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Evolving Alternative Reproductive Tactics in Embodied Agent Colonies with Emergent Sex Roles

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Abstract

Alternative Reproductive Tactics (ARTs) are different reproductive strategies used by individuals of same sex to maximize the reproductive success, such as territorial defense, sneak mating, or cooperative breeding. In this study, the embodied evolution represents a real-life biologically inspired agent-based simulation where the agents move around freely in the simulated environment governed by the dynamic outputs from their neural network which has the inputs of the information of the environments such as food proximity, distance and orientation of other agents, their energy, age, and mating state which have weights which are the genome of the agents. The agents have no built-in genders but rather act as female or male when they choose the respected outputs, mate_as_female or mate_as_male respectively. Reproduction occurs probabilistically based on the energy thresholds and proximity with the female-role bearer agent taking the reproduction cost of energy deduction. 1000 generations are run, where agents evolve through crossover and mutation with probability 0.1. The simulation has no explicit fitness function rather the total reproductive success servers as the fitness. Natural selection plays a vital role to populate the fitted agents for the next generation, as randomly offspring are chosen. Our analysis showed few agents always acted as female, as male always whereas we had not hardcoded the genders initially and rest as hermaphrodites. The females and hermaphrodites even had two types of phenotypes that had evolved.

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1. Introduction

1.1. Background of the project

Alternative Reproductive Tactics (ARTs) refers to diverse tactics that individuals of the same sex employ to maximize their power to reproduce (maximize reproductive success). Such tactics- such as territoriality, sneak mating, parasitism and cooperation -have been observed across numerous animal taxa which includes fishes, mammals, insects, etc. (Davies)ARTs can be genetically fixed, which means that the tactics the animal is born with and keep for life, and ARTs can be conditionally flexible, which means the tactics change depending on the body and environment conditions (Davies) (Taborsky, 2008).Studying ARTs help us understand how the variations in traits/ phenotypes are maintained and evolved which is a very important part in evolutionary biology.

Historically, a lot of theoretical models of ARTs, biological (Brockmann, 2001) (TABORSKY, n.d.) and mathematical (Howard, 1995) (Lucas J. R., 1996)have been worked upon, where the models assume the prior existence of two or three discrete phenotypes and work on the frequencies of the tactics used in different situations. The models have very low agent-environment and agent-agent sensory interactions, which lacks the essence of real life. (TABORSKY, n.d.)

Addressing these limitations, some researchers have incorporated into their models the number of environmental sensory inputs and it investigates whether a simple physical difference between the sexes – the females have a non-reproductive period after mating, while males do not— is enough to have the male and female gender evolve behavioral differences between male and female robots. (Rold, n.d.).

More sophisticated models where rich sensory environments and social interactions in evolving robotic colonies are developed. This existing work is where even a good environmental and co-existing sensory inputs are used to show that Alternative mating strategy evolves and stably co-exists in small robot colonies. This study shows how the robots develop Behavioral strategy to coexist (Stefan Elfwing K. D., 2014).

Since the time of Darwin, the biologists have been interested in polymorphism (Darwin-online, 1859; C, 1874; Stefan Elfwing K. D., 2014). Polymorphism mean when more than one type of the same species exists in the same place at the same time. It is quite interesting that there exist multiple distinct phenotypes of a species in a same place where the “Natural Selection” is working.

Natural Selection suggests us that only the fittest would survive and in such situation the emergence of multiple phenotypes is quite interesting. Generally, polymorphism is maintained when the fitness curve of the polymorphic phenotypes intersects. The crossover point of this intersection is called the “Evolutionary Stable State” (ESS). (Stefan Elfwing K. D., 2014; J. MAYNARD SMITH, 1973; JM, 1982).

In recent years the use of robot evolution experiment to study biological phenomenon has gained attention. In comparison to the biological study, the robot evolution has the advantage that we can get evolution results of hundreds of generations in a few hours. The experiment ca even be done in different parameter settings and environment conditions (Stefan Elfwing K. D., 2014).

Distinctive feature of proposed embodied evolution framework is that, it has no explicit fitness function or any algorithm for selecting robots for recombination and mutation rather the new offsprings would be generated between two mating robots. (Elfwing S, 2011; Stefan Elfwing K. D., 2014).

Another study explores the emergence of polymorphic mating strategies in robot colonies through an embodied evolution system (Stefan Elfwing K. D., 2014). They conducted experiments in simulation with Cyber Rodent robots. No explicit fitness function was introduced, rather the probability of reproduction was tied to each robot's energy level, making it closer to natural evolutionary dynamics. They system evolved over 1000 generations by varying energy source densities. To maintain further diversity each physical robot was embodies with multiple virtual individuals. Over springs were produced through the mating events with crossovers and mutation and the next generation was selected from the reproduced offsprings. (Stefan Elfwing K. D., 2014)

1.2. Project Overview

This study shows an embodied evolution framework where the agents have a very much life like evolutionary setup where they have sensory inputs of the surrounding environment where they know how far is the food from them, how far is the other agent who is face facing from them, how is an agent who is back facing from them, they even have inputs about their self-aware data, which are their age, energy and mating state at the instant where the agents uses these inputs to generate or choose an output module from "moving_to_food", "approach_towards_nearest_agent", "mate_as_female", "mate_as_male". The agents were not given a built-in gender initially, they chose to act as male or female as per their choosing of output "mate_as_female", "mate_as_male". Females are made to be the cost bearers for the reproduction, but both male and females had their contribution for the reproduction to begin as both had their energy thresholds contributed to decide if the reproduction will proceed. Decisions are governed by a neural network and are evolved over 1000+ generations where they reproduce when they interact with each other in the environment as they are moving freely all around the simulated environment. The reproduction has crossovers and mutation to help develop and evolve the future generations and enables agents to adapt to complex, interactive environments.

The model doesn't have an explicit fitness function but rather the total reproduction by the agents in a generation represent the fitness. The next generation is always populated by 100 offspring of the previous generation randomly chosen which makes natural selection play a vital role here and ensures that only the fittest genomes (agents) are transferred to live and populate the future generations.

2. Methodology

2.1. Environment Setup

The simulation environment is set to be 600 x 600 pixels which we convert to 600 x 600 meters. The environment contains 120 randomly distributed and positioned foods. Each food is a green colored circle with 2-pixel radius and each holds energy of about 50 units. The simulation is started with 100 agents with initial positions randomly chosen in the simulation. Each has 7*4 genomes matrix randomly initialized at the beginning of the generation. The genome represents the weights to the 7 inputs to the 4 outputs of the agent. The color of the agents portrays the decision taken by their neural network: Green: “moving_to_food”, Yellow: “approach_towards_nearest_agent”, Red: “mate_as_female”, White: “mate_as_male”.

