Chapter 10
Urban Beekeeping as a Tool for STEAM Education

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Abstract Urban beekeeping is an innovative tool with which to test hypotheses and practice concepts relating to STEAM (science, technology, engineering, art, and math) education. STEAM education uses art and design as an approach to STEM disciplines in a creative and engaging way. Here, we provide an overview of what urban beekeeping is, and how students of all ages successfully use bees as a means of project-based learning. We provide an overview of the uses of bees, their nest within the greater hive structure, their pathogens and parasites and their phenotypic gambit, with a special focus on practical applications. We delve into case studies of multiple, actual classrooms to demonstrate practical uses for bees with STEAM learning in elementary through advanced education. Bees are a viable means with which to advance STEAM education for learners of all ages, backgrounds, origins, nationalities, colors, races, and interests.

Keywords Bees · Beekeeping · Urban · Agriculture · STEM · STEAM · Geometry · Curriculum · Architecture · Children

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10.1 Introduction

To find sustainable solutions to real-world problems, students must be able to think and model across different disciplines and in terms of complex systems. Science, technology, engineering, art, and mathematics (STEAM) education uses art and design as an approach to STEM (without art) disciplines in a creative and engaging way (http://stemtosteam.org/). By taking a STEAM approach, teachers can engage divergent thinkers and spur innovations necessary for a strong economy (House Resolution 319 2011; Maeda 2013). Nature can inform us about applied geometry and be a source of inspiration for innovative designs and new technologies.

Field-based observations of the natural world, the environment, and human activities are powerful motivators for encouraging scientific learning. Urban ecology is the study of the interactions of species and their urban environment. This takes into account how humans are altering the landscape. Urban areas can be viewed as a heterogenous mix of land uses. Thus, urban areas can be viewed as living laboratories to study how land-use change affects biodiversity. This multidisciplinary systems-approach addresses Next Generation Science Standards (NGSS) key concepts (LS2.A, LS4.D and ESS3.C) of how living and nonliving components of the ecosystem interact to determine biodiversity. Urbanization has been associated with biodiversity loss for many biota (Czech et al. 2000; Czech 2004). In the United States, 275 species are listed as endangered due to urbanization (Czech 2004). However, invertebrate abundance and diversity can be high in urban green spaces, from green rooftops to domestic urban gardens (Jaganmohan et al. 2013; reviewed in Jones and Leather 2012).

Honey bees are a good springboard for STEAM learning while addressing and practicing the NGSS across the different disciplines: Life Sciences, Physical Sciences, Earth Sciences, and Engineering, Technology and Applications of Science. Managed honey bees can be viewed either in an observational hive in the classroom or outside in a traditional Langstroth hive. Where this is not an option, wild bees can be observed beyond the walls of traditional classrooms. Viewing bees both in their hives and in nature can foster curiosity and promote the process of science by students designing and conducting experiments.

Urban beekeeping, along with urban agriculture, can help people living in cities feel more connected with nature. This connection allows for opportunities to learn about the interconnectedness of plants, pollinators, and people. Project-based learning with bees can encourage critical thinking skills, problem solving, decision making, inspire art and technology, and ultimately result in the pursuit of STEAM training, education, and careers.

For younger learners, bees can be used to teach: animals are living, have life cycles, interact with the environment, and have specific habitat needs. For older learners, bees can be used to teach about: classification by their physical characteristics, their stages of development including metamorphosis, how changes in their environment can lead to either their death or relocation, and how bees cause changes in their environment (via pollination). Honey bees are a good tool to address the

NGSS: Life Sciences (LS2: Ecosystems and LS4: Biodiversity and Humans) because they are uniquely adapted to collect pollen and nectar and in doing so, they are important pollinators to over 70 crops. Honey bees (*Apis mellifera*) contribute an estimated $14.6 billion per year to the American economy (Morse and Calderone 2000). As a model system for research, their contributions to our understanding of the natural world are invaluable. Yet, honey bees are dying. The stability of the world's food production remains in question. Of the world's most important monoculture crops, 68% require animal pollination, and honey bees contribute a major portion of this (Klein et al. 2007).

One way to foster curiosity and critical thinking skills is to view honey bees in their hives. An observation hive is a unique tool for researchers and students to engage in collecting data from live honey bees in their natural, crevice habitat. These enclosed indoor structures are made of wooden, rectangular frames with glass on two sides. Nearly everything that occurs inside the honey bee hive is visible through the glass, including intimate interactions between and among the bees. Hundreds to tens of thousands of live honey bees thrive year-round inside this wood and glass structure, living on natural beeswax foundation incorporating hexagonal architecture. These bees access the outside via a tube to collect nectar and pollen. The information gained from the use of observation hives in scientific research is invaluable. In a classroom or museum setting, observation hives can allow students to learn about tessellations, the life-history of honey bees, the behavior of bees (such as the waggle dance, a Nobel-prize winning discovery for Karl von Frisch in 1973), the chemistry of honey, photoreception, and presence of disease and parasites (such as *Varroa* mites). With project-based learning, the students are able to make observations, form hypotheses, design their own experiments, analyze their results, and present their data visually. Students can graph the productivity (pollen and honey), fitness and fecundity (brood, adults, queen cells), and health (disease/parasite abundance) of the observation hive over time.

In this chapter, we discuss four cases in which bees can be used as a platform for STEAM learning. Case 1 is the use of managed honey bees in an observation hive in the classroom. Case 2 is the use of managed honey bees in a traditional Langstroth hive. Case 3 is the study of wild bees in Citizen Science projects. Case 4 is the study of wild bees at either pollinator gardens, insect or bee hotels (Fig. 10.1). We will use examples from three Massachusetts Public Schools: Mission Hill Elementary, Fenway High School, and Hingham High School. In addition, we will use examples from higher education with students from Northeastern University and Massachusetts College of Art and Design. Here, we provide specific examples of how teachers and students have put the urban beekeeping case study to practice both inside and outside of the classroom. Rather than posit how one could hypothetically test hypotheses relating to STEAM education using bees, we detail how actual students have already begun this exploration (Fig. 10.1). These examples are only the initial steps toward establishing urban beekeeping as a model system for STEAM practice. As more citizen scientists engage with urban bees, more observations will come to light, leading to an inevitable marriage between STEAM learning and practice, and bees, for future generations to come.

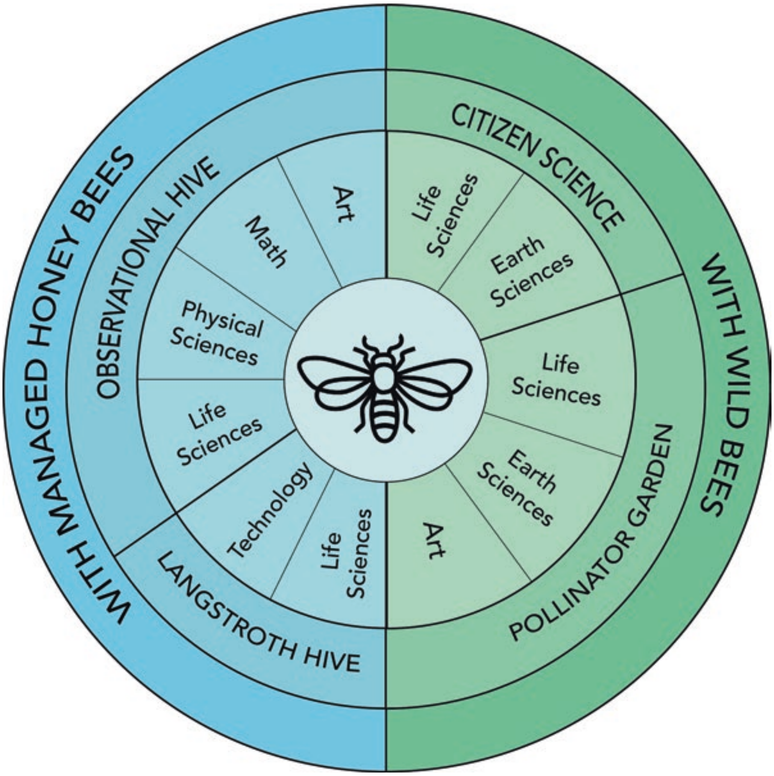

Fig. 10.1 Using honey bees to teach science, technology, engineering, art and math (STEAM). (Figure created by Jessica Lindsay)

10.1.1 CASE 1: Observation Hive in the Classroom

Honey bees in an observation hive do require maintenance. Classroom Hives is a nonprofit resource helping to guide teachers through the process of building, maintaining, and cleaning observation hives (http://www.classroomhives.org/). In addition, Classroom Hives has available teacher resources (http://www.classroomhives.org/?page_id=182).

