Model Description :

The model description follows the **ODD (Overview, Design concepts, Details)** protocol for describing agent-based models (Grimm et al., 2010, 2006). The model was implemented in NetLogo 6.0.2(Wilensky, 1999) and the program used to simulate the wolf - rabbit population is available in the Supplementary Material.

Purpose :

The proximate purpose of the model is to study and observe the impact of reproductive isolation in the population dynamics of an isolated ecosystem.It aims to answer how the species of the crossbreed offspring would be decided on the amount of genes inherited from the particular parent species and how natural selection plays a role in deciding the dominant and recessive traits. The ultimate aim of the model presented is to study the change in genetic structure of a particular species living in the natural ecosystem due to reproductive isolation.

-- Entities, State variables and Scales

Model entities are the square spatial units or habitat cells comprising the landscape, grass, black and brown rabbits with territories.These are characterised by five continuous state variables “energy, run speed, vision, reproduction cost and dosage”. Also an external dynamic agent, wolves, to take control over the rabbits population. The RII count refers to the liberty of inter-breeding: 0 means complete liberty and 100 means complete restriction. One time step of the model represents the time in which all individuals have randomly chosen another individual and possibly interacted with it. Simulations run until one of the rabbit or the wolf species population becomes extinct or zero.

Factors to add randomness in the model:.

- Genetic Drift - A sudden change in the genetic patterns across a species
- Natural Selection - Advantage due to a natural trait that prefers survival
- Mutation - A complete alteration in a particular trait of a subspecies
- Dominant Traits - Trait domination as explained in the mendelian theory

R1	Initial number of white rabbit
R2	Initial number of black rabbit
W	Initial number of wolves
R1e	Initial energy of white rabbit
R2e	Initial energy of black rabbit
We	Initial energy of wolf
R1r	Running speed of white rabbit
R2r	Running speed of black rabbit
Wr	Running speed of wolf
Wv	Wolf vision range
R1v	White rabbit vision range
R2v	Black rabbit vision range
R1g	Energy gain from food for white rabbit
R2g	Energy gain from food for black rabbit

Wg	Energy gain from food for wolf
RII	Reproductive Isolation Index

Process overview and scheduling :

Each time step the following processes are processed in the given order.Model entities are processed in a random-ized order, unless stated otherwise, and changes in state variables are updated immediately. The submodels implementing these processes are described in detail below in the submodels section. There are mutual links between wolves and rabbits which have to be updated every time if the rabbit dies, flees away or the wolf dies.

#Chasing :

```
Wolves have a vision range, and if they see a rabbit in that
range, they start running towards them. Similarly, rabbits
have a vision range and if they see a wolf in that range they
start running away.

chasing() :

If(rabbits in radius of vision wolf) :
    -- eat-rabbit()
If(wolves in radius of vision rabbit):
    -- flee-from-predator()
```

#Reproduce - Wolf :

```
Having sufficient energy , wolves start looking for mates in
specific radius to reproduce new ones.

reproduce(agentset of wolves in the x meter radius of the
function caller wolf):
-- The agentset consists of wolves breed here
```

```
Mate = random wolf from the agentset

If(energy of mate > wolf-reproduction-cost) and (Mate!=nobody):
     -- energy of caller wolf = energy - reproduction cost
    -- energy of mate = energy - reproduction cost
    -- produce a new wolf
    -- set the initial energy

end function
```

#Reproduce - Rabbit :