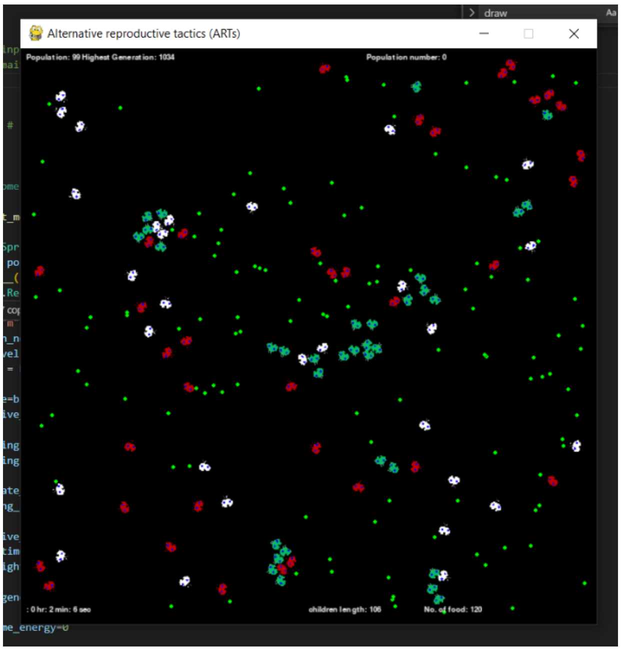


Figure 1: Simulation Screen

2.2. Agent Architecture

Each agent in the simulation has a fixed physical dimension of 6 pixels in diameter throughout its lifespan. The agents have two independently controlled wheels for locomotion which uses a differential drive steering system to move. The agents have a sight radius of 100 pixels, which allows them to perceive their surroundings.

At initialization, each agent is assigned an energy level of 200 units while each agent has the max energy capacity of 300 units. Each agent has a highest lifetime of 5000 timesteps.

The agent is controlled through decisions made by the neural network that receives a set of inputs which are the normalized sensory data of the agent. The input reflects the agent's internal states and its immediate environment.

The agents can be in 3 states, “pre-mating state”,” mating state” and “post-mating state”. The pre-mating state is when the agents can reproduce. The mating state is when the agents are reproducing, and this state is of 2 time-step. Post-mating state is the cooldown period for the agents. After reproduction a female and male both enter the post-mating state, where for females the post-mating state is for 4-time steps and for male it is for 3-time steps.

Each agent has its own 7x4 genome matrix which is randomly initialized at the beginning of the simulation. These genomes are the weights of the 7 inputs to the 4 outputs that control the agents.

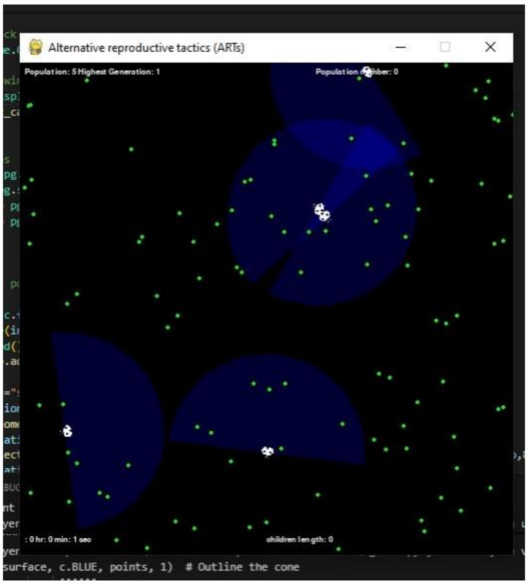


Figure 2: The Sight radius of the agents in blue

2.3. The Normalized inputs are:

1. Distance to food / sight radius
2. Distance to nearest face-facing agent / sight radius
3. Distance to nearest back-facing agent / sight radius
4. Current energy / max energy (300)
5. Current age / max age (5000 timesteps)
6. Mating state (0 or 1)
7. Bias

2.4. Outputs include:

1. Move to food
2. Approach nearest agent
3. Mate as female
4. Mate as male

The energy of the agents decreases by 1 unit every 5 timesteps and by 10 upon successful mating as a female. Agents die upon reaching 0 energy or completing their life time of 5000-time steps.

2.5. Genome Architecture

	Move to food	Approach agent	Mate as female	Mate as male
Distance to Food	g_{11}	g_{12}	g_{23}	g_{14}
Distance to Face Agent	g_{21}	g_{22}	g_{23}	g_{24}
Distance to Back Agent	g_{31}	g_{32}	g_{33}	g_{34}
Current Energy	g_{41}	g_{42}	g_{43}	g_{44}
Current Age	g_{51}	g_{52}	g_{53}	g_{54}
Mating State	g_{61}	g_{62}	g_{63}	g_{64}
Bias	g_{71}	g_{72}	g_{73}	g_{74}

Figure 3: The genome structure of agent (weight to the neural network)

Each agent's decision-making is controlled by a two-dimensional matrix of size (7*4) genome. This genome is the weight of the neural network. The genome acts as the blueprint for the agent's neural network, encoding heritable traits influencing decision-making. The (7x4) genome has its each row corresponding to the normalized input describing the agent's state and perception of its surrounding environment and each column corresponds to a possible behavioral output.

This genome mimics real life by abstractly implementing the core principle of the biological evolution and behavior. The genome acts like a digital DNA that encodes how the agent responds to environment and internal inputs through a set of structural weights. Inheritance is stimulated by doing crossover, whereof springs combine traits from two parents just as a baby would from his parent. Variation is introduced through mutation.

2.6. The Differential Steering System

The differential steering system used in the locomotion of the robots in this project is simple yet a very powerful mechanism which is commonly used in small robots. The system works as follows; two wheels are mounted on the same axle and each wheel are independent of each other. This same concept is seen in the wheelchair too. The robot can be moved forward, backwards, turn, pivot on the spot, by just varying the speeds independently of the two independent wheels.

If both the wheels are rotating at same speed and same direction, the robot moves in the same line. If one wheel rotates faster than the other the robot follows a curved path towards the slower wheel. If the wheels spin in opposite direction and same speed, the robot rotates in place around its center. (Lucas G. , n.d.)

The robots forward velocity is given by the average of the wheel speeds.

$$V = \frac{Vr + Vl}{2}$$

Where V_r and V_l are the velocities of right and left wheels respectively.

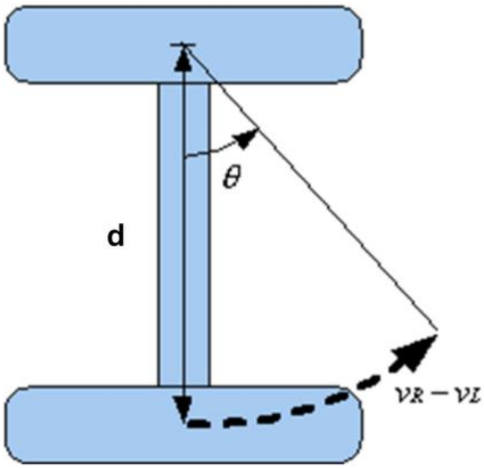


Figure 4: Angular Velocity (Lucas G. , n.d.)

