Team Control Number

12526

Problem Chosen

A

2022
HiMCM/MidMCM
Summary Sheet

The Need for Bees (and not just for honey)

"If the bee disappeared off the surface of the globe, then man would only have four years of life left." - Albert Einstein

Bees are the world's most important pollinators. Over 80% of plants rely on bees for pollination (*The Value of Birds and Bees*, 2020), and without them, many would quickly die as well. Because of this, it is critical to analyze how different sources affect the bee population and track the population of bee colonies.

After extensive research, we have created two models: one to track the population of a colony, and one to calculate how many honey bee hives are needed to pollinate a given area of land. In addition, we analyzed external factors to see which one impacted the honey bee population the most. After all of the analysis was concluded, an infographic was created to display our findings.

To model the population of a colony of honeybees, we first started by creating a utopian model. This model ignored all external sources of death, meaning the only way bees died was when they reached the end of their lifespan. This model provides a baseline, allowing a multitude of other factors to be analyzed and comparisons to be drawn. After our utopian model was created, we made four dystopian models. These are models where external death is factored in. From research, we found that bees are affected the most by pesticides, pests (varroa mites), diseases, and high temperatures. Because of this, we factored in each source separately in order to determine which source was the most detrimental to the bee population.

The model we created analyzes the change in bee colony population day by day. This allows for a multitude of factors to be analyzed since the bee population can be manipulated day to day, rather than month to month or even season to season.

In the end, we determined that pesticides are the factor that causes the greatest decrease in the bee population. However, varroa mites are also very damaging to bee populations.

Next, we used our model to calculate the number of bee hives required to pollinate 20 acres of a crop. After research, dimensional analysis was conducted and we concluded that 27 hives were needed to pollinate the plot.

Finally, our infographic is at the end of this document. It not only summarizes the information above but is also eye-catching and informative. This infographic can help spread the word to save the bees.

A Bee-autiful Introduction

Although bees are essential for pollinating 80% of the world's plants (*The Value of Birds and Bees*, 2020), many external factors such as pests and pesticides have gradually decreased their population. In order to analyze these factors, we were tasked with modeling a honeybee colony to track its population over time. Then, we analyzed the factors that affected the colony and performed a sensitivity analysis to see which one affected the population the most. After, we took our colony and determined how many similar colonies would be needed to successfully support and pollinate a 20-acre farm. Finally, we were tasked with creating an infographic for a website that summarized this information.

In addition, the following information was given for us to consider:

- ❖ Honeybees are able to travel up to 20 km, but they typically stay within 6 km of their hive.
- ❖ On average a honeybee hive contains between 20,000 and 80,000 honeybees.
- ❖ In a single day, a singular honeybee can visit 2,000 flowers.
- ❖ During the summer, most honeybees have a shorter lifespan because they work themselves to death.
- ❖ During autumn and winter, honeybees may have a longer lifespan of four to six months.
- ❖ Factors such as level of activity, pollen consumption, and protein abundance impact a bee's lifespan.

We split this problem up into two parts: the "Population Predicament" (Section I) and the "Pollination Plight" (Section III). The sensitivity analysis is in Section II and the infographic will be at the end in Section IV.

The Secret Life of Bees

First, here is a little background information on bees. In a beehive, there are three types of bees: a queen bee, drones, and workers. There is only one queen bee at a time and her sole duty is to lay eggs to populate the colony; the queen chooses when to lay these eggs. As such, more eggs are laid when there are more resources. If a colony gets too big, new queen bees are raised and the old queen takes half of the old colony and swarms, splitting the hive (Ecocolmena, 2022). When there are fewer resources, the queen lays fewer eggs. In addition, she can choose what eggs to fertilize. The fertilized eggs turn into female worker bees while the unfertilized eggs turn into male drone bees. A drone's sole job is to mate with the queen. As such, they are not extremely crucial to the hive and are kicked out during the winter in order to preserve resources (The Beekeepers Year, 2018).

