University of Camerino

School of Science and Technology
Performance Analysis and Simulation Course

Honey Hive simulation

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Introduction

Bees are one of the most important pollinators on the planet, responsible for pollinating a significant portion of the world's crops and wild plants. Honeybees are social insects that live in highly organized colonies or hives, with one queen bee, thousands of worker bees, and a few drones.

The life of a honeybee is complex and fascinating. Worker bees perform a variety of tasks throughout their lives, including collecting nectar and pollen, caring for the young, and defending the hive.

However, honeybee populations have been declining in recent years due to various factors, including habitat loss, pesticide use, and disease. This decline in bee populations is a significant concern as bees are crucial for pollinating crops that are essential for human food supply.

Goal

The aim of this project is to define and simulate a population model of a beehive using Sibilla and study how certain factors influence bee behaviour and honey production.

Model

To perform the simulation and provide results, we define a population model representing the rules and behaviours of the system.

Assumptions

There are many factors involved in the dynamics of a beehive, and since we are going to define a model and simulate it, we only need to consider the main aspect of the bee colony scenario.

We will focus on the work of the bees and the influence of different factors such as food availability, temperature and so on, without considering these elements:

- The day-night cycle and the inactivity period (September to February).
- Water, pollen and honey, the only food that we consider is nectar.
- Drones, eggs and larvae, we only consider queen and worker bee.
- The growth and specialisation of bees, we have only a general worker bee that carries out the main activities.
- The swarming of bees.
- The birth of new queens

Other simplifications concern precipitation and pesticide exposure. Both are represented by a rate (*rainfall_rate* for precipitation and *pesticide_exposure_rate* for pesticide) that can take values ranging from 0 to 1.

In addition, temperature and humidity are considered the same inside and outside the hive.

Description

For the model, we consider the honeybee living in honey hives. Unlike other bee species, take the digger bee for example, these live in colonies of several thousand individuals, divided into castes with different tasks.

Roles. As already described, we only take into account the queen and the worker bees. The queen bee has the task to propagate the species by generating new worker bees. The worker bees, on the other hand, have the task of collecting nectar from flowers in the environment, storing it in the hive and then transforming this nectar into honey. During their activities, bees could be exposed to pesticide.

The model also provides a representation of the life cycle of the worker bees and the queen by defining rules for energy consumption, eating and death.

Influences Factors. During the course of their various activities, bees may encounter various factors that influence their living conditions and honey production. In particular, five factors have been defined that can influence the behaviour: temperature, humidity, rainfall, biodiversity and quantity of flowers, and exposure to pesticides. These factors will be described in detail below.

Species

The model defines several interacting agents. These are:

- **species** Q of [0, *ENERGY*]:

  This is the species that represent the queen of the hive and is characterized by a level of *ENERGY*. The higher the energy level, the easier it is for the queen to perform a task. When the level reaches zero, the queen cannot perform activities. During the simulation, the queen's energy decreases following the *queen_metabolism* and can be restored by eating nectar. There is only one queen per colony (future queens are not taken in consideration).

- **species** WB of [0, *ENERGY*] * [0, *POISONING*]:

  This is the species that represent the worker bees and is characterized by a level of *ENERGY* and *POISONING*. The higher the energy level, the easier it is for the worker to perform a task. When the level reaches zero, the worker cannot perform activities.

During the simulation, the worker's energy decreases following the *worker_metabolism* and can be restored by eating nectar. The poisoning level, on the other hand, can only increase and is controlled via the *pesticide_exposure_rate* parameter.

- **species** H:

  This is the species that represent the honey stored in the hive. To produce 1 unit of honey, the workers need to convert 2 nectar units.

- **species** N:

  This is the species that represent the nectar stored in the hive. The maximum value it can reach is defined by the constant *FOOD_STORAGE*.

- **species** F of [0, *SPECIES*] * [0, *NECTAR_AVAILABLE*]:

  This is the species that represent flowers in the environment and is identified by a SPECIES that defines its type. Presence of nectar is indicated by *NECTAR_AVAILABLE*: 1 if present, 0 if absent. Workers can only collect nectar from flowers with *NECTAR_AVAILABLE* set to 1. After collection, *NECTAR_AVAILABLE* is set to 0, and the flower must wait a period defined by *flower_pruduce_nectar_rate* before setting it back to 1.

Parameters

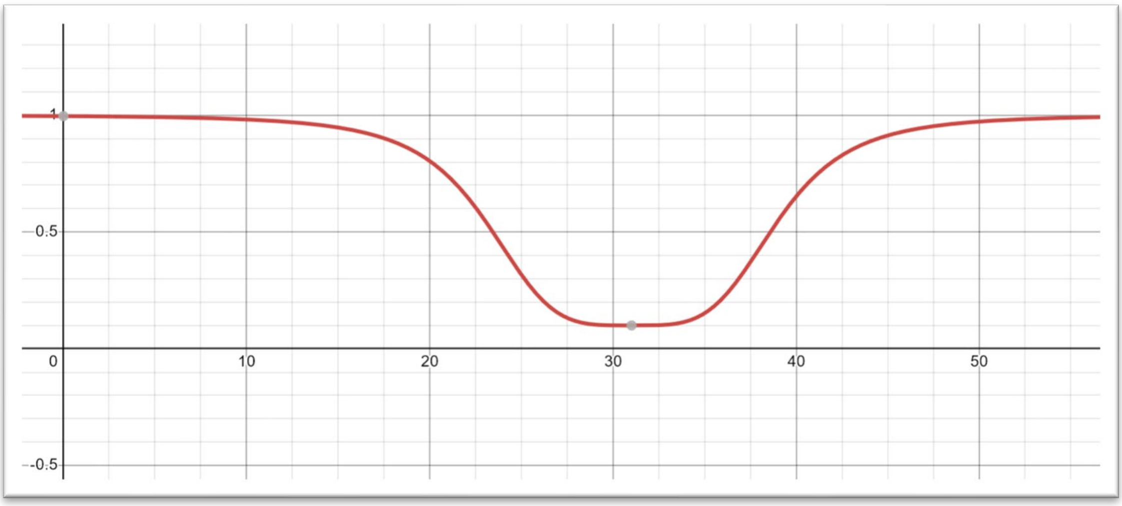
- **param** temperature:

  The ideal temperature for a bee is between 28 °C and 34 °C; In the model, the optimum temperature is set at 31 °C with a maximum variation of ± 8 degrees.

  The temperature influences the mortality rate of the worker bees, and it is described by the following formula:

$$1 - \frac{0.9}{1 + \left(\frac{temperature - ideal_{temperature}}{delta_{temperature}}\right)^{2*temperature_{impact}}};$$

  The result is the following curve:



- **param** rainfall_rate:

  It can take a value between 0 and 1 and is used to represent precipitation. The rate influences the production of nectar by the flowers: low rainfall decreases nectar production.

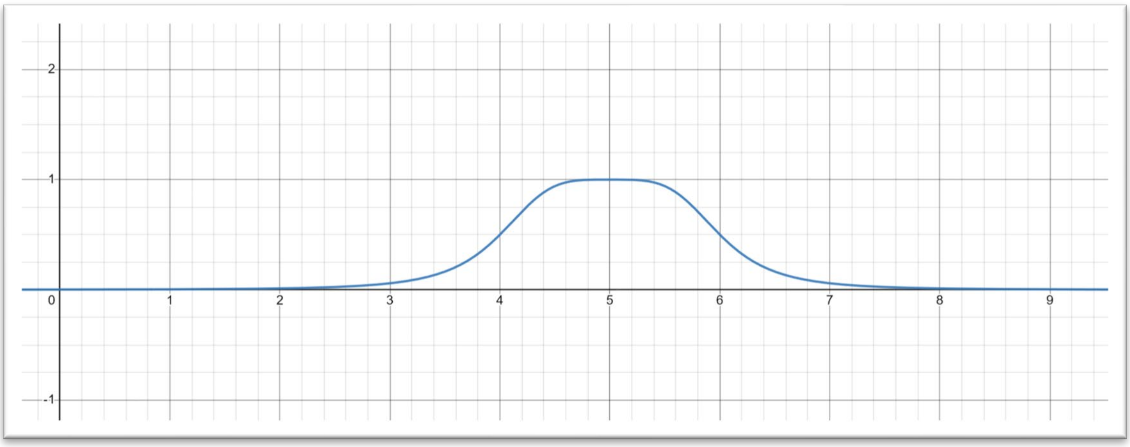
- **param** humidity:

  The ideal humidity for bee is 60%. In the model, humidity is represented with an integer ranging from 0 to 9 (0 represents 10% humidity; 5 represents 60% humidity; 9 represents 100% humidity);

  The humidity influences the production of honey, and it is described by the following formula:

$$\frac{1}{\left(\left(humidity - ideal_{humidity}\right)^{2*humidity_{impact}}\right) + 1}$$

  The result is the following curve:



- **param** flowers_biodiversity:

  Represent the number of flower species. It influences the workers lifetime: High number of species decrease mortality rate.

- **param** pesticide_exposure_rate:

  It can take a value between 0 and 1 and is used to represent workers' exposure to pesticides. High value of pesticide increases the *POISONIG* level that increase the workers mortality rate.