The ‘Angular Velocity’ (rate of change of angular position of a rotating body) is determined by the difference between the wheel speeds divided by the distance between the wheels,

$$\omega=\frac{Vr-Vl}{d}$$

where d is the axle length (distance between two wheels).

This system combines both propulsion and steering in a single mechanism, making it as a great choice to be used for the robot’s locomotion system.

The code implementation of the Differential Steering System:

- Step 1:
  velocity = (self. left_wheel_speed + self. right_wheel_speed) / 2

  rotation = (self. right_wheel_speed - self. left_wheel_speed) / self. wheel_distance

- Step 2:
  ```
  if rotation! = 0:
     angle = rotation * 180 / math.pi
     self. direction. rotate_ip(angle)
  ```

  here, we check if the robot should turn. Then in the next if the rotation occurs the angle which is in radians to degree, as the pygame library’s rotate_ip(angle) works in degree. In the self. direction. rotate_ip(angle), it rotates the agent’s direction vector by that angle.

- Step 3:
  ```
  if self. direction. length () > 0:
     self. direction = self. direction. normalize ()
  else:
     self. Direction = pg. Vector2(1,0). normalize ()
  ```

here, firstly we check the direction length to be not zero so that we do not get an error while normalizing it (division by '0'). The direction is normalized so that we can get the unit vector, and then with the given velocity of the agent we multiply so that the movement of the agents are always uniform, not fast and slow because of the direction vector size.

- Step 4:

  *self. rect. center += self. direction * velocity*

  The step is to move the agent. This adds the movement to the current position of the agent. The agent's center point shifts forward in the calculated direction and distance.

2.7. Neural Network Design

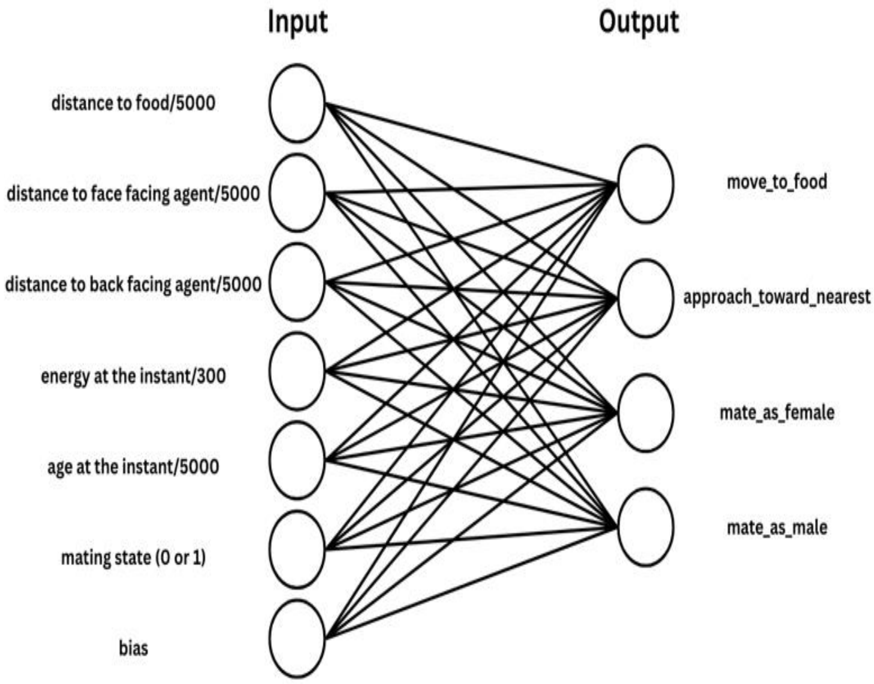


Figure 5: Neural Network Design

The agents are run their decision is decided by single layer Neural network, where the inputs are the normalized values of the surrounding information and the outputs are the decision that the agent will take at the following timestep. The weights of the networks are the genes of the agents which are the main decision-making structure. Before feeding the activation function, the inputs are normalized to a range of 0-1. The output is governed by the activation function relu.

The activation function relu is used for a few important reasons:

- Simplicity: As each simulation has to run for 1000 generations with each generation having 5000 timesteps (each timestep has 0-100 agents to calculate). Using relu will save computation power and make it faster.
- Closer to Biological realism: only the positive signals would activate a behavior, which is very much similar to how the neurons fire (they either activate or stay silent, neurons don't fire unless stimulation crosses a threshold). Only the strongest positive decision survives, weak or negative ones are suppressed.

2.8. Reproduction Mechanism

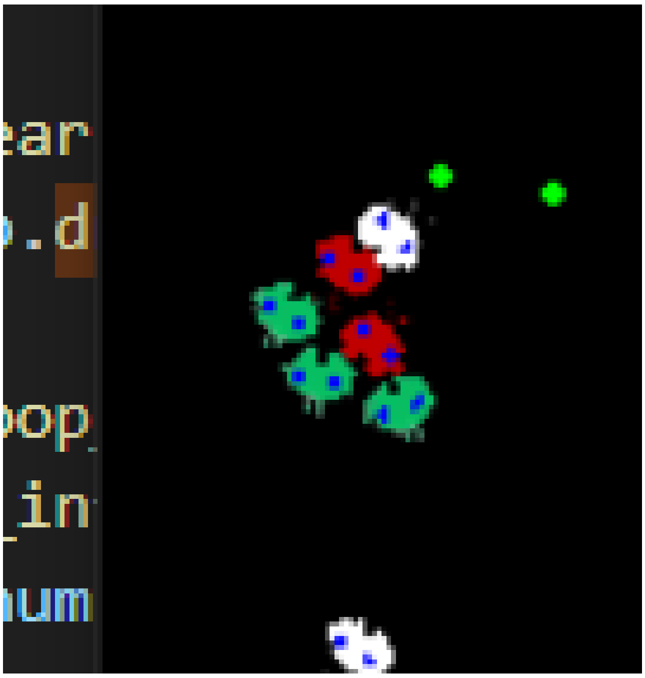


Figure 6: Agents reproducing stage

Agents reproduce if certain criteria are met. When the agent chooses "mate as male" or "mate as female" it stops moving and waits in its position for a mate. The agents have a mating range of 6 pixels around it. If another agent comes into this agents' mating range and has even chosen the mating output opposite to the one of these agents, then they enter the reproduction. It is then checked if both of the agents are in premating states. If they are, both are set to mating state and then the energy threshold is checked. Reproduction is probabilistically determined by the energy threshold and a weighted sum of male and female readiness. (Stefan Elfwing K. D., 2014)

$$\mathrm{Em}_{\mathrm{reproduction}} = 0.5.\left(\frac{\text{Energy male}}{\max energy}\right) + 0.5.\left(\frac{\text{Energy female}}{\max energy}\right) \text{ – setting 1}$$

$$\mathrm{Em}_{\mathrm{reproduction}} = 0.\left(\frac{\text{Energy male}}{\max energy}\right) + 0.5.\left(\frac{\text{Energy female}}{\max energy}\right) \text{ – setting 2}$$

where:

- Energy male is the energy of the instant of the male parent

- Energy female is the energy of the instant of the female parent
- max energy is the maximum energy (300 units) the agent can have.
- $Em_{reproduction} \in [0.0, 1.0]$ is a probabilistic reproduction score and the reproductive threshold.