On the other hand, worker bees are extremely critical for the survival of the hive. Some workers stay in the hive, tending to the brood (the eggs, larvae, and pupae). Other workers go out to forage. They will bring back pollen, water, and nectar for the hive. While foraging, bees tend to stay near their hives, although they can go as far as 20 km away. Bees pollinate a plant when they land in its flower and the pollen sticks to their legs. Then then transport this pollen to other flowers.

With that information, here is our model.

Section I: The Population Predicament

In order to model the population of a honeybee colony, we broke down the process into two steps: model the colony without any external deaths (from pests, pesticides, etc), and then add in the external deaths afterward.

Assumptions: The Population Predicament

Utopian model

- The colony we are modeling is a domesticated honey bee colony
- Since the colony is domesticated, the beekeeper treats diseases and varroa mites, as well as maintains the population of the colony so it never drops below 20,000 bees
- The colony is located in North Dakota, USA
- The queen bee remains the same year round and does not die
- The highest number of eggs a queen can lay per day is 2,000 eggs
- In order to preserve resources for winter, the queen does not lay eggs from November until March
- During spring and fall, the egg laying rate will exponentially increase and decrease respectively
- All the drones are kicked out of the hive in November in order to conserve food for winter
- Besides during winter, 85% of the adult bees in the hive are worker bees
- 20,000 bees is the minimum colony size that is able to survive the winter
- The colony will not swarm (split apart) until the colony population is over 100,000
- Bee lifespan is determined by what time of year they are born

Dystopian Model

- If not affected by disease, mites, etc, bees will die at the end of their lifespans
- Varroa Mite Assumptions
    - There are 50,000 bees in the colony
    - The percent of bees in the colony affected by Varroa mites is same as the percent of colonies affected by Varroa mites in North Dakota
    - The same number of bees are affected by Varroa mites for each month in a group of three months.
    - The same number of bees are affected by Varroa mites for each day in a month
- Disease Assumptions
    - The percent of bees in the colony affected by disease is the same as the percent of colonies affected by disease in North Dakota
    - When the percent of colonies affected by disease is unavailable for a given year, it is the same percentage as in the preceding year.
    - The same number of bees are affected by disease for each month in a group of three months.
    - The same number of bees are affected by disease for each day in a month
- Pesticide Assumptions
    - The colony starts out unexposed to pesticides

- ➢ The Utopian Model is the unexposed colony
- ❖ Temperature
  - ➢ The colony is located in North Dakota

The Utopian Model

Firstly, we chose to locate our hive in North Dakota. This is because North Dakota is the state that produces the most honey in America (Shahbandeh, 2022). Then, we decided to model the population day by day. This was to account for the deaths that occur daily and so that day-to-day changes can be shown. To model the population of the colony sans external sources, we must take into account the number of deaths versus the number of births. Thus, these factors need to be considered: the lifespan of a bee per season, the number of worker bees versus drones, the egg-laying rate per day, and the number of eggs that survive until adulthood.

We first started by determining the queen's egg-laying rate. Various sources had different numbers, ranging from 1,000 to 3,000 (*Honey Bee Eggs*, n.d.). For the sake of simplicity, throughout this model, we averaged ranges to account for the most possibilities. We determined that the queen lays the most eggs during the summertime when resources are abundant (*Honey Bee Eggs*, n.d.) and that queens often stop laying eggs in the wintertime to perverse resources (*The Beekeepers Year*, 2018). Thus, we assumed our queen would lay 2,000 eggs per day at the peak of the summer and lay no eggs in winter when resources were scarce.

For spring, we found that as it warms up, more and more bees become active. Although there are very few drones at the beginning of spring, by the end, the hive is back in full force (*The Beekeepers Year*, 2018). In addition, we referenced a bee population fluctuation graph in order to determine egg-laying rates in spring and fall that showed a drastic increase in bee population in spring, and a drastic decrease in fall (*Seasonality of Brood and Adult Populations*, 2019).

Because of these facts, we decided to assume that the egg-laying rates would increase exponentially in spring and decrease exponentially in fall.