Code

The following code is the actual implementation of the model previously defined. The script specifies the.pm file, used by Sibilla. The code is also available on GitHub.

```
/* ---------------------------------------------------------------------- */
/*                            CONST & AGENTS                              */
/* ---------------------------------------------------------------------- */

/*Bees*/
const ENERGY = 10; /* The energy available to a bee. A bee with 0 energy
cannot perform activities */
const POISONING = 10; /* The poisoning level of a bee */

/*Flowers*/
const SPECIES = 3; /* The max number of flower species in the simulation */
const NECTAR_AVAILABLE = 2; /* 1 if the flower has nectar available; 0 if not
available */

/*Hive*/
const FOOD_STORAGE = 1000; /* The amount of nectar that can be stored in the
hive */

/* -------------------------------- Agents --------------------------------
*/

species Q of [0, ENERGY];                              /* Queen */
species WB of [0, ENERGY] * [0, POISONING];            /* Worker Bee */

species H;                                             /* Honey Storage */
species N;                                             /* Nectar Storage */

species F of [0, SPECIES] * [0, NECTAR_AVAILABLE];     /* Flowers */

/* Secondary Agents */
species N_F;   /* Nectar used for food */
species N_H;   /* Nectar used for Honey */
species N_QF;  /* Nectar used for Queen food */

species DQ;    /* Death Queen */
species DW;    /* Death Worker */
species BB;    /* Born Bees */
```

```
/* ------------------------------- Rates ---------------------------------- */

const eat_rate = 0.90 ;

const queen_mortality_rate = 0.0001 ; /* The probability that the queen dies
is pretty low. The queen will die only when the colony is dying and it remains
alone. */
const queen_metabolism = 0.25 ;
const bee_birth_rate = 1.0 ;

const worker_metabolism = 0.30 ;
const worker_mortality_rate = 0.25 ;

const worker_store_nectar = 0.9 ;
const worker_produce_honey_rate = 0.5 ;

const flower_pruduce_nectar_rate = 0.2 ;


/* ------------------------------- Params --------------------------------- */

param temperature = 31 ; /* Ranges between 5 and 60. The ideal_temperature is
31 degrees */

param rainfall_rate = 1; /* The rateo of rainfall; values between 0 and 1 */

param humidity = 5 ; /* Represent the percentage of humidity; values between 0
and 9; The ideal_humidity is 5; */

param flowers_biodiversity = 3 ; /* The number of species of flowers */

param pesticide_exposure_rate = 0.0 ; /* The rate at with the workers are
exposed to pesticide; Ranges between 0 and 1: 0 means no exposure; */

/* --------------------------- Math functions ---------------------------- */

/*
{ID: WF_1} Workers population function:

Used to increase the probability of the death of the queen; When the
population falls below
one third of critical_workers_population, the probability od dying increases
exponentially.

    1/4^(#workers - critical_workers_population/3)

#workers:
    The total worker bees in the hive;
```

```
critical_workers_population:
    The minimum number of bee that allow the queen to survive; If the number
    of bees falls below this threshold, the probability of queen death
    increase exponentially;

*/
const critical_workers_population = 10;

/*
{ID: HF_1} Humidity function:

Describe the influences of humidity on the production of honey; Used to
decrease the honey production.

    1/(humidity - ideal_humidity)^2humidity_impact

ideal_humidity:
    Represent the percentage of ideal humidity in the hive;
    Integer; Ranges between 0 and 9 -> [0, 9];
    E.g :   4 equal to 50% of humidity;
            5 equal to 60% of humidity;

humidity_impact:
    Defines how fast the function for humidity goes up;
    Integer; Ranges between 0 and 10 -> [0, 10];
    The smaller the number, the more the rate of humidity increases around the
ideal_humidity value;

*/
const ideal_humidity = 5;
const humidity_impact = 1;
const humidity_influence = 1/(((humidity -
ideal_humidity)^(2*humidity_impact))+1);


/*
{ID: TF_1} Temperature function:

Describe the influences of temperature on the lifetime of a worker (WB); Used
to increase the probability
of death of workers.

    0.9 - 0.9/(1 + (2*(temperature -
ideal_temperature)/delta_temperature)^2temperature_impact)

temperature:
    The temperature in the hive;
    Decimal; Renges between 5 and 60 -> [5, 60];
```

```
delta_temperature:
    The maximum variation of degrees from ideal_temperature in with the
probability of death is low;

ideal_temperature:
    Represent the ideal temperature in the hive for the bees survival;

temperature_impact:
    Defines how fast the function for humidity goes down;
    Integer; Ranges between 1 and 100 -> [1, 100];
    The smaller the number, the more the rate of bee survival increases around
the ideal_temperature value;

*/
const ideal_temperature = 31;
const delta_temperature = 8;
const temperature_impact = 2;
const temperature_influence = 1 - 0.9/(1 + ((temperature -
ideal_temperature)/delta_temperature)^(2*temperature_impact));

/* ----------------------------------------------------------------------- */
/*                                LABELS                                   */
/* ----------------------------------------------------------------------- */

/*Flowers*/
label flowers = {F[s, n for s in [0,SPECIES] and n in [0, NECTAR_AVAILABLE]] }
label flowers_nectar_available = { F[s, 1 for s in [0,SPECIES]] }

/*Bees*/
label workers = { WB[e, p for e in [1,ENERGY] and p in [0,POISONING]] }
label infected_workers = {WB[e, p for e in [0,ENERGY] and p in [1,POISONING]]}

/*Hive*/
label used_storage = { N }
```

```
/* ---------------------------------------------------------------------- */
/*                                 RULES                                  */
/* ---------------------------------------------------------------------- */

/* ------------------------------- Queen --------------------------------- */

/*
>> QUEEN EATS <<

Results:
    Increase Queen (Q) ENERGY;
    Descrease NECTAR Storage (N);

Base rates:
    eat_rate;

Impacts:
    Residual ENERGY (Low ENERGY increase eat_rate);
*/
rule queen_eats for e in [0, ENERGY-2]{
    Q[e] | N<3> -[ eat_rate * (e/(ENERGY-1))]-> Q[e+2] | N_QF<3>
}

/*
>> QUEEN consume ENERGY <<

Results:
    Drecrease Queen (Q) ENERGY;

Base rates:
    queen_metabolism;
*/
rule queen_consume_energy for e in [1, ENERGY]{
    Q[e] -[queen_metabolism]-> Q[e-1]
}

/*
>> QUEEN DIES <<

Results:
    Increase Death Queen (DQ);

Base rates:
    queen_mortality_rate;

Impacts:
    Number of Workers {WF_1} (Low number of Workers increase
queen_mortality_rate);
```

```
*/
rule queen_dies for e in [0, ENERGY]{
    Q[e] -[ queen_mortality_rate + 1/4^(#workers -
critical_workers_population/2) ]-> DQ
}

/*
>> QUEEN generate WORKER <<

Results:
    Drecrease Queen (Q) ENERGY;
    Increase number of Worker (WB);

Base rates:
    bee_birth_rate;

Impacts:
    Food availbility (Low Food decrease bee_birth_rate);
    Number of Worker (High number of Worker compared to food decrease
bee_birth_rate);
*/
rule queen_generate_worker for e in [1, ENERGY] {
    Q[e] -[ bee_birth_rate * (e/ENERGY) * ((#N+1)/FOOD_STORAGE) * (1-
#workers//#N)*2]-> Q[e] | WB[ENERGY-1, 0]<2> | BB<2>
}


/* ------------------------------- Worker Bee -------------------------------
*/

/*
>> WORKER EATS <<

Results:
    Increase Worker (WB) ENERGY;
    Decrise NECTAR storage (N);

BaseRate:
    eat_rate;

Impacts:
    Residual ENERGY (Low ENERGY increase eat_rate);
*/
rule worker_eat for e in [0, ENERGY-1] and p in [0, POISONING] {
    WB[e,p] | N<1> -[eat_rate * (1 - e/ENERGY)]-> WB[e+1,p] | N_F<1>
}
```

```
/*
>> WORKER consume ENERGY <<

Results:
    Decrease Worker (WB) ENERGY;

Base rates:
    worker_metabolism;
*/
rule worker_consume_energy for e in [1, ENERGY] and p in [0, POISONING]{
    WB[e,p] -[worker_metabolism]-> WB[e-1,p]
}

/*
>> WORKER DIES <<

Results:
    Add new entity in Death Worker (DW) species;

Base rates:
    worker_mortality_rate

Impacts:
    Residual ENERGY (Low ENERGY increase worker_mortality_rate);
    POISONING level (High level of POISONING increase worker_mortality_rate);
    Temperature impact {TF_1};
    Level of flowers_biodiversity;
*/
rule worker_dies for e in [0, ENERGY] and p in [0, POISONING] {
    WB[e,p] -[ worker_mortality_rate * (1 - e/ENERGY) + (4^(p - POISONING) +
temperature_influence)/2 + (1- flowers_biodiversity/SPECIES)/5]-> DW
}

/*
>> WORKER collect NECTAR <<

Results:
    Increase NECTAR storage (N);
    Set FLOWER (F) NECTAR_AVAILABLE to 0;

Base rates:
    worker_store_nectar;

Impacts:
    Food availbility (Low Food increase worker_store_nectar);
    Residual Flowers with NECTAR_AVAILABLE (Low Flowers decrease
worker_store_nectar);
*/
rule worker_collect_nectar for e in [1, ENERGY] and p in [0, POISONING] and s
in [0, SPECIES]{
```

```
    WB[e,p] | F[s,1] -[worker_store_nectar * (1 - #N/FOOD_STORAGE) *
(#flowers_nectar_available/#flowers)]-> WB[e,p] | F[s,0] | N<1>
}

/*
>> WORKER is POISONED <<

Results:
    Increase Worker (WB) POISONING;

Base rates:
    pesticide_exposure_rate;
*/
rule worker_exposed_pesticide for e in [0, ENERGY] and p in [0, POISONING-1] {
    WB[e,p] -[pesticide_exposure_rate/2]-> WB[e,p+1]
}

/*
>> WORKER produce HONEY <<

Results:
    Decrease Nectar storage (N);
    Increase Honey storage (H);

Base rates:
    worker_produce_honey_rate;

Impacts:
    Residual ENERGY (Low ENERGY decrease worker_produce_honey_rate);
    Humidity impact {HF_1};
    Food availbility (Low Food decrease worker_produce_honey_rate);
    Number of Worker (High number of Worker compared to the food decrease
worker_produce_honey_rate);
*/
rule worker_produce_honey for e in [1, ENERGY] and p in [0, POISONING]{
    WB[e,p] | N<2> -[worker_produce_honey_rate * humidity_influence/2 *
(e/ENERGY) * (#N/(FOOD_STORAGE)) * (1- #workers//#N)*2]-> WB[e,p] | H<1> |
N_H<2>
}


/* --------------------------------- Flower ---------------------------------