The setting 1 shows that the agent acting as male had his decision or control to the reproduction as much as the female, while the setting 2 shows that the decision and control of reproduction was solely under the agent who was acting as the female in the following reproduction.

A random value r [0.0, 1.0] is generated and if $r <= Em_{reproduction}$, reproduction proceeds. Then both the agents have to be in mating state for 2 timesteps and if any disturbance or any other external or internal reason separate or moves any of the partnering agents away from the mating range, the reproduction terminates. During these 2 timestep/ mating state no other decisions are taken by the neural network.

Next, after completion of two timesteps, the reproduction happens. Two offspring are produced, each inheriting the genomes from each parent respectively. They have a single-point crossover with a probability of 0.1 and then they have mutation with a probability of 0.1 and the value is generated using Gaussian distribution with standard deviation of 0.1. These offsprings are stored in a list for offsprings.

2.8.1. Crossover

The crossover allows the offsprings to inherit and recombined traits of the parents, rather than solely depending on the random mutation. The implementation of the crossover in the reproduction process is as follows:

- Firstly, the probability of the crossover is checked. If the randomly generated value is less than or equal to the probability of crossover, which is 10% or 0.1, then only the crossover occurs. (Stefan Elfwing K. D., 2014)
- The genome of the male and female agent (size 7x4) is first flattened.
- A random value is generated from 1 to the size of the flattened array. That random value is the point of crossover.
- The male and female flattened genomes are cut at that crossover point and 2 sets of new genomes are made by the following way:
    - **The first genome**: The first part of the male acted parent agents' broken flattened genome is attached to the last part of the female acted parent agent's broken flattened genome.
    - **The second genome**: The first part of the female acted parent agents' broken flattened genome is attached to the last part of the male acted parent agent's broken flattened genome.
- The two set of new genomes are then reshaped and returned to be fitted to the agent.

This process enables the useful behaviors of different parents to be mixed together, increasing the genetic diversity and this accelerates their adaption. This further more enables the exchange of strategies, driving the population towards more optimal solutions over successive generations.

2.8.2. Mutation

The mutation plays a very important role in maintaining the diversity of the genomes in the evolving population and preventing the agents from converging to a suboptimal solution too quickly. The crossover mixes the existing genomes from parents, but that's just sharing what is already happening in the system, mutation rather introduces entirely new variation of genome by making a small random change to the offsprings gene. The mutation occurs at a probability of 0.1, (Stefan Elfwing K. D., 2014) when triggered each value of each gene in the offsprings genome matrix is slightly adjusted by adding a Noice, which is drawn from a Gaussian distribution with a given standard deviation of 0.1. This subtle change alters how the neural network processes the inputs and makes decisions potentially leading to new innovative behaviors. The standard deviation is set to 0.1 and mean at 0 so that the noise generated is nearer to 0 and the changes is not too loud.

2.9. Evolution Process

After all agents die out either by spending full life time of 5000-time steps or by energy deficiency the particular generation ends. Each generation has its list of offsprings that was populated by the reproductions during that particular generation. The next generation is repopulated by randomly choosing 100 offsprings and randomly positioning them into the simulation. If the offspring list has less than 100 offspring the remaining agents are filled in the simulated environment by initializing them with new randomly generated genomes.

3. Results and Analysis

After the evolutionary process converging for 1000+ generations of simulation experiment runs, we analyzed the last 10 generation of 10 sets of simulation experiment's data. We focus on the emergence of sex-role behaviors and the agents choosing a gender for themselves to act such.

Agents that never chose "mate_as_male" in their lifetime are labeled to be female and the agents that never chose "mate_as_female" in their lifetime are labeled to be male. The agents that chose both "mate_as_male" and "mate_as_female" are labelled as hermaphrodites.

We analyzed the $em_{reproduction}$ of all agents across their lifetime by categorizing the agents as female, male and hermaphrodites. For each category, separate graphs for each gender were drawn, with all of the last 10 generation's agent's $em_{reproduction}$ on a graph according to their gender. This approach allowed us to examine, if the agents exhibited gender-specific preferences for reproducing at different energy level according to their gender.

The simulation was run with multiple settings before finalizing the parameter values. We employed two approaches to investigate the effects of the male and female behaviors to identify the emergence of any distinct phenotypes.

$$Em_{reproduction} = w_m \left(\frac{\text{Energy male}}{\text{max } energy}\right) + w_f. \left(\frac{\text{Energy female}}{\text{max } energy}\right)$$

The two approaches were:

- Setting w_m=w_f=0.5. This approach had 5sets of simulation run. After thorough analysis, no gender specific phenotype in the $em_{reproduction}$ emerged.
- Setting w_m=0 and w_f=0.5. This approach had 5sets of simulation run. After thorough analysis, 2 similar gender specific phenotype in the $em_{reproduction}$ emerged.