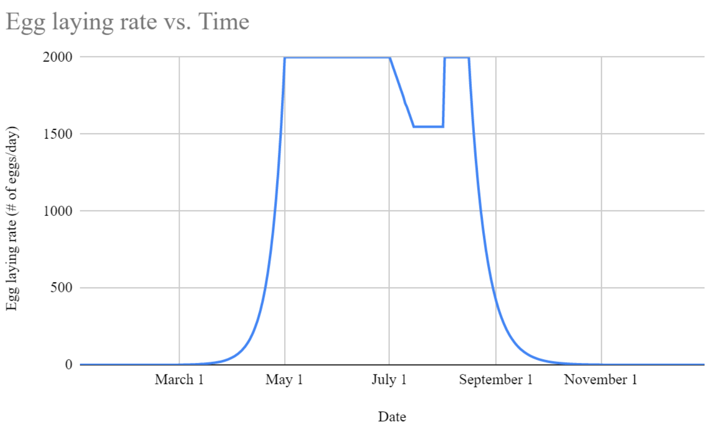


Figure 1: Egg-laying rate per month

Thus, for the egg-laying rate in our model, no eggs are laid between November and March. Since the beginning of May to the end of June is pollen season, our queen lays the most eggs during that period of time (2,000 eggs). Between March and May, the egg-laying rate increases exponentially per day. Between July and August, egg-laying rate decreases due to dwindling resources. However, it jumps back up in September due to the fall pollen season. Then, from September to November egg laying rate decreases exponentially to zero.

However, not all eggs will survive to adulthood. In a study regarding honey bee brood mortality rate, (Mortensen & Ellis, 2018) it was found that only about 85% of the brood survives until adulthood. Thus, we multiplied our egg-laying rates for each day by 0.85 to calculate the number of eggs that will survive until adulthood.

Then, we factored in the differences between workers and drones. For one, workers and drones have different lifespans, and also we assumed that all the drones would be banished from the hive during winter to perverse resources. Although sources provided a range of values, we ultimately decided that 15% of adult bees would be drones in our model (*How Drone Bees Benefit the Colony - PerfectBee*, n.d.). Thus, we multiplied our number of surviving eggs by 0.85 and 0.15 to find the number of workers and drones, respectively. This tells us the increase in each kind of bee per day.

Unfortunately, bees also die. Thus, we also had to factor in bee deaths. We assumed that if bees were unaffected by external sources, they would die after their lifespan. Additionally, the problem statement information stated that bees have a shorter lifespan in the summer due to strenuous work and high temperatures. Therefore we researched how long these various lifespans are. After research, we learned that drones live 21–32 days in the spring and summer (the only times when drones are produced, workers live on average 15–38 days in the summer and 30–60 days in the spring and fall (Remolina & Hughes, 2008). Since we were given a range, we took the average of the upper and lower bounds. In addition, we found that specific bees born at the end of fall, called winter bees, can survive for 200 days since they store more fat (Burlew, n.d.). Thus, we decided that after bees are fully mature, they will die after this 200-day lifespan ends.

Thus, to calculate the population of our hive day by day, we started on January 1st. Since we assumed the beekeeper maintained the hive to prevent colony collapse, we start with 20,000 bees. Each day, the number of eggs that survived to adulthood is added to the population, and any bees that have died are subtracted. That gives us our model for one year.

The Solution

After calculating the population of our colony every day for one year, we ended up with this graph:

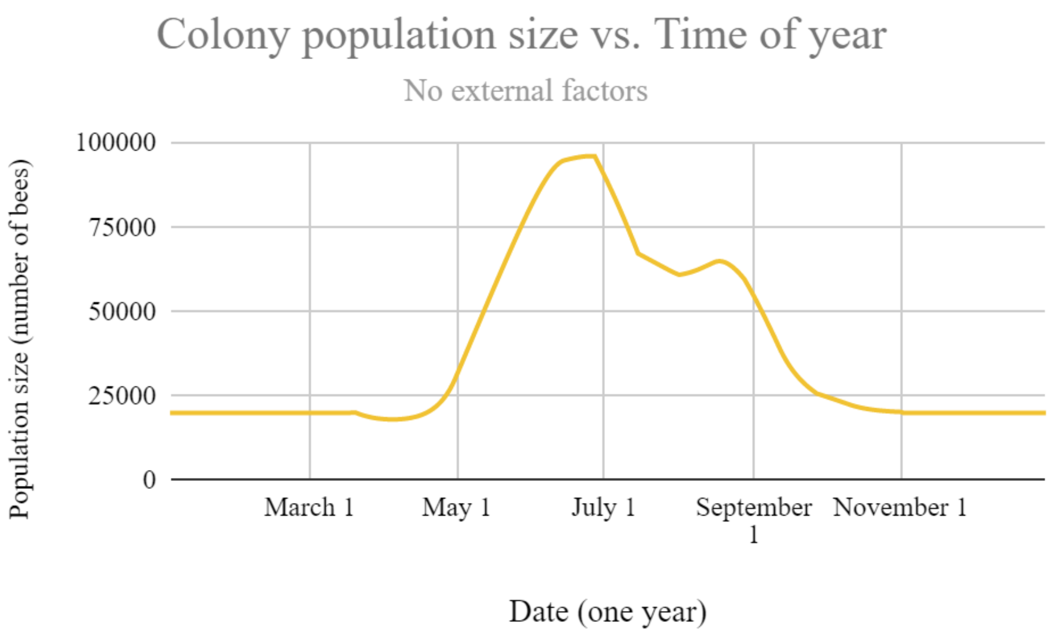


Figure 2: Colony population size for one year

It is worth noting that we started with 20,000 bees in January and we ended with 20,000 bees. Thus, without any external factors decreasing the population, the colony will survive on its own. Our model can be used for different starting population sizes.

There are some limitations. For one, since our model never went above 100,000 bees, we never accounted for swarming. Thus, if we use a different set of data where the population does go above 100,000, we cannot account for the population after the hive swarms. In addition, this model is only applicable for colonies located in continental climates, since bees behave differently in different weather conditions. Another weakness in this model is that we are assuming that at any given point there are 20,000 bees in this colony.

The Dystopian Model

An additional limitation of our above model was that it did not account for additional variables that affect colony population. Thus, we expanded the model to include the external factors of Varroa mites, diseases, pesticides, and temperature-related death, all of which contribute to colony collapse in nature (*Honey Bee Colonies*, 2022)

Varroa Mites

Varroa mites are mites that feed on the fat tissue of bees. They are often identified as the primary factor in bee population decline due to factors including their direct impact on bee larvae and the fatal diseases they spread to bees (Ramsey et al., 2019).

To determine the number of bees killed by Varroa mites in the colony, we first determined what percent of honey bee colonies were affected by Varroa mites, utilizing the USDA's August 2022 report on honey bee colonies. It provided the percentages of colonies affected by Varroa mites in groups of three months each, beginning with 12% of colonies affected by Varroa mites in the months of January to March, inclusive. To find the number of bees in our colony affected by Varroa mites, we multiplied the percentage of colonies affected by Varroa mites by a representative colony size. As the problem provided that the average bee colony has a population of 20,000 to 80,000 adult bees, we took the average of the population sizes, 50,000, as our representative colony size. We then multiplied this number by 56%, the percent of bees affected by Varroa mites that are killed by them. As this calculation only provided us with the number of bees killed over three-month intervals, we assumed that the number of bees killed each month during the three months interval would be the same. Thus, the number of bees killed per month was found by dividing our number of bees killed over three months by 3. In order to produce a model that would determine the change in bee population each day, we next assumed that the same change in number of bees was made each day for each month. To find the change in bees per day, we divided the change in bees per month by the number of days in the month. Finally, we multiplied our change in bees per day by the percentage of workers in a colony and then by the percentage of drones in a colony. The changes in worker population per day were subtracted from the number of workers in the colony on that day for the number of workers alive after Varroa mites. The number of drones alive after Varroa mites was calculated with the same method. The workers and drones that survived Varroa mites each day were added to find the number of adult bees left in the colony after that day's Varroa mite deaths. Analyzing population changes in worker and drone castes resulted in a more comprehensive model– one that showed Varroa mites' effects on the population of adult bees, only workers, and only drones.