*/

/*
Flower (F) produce NECTAR:
    NECTAR become AVAILABLE;

Base rates:
    flower_pruduce_nectar_rate
```

```
Impacts:
    Param rainfall_rate (Low rainfall decrease flower_pruduce_nectar_rate);
*/
rule flower_produce_nectar for s in [0, SPECIES]{
    F[s,0] -[flower_pruduce_nectar_rate * rainfall_rate]-> F[s,1]
}


/* ------------------------------------------------------------------------- */
/*                          MEASURES & PREDICATE                              */
/* ------------------------------------------------------------------------- */

measure n_bees = #workers;

measure honey_available = #H;
measure nectar_available = #N;
measure flower_with_nectar = #flowers_nectar_available;
measure workers_death = #DW;
measure worker_death_x_born = #DW/#BB;
measure queen_death = #DQ;

/* Others*/
measure nectar_food = #N_F;
measure nectar_honey = #N_H;
measure nectar_queen_food = #N_QF;

measure born_bee = #BB;

measure poisoned_workers = #infected_workers;


/* ------------------------------ Predicate ------------------------------- */

predicate hive_survived = (#Q[e for e in [0, ENERGY]] > 0);

/* ------------------------------------------------------------------------- */
/*                                 SYSTEM                                     */
/* ------------------------------------------------------------------------- */
system init = Q[ENERGY-1]<1> | WB[ENERGY-1, 0]<40> | H<0> | N<40> |
F[0,1]<500> | F[1,1]<500>;

system new_hive = Q[ENERGY-1]<1> | WB[ENERGY-1, 0]<40>  | H<0> |
N<40>            | F[0,1]<500> | F[1,1]<500>;
system old_hive = Q[ENERGY-1]<1> | WB[ENERGY-1, 0]<200> | H<0> |
N<FOOD_STORAGE/2> | F[0,1]<500> | F[1,1]<500>;
```

```
/* ----------------------------- Arid biomes ------------------------------ */

/*
Desert biome: very few flowers, a hot and dry climate;

Params:
    temperature = 40;
    rainfall_rate = 1;
    humidity = 1;
    flowers_biodiversity = 1 ;
    pesticide_exposure_rate = 0.0; 0.8;
*/
system new_hive_desert = Q[ENERGY-1]<1> | WB[ENERGY-1, 0]<40>  | H<0> |
N<40>             | F[0,1]<10>;
system old_hive_desert = Q[ENERGY-1]<1> | WB[ENERGY-1, 0]<200> | H<0> |
N<FOOD_STORAGE/2> | F[0,1]<10>;

/*
Savanna biome: very few flowers, a temperate and dry climate;

Params:
    temperature = 31;
    rainfall_rate = 1;
    humidity = 1;
    flowers_biodiversity = 1 ;
    pesticide_exposure_rate = 0.0; 0.8;
*/
system new_hive_savanna = Q[ENERGY-1]<1> | WB[ENERGY-1, 0]<40>  | H<0> |
N<40>             | F[0,1]<10>;
system old_hive_savanna = Q[ENERGY-1]<1> | WB[ENERGY-1, 0]<200> | H<0> |
N<FOOD_STORAGE/2> | F[0,1]<10>;

/*
Taiga biome: few flowers, a cool and dry climate;

Params:
    temperature = 22;
    rainfall_rate = 1;
    humidity = 1;
    flowers_biodiversity = 1 ;
    pesticide_exposure_rate = 0.0; 0.8;
*/
system new_hive_taiga = Q[ENERGY-1]<1> | WB[ENERGY-1, 0]<40>  | H<0> |
N<40>             | F[0,1]<400>;
system old_hive_taiga = Q[ENERGY-1]<1> | WB[ENERGY-1, 0]<200> | H<0> |
N<FOOD_STORAGE/2> | F[0,1]<400>;
```

```
/* -------------------------- Wetland biomes ---------------------------- */

/*
Jungle biome: many flowers, a hot and wet climate;

Params:
    temperature = 40;
    rainfall_rate = 1;
    humidity = 9;
    flowers_biodiversity = 3 ;
    pesticide_exposure_rate = 0.0; 0.8;
*/
system new_hive_jungle = Q[ENERGY-1]<1> | WB[ENERGY-1, 0]<40>  | H<0> |
N<40>             | F[0,1]<300> | F[1,1]<300> | F[2,1]<300>;
system old_hive_jungle = Q[ENERGY-1]<1> | WB[ENERGY-1, 0]<200> | H<0> |
N<FOOD_STORAGE/2> | F[0,1]<300> | F[1,1]<300> | F[2,1]<300>;

/*
Swamp biome: many flowers, a hot and wet climate;

Params:
    temperature = 31;
    rainfall_rate = 1;
    humidity = 9;
    flowers_biodiversity = 3 ;
    pesticide_exposure_rate = 0.0; 0.8;
*/
system new_hive_swamp = Q[ENERGY-1]<1> | WB[ENERGY-1, 0]<40>  | H<0> |
N<40>             | F[0,1]<200> | F[1,1]<200> | F[2,1]<200>;
system old_hive_swamp = Q[ENERGY-1]<1> | WB[ENERGY-1, 0]<200> | H<0> |
N<FOOD_STORAGE/2> | F[0,1]<200> | F[1,1]<200> | F[2,1]<200>;

/*
Mangrove Swamp biome: very few flowers, a hot and wet climate;

Params:
    temperature = 31;
    rainfall_rate = 1;
    humidity = 9;
    flowers_biodiversity = 3 ;
    pesticide_exposure_rate = 0.0; 0.8;
*/
system new_hive_mangrove_swamp = Q[ENERGY-1]<1> | WB[ENERGY-1, 0]<40>  | H<0>
| N<40>             | F[0,1]<3> | F[1,1]<3> | F[2,1]<3>;
system old_hive_mangrove_swamp = Q[ENERGY-1]<1> | WB[ENERGY-1, 0]<200> | H<0>
| N<FOOD_STORAGE/2> | F[0,1]<3> | F[1,1]<3> | F[2,1]<3>;
```

```
/*
Frozen River biome: many flowers, a cool and wet climate;

Params:
    temperature = 22;
    rainfall_rate = 1;
    humidity = 9;
    flowers_biodiversity = 3 ;
    pesticide_exposure_rate = 0.0; 0.8;
*/
system new_hive_frozen_river = Q[ENERGY-1]<1> | WB[ENERGY-1, 0]<40>  | H<0> |
N<40>             | F[0,1]<200> | F[1,1]<200> | F[2,1]<200>;
system old_hive_frozen_river = Q[ENERGY-1]<1> | WB[ENERGY-1, 0]<200> | H<0> |
N<FOOD_STORAGE/2> | F[0,1]<200> | F[1,1]<200> | F[2,1]<200>;

/* ------------------------- Temperate biomes --------------------------- */

/*
Plains biome: many flowers, hot and temperate climate;

Params:
    temperature = 40;
    rainfall_rate = 1;
    humidity = 5;
    flowers_biodiversity = 2 ;
    pesticide_exposure_rate = 0.0; 0.8;
*/
system new_hive_plains = Q[ENERGY-1]<1> | WB[ENERGY-1, 0]<40>  | H<0> |
N<40>             | F[0,1]<400> | F[1,1]<400>;
system old_hive_plains = Q[ENERGY-1]<1> | WB[ENERGY-1, 0]<200> | H<0> |
N<FOOD_STORAGE/2> | F[0,1]<400> | F[1,1]<400>;

/*
Stony plains biome: very few flowers, and temperate climate;

Params:
    temperature = 31;
    rainfall_rate = 1;
    humidity = 5;
    flowers_biodiversity = 3 ;
    pesticide_exposure_rate = 0.0; 0.8;
*/
system new_hive_stony_plains = Q[ENERGY-1]<1> | WB[ENERGY-1, 0]<40>  | H<0> |
N<40>             | F[0,1]<3> | F[1,1]<3> | F[2,1]<3>;
system old_hive_stony_plains = Q[ENERGY-1]<1> | WB[ENERGY-1, 0]<200> | H<0> |
N<FOOD_STORAGE/2> | F[0,1]<3> | F[1,1]<3> | F[2,1]<3>;
```

```
/*
Flower Forest biome: a lot of flowers, and temperate climate;

Params:
    temperature = 31;
    rainfall_rate = 1;
    humidity = 5;
    flowers_biodiversity = 3 ;
    pesticide_exposure_rate = 0.0; 0.8;
*/
system new_hive_flower_forest = Q[ENERGY-1]<1> | WB[ENERGY-1, 0]<40>  | H<0> |
N<40>             | F[0,1]<400> | F[1,1]<400> | F[2,1]<400>;
system old_hive_flower_forest = Q[ENERGY-1]<1> | WB[ENERGY-1, 0]<200> | H<0> |
N<FOOD_STORAGE/2> | F[0,1]<400> | F[1,1]<400> | F[2,1]<400>;

/*
Stony Peaks biome: few flowers, a cool and temperate climate;

Params:
    temperature = 22;
    rainfall_rate = 1;
    humidity = 5;
    flowers_biodiversity = 2 ;
    pesticide_exposure_rate = 0.0; 0.8;
*/
system new_hive_stony_peaks = Q[ENERGY-1]<1> | WB[ENERGY-1, 0]<40>  | H<0> |
N<40>             | F[0,1]<250> | F[1,1]<250>;
system old_hive_stony_peaks = Q[ENERGY-1]<1> | WB[ENERGY-1, 0]<200> | H<0> |
N<FOOD_STORAGE/2> | F[0,1]<250> | F[1,1]<250>;

/* ---------------------------- Mixed biomes ------------------------------ */

/*
Desert x Flower Forest biome: a lot of flowers, a dry and hot climate;

Params:
    temperature = 40;
    rainfall_rate = 1;
    humidity = 1;
    flowers_biodiversity = 2 ;
    pesticide_exposure_rate = 0.0; 0.8;
*/
system new_hive_desert_x_flower_forest = Q[ENERGY-1]<1> | WB[ENERGY-1,
0]<40>  | H<0> | N<40>             | F[0,1]<600> | F[1,1]<600>;
system old_hive_desert_x_flower_forest = Q[ENERGY-1]<1> | WB[ENERGY-1, 0]<200>
| H<0> | N<FOOD_STORAGE/2> | F[0,1]<600> | F[1,1]<600>;
```

```
/*
Flower Forest x Desert biome: very few flowers, and temperate climate;

Params:
    temperature = 31;
    rainfall_rate = 1;
    humidity = 5;
    flowers_biodiversity = 1 ;
    pesticide_exposure_rate = 0.0; 0.8;
*/
system new_hive_flower_forest_x_desert = Q[ENERGY-1]<1> | WB[ENERGY-1,
0]<40>  | H<0> | N<40>             | F[0,1]<10>;
system old_hive_flower_forest_x_desert = Q[ENERGY-1]<1> | WB[ENERGY-1, 0]<200>
| H<0> | N<FOOD_STORAGE/2> | F[0,1]<10>;


/* ----------------------------------------------------------------------- *\
/*                              REFERENCES                                 *\
/* ----------------------------------------------------------------------- *\

CAPTION:
    (**) - Inaccesible;

/* ---------------------------- Articles -------------------------------- */
/*
a) Temperature-driven changes in viral loads in the honey bee Apis mellifera
    https://www.sciencedirect.com/science/article/pii/S0022201118302155

b) Summer weather conditions influence winter survival of honey bees (Apis
mellifera) in the northeastern United States
    https://www.nature.com/articles/s41598-021-81051-8#Tab2

c) The Effect of Supplementary Feeding with Different Pollens in Autumn on
Colony Development under Natural Environment
    https://www.mdpi.com/2075-4450/13/7/588?type=check_update&version=2#

d) Behavioural Effects of Pesticides in Bees
    https://link.springer.com/article/10.1023/A:1022575315413

e) Nectar Sugar Composition and Volumes of 47 Species of Gentianales from a
Southern Ecuadorian Montane Forest
    https://www.ncbi.nlm.nih.gov/pmc/articles/PMC2803417/

> Others:
    https://www.nature.com/articles/s41598-023-32824-w
    (**) https://link.springer.com/article/10.1007/s10980-023-01638-6
*/
```

```
/* ----------------------------- Websites --------------------------------- */

/*
Apis mellifera: https://animalivolanti.it/insetti/api-miele

https://bee-health.extension.org:
    (1) https://bee-health.extension.org/honey-bee-nutrition/

https://www.legambientefaenza.it:
    (2) https://www.legambientefaenza.it/storie-di-api/2021/07/dal-nettare-al-
miele/
    (3) https://www.legambientefaenza.it/storie-di-api/2021/05/quanto-nettare-
trasporta-unape/

https://beekeepclub.com
    (4) https://beekeepclub.com/how-honeybees-maintain-temperature-and-
humidity-in-a-beehive/

https://blog.3bee.com/
    (5) https://blog.3bee.com/api-produrre-il-miele/

> Others:
    https://www.apisole.it/index.php/forum/apicoltura-in-pillole/76-
impollinazione-quanto-vale
*/
```