10.1.1.1 Case Study: Mission Hill Elementary School

The Boston Public School system has multiple schools with classroom observation beehives. In 2001, the Mission Hill Elementary School installed an observation beehive used by teacher Ms. Jenerra Williams' third and fourth grade classes. Ms. Williams first has the students read the 4H Youth Project Book 1, *The Buzz About Bees: Honey Bee Biology and Behavior* (Fisher et al., 2014). Ms. Williams bases her

“Nature Science Curriculum” on the scientific method, starting with teacher-led observations of bees inside and outside of the beehive. Students engage with bees by observation through a glass, observation hive. Students then work together in groups to have discussions and ask questions about their bee observations. They come up with suppositions as a group – basic hypotheses to explain the mechanisms driving their bee observations. From here, Ms. Williams guides the young students’ ideas to design experiments for testing their hypotheses.

One example of project-based learning is an experiment investigating how the age of worker bees determines the tasks they perform. Honey bees change their behavior with age, a process called temporal polyethism. Students first make and record observations, noticing that not all workers perform the same tasks. They begin by asking questions, such as, “Does the age of the bee determine what tasks she performs?” See Table 10.1 for an overview of the tasks of worker bees at different ages. Students can observe the behavior and tasks of different bees and display this visually with a chore chart (Fig. 10.2). In Ms. Williams’ classroom, students design experiments to test the hypothesis that bee age determines behavior. Beyond her class, any classroom can work with a beekeeper’s help to mark newly emerged bees with non-toxic paint on their thorax. This allows students to follow that age cohort of bees over time. This method is also safe for students to do, if comfortable, because honey bees are soft and unable to sting during their first 24 h after emergence as an adult. Results from this experiment facilitates the understanding that these students have of bees, while utilizing the scientific method as a learning framework.

Ms. Williams highlights the actions of bees (via pollination) to our food security with her Pollination Lesson Plan (outlined below).

Table 10.1 Honey bee temporal polyethism: the median age (in days) that workers perform certain tasks (Data from Winston 1987)

Capping brood	5.55
Early cell cleaning	7.55
Tending brood	9.83
Queen tending	11.1
Patrolling	12.9
Receiving nectar	13.05
Cleaning debris from hive	13.3
Resting/heat shielding	14.15
Late cell cleaning	14.17
First orientation flight	14.17
Comb building	15.5
Handling pollen	16.3
Ventilating	16.85
Guard duty	18.5
First foraging trip	23.43

Fig. 10.2 A chore chart showing the different activities of casts of honey bees. This is an example of a chore chart done by elementary students at Mission Hill Elementary School. The picture is from Classroom Hives (http://media-cache-ec0.pinimg.com/236x/89/f8/f3/89f8f37ab95a3cd18c00d-d3ca5c1d395.jpg)

1. Explain to your class that most of the foods we eat (one out of every three bites) are the result of pollination.
2. Show and read the pages from 4H book, *The Buzz About Bees: Honey Bee Biology and Behavior*. Discuss with the class.
3. Tell your students that they are going to explore a world without bees and, in particular, what the food supply would resemble if bees no longer existed.
4. Direct your students to the "Bee-Free Barbeque" area. Explain that they are going to attend a barbecue in the Bee-Free Zone and that hamburgers and hot dogs are on the menu. Have the students take a few minutes to look at the things they can have with their burger or hot dog.
5. Tell your students to take a plate and choose a hamburger or hot dog from the grill. Explain that they can now choose what they will have with their hamburger or hot dog. Remind them that this is the bee-free barbecue and that the foods on the "Plants Pollinated by Bees" list won't be available. These include tomatoes, onions, cucumbers, lettuce, oil for frying potatoes, oranges, lemons, limes, mustard seed, cacao bean used in making chocolate, vanilla, almonds, watermelon, and apples.
6. Have your students select the items they want with their burger or hot dog. Then have them check the "Plants Pollinated by Bees" list to see what they have to put back.
7. After they've eliminated the bee-pollinated items from their plates, have them describe the meal that would remain.

Students are often amazed to realize that 1 out of every 3 bites of food that we eat is either directly or indirectly dependent on bee pollination. This includes fruit, many nuts (such as almonds), vegetables, oil-seed crops, herbs and spices. In addition, cows graze on clover and alfalfa that are dependent on pollination by bees, so the Bee-Free Barbecue game could potentially also remove hamburger meat, as a final, dramatic impression to leave on students.

Plants Pollinated by Bees (For Use with Pollination Game)
Tomatoes
Onions
Cucumbers
Lettuce
Oil for frying potatoes
Oranges
Lemons
Limes
Mustard seed
Cacao bean (used in making chocolate)
Vanilla
Almonds
Watermelon
Apples

Beyond fruits and vegetables, bees make honey, which is a supersaturated solution. There is too much sugar dissolved in the water than is possible by the laws of physics (over 70% sugar and less than 20% water content). To make honey, a forager bee first sucks up nectar from a flower using its proboscis, a tongue-like set of mouthparts that acts like a straw. Bees store this nectar in a sac organ called a crop, located between the mouth and the stomach. Bees then regurgitate and swallow this nectar, over and over, adding enzymes to break down the sucrose into simple sugars in a process called inversion (Wilson-Rich 2014). Once back in the hive, bees regurgitate a droplet that is taken up by a house bee who also regurgitates and swallows this repeatedly. Then the "honey" is dried by fanning behavior to evaporate the water. Over time, the sugar forms a lattice, crystalline structure, and separates from water. Young students can use this system as a model for designing and creating their own water purification system, such as the following lesson, also from Ms. Williams classroom (see Fig. 10.3).

Materials: You'll need sugar, water, food coloring, a bowl, and a sunny spot.

- Put 20 teaspoons of water into a bowl.
- Stir in 4 tsp sugar.
- Add a drop or two or three of food coloring. Stir.
- Leave the bowl in a sunny spot for a few days.