Disease

To determine the number of bees killed by the disease in the colony, we first determined what percent of honey bee colonies were affected by disease, utilizing USDA's August 2022 and 2021 reports on honey bee colonies. A challenge we faced was that each report had gaps where information on the percentage of colonies affected by disease was unavailable. Thus, we supplemented the percentages missing in the 2022 report with information from the 2021 report.

We then used the same steps as we did for Varroa mites to calculate the deaths due to disease: we found the number of affected bees in a colony per three months, the number of killed bees in a colony per three months, the number of killed bees in a colony per month, the number of killed bees in a colony per day, the number of killed workers in a colony per day, and the number of killed drones in a colony per day. The number of killed workers in a colony per day and the number of killed drones in a colony per day were used to find the surviving number of workers, drones, and adult bees on that day, respectively.

A limitation of these two models is that the deaths due to Varolla mites and diseases were rounded to the nearest whole number, as a fraction of a bee can not be killed. As many of the values were rounded down, we ended up with a negative number of deaths.

Pesticides

In the United States, most farmers spray pesticides on their crops in order to protect their crops from unwanted diseases ("Why Do We Spray?," 2013). The main resource we used to analyze pesticides informed us that the behavior of workers and queens is affected by exposure to these sprayed chemicals. This results in a colony operating at suboptimal conditions as worker and queen behavior is altered. Exposure to insecticides can affect foraging, learning, and memory in worker bees, and egg laying rate in queens (Wu-Smart & Spivak, 2016). For this model, we only considered the pesticide effect on queens because egg-laying rates will have a higher effect on a colony's population.

The study we looked at told us that queens that were not exposed to the neonicotinoid insecticide Imidacloprid laid 35% more eggs than queens exposed to the insecticide (Wu-Smart & Spivak, 2016). Another way to state that untreated queens were laying 35% more eggs, is stating that queens exposed to insecticides lay 74% of the eggs that unexposed queens will. Additionally, we learned that farmers usually first spray their crops in late May to mid-June ("Why Do We Spray?," 2013). In accordance with this information, we decided that the honey bees would first be exposed to the pesticide in June. This meant that up until June, the queen was laying at its normal rate. Therefore, we created a new table that included a new egg-laying rate of 74%. We then used that new information to calculate what the population of our Utopian Colony would be after pesticide exposure. All of that data is shown in the graph below:

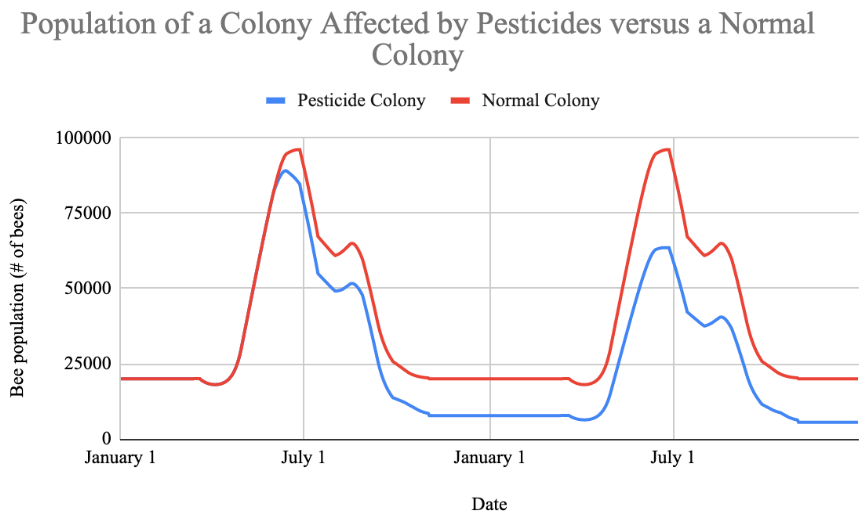


Figure 3: Population of a colony exposed to pesticides and population of a colony not exposed to pesticides over a two-year period

As shown in Figure 3, as soon as the colony is exposed to pesticides, there is a decrease in colony population. The colony started out with a population of 20,000 and ended with a population of 7,799. This is because the number of births is no longer equal to the number of deaths. When the analysis was extended to a second year where the queen was now laying 74% of the eggs she used to, the colony population was far below what the Utopian Model. In the second year, the population started out at 7,799 bees in the colony and ended at 5,601.