Simulations

The following simulations take place in 1000-time units with a delta time of 1 unit and replica 50, in order to make the simulation more general.

For each simulation, we collect summary statistics of the various related measures:

- The number of workers;
- The number of dead workers;
- The number of born workers;
- The ratio between dead and born workers;
- The produced honey;
- The nectar in the storage;
- The number flower with available nectar;
- The number of infected workers;
- The quantity of nectar used for food and produce honey;

During the simulation the temperature, humidity, rainfall, biodiversity of flowers, and exposure to pesticides parameters do not change.

Let us consider 10 simulations, a small part of the possible simulations. The simulations are defined by biome names that characterise their parameter values and a defined initial configuration of the species: for example, the jungle biome is defined as follows.

```
/*
Jungle biome: many flowers, a hot and wet climate;

Params:
    temperature = 40;
    rainfall_rate = 1;
    humidity = 9;
    flowers_biodiversity = 3 ;
    pesticide_exposure_rate = 0.0; 0.8;
*/
system new_hive_jungle = Q[ENERGY-1]<1> | WB[ENERGY-1, 0]<40>  | H<0> | N<40> |
F[0,1]<300> | F[1,1]<300> | F[2,1]<300>;

system old_hive_jungle = Q[ENERGY-1]<1> | WB[ENERGY-1, 0]<200> | H<0> |
N<FOOD_STORAGE/2> | F[0,1]<300> | F[1,1]<300> | F[2,1]<300>;
```

Five charts have been defined for each simulation:

1. **Honey:** describe the amount of honey produced.
2. **Bees:** represent the number of workers in the hive; there are also the dead workers and born workers.
3. **Poisoned workers:** the number of workers infected with pesticides.
4. **Nectar storage:** the amount of nectar stored in the hive; there is also the quantity of nectar used to produce honey.
5. **Flowers with nectar available:** the number of flowers with available nectar

Desert

We will define three simulations concerning the **desert biome**: two with an old hive and the param *pesticide_exposure_rate* set to 0 and 0.8; and another with a new hive.

This is the system configuration and the parameters values:

```
/*
Desert biome: very few flowers, a hot and dry climate;

Params:
    temperature = 40;
    rainfall_rate = 1;
    humidity = 1;
    flowers_biodiversity = 1 ;
    pesticide_exposure_rate = 0.0; 0.8;
*/
system new_hive_desert = Q[ENERGY-1]<1> | WB[ENERGY-1, 0]<40>  | H<0> |
N<40> | F[0,1]<10>;

system old_hive_desert = Q[ENERGY-1]<1> | WB[ENERGY-1, 0]<200> | H<0> |
N<FOOD_STORAGE/2> | F[0,1]<10>;
```

We begin by analysing the case of a **new beehive** located in the desert biome. The hive consists of 40 bees and has 40 nectar units. As we can see from the graphs in *FIGURE 1*, the simulation is very fast as the combination of high temperature and food scarcity causes the hive to die very quickly. As might be expected, honey production is almost zero.

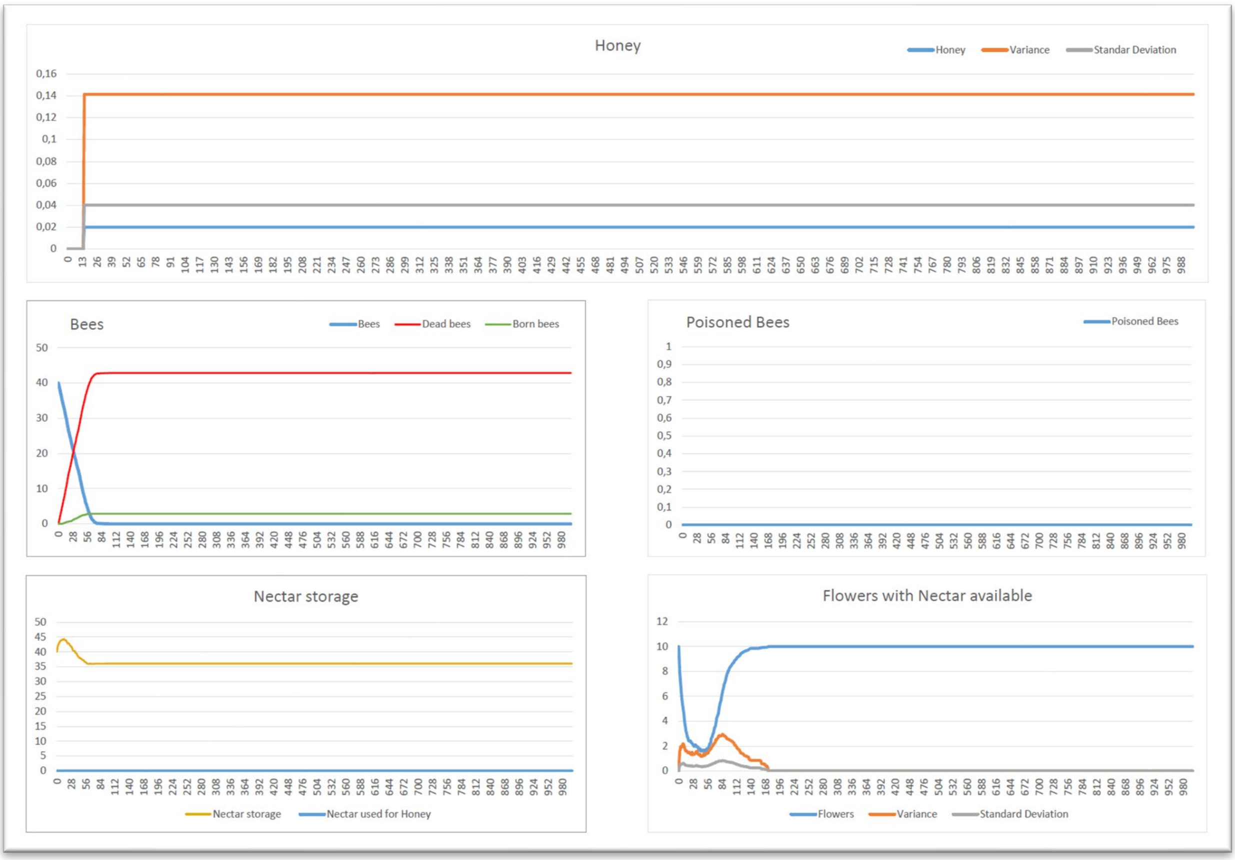


Figure 1 - New hive in a desert biome

Let us now analyse the case where an **old hive** is located in the desert biome. The hive consists of 200 bees and has half the maximum nectar storage, in this case 500. As we can see from the graphs in *FIGURE 2*, the high temperature means that the hive cannot grow. However, in contrast to the first case, the abundance of nectar present at the beginning of the simulation allows for a greater survival of the hive, due to the fact that the queen bee is able to generate more workers in the presence of sufficient food. As might be expected, honey production is very limited even in the presence of sufficient nectar; this due to the low humidity that makes the honey production process difficult.