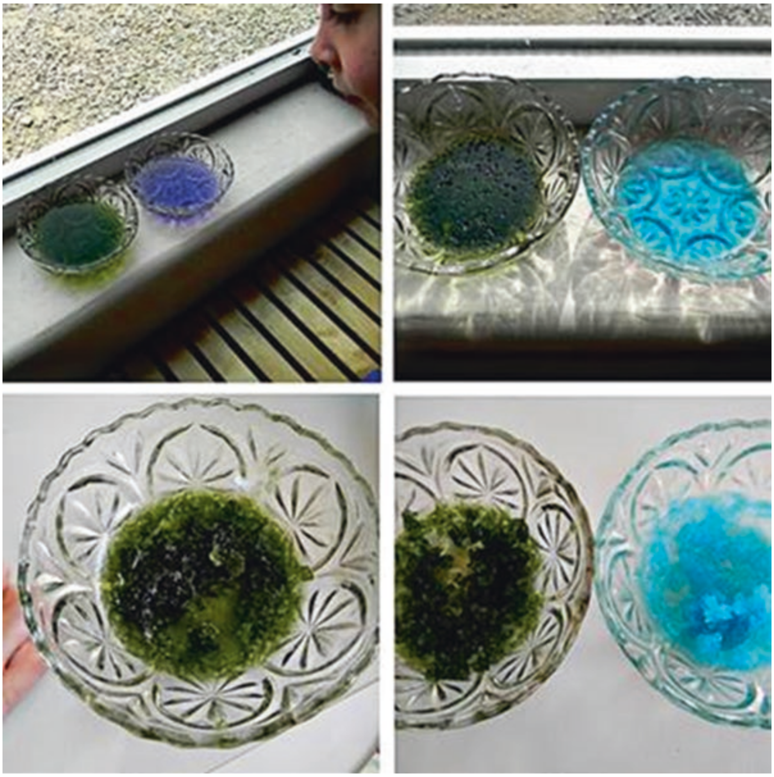

Fig. 10.3 Students at Mission Hill Elementary School practicing crystallization

- As a control, also leave a bowl of water without sugar in it to compare.
- Check the bowl every day and observe what happens. What happens to the water? What happens to the sugar? Stir the bowl and make observations.
- Optional ... taste test the sugar crystals after the water has evaporated.

Students are often amazed that bees are able to make honey by adding enzymes to nectar in combination with fanning behavior to evaporate the water. They are also surprised to find out that to make a pound of honey, it takes about 556 forager bees visiting two million flowers (National Honey Board 2020)! Therefore, making honey really is a collaborative process.

A good marriage of art, music and STEM education, is through Kinesthetic Activities and games (http://www.classroomhives.org/?page_id=182). One game is the " Flight of the Bumblebee Clean-up/Hive Game". It begins by listening to the video (http://www.youtube.com/watch?v=6QV1RGMLUKE&noredirect=1) and then feeling what it's like to be a bee. Ms. Williams asks the students, "How does this song make you feel?" Example answers include: calm, energetic, crazy, sleepy, thoughtful, like dancing, like running. "Does it want to make you slow down or speed up? What about the music makes you feel that way (tempo, instruments used, similar sharp notes, etc.)?" After listening to and discussing the song as suggested, Ms. Williams then uses it as background music to quickly clean up after a craft, transition to a new activity, or play musical chairs. For Middle School students, while listening to the song they can act out the honey bee round and waggle dances.

The following testimonial provides deep insight into the experiences of Ms. Williams with her classroom beehive. Notice how she takes time to observe the bees personally, and builds an internal sense of inspiration, wonder, and awe that she then transfers and translates to her students. Consider how Ms. Williams leverages bees as a teaching tool to engage her students with an authentic level of excitement that may be able to transcend traditional textbooks and lectures alone. According to Ms. Williams, 3rd and 4th grade teacher at the Mission Hill Elementary School:

> The morning is quiet. It's a warm, sunny, spring day and I am the first on my floor to arrive at school. I put my things down and go to check the hive. As the warm spring weather comes I have to be more diligent about checking in on 1000+ plus 'assistant teachers.' (I'll explain that in a moment.) They honeybees are busy – cleaning cells, leaving to look for pollen and nectar, returning from foraging flights, feeding the brood, looking after the queen. Yes! The Queen in all her magnificence is doing the single most important job she has – laying eggs. I stand and watch in total awe and amazement. As I watch my mind races with questions: 'How old is the queen again? How many eggs did she lay this week? How many drones are in the hive now? How much honey has been made so far? I wonder which student will be the most fascinated by them today?' I look up at the clock and a whole half an hour has passed! I quickly do a water check to make sure the bees are hydrated, and then get back to the work of getting ready for the school day. I had only intended to look at the bees for five minutes or so, but this is the power they hold.
>
> The same goes for students. The honeybees captivate them. In the 13+ years I have had the hive in my classroom I have seen the amazing way that the bees become more than insects in our classroom. The bees become 'teachers' in ways I didn't expect when I first had it installed. They become the teacher who sparks a student's scientific curiosity. They become the teacher who provides challenging math problems. They become the "teacher" who draws out the inner artist in children. They become the teacher who inspires literary greatness, as students write stories, poems, newsletters and songs about them. They become the teacher that illuminates history as the importance of honeybees throughout history is revealed. They become the teacher that calms and soothes students, when anger, frustration, confusion, sadness and fatigue are trying to get the best of them. Having the hive is like having an assistant teacher – another place where students can go to learn, be inquisitive, be inspired, rise to a challenge and feel connected to our classroom community.
>
> One example of this was student M, who was new to our school. He came as a third grader and had some different needs. His hands were physically altered – he only had fingers up to his knuckles. His eyes were not fully straight and he had a hard time seeing. His speech was hindered in a few ways, which made speaking and understanding him difficult. He was smaller in stature than all the other students in the classroom. Another special thing about M. was that he was always smiling – always happy. M. loved the honey bees and took every moment he could to look at them. When he went over to the bees he had a permanent smile. He pointed, he talked to himself, asked questions of us and shared with other children his discoveries. The honeybees were his way 'into' our community. The other students were excited about the things he found. He could always find the queen. This was like his super-

hero power! Other students would go get him and ask him to find her for them. Writing was difficult for him and he avoided it as much as he could, but when it came to the bees he rose to the challenge! He enjoyed drawing pictures of the bees, and never complained when we had him add sentences about what he saw. The bees were the focus of our natural science theme that year and by the end of that three-month period, M. was an expert – sharing all he knew and working with a group of two other boys who created a 3D model of the life cycle of a bee. They used clay and other materials that were difficult for M. to work with, but he dove right in and made important contributions to the project. Most importantly, in the end he was proud of what he had accomplished and his team members saw him as a valued member of the team and our community. The honeybees transformed M. He came in shy, unsure and in the eyes of the other students, 'different.' Through his love of the honeybees he became outspoken, confident, and fully included into our community in ways that would have taken me much longer and may not have been as holistically successful had I relied solely on my 'teacher strategies.'

M.'s needs were unique, but his experience with the honeybees is not. Every year students, and adults alike, make similar connections with the bees. It is a classroom 'project' that has turned into a school-wide treasure.

10.1.1.2 Case Study: Fenway High School

Honey bees in an observation hive can be an effective tool to integrate art and science and give students a creative and engaging way to test their knowledge. Fenway High School has had an observation hive (Fig. 10.4) since 2009 and it is used by Ms. Benadette Manning's mathematics classes. She used a digital microscope projected onto a screen in the classroom in order to visualize the inside of the hive. Students are able to have whole class conversations around their observations and questions using the beehive as a model system, in real time.

Fig. 10.4 The observation hive in the Fenway High School

Patterns in both art and nature can be used to teach students about geometry. The famous graphic artist M.C. Escher's artwork has strong mathematical components including tessellations, using geometric shapes that tile together without any gaps or overlaps. From nature, we can use honeycomb as a tool to get students thinking about different geometric shapes and tessellations. In Ms. Manning's math classes, students practiced calculating volumes, areas, and perimeters of different geometric shapes to determine why bees use hexagons. Students also learned about volume and surface area, using the hexagonal honeycomb shape as a case study. She asks her students, "Why do honey bees use these iso-lateral, 6-sided figures as a tessellated pattern?" Ms. Manning goes through computations of surface area to volume ratios for triangles, squares, rectangles, pentagons, and hexagons. Using these tools of geometry, students come to realize that hexagons have the greatest storage area (volume) to surface area ratio, allowing bees the greatest efficiency between the material resources needed to build comb and the storage reward.