Temperature

In the summer months, bees are susceptible to death from high temperatures. When researching how temperature affects bee mortality, we learned that after a 6-hour exposure at 42 °C 54% of drones died. Drones are a lot more sensitive to heat than queens and workers are so 42 ºC was chosen as the threshold the climate had to reach for any bees to die (McAfee et al., 2020). Then we started looking into the climate of our chosen location North Dakota; we quickly found that North Dakota occasionally reached 90 ºF, but July, their hottest month, averages 73 ºF (*Climate*, n.d.). 90 ºF, is equivalent to 33 ºC which is a number greater than what July would reach. Therefore, it was concluded that temperatures would never be great enough to kill any bees in our colony.

Section II: Sensitivity Analysis

We analyzed four factors that impact bee population: presence of Varroa mites, diseases, temperature, and pesticides. We determined the sensitivity of bees to the four factors by comparing their effects on bee populations.

Temperature had the least effect on our bee population, due to our bee population's location. When the temperature exceeds 42 ºC, 54% of drones will from heat (McAfee et al., 2020). However, we modeled our bee population in North Dakota, a state where temperatures typically do not exceed 33 ºC (*Climate*, n.d.). Thus, as the temperature is not high enough to kill bees, it does not affect the population.

Disease also does not have as great of an impact on bee colonies. It only affects an average of 2.1% of colonies (*Honey Bee Colonies*, 2022). Looking at the upper bound of a common bee disease, only 26% of bees affected by a disease are killed (*Chalkbrood*, n.d.). Thus, disease only kills 0.55% of bees and thus has a minimal impact on bee populations.

Though it reduces bee populations, bees are not as sensitive to disease as they are to Varroa mites.

Varroa mites have a significant impact on bee colonies. It affects an average of 25.23% of colonies (*Honey Bee Colonies*, 2022). Out of the affected number of bees, 56% will die, even with treatment against Varroa mites in both fall and December (Kaplan, 2022). This means that 14.13% of bees die from Varroa mites. In addition to deaths, Varroa mites cause harm to bee populations through spreading disease, such as deformed wing virus, a disease that deforms bees' wings (Hunt & Given, n.d.). With its debilitating impact on bee populations, Varroa mites are as problematic to bees as stroke is to humans: both are fatal in about 14% of cases, and, even if the victim survives, they may be left with major disabilities (*Stroke: Challenges, Progress, and Promise*, n.d.).

The use of pesticides is the factor out of the four we analyzed which bees are the most sensitive to. Pesticides cause a 26% decrease in egg laying, which can be interpreted as a 26% decrease in the colony's population. Thus, 26% of bees die from pesticides. In addition to its effect on egg-laying rates, exposure to insecticides can prove detrimental to the hive in several different ways, including harming foraging, learning, and memory abilities in worker bees (Wu-Smart & Spivak, 2016).

Section III: The Pollination Plight

Once the colony without any external deaths was created, it was used to model how many hives would be needed to support 20 acres of a plant.

Assumptions: The Pollination Plight

- ❖ The colony that is pollinating the plot is a colony that is not affected by external factors
- ❖ The 20-acre plot is for crops and is not a honey farm
- ❖ The plot exclusively grows oilseed sunflowers
- ❖ Even though a sunflower can self-pollinate, in order for the 20-acre plot to be sustained by honey bees, each floret in the field has to be pollinated
- ❖ Every sunflower must be pollinated within two days of blooming
- ❖ Sunflowers are grown from June to August
- ❖ Bees will visit different flowers every time they leave the hive