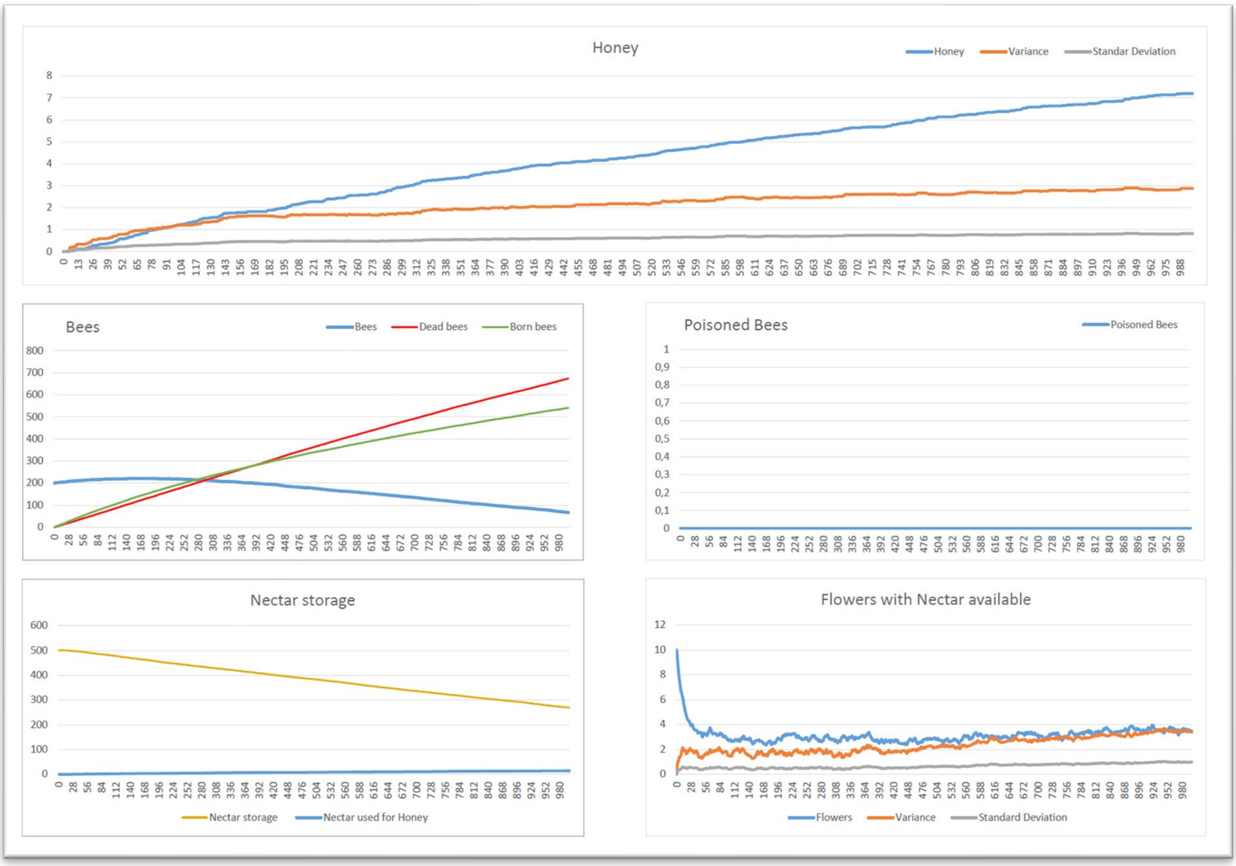


Figure 2 - Old hive in a desert biome

Let us therefore analyse the possible presence of **pesticides** in the desert biome in the presence of an **old hive**. As we can see from the graphs in *FIGURE 3*, production is almost unchanged compared to the previous case, because it is greatly influenced by the low humidity. On the other hand, the health of the bees in the hive is different. In fact, we can see that the hive degenerates much faster than in the previous case, because despite the good quantity of food, the high temperatures and the presence of pesticides have a great influence on the life span of a bee. All this leads to an early death of the hive.

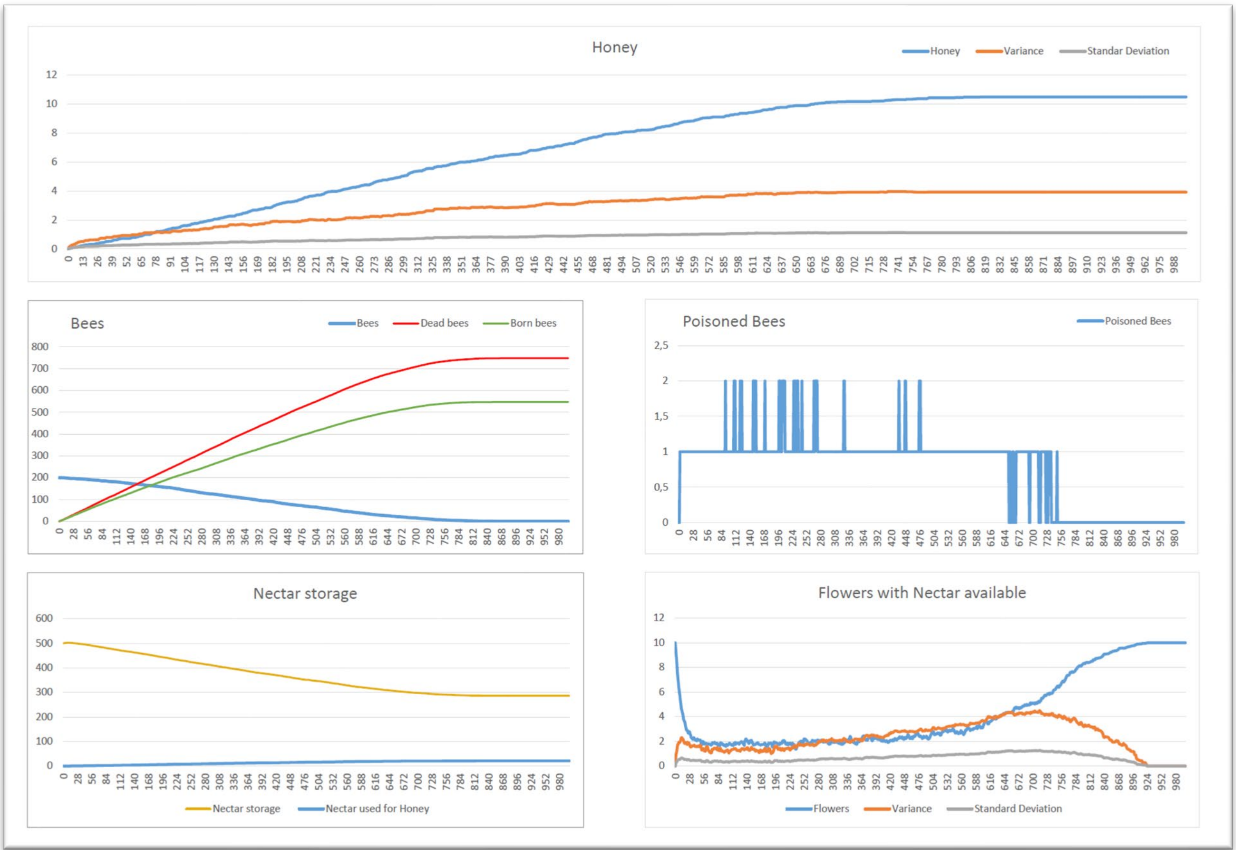


Figure 3 - Old hive in a desert biome with pesticide

Savanna

We will define two simulations concerning the **savanna biome**: one with the param *pesticide_exposure_rate* set to 0; and another set to 0.8. Both simulations are performed with an old hive.

This is the system configuration and the parameters values:

```
/*
Savanna biome: very few flowers, a temperate and dry climate;

Params:
    temperature = 31;
    rainfall_rate = 1;
    humidity = 1;
    flowers_biodiversity = 1 ;
    pesticide_exposure_rate = 0.0; 0.8;
*/
system old_hive_savanna = Q[ENERGY-1]<1> | WB[ENERGY-1, 0]<200> | H<0> |
N<FOOD_STORAGE/2> | F[0,1]<10>;
```