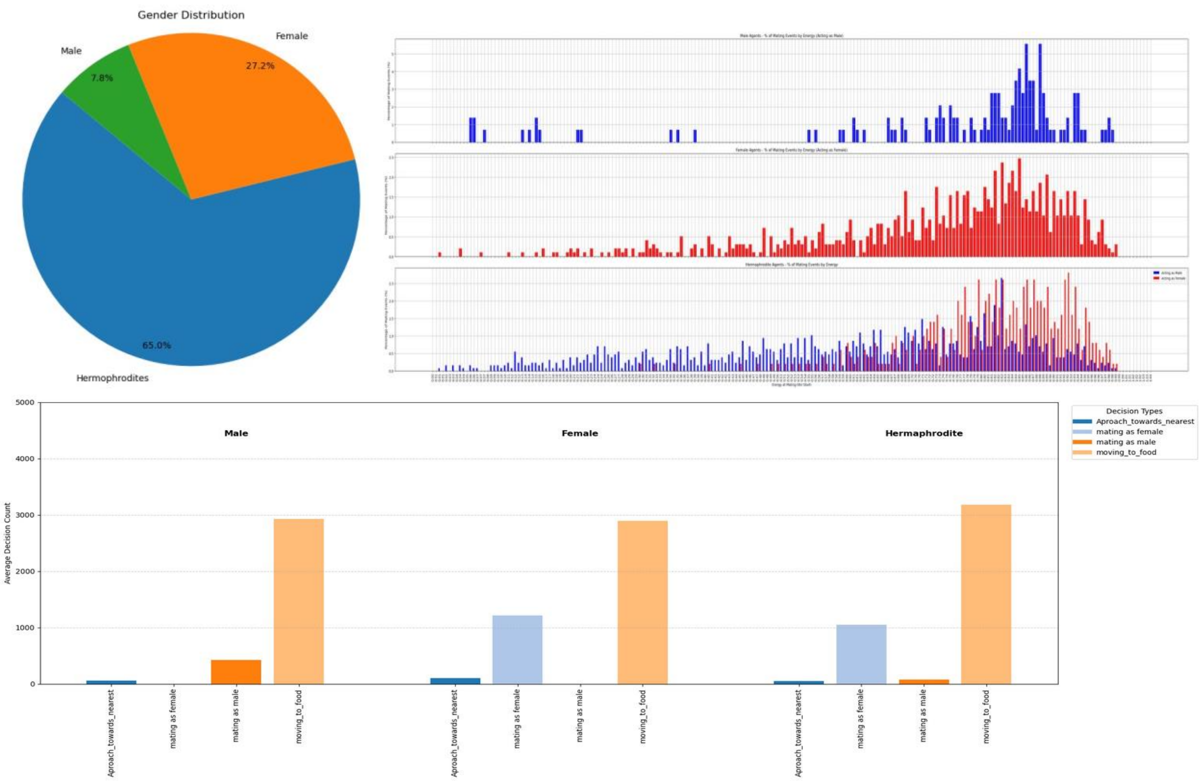


Figure 7: Simulations with setting wm=wf=0.5

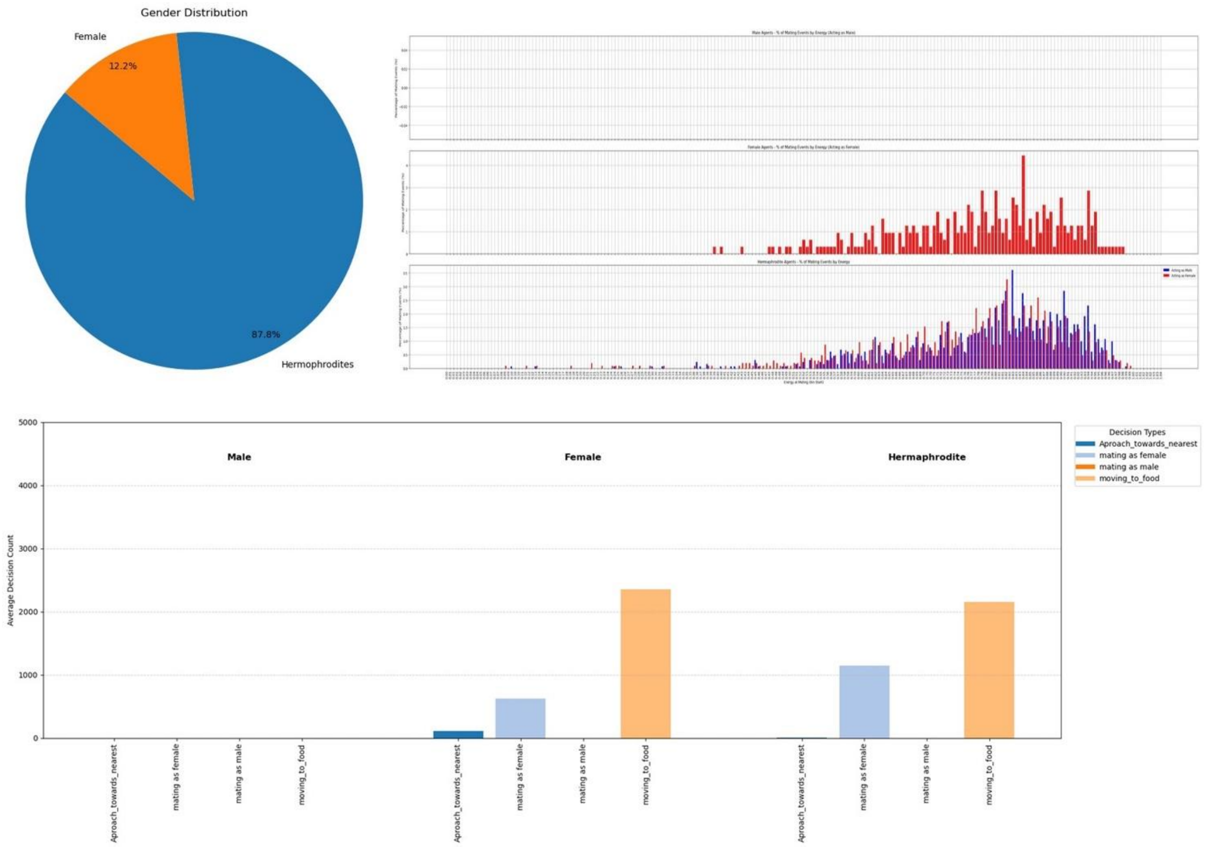


Figure 8: Simulations with setting wm=wf=0.5

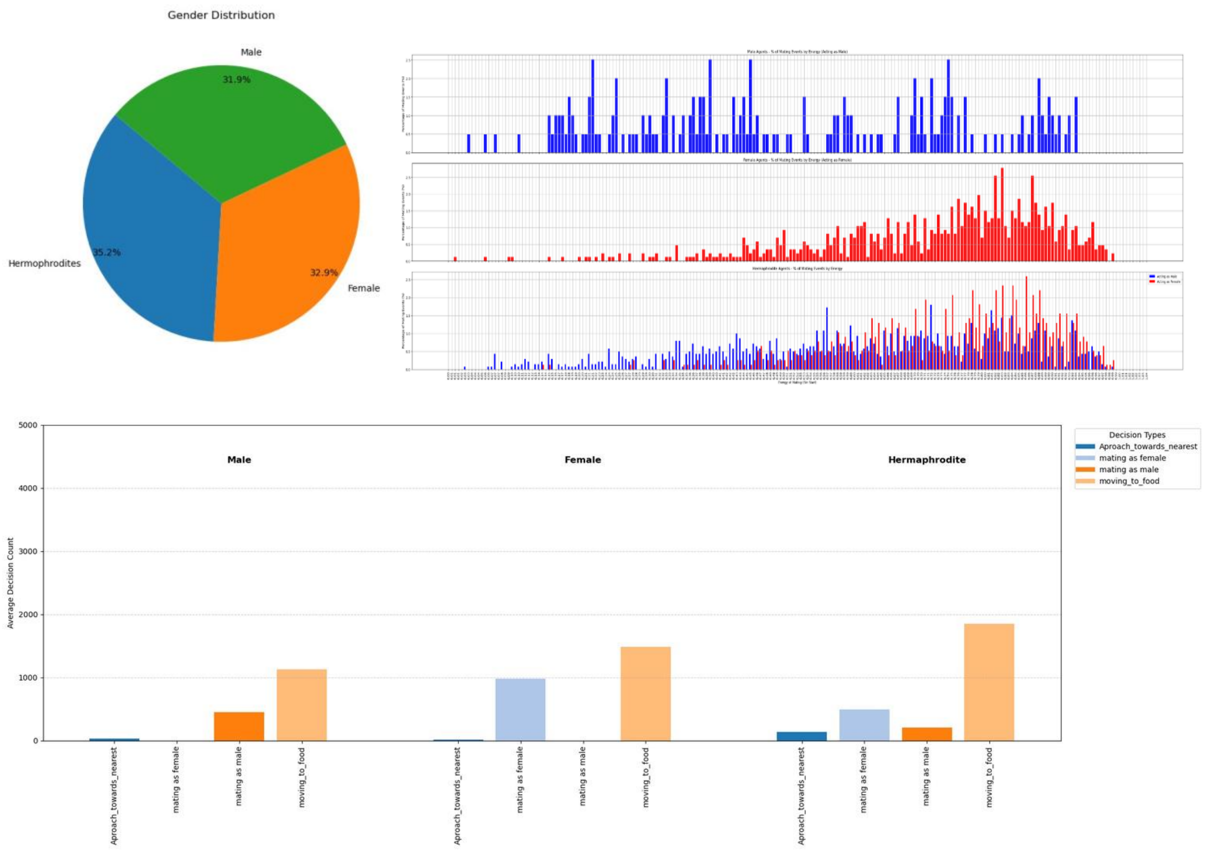


Figure 9: Simulations with setting wm=0, wf=0.5

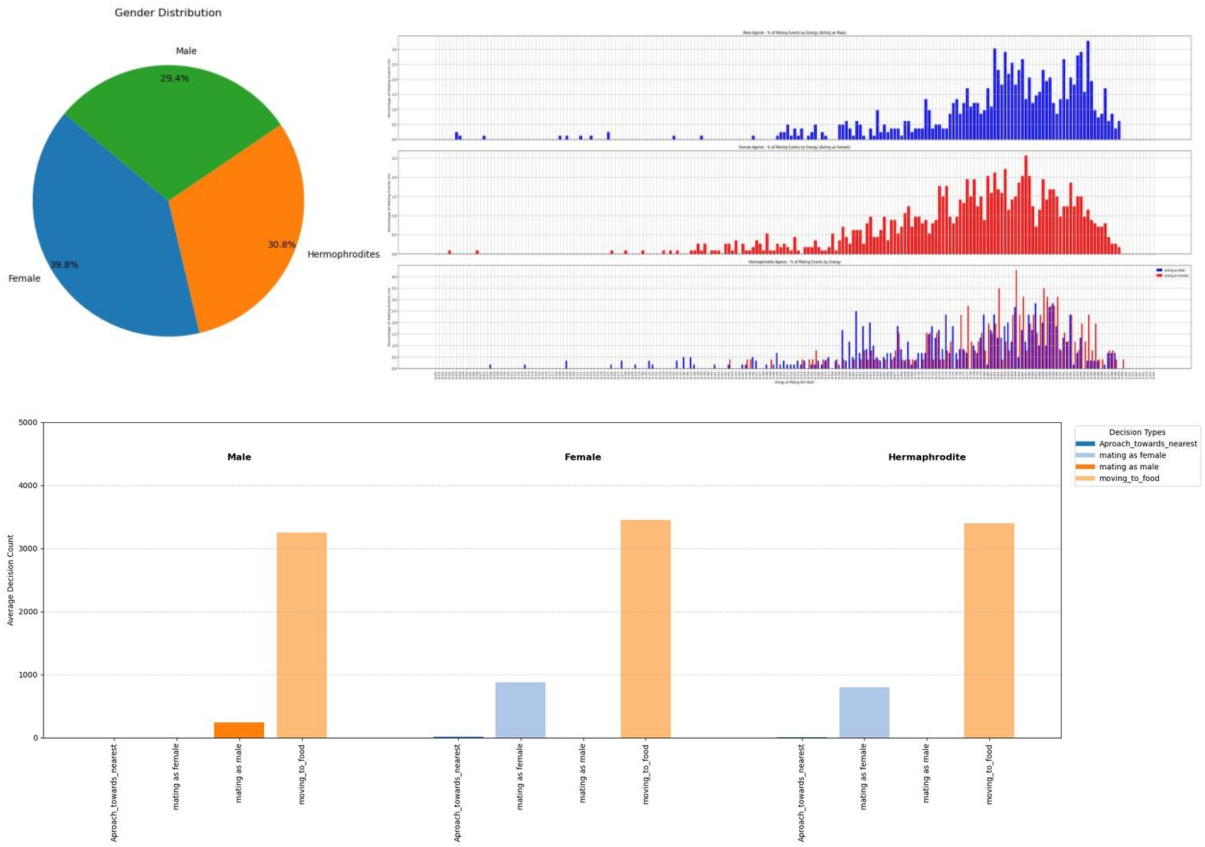


Figure 10: Simulations with setting wm=0, wf=0.5

3.1. Agent Classification and Emergent Gender Types

In the last 10 generations of the evolutionary simulation, with each generation having 100 agents, we analyzed a total of 1000 agents for each set of datasets. Initial agents, based on lifetime agents, were classified as males, females or hermaphrodites. However, it is likely possible that few agents might have died early due to energy depletion or that the agents might not have found a sufficient interaction opportunity to act as the gender opposite that is classified as (male or female) thus is not under the classification of the hermaphrodites.

To ensure that the agents are accurately classified, a validation process using synthetic input scenarios. Each agent was subjected to the 32 combinations of the 5 inputs (excluding the mating_state input, which was fixed at 1 and bias), where the remaining five inputs took values from 0.0 to 1.0 in 0.5 intervals. This ensured that each agent faced situations and experienced realistic conditions with different stimulus proximities for which it might act as male if its female classified and vice versa.