The Model

In order to model this system, the type of plant grown must be considered. We chose oilseed sunflowers since they are commonly grown in North Dakota for sunflower seed oil (*Section 4: Oilseed and Row Crops*, n.d.). Then, we had to figure out how many sunflowers would be planted on said 20 acres of land. According to Iowa State University, around 20,000 sunflowers can be planted per acre. However, though oilseed sunflowers only have one head, they have many florets. A floret is a small flower making up the head of the flower. It is estimated that sunflowers have around 2,000 florets per sunflower head (Myers & Minor, n.d.). It was given that bees can visit around 2,000 flowers per day. However, since a sunflower's florets are small flowers, we considered the 2,000 flowers per day metric to actually mean 2,000 florets per day. Sunflowers only bloom for 2 days (*Sunflowers and Bees*, 2018) and thus we only have a two-day period to pollinate all the florets. Thus, each bee will make 4,000 visits in this period (pollinating around 4,000 florets). According to our colony model, there are 76081 workers in June, the month when sunflowers bloom. However, not all worker bees leave the hive. In fact, only 30% of worker bees are foragers (workers that leave the hive) (Binns, 2013). However, even with 30% leaving the hive, not all of them are constantly foraging for pollen. Foragers also need to fetch water and nectar for the colony. Because of this, only one in three forager trips is for pollen (Klein et al., 2019). Thus, we set up a dimensional analysis equation.

The Solution

$$\frac{76081\,workers}{hive} \times \frac{3\,forager}{10\,workers} \times \frac{1\,pollen\,forager}{3\,foragers} = 7608\,pollen\,foragers$$

$$20\,acres \times \frac{20{,}000\,sunflowers}{1\,acre} \times \frac{2{,}000\,florets}{1\,sunflower} \times \frac{1\,forager}{4{,}000\,florets} \times \frac{1\,hive}{7608\,pollen\,foragers} = 27\,hives$$

For our 20 acre plot, we need 27 hives. Thus, we need around 1-2 hives per acre. This works because one acre is around 0.004 of a kilometer. Since bees will forage and stay within 6 km of their hive, they will definitely visit and pollinate all the sunflowers within this field. This equation can be used with any dataset to figure out the number of hives required to support a plot.

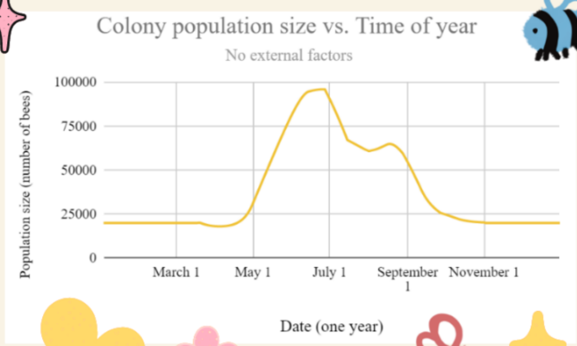
Section IV: Infographic

Did you know?

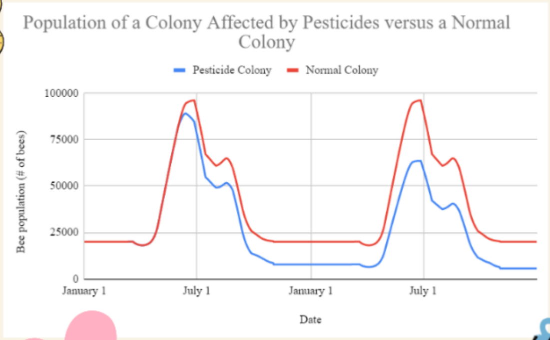
More than ***80%*** of plants rely on bees for pollination, including flowers and fruit trees!

However, the bee population has been ***decreasing*** due to human and environmental factors

While the bee population **normally fluctuates** throughout the course of a year, the colony is able to bounce back



However, when bees are affected by **pesticides**, the population will **continue to decrease**, and eventually the colony will **collapse**



This is bad because so many plants, like sunflowers partially rely on bees for pollination. Imagine a world with no flowers or fruit. How terrible!

But, by **protecting** the bees and not using pesticides, bees and plants can work together in a **mutualistic relationship**.
For example, *20 acres* of sunflowers need *27 hives* of bees to be pollinated, but also provide nectar and pollen for the 27 hives of bees!

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