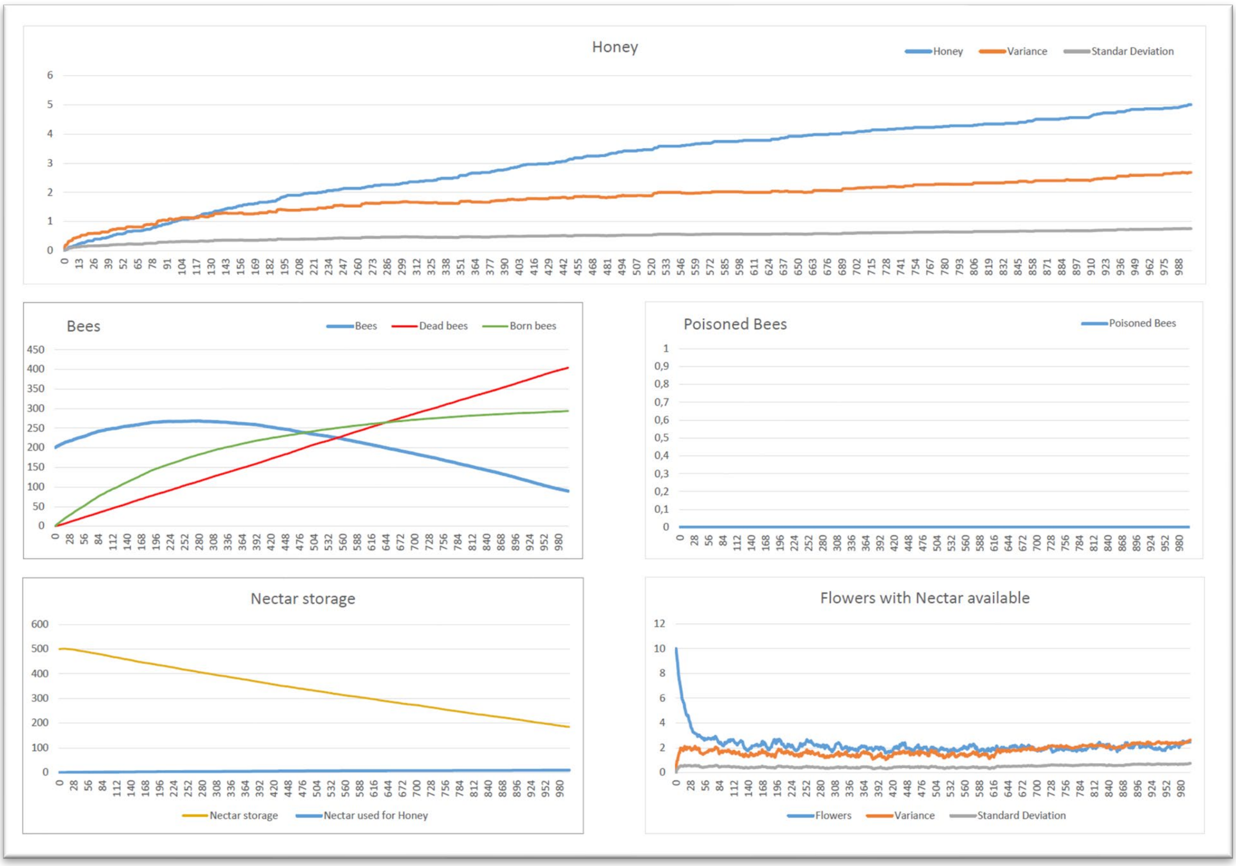


Figure 4 - Old hive in a savanna biome

Let us therefore analyse the behaviour of an old hive in the savannah biome both in the presence and absence of pesticides. As we can see in both cases, honey production is very limited despite the good quantity of food, this being due to the low humidity that characterises the biome. The excellent temperature allows better bee survival, unlike the cases analysed in the desert biome. However, the scarcity of food does not allow hive growth.

The survival of bees in the two simulations is markedly different: the impact of pesticides is very high, which is why we can see in the diagrams in *FIGURE 5* how the hive dies before the end of the simulation.

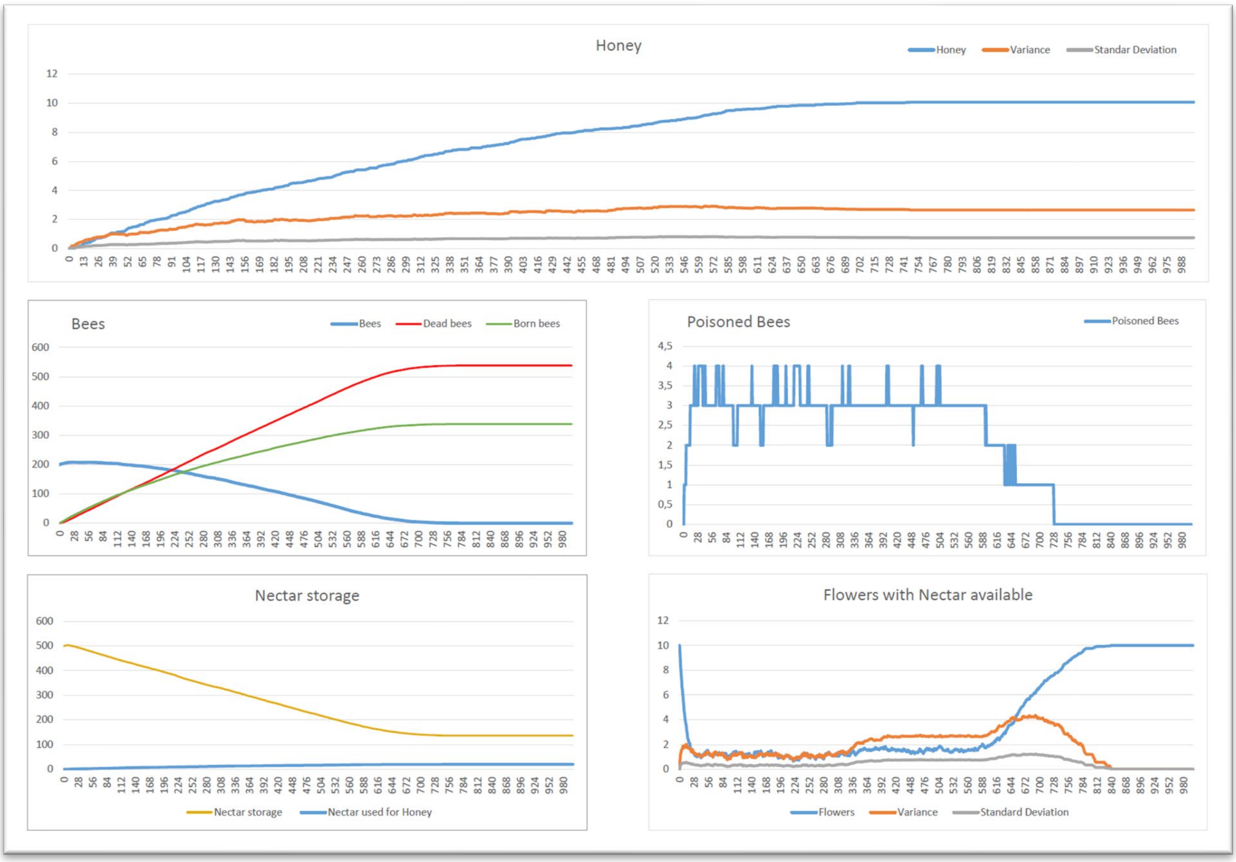


Figure 5 - Old hive in a savanna biome with pesticide

Taiga

We will define one simulation concerning the **taiga biome**: set *pesticide_exposure_rate* to 0.

This is the system configuration and the parameters values:

```
/*
Taiga biome: few flowers, a cool and dry climate;

Params:
    temperature = 22;
    rainfall_rate = 1;
    humidity = 1;
    flowers_biodiversity = 1 ;
    pesticide_exposure_rate = 0.0;
*/
system old_hive_taiga = Q[ENERGY-1]<1> | WB[ENERGY-1, 0]<200> | H<0> |
N<FOOD_STORAGE/2> | F[0,1]<400>;
```

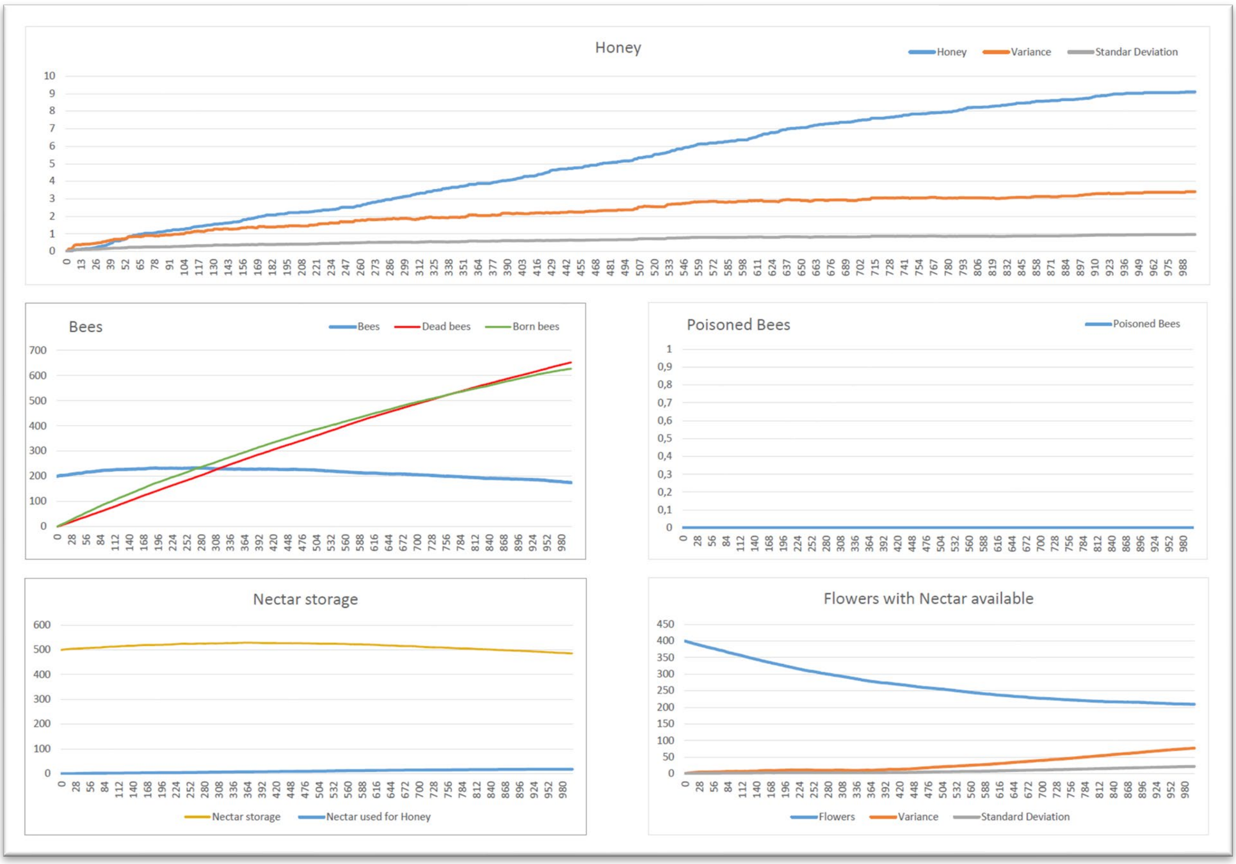


Figure 6 – Old hive in a taiga biome

Let us now analyse the case where an old hive is located in the taiga biome. The hive consists of 200 bees and has half the maximum nectar storage, in this case 500. As we can see from the graphs in *FIGURE 6*, the low temperature means that the hive cannot grow. However, the abundance of nectar present at the beginning of the simulation allows for a good survival of the hive, due to the fact that the queen bee is able to generate more workers in the presence of sufficient food. As might be expected, honey production is very limited even in the presence of sufficient nectar; this is mainly due to the low humidity that makes the honey production process difficult.