Having sufficient energy , rabbits start looking for mates in specific radius to reproduce new ones. Since there are two breeds or species of rabbits they can interbreed or even crossbreed with other rabbits.

```
reproduce(agentset of rabbits in the x meter radius of the
function caller rabbit):
-- The agentset consists of rabbits of both breeds here

Final_rabbit = random rabbit from the agentset
If breed(final_rabbit) != breed(caller object rabbit):
     -- cross-breed case
     -- Here crossbreed success probability is seen
     -- Crossbreed_ratio = x% say suppose
     temp_num = random number from 1 to 100
     If (temp_num > crossbreed_ratio):
          -- Hatch one offspring of crossbreed
          -- It’s genetic traits will be decided
          -- randomly based on parent’s dominant trait
          -- e.g out of five traits, trait 1,2,4 may be
          -- copied from parent 1 and 3,5 from parent 2
          -- since breed 1 has 1,2,4 dominant traits and
          -- breed 2 has 3,5 dominant traits.
          -- Based on which parent got more similarity,
          -- The breed of child is decided as 1 or 2.
```

```
          -- We need to write a function for this
     Set energy of both parents = energy - cost of mating
Else:
     -- same breed case
     -- even here the two parents may be of same breed but
     -- some of their traits may vary, so the child breed
     -- is fixed here, but traits are decided in the same manner
     -- as done in the crossbreed case. Just the breed is fixed
     -- unlike the earlier case.

end function
```

#Flee-from-predator :

Rabbits have a vision range, and if they see a wolf in that range they start running in the opposite direction to flee away from the predator.

```
flee-from-predator():

If(wolves in radius vision):
   -- Link with one of wolves
   -- turn in opposite direction
   -- start running away
   -- set run-speed = run-speed *(1 - grass-amount/10),
because the more the grass , it will be more difficult to
run.
```

#Eat - Grass :

Rabbits have a fixed amount of grass to eat(rabbit-dosage) to gain energy.

```
eat-grass():

If(grass-amount > dosage):
    -- set grass-amount = grass-amount -  dosage
```

```
    -- set energy = energy + energy-from-grass
Else: (since grass is less than needed ,so the rabbit will
eat less)
    -- set v = energy-from-grass * (grass-amount/dosage)
    -- set energy = energy + v
    -- set grass-amount = 0
```

#Eat - Rabbit :

Wolves have a vision range, and if they see a rabbit in that range, they start running towards them , in order to hunt them down.

```
eat-rabbits():

If(link=0) && (rabbits in radius vision) :
      -- link to rabbit with energy less than wolf energy
      If(breed of rabbit = rabbit1):
         -- set energy = energy + energy-from-rabbit1
      Else:
         -- set energy = energy + energy-from-rabbit2
     If(daytime=true):
         --link with black rabbit
     Else:
         --link with brown rabbit
     chase()
     -- die rabbit
```

#Trait - Selection :

For crossbreeding and genetic mutation, we are performing trait - selection in our model. Each breed of rabbit has three traits; run-speed, vision, reproduction - cost.

```
trait-selection():
     -- randomly we are selecting dominant traits, i.e.
        which breed has dominant traits for
```