The following insight brings us into the world of what one teenage student in 10th grade experiences and feels when using Ms. Manning's classroom beehive as a learning tool:

> I really enjoyed geometry overall, but a concept I enjoyed out of every topic was learning about bees. I enjoyed learning about bees because I learned why they were important to geometry and my everyday life. For example, I learned that bees connect with geometry because of the shape of their hives. They chose a hexagon because it had way more space than any other figure. Since honey is important to the life of bees they want a maximum amount of honey to store in their hives.

In addition, students can learn about the geometric angles in a worker's bee Waggle Dance (Fig. 10.5). A good video about information on the honey bee waggle dance and experiments to study the waggle dance is, "The Waggle Dance of the Honeybee" by Georgia Tech College of Computing (https://www.youtube.com/watch?v=bFDGPgXtK-U).

Honey bees can be used as a model system to teach NGSS Physical Sciences because they are able to detect odors, tastes, and visual cues (including ultraviolet light). These characteristics enable students to study the detection and responses to different cues. Menzel and Blakers (1975) demonstrated that honey bees have trichromatic vision: UV (350 nm), blue (440 nm), and green (540 nm) photoreceptors. This can be compared to human vision; blue, green and red cones. Humans can see the color red, but bees cannot. Students can design experiments with different colored lights (red, white, and near-UV) and test their hypotheses relating to recognition systems.

Karl von Frisch (1950) first demonstrated that honey bees had associative learning between a sugar-water reward and color cue. Students can design and build artificial flowers of different colors with or without rewards (sugar water and/or pollen) and place them outside to train bees to feed from then. The students can then design an experiment where they either change the orientation (placement) or reward of the flowers to determine if the bees change their foraging behavior (as done with bumble bees by Konzamann and Lanau 2014). At the University of

Fig. 10.5 The geometry of the honey bee waggle dance (by Paige Mulhern)

Arizona, in Dr. Carla Essenberg's laboratory, they designed and built robotic flowers ("FloBots") to test bee foraging behavior (Essenberg 2015).

Patterns can be found in both art and nature. The Fibonacci sequence was written about by Leonardo Fibonacci in his book Liber Abaci (1202). He wrote about this sequence and its relationship to phi (1.618034), also known as the golden ratio (for the English translation, see Sigler 2012). However, Indian philosophers are credited as first noticing a repeating, numerical pattern, within the context of intonation patterns in Sanskrit oral conversation. Start with 0 and 1. Then, add these together to get the next number. 1 + 1 = 2, 2 + 1 = 3, 3 + 2 = 5, 5 + 3 = 8, and so on. This basic pattern forms the infinite sequence of 0, 1, 1, 2, 3, 5, 8, 13, 21, 34, 55, 89….

This pattern is seen in many works of art (Fig. 10.6) including the Mona Lisa (video: https://www.youtube.com/watch?v=jxKYFBtdsqU) and the Vetruvian Man by Leonardo Da Vinci (Belmonte and Pappas n.d.). Art can be created by using tiles made up of squares whose side lengths are successive Fibonacci numbers. The Fibonacci Golden rectangle is found in architecture such as the Greek Parthenon's facade. Fibonacci identified this sequence in many examples in the natural world, especially with regard to spirals found in plants and shells. Plants provide the most obvious examples, including whorled leaf arrangements in trees, seed location in sunflowers, blossom orientation in pineapples, and leaf placement in artichokes. One of the few non-plant examples of the Fibonacci sequence in nature is in the bee. Honey bee DNA structure reflects this patterning in their length and width dimensions and ratio. Genetic relatedness in bees is notable for haplodiploidy, whereby males (drones) are haploid (1 set of chromosomes) and females are diploid (2 sets).

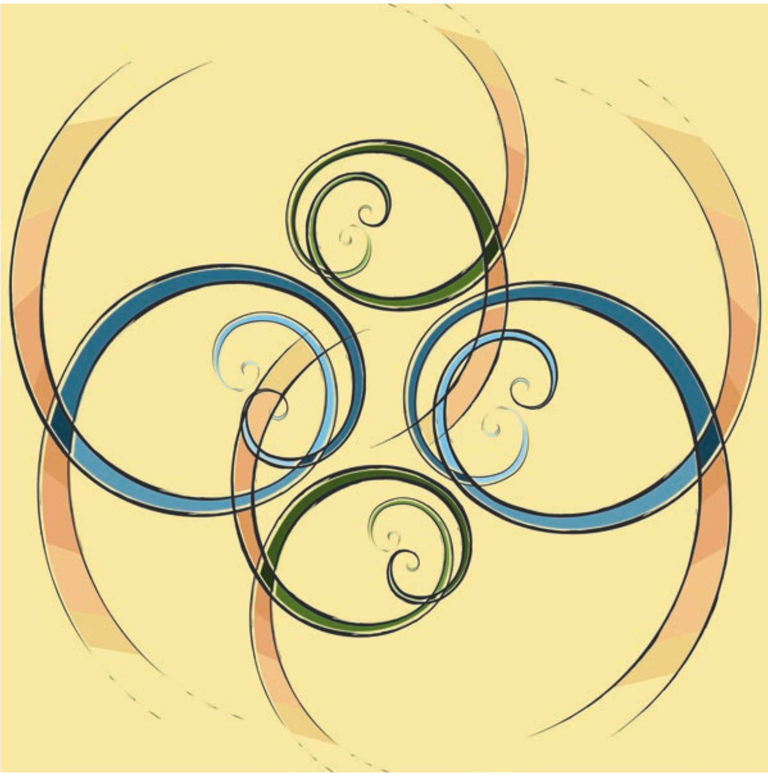

Fig. 10.6 Fibonacci art piece, by Jessica Lindsay

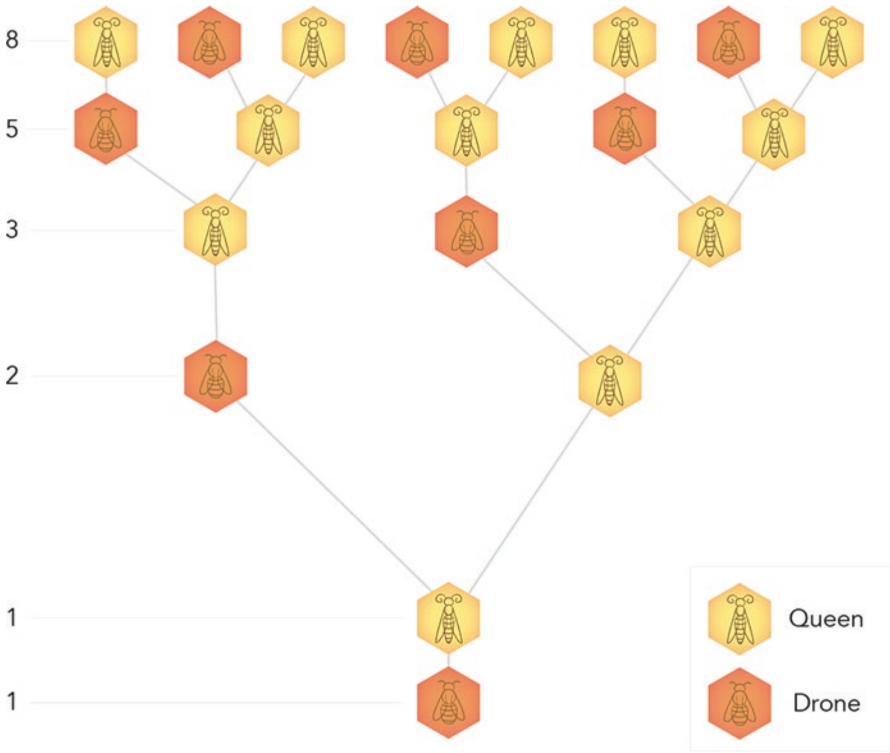

Fig. 10.7 The relationship between honey bee genetics and Fibonacci numbers. Drones (males) are haploid and Queens (female) are diploid. (Figure created by Jessica Lindsay)

Drones arise from unfertilized eggs, and so they have no fathers (however, they do have grandfathers). The family history of drones reflects the Fibonacci sequence: 1 parent, 2 grandparents, 3 great grandparents, 5 great great grandparents… (Fig. 10.7).