During this process some agents who were initially classified as strictly as male or female responded as choosing to be opposite sex mating behavior. These agents were then reclassified hermaphrodites.

To further refine labeling, two more list of input lists were created:

- One for input conditions under which agents chose mate_as_male.
- One for conditions where agents chose mate_as_female.

Agents still labeled strictly as male were tested again against the female-behavior-triggering inputs, and vice versa. Here, if any of the male or female classified agents selected mate_as_female or mate_as_male respectively it was relabeled as hermaphrodites.

This robust two-step validation ensured that only agents that truly exhibits exclusively male, female or both were rightly labelled as male, female and hermaphrodite. Then the pie chart (figure:5 Gender distribution) was made to reflect a more accurate portrayal of emergent gender roles and ARTs in the population.

Final classification of agents based on lifetime behavior and different testing stimulus proximities yielded 8.6% males, 29.6% females, and 62.4% hermaphrodites.

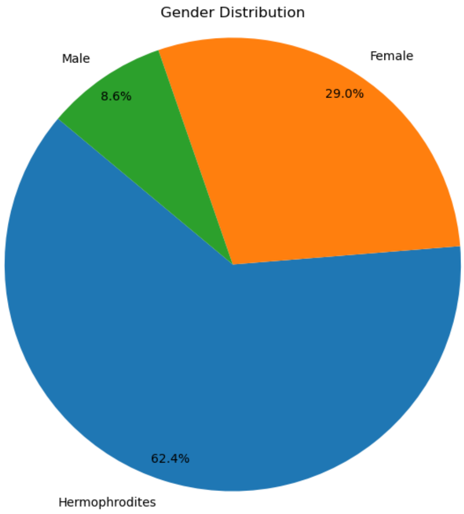


Figure 11: Gender distribution

3.2. All agents' Decision analysis

As the agents are now classified by genders properly, it is next seen if there were any behavioral differences in their decisions. To analyze this the average counts the decisions taken by each gender were calculated and a bar plot is drawn fig (6). The graph shows the bars of decision counts of each decision and each gender.