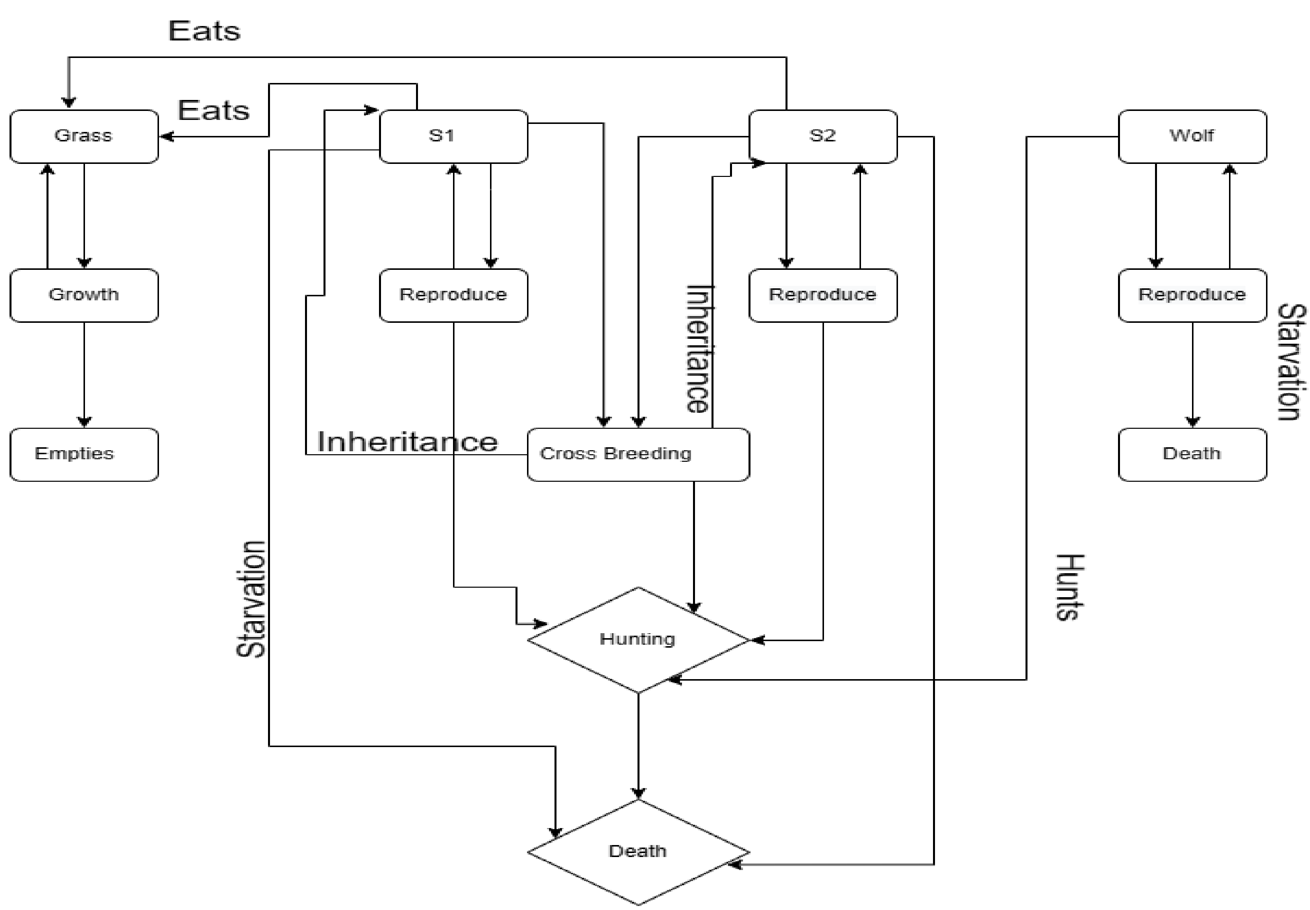
```
        run-speed, vision, reproduction cost.
If(all three traits are dominant of same breed):
     -- run-speed = trait value of other breed, to maintain
equilibrium
```

#Check - Death :

```
If the energy of any particular breed goes below a certain
limit, they die.

check-death():
If(energy <= 0):
    -- die
end function
```

Overview of Model Process



Design concepts :

- Basic Principle: This model reflects fundamental ecological relationships between population dynamics of species and their environment and replicate an isolated environment with two subspecies of any generic herbivore (rabbit in our case), their source of nutrition (a point of competition), and a predator. As we are dealing with complex phenomena by integrating the modeling and simulation based environment, we can say that agent based modelling focuses on the individual active components of a system. This is in contrast to both the more abstract system dynamics approach and process-focused discrete method.

- Emergence: Rabbit population size emerges from demographic process and more abstract territory dynamics. If the Reproductive Isolation Index is zero then, we can say that the traits of both rabbit species are completely intermatched & if both species are completely isolated then the traits of individuals are not transferred, hence resulting in a drastic change in the genetic patterns of the population.

- Sensing: Wolves can sense through their vision for total prey available to them within their territory range. Similarly Rabbit species also have their own sense of vision for escaping from the predators. Along with vision sensing, the brown coloured rabbits have the ability to hide from the predators due to their body colour in day time, and same natural selection favours black rabbits to hide at night.