In addition to geometry, honey bees can be used as a platform for studying evolution. Flowers and their animal pollinators have co-evolved together. There are an estimated 200,000 species of animal pollinators, with most of them being insects. Pollination involves the transfer of pollen produced by the anther (the male part of the flower) to the stigma (the female part of the flower). Flowers that are insect pollinated attract pollinators with visual cues (including UV), chemical cues, and nectar reward. Bees are well adapted for pollination with adaptations such as eyes that can see UV light, antennae that enable a keen sense of smell, hairy bodies to pick up pollen, and modified mouthparts to suck up nectar. Both bees and flowers benefit from this interaction. Therefore, this relationship between bees and plants is a form of mutualism. Students can observe and draw the adaptations of different types of flowers and insect pollinators that enable their interactions.

Fig. 10.8 Honey bees with the mite *Varroa destructor*. (**A**) A size comparison of a honey bee with a *Varroa* mite. (**B**) A *Varroa* mite attached to a honey bee. (Photo credit: Andrew Bradley)

One of the biggest present threats to honey bee health is the parasitic mite *Varroa destructor*. *Varroa* is an obligate parasite and they have two life stages: reproductive and phoretic stages. During the *Varroa* phoretic stage, they puncture the honey bees' body to suck their hemolymph (Fig. 10.8A, B). During the *Varroa* mite reproductive phase, they mate on pupae. For a good summary of the *Varroa* life cycle and its impact on honey bees, teachers can show this brief animation (https://www.youtube.com/watch?v=h-wDgd5yURo). Before jumping species to the western honey bee, *Varroa* was a long time parasite of the Asian honeybee, *Apis cerana*. Because of such a long history, both species have coevolved together in an evolutionary arms race (Rosenkranz et al. 2009).

The Asian honeybee, *A. cerana* has evolved defenses against *Varroa* by its grooming ability to detect and eliminate the mite on their fellow workers (Oldroyd 1999). Grooming behavior refers to honeybees removing and disposing of mites on themselves and other workers. Hygienic behavior is the uncapping and removal of dead, diseased, or parasitized brood (Rosenkranz et al. 2009). It is important to note that while these mite defensive behaviors have been noticed in some European honey bee (now predominant in the New World, as well; *A. mellifera*) colonies, they occur at a limited extent when compared to the sister species *A. cerana* (Boecking and Spivak 1999). Restricting the mites to drones and drone brood cause the mites to be highly limited in their ability to disrupt the colony, and thus *Varroa* and *A. cerana* could coexist. However, as a result of human globalization, *Varroa* was introduced to *A. mellifera* colonies.

When *Varroa* jumped host species to the western honeybee, the western honeybee did not have the same defenses as the Asian honey bee, and the results were catastrophic (Oldroyd 1999). The effect of the mite's species jump coupled with the lack of any parasitic influence on the genetic lineage of *A. mellifera* has left the species mostly defenseless against the *Varroa* parasite infection. The mite becomes extremely detrimental to the health of the hive because it is a vector for multiple viruses including Kashmir bee virus, Sacbrood virus, Acute bee paralysis virus, Israeli acute paralysis virus, and deformed wing virus (Oldroyd 1999; Rosenkranz et al. 2009). If left untreated, *Varroa* infections often contribute to the death or absconding of an entire colony (Oldroyd 1999). For a good summary of the *Varroa* life cycle and its impact on honey bees, teachers can show this brief animation (https://www.youtube.com/watch?v=h-wDgd5yURo).

The relationship between *A. cerana, A. mellifera*, and *Varroa,* provides teachers with a very real and relevant example of many globally important ecological concepts, including vector biology, co-evolution, and epidemiology. Additionally, this study system can be scaled up to engage students in conversation and thoughts relating to globalization in our modern world, and the all-around effects of human behavior on the environment. *Varroa* was originally introduced to *A. mellifera* due to human movement and transportation of bees. This species jump from *A. cerana* to *A. mellifera* is one of the many potential consequences of introducing non-native species to new ecosystems. Students are exposed to the many consequences of globalization as the world continues to become increasingly interconnected.

Since *Varroa* is such an extreme detriment to honeybee health, effective treatments for *Varroa* has become a keynote area of study for scientists and beekeepers alike. Because of the colony destruction and overall economic impact of depleting honeybee colonies, many commercial and hobbyist beekeepers alike have turned to the use of miticides like Apistan and Checkmite+ to control mite populations in colonies. Given the short life cycle and inbreeding of *Varroa*, resistance to these miticides occurs rapidly (Hubert et al. 2013). In what is referred to as a bottleneck effect, small populations of mutated mites spawn a larger population of resistant family members. With reproductive success of *Varroa* on *A. mellifera* so high, killing off non-resistant populations favors the establishment of a resistant population.

Varroa resistance to miticides presents teachers with another real world example of an evolutionary concept: the bottleneck effect. The bottleneck effect is an important concept in population ecology because it can help students understand macro-evolutionary concepts, including speciation and extinction, can occur in relatively short periods of time. The short life-span and reproductive success of *Varroa* makes their bottlenecking due to miticides particularly interesting for students. The relationship between *Varroa* and miticides can be extrapolated to human health by examining bacteria and their developing resistance to antibiotics. These types of concerns will continue to arise if humans continue to rely primarily on extermination methods like pesticides, miticides, and antibiotics to kill unwanted populations of pests, mites, and diseases.

Of course, with such a widespread issue, many different non-chemical maintenance methods have been tested and suggested. For example, some beekeepers have tried wire-screened, bottom boards to eliminate mites that have fallen from the colonies. Others have tried pouring powdered sugar dusting to induce cleansing behavior of worker bees. In an effort to find a sustainable solution to the *Varroa* mite problem in honey bees, students in Dr. Marla Spivak's bee laboratory at the University of Minnesota (http://www.beelab.umn.edu/) selectively bred honey bees that have exhibited hygienic behavior, which includes grooming off *Varroa* mites. Bees with hygienic behavior maintain lower mite populations in their colonies (Spivak and Reuter 2001; also see https://www.youtube.com/watch?v=W_0FPF1Smwk).

Some scientists have gone even farther and begun the process of isolating genes responsible for hygienic behavior on both *A. cerana* and *A. mellifera.* For example, in an attempt to compare and contrast the two species' activity in response to a

Varroa infection, one group studied differential gene expression of *A. cerana* and *A. mellifera* in the presence of the mite (Zhang et al. 2010). Another group did a similar study on two genetic stocks of *A. mellifera*, which differ in susceptibility to *Varroa* infection. Both studies showed significant differences in gene patterns of expression, signifying a genetic predisposition for hygienic behavior.