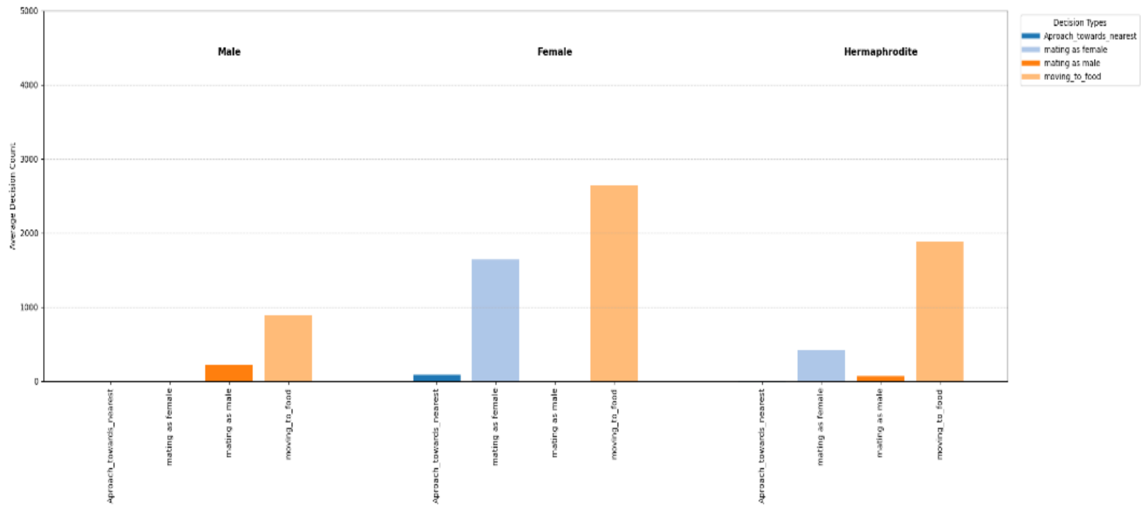


Figure 12: Average Decision counts across gender

The graph shows clear behavioral differences among the classified genders. Males spend most of their time foraging(move_to_food) and the remaining time to want to reproduce(mate_as_male). In contrast, females exhibit a higher average count of move_to_food and followed by engaging in mate_as_female. Here we can see, females use the aproach_towards_nearest module, and male not even once use - this highlights the distinct behavioral pattern. The hermaphrodites mostly spend time moving to food, followed by mate_as_female and followed by mate_as_male and little bit of aproach_towards_nearest.

To analyze further, we took top ten agents from each gender. The ranking was done based on the agent' number of reproducing, the more an agent reproduced the more fit it is counted as, as there is no dedicated fitness function here, the fitness is measured by the number of reproductions the agent did. After taking the top 10 agents of each gender of the set, we drew decision histograms of these 10 agents of each gender to see if the agents had been following the aforesaid trend in decision according to their gender fig (7). In fig (7.3) we can see the histogram showing that the agent only chose mate_as_male of mate_as_female but no bar for the other respected mating module, but still it is in the list of the Hermaphrodites, this is because in the simulation run they did not act as the other gender by choosing the other mating module, but in the analysis period we did a validation process using synthetic input scenarios(as discussed in chapter 3.1), where they did exhibit mating decision as the other gender so justifying their inclusion in the hermaphrodite category.

Figure 13: Top 10 Female Agents- decision Histogram

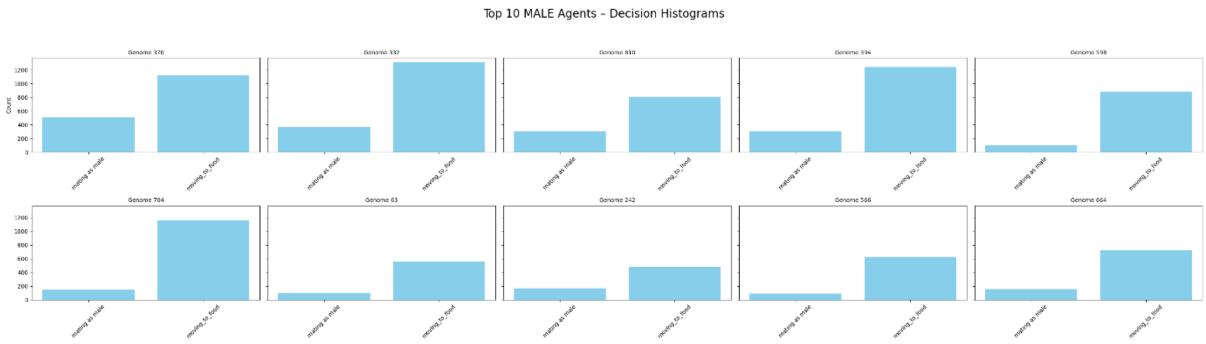


Figure 14: Top 10 Male Agents- decision Histogram

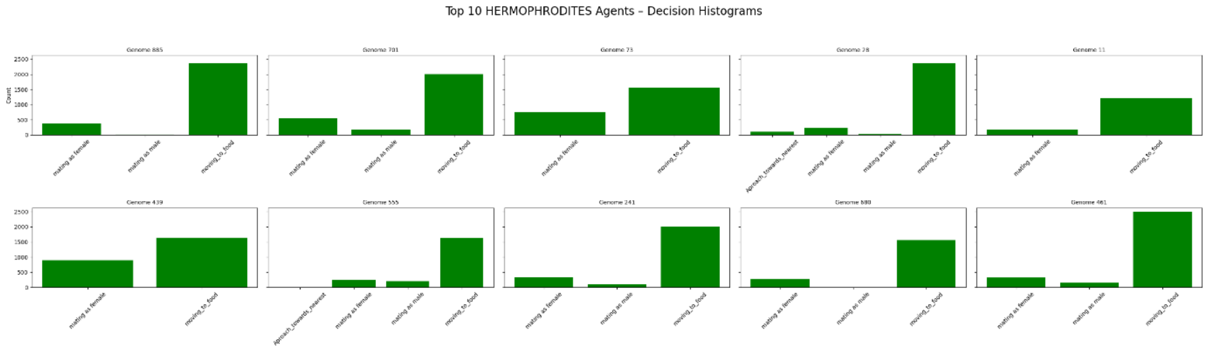


Figure 15: Top 10 Hermaphrodites Agents- decision Histogram

We can see that what we found in the fig (6) is further confirmed here that we see behavioral differences in gender-specific

The following histogram confirms the observations we did in the fig (6), showing a clear behavioral difference between genders. We see that the male only mates as male, and moved for food, they never approached to mate, while the female along with moving to food and mating s female did exhibit the approaching to mate decision, which made it clear that males would not approach or go look for mates, while the females would approach to mate. The hermaphrodites were agents that acted as both male and female agents thus the histogram showed that too that these agents exhibited all behaviors that an agent would do as male and female.

