | 6 | 5 adult bees seen both entering and exiting (*Megachile*). 1 cap 5/16 Douglas Fir, 5 caps in 1/4 Douglas fir, 5 caps in 1/4 pine. |
| | CHADWICK | 3 | 0 | No sign of adult bee, still 3 mudcaps, rest of holes very pest ridden… |
| | TRESCONY | 8 | 1 | 1 adult *Megachile* (captured). 5 caps in 5/16 pine, 3 caps in 1/4 Doug fir |
| | HGP | 0 | 0 | No new activity. Large amounts of spider webs and cobwebs |
| | GRANGE | 0 | 0 | No activity |
| | KRESGE | 0 | 0 | Earwig in 1 cavity and small amounts of spider webs in 4 holes |

| DATE | 6/7/2018 | # Cell Caps | # Bees | Notes |
|---|---|---|---|---|
| | CASFS | 12 | 6 | 5 adult bees seen both entering and exiting (*Megachile*). 1 cap 5/16 Douglas Fir, 5 caps in 1/4 Douglas fir, 6 caps in 1/4 pine. |
| | CHADWICK | 3 | 0 | No sign of adult bee, still 3 mudcaps, rest of holes very pest ridden… |
| | TRESCONY | 8 | 1 | 1 adult *Megachile* (captured). 5 caps in 5/16 pine, 3 caps in 1/4 Doug fir |
| | HGP | 0 | 0 | No new activity. Large amounts of spider webs and cobwebs |
| | GRANGE | 0 | 0 | No activity |
| | KRESGE | 0 | 0 | Earwig in 1 cavity and small amounts of spider webs in 4 holes |

Wood Preference

It seems that difference in wood type (pine and Douglas fir) did not play a significant role in determining the rate of establishment of solitary bees within the boxes, as both the blue orchard bees and leafcutter bees used pine and Douglas fir nearly equally. As of June 3$^{rd}$, the nest box at CASFS contained six caps in Douglas fir and five in Pine. At Trescony, five of the caps were in pine and three were in Douglas fir. Although there are studies that examine the influences of nest substrate on colonization, the majority of these studies look at the differences between the use of woodblocks, bundled reeds, and rolled cardboard tubes. There is a lack of research examining the difference in colonization rates based solely on different wood types.

Cavity size Preferences

The cavity dimensions are important in determining the species of native bee that will establish. On June 3rd, eleven leafcutter bee cell caps were present in the CASFS box and eight present in the Trescony box. For leafcutter bees, the smaller sized cavities were preferred. At CASFS, ten of the eleven occupied cavities were 1/4" in diameter. At Trescony, three of the caps were inside 1/4" cavities and five were inside 5/16" cavities. These results make sense when compared to other studies. In an experiment testing nest substrate for various solitary bees, MacIvor found that leafcutter bees were most common in cavities with diameters ranging from 0.20" to 0.31" (1/4"=0.25" & 5/16"=0.31") (2016).

Blue orchard bee mud caps were observed in a range of cavity sizes (1/4" & 3/8") at the Chadwick site, which matches up with other studies that have been conducted regarding the impact of cavity size on bee species. In a literature review looking at the how to create an optimal bee hotel, MacIvor states that the ideal cavity dimensions for *Osmia* species are 5-8 mm (0.2"- 0.31") (2018). An article written by Golick and Weissling discusses bee hotel construction and states that the ideal cavity size for blue orchard bees specifically is 0.38"-0.50" (2015). The *Osmia* observed at the Chadwick site had established in a 0.25" cavity and a 0.38". Which is very similar to the range observed for blue orchard bees in other experiments. This shows that leafcutter bees prefer slightly smaller cavities when compared to blue orchard bees, however, the difference is minimal.

Location Preference

Based on the results of the experiment, it is hard to tell if location had a significant influence on the rate of establishment in the nest boxes. Chadwick Garden and Kresge Garden are both agroforestry sites, however, only Chadwick Garden saw any bee activity. The likelihood of blue orchard bees establishing at the Chadwick site is higher than the other sites, as the managers of Chadwick garden have augmented the blue orchard bee populations at Chadwick Garden, to be used as pollinators. Trescony Garden, Homeless Garden Project and The Grange are all urban gardens, but Trescony was the only urban garden site that experienced any colonization. The reason for this is unknown, however, it could be due to variables not accounted for in this particular study.

**Conclusions**

Colonization of the nesting boxes by blue orchard bees at the Chadwick site is likely due to the large number of blue orchard bees that had been introduced to the garden prior to the beginning of this particular experiment. It is unclear why the nest boxes at CASFS and Trescony experienced colonizarion by leafcutter bees and the other sites didn’t. There are a number of reasons that may have influenced why only half of the nest boxes experienced any colonization. (1) Time plays a large role in the rate of establishment. At times, native bees may take over a year to colonize a newly installed nest box. (2) Weather can play a significant role in the rates of colonization. For nearly two months no bee activity was seen in the bee boxes. During this time, the weather was very stormy and, even with the sheet metal rooves, the boxes became very wet. It is also possible that the number of floral resources were higher at the Trescony and CASFS sites, compared to the other sites, which may have influenced the quantity of bees seen at the nesting boxes. This variable was not tested in this particular study. This study also did not examine how the size of the garden impacts establishment rates, another variable that may have influenced colonization.

Overall, the experiment was particularly successful in determining preferred cavity size of blue orchard bees and leafcutter bees. It was also useful in determining optimal installation methods and how to minimize pest activity. Whether farmers are looking to artificially introduce solitary bees, or wait for natural colonization, it is important to understand the nesting behavior and preferences of the bee species expected. The experiment conducted in Santa Cruz City could have been improved if it was not restricted to twenty weeks, as this time period is relatively short when looking at natural rates of colonization.

In order to continue this experiment, observations will continue to be taken place after the deadline for the project. Due to the fact that this experiment has a deadline in early June, the nest boxes will not be able to be opened and examined, as the nesting season for these solitary bee species is not over yet. In early winter, once the egg-laying season is complete, these boxes will be ready to be opened, in order to count the quantities of larva oviposited. Opening the boxes will also provide more information on the frequency of oviposition within the cavity, as well as cell wall construction.

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