Blending science with other fields of study and inquiry are common at many schools that integrate subjects for middle-aged children. Ms. Jacqueline Beaupré brought her experiences in beekeeping into the classroom, where she consistently turns her students' attention to the bees for a living application of teaching concepts relating to STEAM. Notice how Ms. Beaupré's sense of wonder seems to translate to her students, by building excitement for learning in an authentic and inspiring way. Her passion for the bees and these topics help tie concepts together in a way that goes beyond traditional teaching methods alone. According to Ms. Beaupre:

> Bees are fascinating to watch! I think every curious kid goes through a 'bug phase' and they all slip back into it when looking at our (classroom) observation hive. There is no 'free time' in (our) high school classes, but I notice students taking a moment to observe the bees when transitioning between activities or before the bell rings. They usually come away with a question about the myriad of hive activities they see- workers dancing to communicate, cleaning, building wax, making honey, and feeding brood, as well as the queen laying eggs. Very often, they notice important hive activities before I do!
>
> Honeybees are the perfect animals for my Integrated Science classroom as I can connect them to many aspects of physics, chemistry, and biology in our curriculum. Bees take nearly direct routes to foraging sites (distance vs. displacement, Traveling Salesman Problem) and can easily attract pollen to their hairy bodies (electrostatic force, charges). They eat pollen and nectar, giving them the nutrients they need to excrete royal jelly for feeding their young and beeswax for building their home (biomolecules- protein, carbohydrates, lipids). They carefully thermoregulate their hive, surviving winter by eating honey and vibrating muscles to keep their colony warm (transformation of energy, heat transfer). They can see ultraviolet light in addition to colors (waves, electromagnetic spectrum). They have mutually beneficial partnerships with the flowers they pollinate, as well as tenuous ones with many gut microbes, viruses, and hive pests (botany, evolution, ecological relationships).
>
> As my own knowledge about science and bees increases, I continue to find connections to share with students. And although I could include these anecdotal examples in my lessons without a classroom hive, its physical presence produces a much more meaningful experience. When students can actually taste honey from our hive, it makes a lesson about biopolymers and disaccharides far more memorable. In this way, I feel our students' learning is truly enhanced by our classroom observation hive.

10.1.2 CASE 2: Langstroth Hive

In 1852, L.L. Langstroth patented his design for the stacked-box beehives with removable, hanging frames that are commonly used today. With traditional Langstroth hives, disease monitoring is crucial to colony health. The removable parts allow for full inspection and visualization of every part of the inner beehive. This innovation outpaced that of the prior beehive designs without removable parts, typically of the basket hive design, called, 'skeps.' Few other designs for beehives have since been created, including 'top bar' beehives. The ease of beekeeper inspections with Langstroth beehives makes these the leading style for outdoor beekeeping throughout developed countries.

Myriad pests and pathogens are prevalent throughout honeybee hives worldwide, and beekeepers are on the lookout for each during routine inspections of Langstroth beehives. One modern plague of honey bees is the fungal infection, *Nosema ceranae*, which is associated with decreased honey production, precocious foraging (younger bees begin foraging at a younger age than normal), decreased lifespan, and colony death (Botías et al. 2013; Goblirsch et al. 2013; Higes et al. 2009). *N. ceranae* is considered to be one of the most prevalent honey bee pathogens (Traver and Fell 2011). *Varroa destructor* are mites that feed on the hemolymph of bees and are vectors of several viruses, like deformed wing virus (DWV). If mites feed on developing bee pupae, the developed adult's immune system can be suppressed (Yang and Cox-Foster 2007). Dainat et al. (2012) found in the winter, *Varroa destructor* and DWV were predictive markers for honey bee colony death. It is important to estimate mite concentrations for each colony, due to their destructive nature on the health of the colony.

Modern solutions for updating Langstroth's designs are on the horizon. These provide students and researchers with ample opportunities for engaging STEM education and learning, with special emphasis on technology and engineering. Smart hives connect the Internet of Things to beehives, by installing a computer data collection system inside the hive. Data are collected in real-time, transmitted through the cloud, and reported back to classrooms through an online portal. Sensors throughout the beehive monitor and collect data relating to temperature, humidity, weight, sound, and other metrics, including live video streaming. The Best Bees Company deployed the world's first SmartHive at the Museum of Science, Boston, working closely with their education and curatorial staff to integrate STEM learning opportunities alongside their live beehive exhibit. Using this technological and engineering data collection tool, students can now test hypotheses relating to beehive thermoregulation, behavioral ecology, environmental biology, and more.

A similar advancement in technology and engineering powering modern beekeeping is happening in the United Kingdom. Arnia hive monitoring systems allow beekeepers and students to track the progress of their hives using cloud-based streaming data. The Arnia monitors can detect external weather conditions, in-hive temperature and humidity, hive weight, and even interpret the sounds of the bees to assess colony behavior and health (Figs. 10.9, 10.10, and 10.11). Arnia Remote Hive Monitoring (http://www.arnia.co.uk/) has partnered with schools and businesses in a Citizen Science program called Build the Buzz, a bee listening project. The data from these monitors can be viewed from any internet-enabled device. These data allow participants the ability to view and compare colony development and activity from different colonies that are affected by pests (e.g., wax moths),

Fig. 10.9 This shows the user interface from the monitored hives with current sensor readings and weather conditions (from Arnia Hive Monitoring Systems)

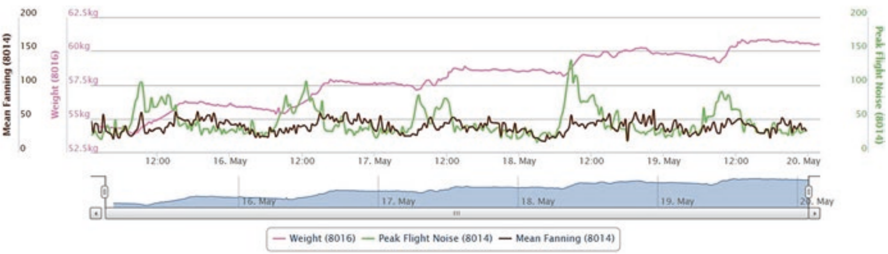

Fig. 10.10 This graph from the Arnia Hive Sensors shows the nectar flow and processing in a hive. The weight (pink line) increases during the day as nectar is collected by foraging bees (green line shows corresponding daytime peaks in flying activity). Weight decreases slightly at night as the nectar is processed by bees fanning (brown line shows increase in nighttime fanning)

parasites (e.g, *Varroa* mites) and pathogens (e.g., bacterial and fungal infections such as foulbrood and *Nosema*, respectively).

10.1.2.1 Case Study: Northeastern University Co-op Students at The Best Bees Company

To quantify *Nosema* levels, spores can be visually calculated using the technique from Reuter et al. (University of Minnesota Instructional poster #167, https://www.beelab.umn.edu/sites/beelab.umn.edu/files/cfans_asset_317468.pdf). However, this

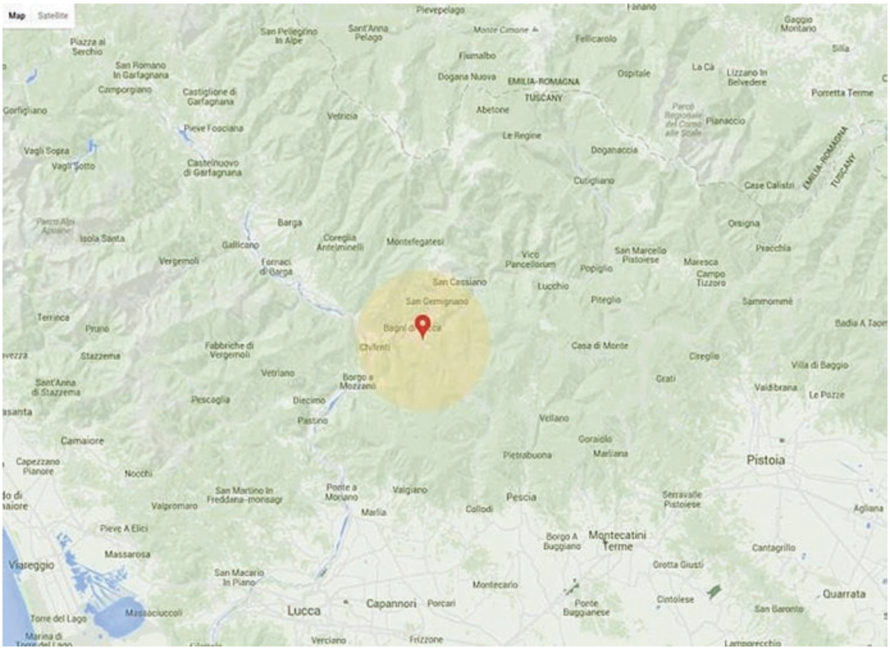

Fig. 10.11 With the Arnia In-hive monitors, you can locate your hive and its forage map area

technique cannot distinguish between the two different species of *Nosema* (*N. apis and N. ceranae*). Northeastern University Co-op student interns at The Best Bees Company have collected and analyzed data on *Nosema* spore counts and *Varroa* mite counts since 2013. These college students found a statistical difference between alive and dead beehives in the presence of *Nosema* and *Varroa* (Chi-square, df = 3, Chi-Square = 66.03, $p < 0.0001$; Fig. 10.12). Dead hives had a higher prevalence of having both *Nosema* and *Varroa* compared to alive and healthy hives.