- Interaction: Competition for habitat cells (grass) is a direct interaction for both species of rabbits. Similarly, Wolves also interact directly with the rabbit species as a predator to gain access to their habitat territory cells and their livelihood. Due to the rise of survival competition the one who runs faster and has greater visibility range will survive more in a longer duration of time.

- Objective: Our main objective is to make balance between the ecological system of population dynamics of species and their environment. Like for herbivore species such as rabbits, we observe that, when rabbits have greater visibility and high running speed, they can escape easily from predators. Similarly for the survival of carnivores species such as wolves, they have to catch the prey (rabbits) with the weakest individual traits.In this way, they can maintain balance between their individual species.

- Adaptation: To increase the survival chance and having greater adaptation, the rabbit species only try to reproduce with the partner having stronger traits selection. Stronger the traits of the offspring, greater the chance of survival, hence leads to high adaptation rate in their territories.

- Stochasticity: Stochasticity was incorporated into many processes to account for natural variation. Dominant traits are the trait domination as explained in the mendelian theory. Mutation is a complete alteration in a particular trait of a subspecies. Natural Selection is the advantage due to a natural trait that prefers survival, Genetic Drift is a sudden change in the genetic patterns across a species.

- Observation: Individual and population-level species were observed through These included reproduction (due to genetic drive, mutation,selection & dominant trait choice), resource selection (grass eating capacity on day and night time), black and brown rabbit land tenure (i.e., time that breeding animal held onto territory before dying or dispersing),territory size and spatial distribution, and rabbit population size and age structure.

Initialization :

Simulations are run with a random number of individuals, of which a specified initial proportion, rabbit1 are brown rabbits; rabbit2 are black rabbits and initial-wolf are wolves. Each individual originates at a random location. Initially , each individual has initial energies set for survival, like vision-range, speed, gain-from-food etc. The dominant and recessive traits are chosen randomly for the herbivore traits.
The model is run for two extreme cases - one when RII is 0 and other when RII is 100.

Input data

All the variables defined are to be input from the user using sliders, so that the different nuances are balanced to reach a state of equilibrium in the model, so that further studies on our hypothesis can be carried out further.

Submodels

All the models parameters are listed in the below table :

R1	Initial number of white rabbit
R2	Initial number of black rabbit
W	Initial number of wolves
R1e	Initial energy of white rabbit
R2e	Initial energy of black rabbit

We	Initial energy of wolf
R1r	Running speed of white rabbit
R2r	Running speed of black rabbit
Wr	Running speed of wolf
Wv	Wolf vision range
R1v	White rabbit vision range
R2v	Black rabbit vision range
R1g	Energy gain from food for white rabbit
R2g	Energy gain from food for black rabbit
Wg	Energy gain from food for wolf
RII	Reproductive Isolation Index
R1rc	Reproduction cost for rabbit1
R2rc	Reproduction cost for rabbit2
Rd	Rabbits dosage
Gr	Grass regrowth rate

 # Chasing :

Wolves have a specific vision range **Wv** which can be set using a slider. Similarly, rabbit species also have a specific vision range **R1v, R2v** which can also be set using a slider.When wolves see a rabbit in their vision range, they start running towards them. Similarly when rabbits find a wolf in their vision range they start running away from it in the opposite direction.
7 cases are possible now:

1. **Wv = R1v = R2v :** In this case there is an equal chance of both the rabbits getting hunted by the wolf or fleeing away from the wolf.
2. **Wv > R1v = R2v :** In this case there is an equal chance of of both the rabbits getting hunted by the wolf what's different in this case is there is less chance of rabbits getting away from the wolf vision as it depends on the so many factors like the energy and no of hunters around.
3. **Wv > R1v > R2v:** In this case species 1 has an advantage on species 2 of rabbits in fleeing away from the wolf and now it depends on the surrounding factors to decide whether the wolf will be able to hunt down the rabbit of species 2 or not.
4. **Wv > R2v > R1v:** In this case species 2 has an advantage on species 1 of rabbits in fleeing away from the wolf and now it depends on the surrounding factors to decide whether the wolf will be able to hunt down the rabbit of species 1 or not.
5. **R1v > Wv > R2v:** In this case rabbit of species 1 have higher chances of not being hunted by the wolves because now rabbit of species 1 can now see the wolves before coming into the vision of wolves and start running.
6. **R2v > Wv >R1v:** In this case rabbit of species 2 have higher chances of not being hunted by the wolves because now rabbit of species 2 can now see the wolves before coming into the vision of wolves and start running.
7. **R1v & R2v > Wv:** In this case the ecosystem will be unstable as there is no one to balance the population of rabbits and also there's no food for the wolves to eat which will result in their extinction.

 # Fleeing :

Rabbits have a vision range,**R1v** and **R2v,** and if they see a wolf in that range they start running in the opposite direction to flee away from the predator.
The following steps are involved while fleeing away :

1. If they see wolves in their vision, they link with one of the wolves among them.(with the nearest one)
2. They face in a direction to that of the wolf.
3. Turn 180 degrees to face the opposite direction.
4. They start running away from it.
5. The run-speed(**R1r** or **R2r**) is affected due to the amount of grass(grass-amount) present in the patch where they are running.
6. If they are at a distance greater than wolf-vision(Wv), the link is broken and they escape.

Grass - Regrowth :

There are 2 factors affecting the grass in the environment.

1. **Rd** :Rabbits dosage i.e. both the species have different amounts of appetite to fulfill their needs for energy and reproduction.
2. **Gr**: Grass regrowth rate is fixed in the entire run.

So if any of the species has higher dosage i.e **Rd** then they might end up eating all the grass in the nearby patches and since the grass regrowth i.e **Gr** is constant it may result in the land being barren i.e land without grass and this might cause the death of specific specie in the long run.

Wolf Reproduction :

When wolves' energy reaches above a certain limit they start looking for mates in a particular radius for reproduction. These are the steps involved in selecting mates and reproducing :

1. The wolf identifies a wolf in a radius wolf-vision(Wv). We have specified the radius limit as 5km, because this is the maximum distance a wolf in our model can travel using initial wolf-energy(We).
2. Among the list of mates in the radius, the wolf selects a mate with wolf-energy(We) less than wolf-reproduction-cost(Wr).
3. If it finds such a mate as listed in point 2 above, reproduction happens.
4. All the initial variables are set for the new wolf.

 # Rabbit Reproduction :

With sufficient energy , rabbits start looking for mates in specific radius to reproduce new ones. Since there are two breeds or species of rabbits they can interbreed or even crossbreed with other rabbits.

2 cases are possible here either they breed within themselves or they breed with the other species.

1. **Crossbreed:** The genetic traits of the offspring will be decided randomly based on the parent's dominant trait. Let’s suppose There are 5 traits and out of five traits, let’s suppose trait 1,2,4 are being copied from parent1 and 3,5 from parent 2.Since breed 1 has 1,2,4 dominant traits and breed 2 has 3,5 dominant traits.Based on the fact The breed of child is decided as 1 or 2.

2. **Same breed:** Here the parents are of the same breed so the offspring will be of the same breed that their parents belong to. But here also their traits will vary just as

explained with an example in the cross breed.Here just the breed is fixed unlike the earlier case.

 # Trait Selection :

For crossbreeding and genetic mutation, we are performing trait - selection in our model. Each breed of rabbit has three traits; run-speed, vision, reproduction - cost.
According to genetics :
Dominant + Dominant = Dominant
Dominant + Recessive = Dominant
Recessive + Recessive = Recessive

1. We randomly choose the dominant traits among the two species.

2. If all the dominant traits are from the same species we define run-speed to be of different species.

3. After this cross-breeding happens and the new one inherits the dominant traits of different species.

4. Based on the number of traits inherited from an individual parent, the breed of the offspring is decided.