By comparing this simulation and those that occurred in the desert (both have an unfavourable temperature and humidity) we can see how the greater quantity of flowers allows the hive to maintain the population constant.

Flower Forest

We will define two simulations concerning the **flower forest biome**: one with a new hive characterized by 40 workers and 40 units of nectar; and another with and old hive characterized by 200 workers and 500 units of nectar.

This is the systems configuration and the parameters values:

```
/*
Flower Forest biome: a lot of flowers, and temperate climate;

Params:
    temperature = 31;
    rainfall_rate = 1;
    humidity = 5;
    flowers_biodiversity = 3 ;
    pesticide_exposure_rate = 0.0;
*/
system new_hive_flower_forest = Q[ENERGY-1]<1> | WB[ENERGY-1, 0]<40> | H<0> |
N<40> | F[0,1]<400> | F[1,1]<400> | F[2,1]<400>;

system old_hive_flower_forest = Q[ENERGY-1]<1> | WB[ENERGY-1, 0]<200> | H<0> |
N<FOOD_STORAGE/2> | F[0,1]<400> | F[1,1]<400> | F[2,1]<400>;
```

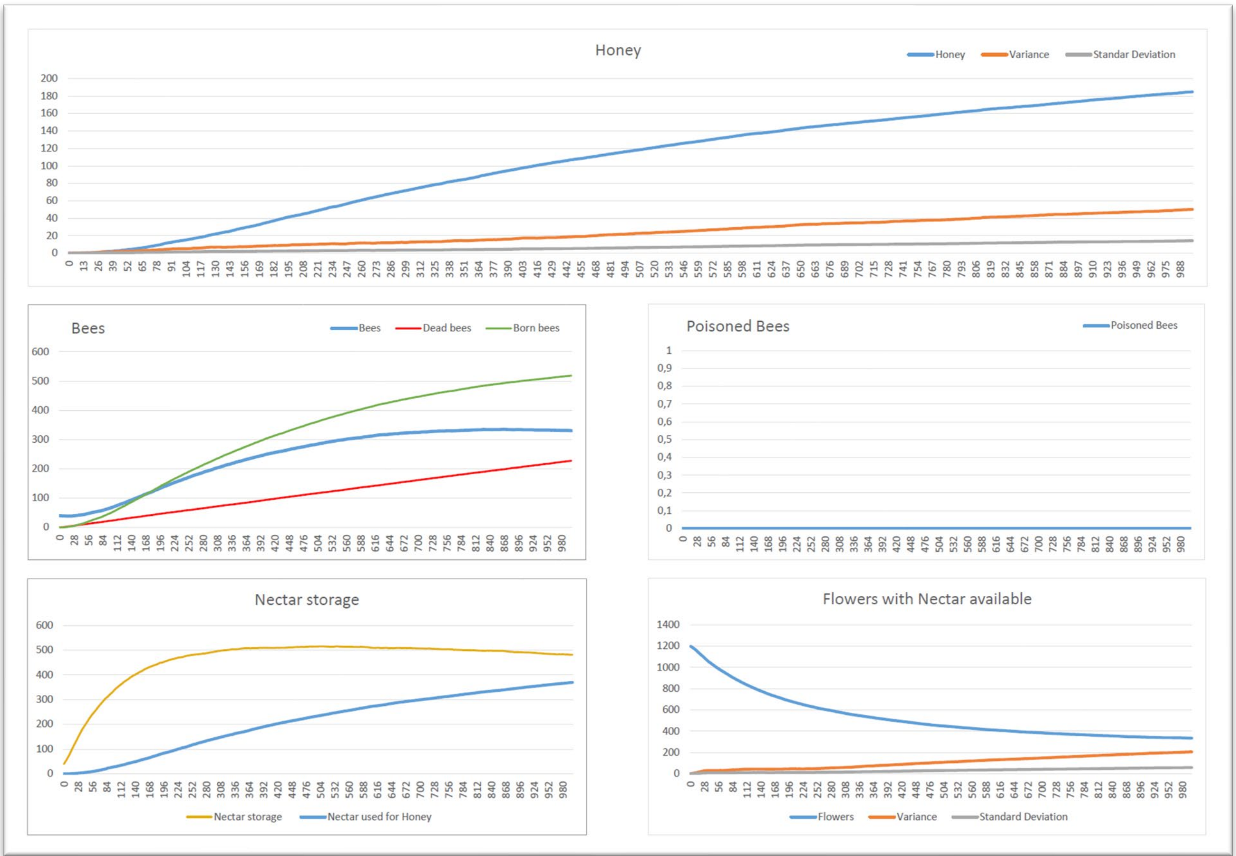


Figure 7- New hive in a flower forest biome

Both simulations take place in the flower forest biome characterized by excellent temperature, humidity, biodiversity, and a high number of flowers. This ecosystem is an excellent environment for the survival of the beehive and honey production. As we can see in both the graphs in *FIGURE 7* and *FIGURE 8*, unlike the previous simulations, the number of bees and honey production are significantly higher.

Let's analyse the differences between these two simulations. The first difference is in the amount of honey produced. We go from about 190 units of honey produced by a new beehive to about 250 units for the old beehive. We have an increase of 30% between the first and second case.

Another difference is obviously the number of bees in the hive. While the ratio of dead bees to born bees is constant for both simulations, as you can imagine, the number of bees in the new hive at the end of the simulation is lower than that in the old hive, given the initial difference in bees. However, we can note how the growth in the new hive is proportionally faster.

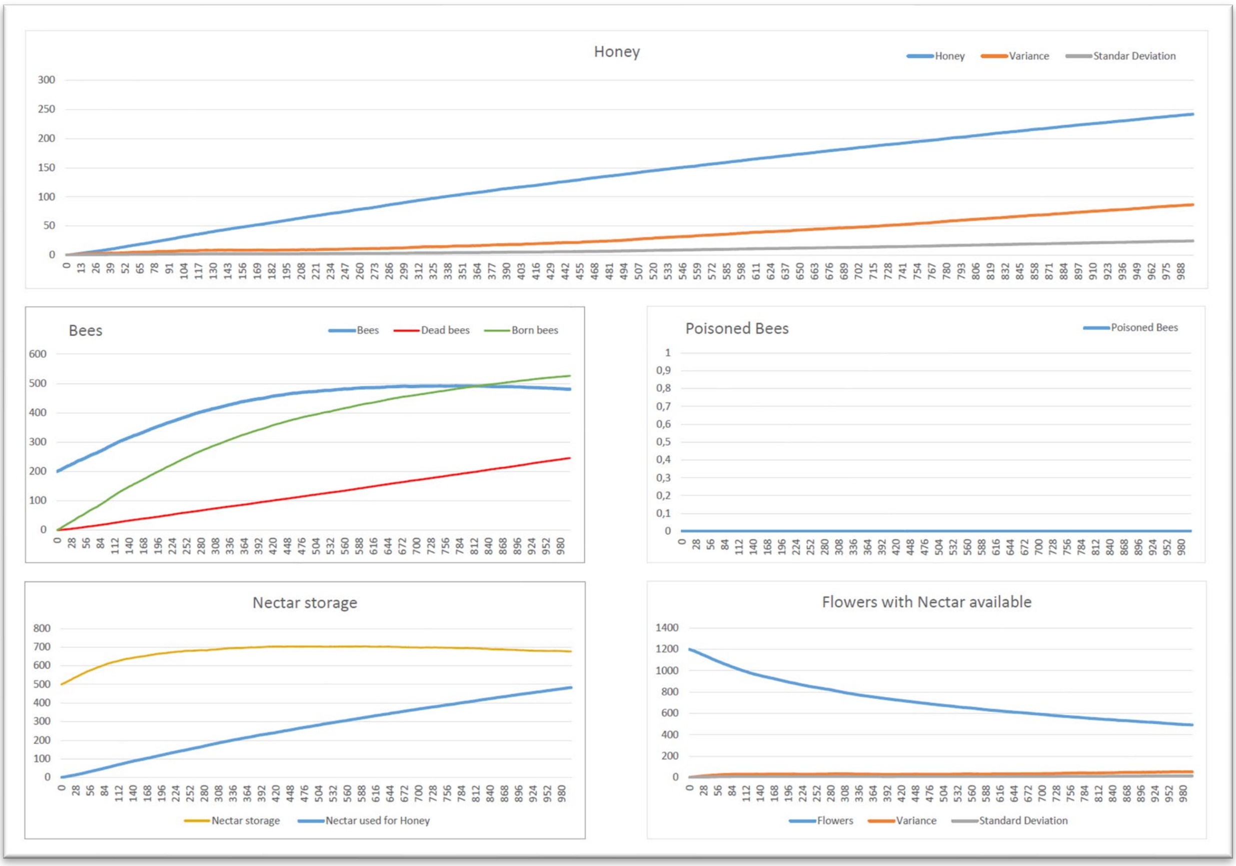


Figure 8 - Old hive in a flower forest biome

Stony plains

We will define two simulations concerning the **stony plains biome**: one with a new hive characterized by 40 workers and 40 units of nectar; and another with and old hive characterized by 200 workers and 500 units of nectar.