In a marriage of science and art, one of Northeastern University's Digital Art and Interactive Media students, Jessica Lindsay is working with The Best Bees Company as the Webmaster and Graphic Design Assistant (she created Figs. 10.1, 10.6, and 10.7). In addition, at The Best Bees Company, Jessica has painted many custom beehives, designed various marketing materials, translated research data into infographics, and created webpages for the company. She is currently collaborating with another artist at The Best Bees Company, Paige Mulhern, a former MassART student (who made Figs. 10.5 and 10.12), hand-paints illustrations of flowers that accompany data reports for the honeyDNA program (https://bestbees.com/product/honeydna/, https://www.ted.com/talks/noah_wilson_rich_how_you_can_help_save_the_bees_one_hive_at_a_time, and https://www.nationalgeographic.com/magazine/2018/02/a-dollop-of-sweet-science/). HoneyDNA is a publicly available genomics service that sequences the DNA of all pollen spores in honey samples. Paige translates the data reports into art, allowing for improved scientific

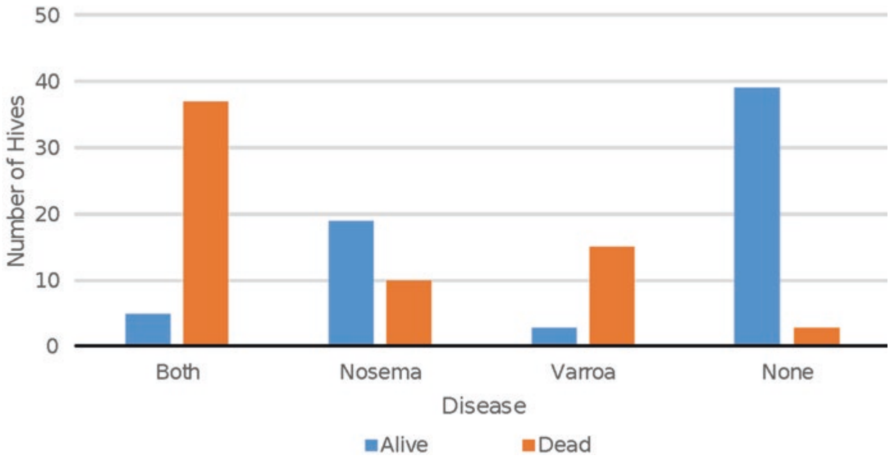

Fig. 10.12 Mean number of alive (blue) or dead (orange) colonies that had both *Nosema spp*. and *Varroa*, just *Nosema*, just *Varroa*, or neither. Hives were located in the greater Boston area

communications with the general public through infographics. Students and learners of all ages can use these data responsively, by selectively planting seeds that the honeyDNA genomics technology results show are exactly what bees forage upon.

The following is a description of the honeyDNA genomics technology program.

> Knowing exactly what type of honey your bees produce adds value, both on the markets and in the experience. You can identify the floral source of your honey with our new, state of the art product, honeyDNA. We send you a bar-coded test tube for privacy, along with a stamped return envelope to our laboratory. You fill the test tube with 10 mL – 20 mL of honey. Our research team analyzes the DNA of all the pollen found in your honey. We then compare the pollen genomes to our comprehensive database of known plant families. Within six to eight weeks, we will deliver to you the results in the form of a custom infographic, with hand-painted illustrations of the flower families found in your sample of honey.

We can look to nature for sustainable solutions for human problems in a field of study called biomimicry or biomimetics (Pawlyn 2011). Honey bees can inspire new technology while teaching students about cognitive function and neurobiology. In a joint project with Harvard University and Northeastern University, students are working on developing an Autonomous Flying Microrobots that mimics bees, "Robobees" (http://wyss.harvard.edu/viewpage/457). Robobees have three components, each scaling levels of biological organization: brain, body, and colony. The brain component has "smart" sensors that mimic the bee antennae and eyes that are connected to control electronics so they can sense and respond to stimuli in their environment. The colony component is working on coordinating multiple independent Robobees so they can work together.

Geographic Information System (GIS) technology is a useful tool to study honey bees and their habitat (reviewed in Rogers and Staub 2013). Naug (2009) used GIS to study honey bee losses for each state in the United States. States with the lowest

Fig. 10.13 Honey production in urban, suburban, and rural areas in Massachusetts from 2010–2013. (created by Paige Mulhern)

amount of open space (not developed) had the lowest levels of honey production. Giannini et al. (2012) used GIS to study the impacts of predicted climate change on 10 Brazilian native bee species. Urban areas in the United Kingdom were shown to have a higher species richness of flower visiting insects compared to farmland (Baldock et al. 2015). Senapathi et al. (2015) also found a high species richness in bees and wasps in urban areas compared to farmland in England. But Rathcke and Jules (1994) found that flowering plants in fragmented habitats have reduced visits by insect pollinators.

A surprisingly large number of bee species (200) have been found in New York City (Great Pollinator Project), including six phylogenetic families of bees including 30 exotic bee species. This may reflect the fact that most urban areas also support a higher plant species richness (Grimm et al. 2008). In Boston and Cambridge, Massachusetts, USA there has been high recorded survival and productivity of urban managed honey bee hives (from 2010–2013; Fig. 10.12). These urban hives had a higher overwinter survival and produced more honey compared to rural hives (Wilson-Rich 2014; Fig. 10.13). Some possible hypotheses for the increased fitness and productivity of urban bees are urban heat-island effect, less pesticide use in the city, a varied diet of flowers, and less energy exposure for foraging (Wilson-Rich 2014).

10.1.3 CASE 3: Citizen Science Projects (with Wild Bees)

If neither observation nor Langstroth beehives are available, then there are still more learning opportunities that exist with urban bees. A helpful website is PollinatorLIVE: a distance learning adventure (http://pollinatorlive.pwnet.org/index.php), which includes teacher resources, webcasts (in English and Spanish), and links to several citizen science projects. This website includes lesson plans and how they correlate with national science standards. Multiple Citizen Science Projects focus on pollinators, such as the Great Sunflower Project (https://www.greatsunflower.org/) and the Bees' Needs (http://beesneeds.colorado.edu). The Great Sunflower Project has a Google Earth map that shows the average pollinator visits (from 2008–2012) for Lemon Queen Sunflowers (https://www.greatsunflower.org/Map) across the United States. The results indicate that urban areas tend to have the least pollinator service. The Goldenrod Challenge (http://www.discoverlife.org/goldenrod/) is using photography and a systems-approach to learn about the species interactions at goldenrods. Two Citizen Science projects focus on the impacts of climate change on phenology: (1) Project BudBurst (http://budburst.org/) and, (2) the USA-National Phenology Network (NPN; https://www.usanpn.org/). In conjunction with Project BudBurst, students can learn about the coevolution of plants and pollinators. The USA-NPN has an on-line Nature's Notebook to track seasonal changes in the timing of insect emergence, flowering, and bird migration in relation to climate. This data has been used by scientists at Yale University to determine that the timing of budburst has changed over time (1982–2012) in the Eastern region of the U.S. and that this is a direct response to warming trends (Yue et al. 2015).

10.1.4 CASE 4: Pollinator Gardens and Insect/Bee Hotels

Build it and they shall come. The U.S. Fish and Wildlife Program has a Schoolyard Habitat Program (https://www.fws.gov/CNO/conservation/Schoolyard.html) with helpful links and a useful document on how to design, build, and implement a schoolyard habitat (https://www.fws.gov/cno/pdf/HabitatGuideColor.pdf). A good non-GMO pollinator seed mix called "Save the Bees" is available from Botanical Interests® (Fig. 10.14a–d) (https://www.botanicalinterests.com/products/view/7020/Flower-Mix-Save-the-Bees-Seeds-LG). This seed packet needs to be planted in full sun and these flowers do attract a diversity of bees (Fig. 10.14B–D). Once the flowers have bloomed, each student can calculate the insect pollinator service by counting the number of pollinators attracted to a single flower in a 15 minute time span. The class can then add up each student's pollinator service data to get a total pollinator service, which is divided by the number of student observations to calculate an average pollinator service quotient for your garden. Make sure to record controlled variables, such as the species of pollinator (you can take pictures to later identify species), temperature, weather conditions, and time of day. In addition, this can be repeated over the course of a season or more to view changes in pollinator service over time. These data can then be plotted to visualize trends in the results.

Photography is a successful way to engage students with nature. The students can design art projects in the garden, such as taking sequential pictures from the same spot of the garden over time to track the phenology (timing of flowers blooming, insect emergence, etc.). Photography is useful in identifying different species of

Fig. 10.14 (**A**–**D**) Flowers grown from the seed packet "Save the Bees" from Botanical Interests®. (**B**) A rusty patched bumble bee on a giant sunflower leaf in the garden. (**C**) A honey bee pollinating a star flower. (**D**) A bumble bee and a metallic green bee ("sweat bee") pollinating a sunflower. (Photo credit: Kristian Demary)

plants and pollinators. Mobile app technology, such as FlowerPedia 2.0, Botany Buddy, and Audubon Wildflowers (https://dengarden.com/gardening/Free-Smartphone-Apps-for-Plant-Lovers) are useful to help identify flowers.

10.1.4.1 Case Study: Massachusetts College of Art and Design

In addition to planting flowers, students can design and build habitat (or nesting sites) for urban insects and bees. Mason bees are solitary bees that build a nest inside tunnels left behind by tree boring insects. Mason bees cannot dig the tunnels themselves, therefore they must look for an abandoned one. Humans can supply them with all the tunnels they need by providing wood with drilled holes or hollow reeds. A good reference on how to build insect hotels can be found at: http://www.foxleas.com/make-a-bee-hotel.asp.

The students in Dr. Kristian Demary's Sustainability Science course at Massachusetts College of Art and Design (MassART), along with resources from The Best Bees Company and the Urban Beekeeping Laboratory and Bee Sanctuary

Fig. 10.15 The bee hotel was built by Massachusetts College of Art and Design students on April 29, 2016. (Photo credit: Kristian Demary)

(www.urbanbeelab.org) created habitat for solitary bees with a bee hotel out of cardboard boxes that included wood with holes drilled in it along with hollow reeds (Fig. 10.15). In addition, Dr. Demary and her students upcycled unwanted products and waste into useful habitat for a diversity of insects and other small animals that is on display in the MassART courtyard (Fig. 10.16). They used five wood pallets as a base for the insect hotel. The students collected recyclable and natural materials over the course of the semester. They planted flower seeds in glass bottles and cans to include a nectar source for the wild bees.

Dr. Demary's students were surprised to know that they could upcycle materials that would normally be either thrown in the trash (old bricks, wood pallets, and fabric and flooring samples) or recycled (glass and plastic bottles, coffee cups, cardboard boxes, egg cartons, aluminum cans, and cork) along with natural items (reeds and sticks), as building material to make useful habitat for insects and other small animals to use. After two months, at least three mason bees made nests in the drilled holes (Fig. 10.17). After three months, they found ants, slugs, spiders, pill bugs, and a white millipede in, around, and under the MassART insect hotel (Fig. 10.18A–D). In addition, some of the seeds they had planted germinated and bloomed into flowers (Fig. 10.19). Dr. Demary continues to monitor the insect and bee hotels to determine the best building materials for insect habitat.

Fig. 10.16 The insect hotel designed and built by Massachusetts College of Art and Design students on April 29, 2016. It was made out of recyclable and natural materials. (Photo credit: Kristian Demary)

10.2 Summary

In summary, urban bees are an established and successful platform for STEAM education. STEAM education not only fosters curiosity and creativity, but it can also lead to an interdisciplinary approach to solving real-world problems. Bees are an effective means with which to advance STEAM education for learners of all ages, socioeconomic backgrounds, origins, nationalities, races, and interests.

Fig. 10.17 Students drilled holes in wood for Mason Bees and three were used as nests (the ones with mud). This picture was taken on June 24, 2016. (Photo credit: Kristian Demary)

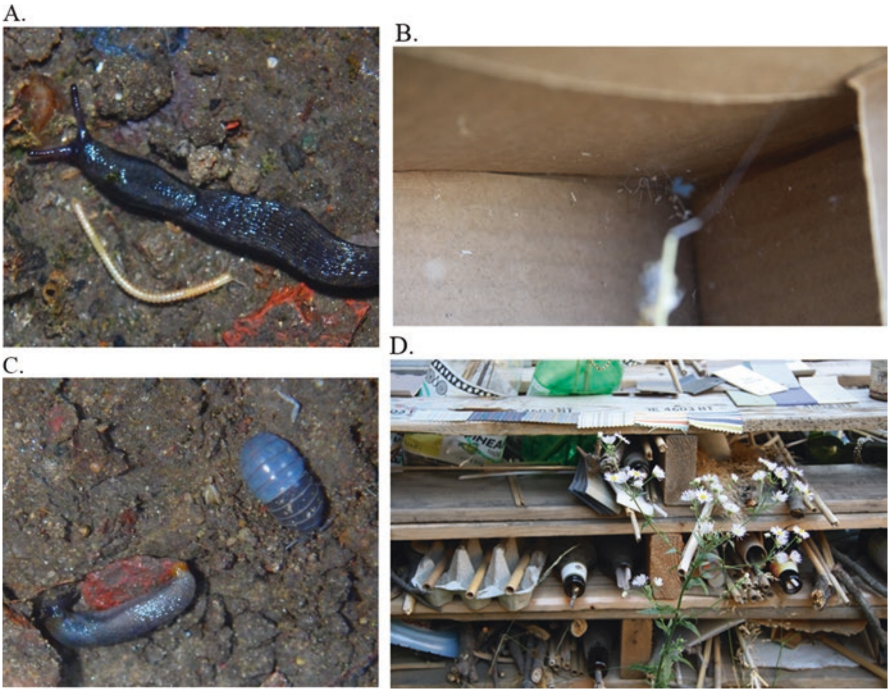

Fig. 10.18 Life found in, around, and under the Bee Hotel and the Insect Hotel three months after they were built. The Insect and Bee Hotels are on display in the courtyard at Massachusetts College of Art and Design. (**A**) A slug and millipede found under a cardboard box of the Bee Hotel. (**B**) A spider in a cardboard box of the Bee Hotel. (**C**) A pill bug (going through molting) and a slug found under a wood board. (**D**) plant life around the insect hotel. (Photo credits: **A** and **C**: Kristian Demary; **B** and **D**: Andrew Bradley)

Fig. 10.19 Three months after the Insect Hotel was built and the seeds were planted, we found flowers in bloom. This is on display in the courtyard at Massachusetts College of Art and Design. (Photo credit: Kristian Demary)

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