This is the systems configuration and the parameters values:

```
/*
Stony plains biome: very few flowers, and temperate climate;

Params:
    temperature = 31;
    rainfall_rate = 1;
    humidity = 5;
    flowers_biodiversity = 3 ;
    pesticide_exposure_rate = 0.0;
*/
system new_hive_flower_forest = Q[ENERGY-1]<1> | WB[ENERGY-1, 0]<40>  | H<0> |
N<40> | F[0,1]<3> | F[1,1]<3> | F[2,1]<3>;

system old_hive_flower_forest = Q[ENERGY-1]<1> | WB[ENERGY-1, 0]<200> | H<0> |
N<FOOD_STORAGE/2> | F[0,1]<3> | F[1,1]<3> | F[2,1]<3>;
```

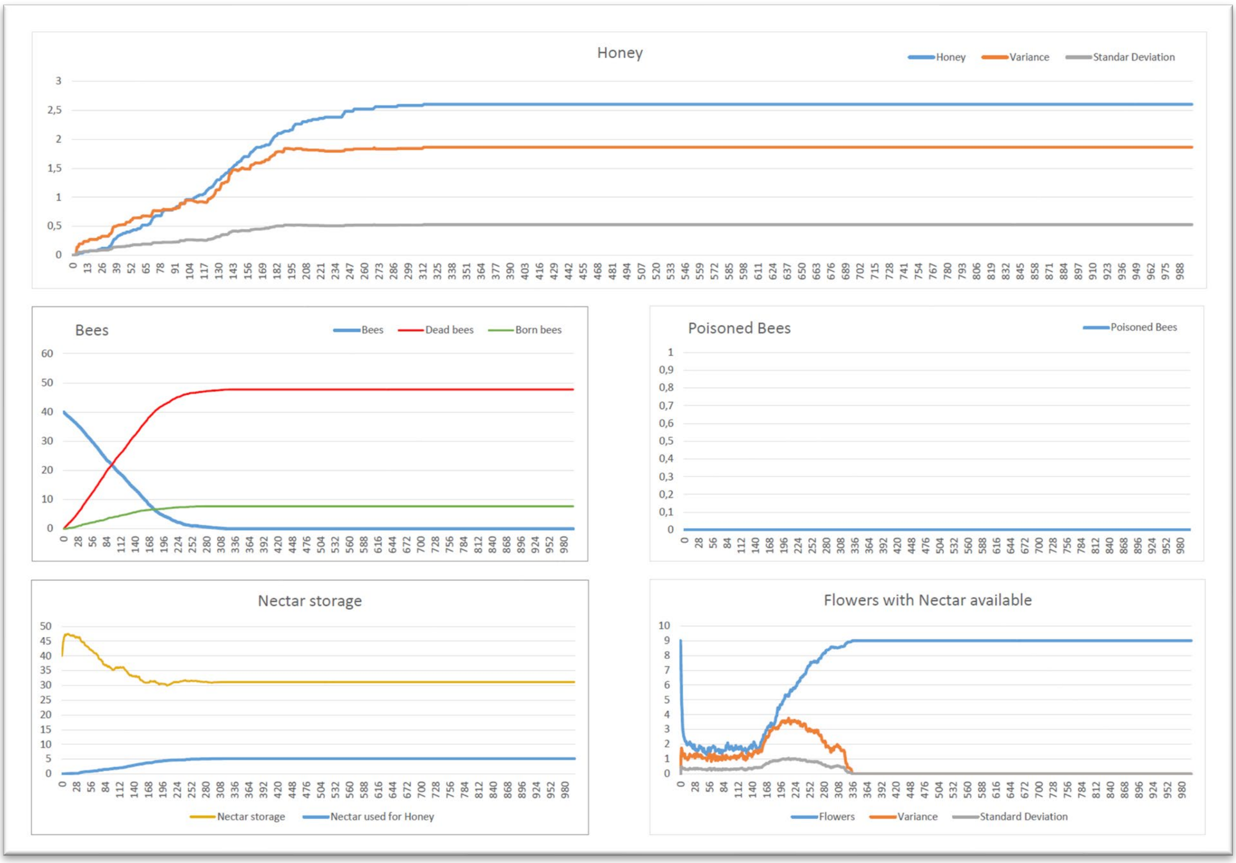


Figure 9 - New hive in stony plains biome

Let's analyse these last two simulations, starting with the new beehive. As we can see in the graphs in *FIGURE 9*, despite the excellent environmental conditions, the scarcity of flowers greatly impacts the survival of bees. A new beehive with a limited amount of stored nectar will not survive if there are not enough flowers present (we can consider the previous case of the flower forest). We can also see that honey production is very low; this is due to the fact that there is not enough nectar available and there are not enough bees present.

On the other hand, the condition of an old beehive is different. Being able to rely on a good amount of stored nectar, the beehive can survive for the entire duration of the simulation and also produce a good amount of honey despite the environment providing little availability of flowers. Of course, the beehive can survive, but as we can see from the graphs in *FIGURE 10*, the curve that describes the number of bees in the beehive has a downward trend. Additionally, we can see that after time unit 800, the number of dead bees exceeds that of born bees. This suggests that with a longer simulation time, the beehive will likely die.

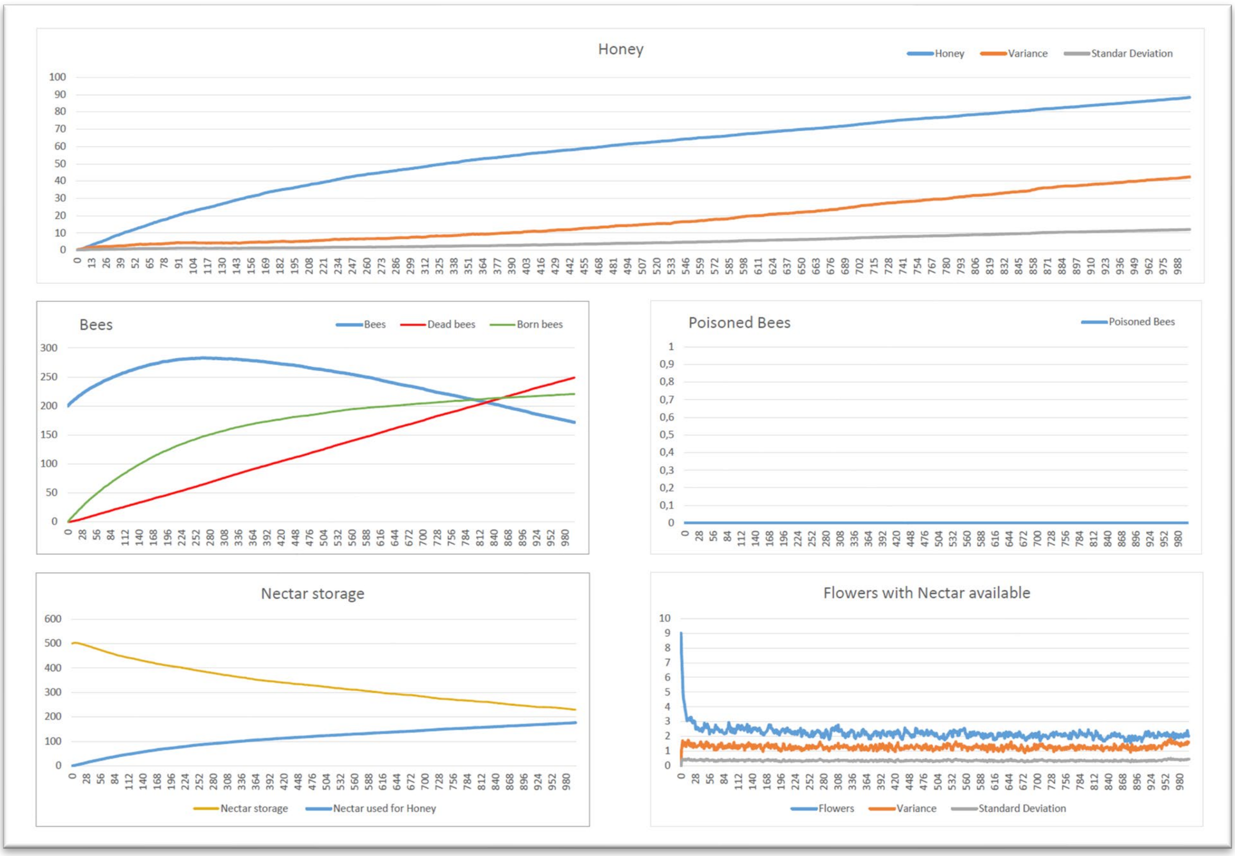


Figure 10 - Old hive in stony plains biome

Conclusion

From the simulations we have analysed, it is possible to see how a very determining factor is the number of flowers present in the environment. As we can see by comparing the simulations of the taiga biome and the savannah biome, despite the unfavourable temperature of the former, it presents a greater likelihood of survival for bees. This is evident by looking at the ratio of live to dead bees in the two simulations.

Regarding honey production, the humidity of the environment is very important. By comparing the simulation in the taiga biome and that of the flower forest, we can understand that despite the good number of flowers and the good amount of stored nectar, the low humidity does not allow for honey production.

As already mentioned, the ones seen above are just some of the many possible simulations that can be tested by combining the different values of the various parameters. The model provides other examples of biomes that can be simulated, and even more can be created.

References

Articles:

a) Temperature-driven changes in viral loads in the honey bee Apis mellifera

https://www.sciencedirect.com/science/article/pii/S0022201118302155

b) Summer weather conditions influence winter survival of honey bees (Apis mellifera) in the northeastern United States

https://www.nature.com/articles/s41598-021-81051-8#Tab2

c) The Effect of Supplementary Feeding with Different Pollens in Autumn on Colony Development under Natural Environment

https://www.mdpi.com/2075-4450/13/7/588?type=check_update&version=2#

d) Behavioural Effects of Pesticides in Bees

https://link.springer.com/article/10.1023/A:1022575315413

e) Nectar Sugar Composition and Volumes of 47 Species of Gentianales from a Southern Ecuadorian Montane Forest

https://www.ncbi.nlm.nih.gov/pmc/articles/PMC2803417/

Websites:

Apis mellifera: https://animalivolanti.it/insetti/api-miele

(1) https://bee-health.extension.org/honey-bee-nutrition/

(2) https://www.legambientefaenza.it/storie-di-api/2021/07/dal-nettare-al-miele/

(3) https://www.legambientefaenza.it/storie-di-api/2021/05/quanto-nettare-trasporta-unape/

(4) https://beekeepclub.com/how-honeybees-maintain-temperature-and-humidity-in-a-beehive/

(5) https://blog.3bee.com/api-produrre-il-miele/