3.3. Stimulus-Driven Behavioral Patterns analysis

Further investigating the behavioral phenotypes, graphs are plotted to visualize how individual agenda for categorized genders respond to a range of controlled environment conditions.

The following test scenarios were:

- Only food was presented at distances ranging from 0 to 1.0 (in intervals of 0.01).
- Only a face-facing agent was presented at distances ranging from 0 to 1.0 (in intervals of 0.01).
- Only a back-facing agent was presented at distances ranging from 0 to 1.0 (in intervals of 0.01).
- Both food and a face-facing agent were shown, each at distances from 0 to 1.0 (in intervals of 0.01).
- Both food and a back-facing agent were shown at varying distances (in intervals of 0.01).
- Both face-facing and back-facing agents were presented at distances from 0 to 1.0 (in intervals of 0.01).

Each resulting image has **36 subplots** arranged in a **6×6 grid**. Each subplot represents the agent's decision output in one of the above stimulus conditions.

- Rows correspond to increasing energy levels supplied to the agent.
- Columns correspond to increasing age values.

These plots allow to examine the behavior of agents and reveal us nuanced gender-specific behavioral patterns.

3.3.1. Female:

By analyzing the female agents, we identified the two types of the female agents on how they responded to variation in the environmental stimuli, energy levels and age. These subtypes—**Type 1** and **Type 2 female agents** - shows different reproductive decision-making strategies, which shows the distinct alternative reproductive tactics (ARTs) within a single sex group.

Type-1 Female Agent:

Figure 16: Type 1 Female — Decision when only a back-facing agent is in sight

We can observer that the type-1 female agent (genome ID: 415) fig (16) responds to another back-facing agent within its sight radius depending on the distance between them.

When the back-facing agent is closer it tends to choose to “mate_as_female”, otherwise with larger distance between them it opts for “move_to_food”. With increasing age and energy, we observe that the threshold distance for the type-1 agent to choose “mate_as_female” also increases, otherwise when the agents are further apart the agent prefers “move_to_food”.

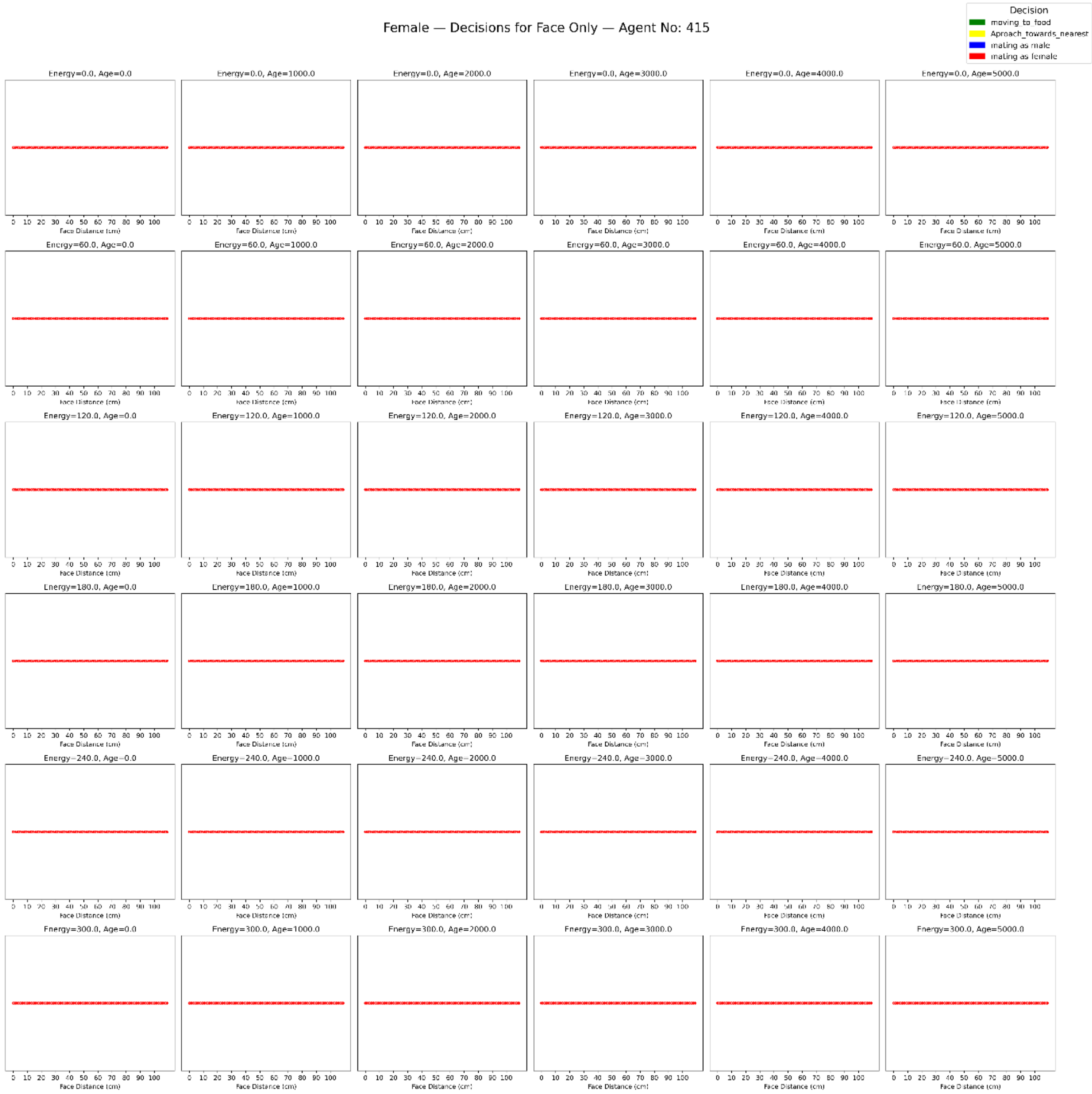


Figure 17: Type 1 Female — Decision when only a face-facing agent is in sight

We can observer that the type-1 female agent (genome ID: 415) fig (17) responds to another face-facing agent within its sight radius depending on the distance between them. It is clearly observable that when the type-1 female agent sees another face-facing agent only in its sight radius, it always chooses to “mate_as_female” regardless of age, energy or distance between the two agents.

Figure 18: Type1 Female — Decision when only a face-facing and a back-facing agent is in sight.

We can observer that the type-1 female agent (genome ID: 415) fig (18) responds to another back-facing and front-facing agent within its sight radius relative to the distance between them. At low energy and younger age, the type-1 female tends to choose "mate_as_female" only when the face-facing agent is very close and the back-facing agent is even closer, otherwise they choose to "move_to_food". As the age and energy increases the threshold of face-facing agent to choose "mate_as_female" expand eventually covering the full distance of sight radius for face-facing agents, with the back-facing agent threshold increasing too.

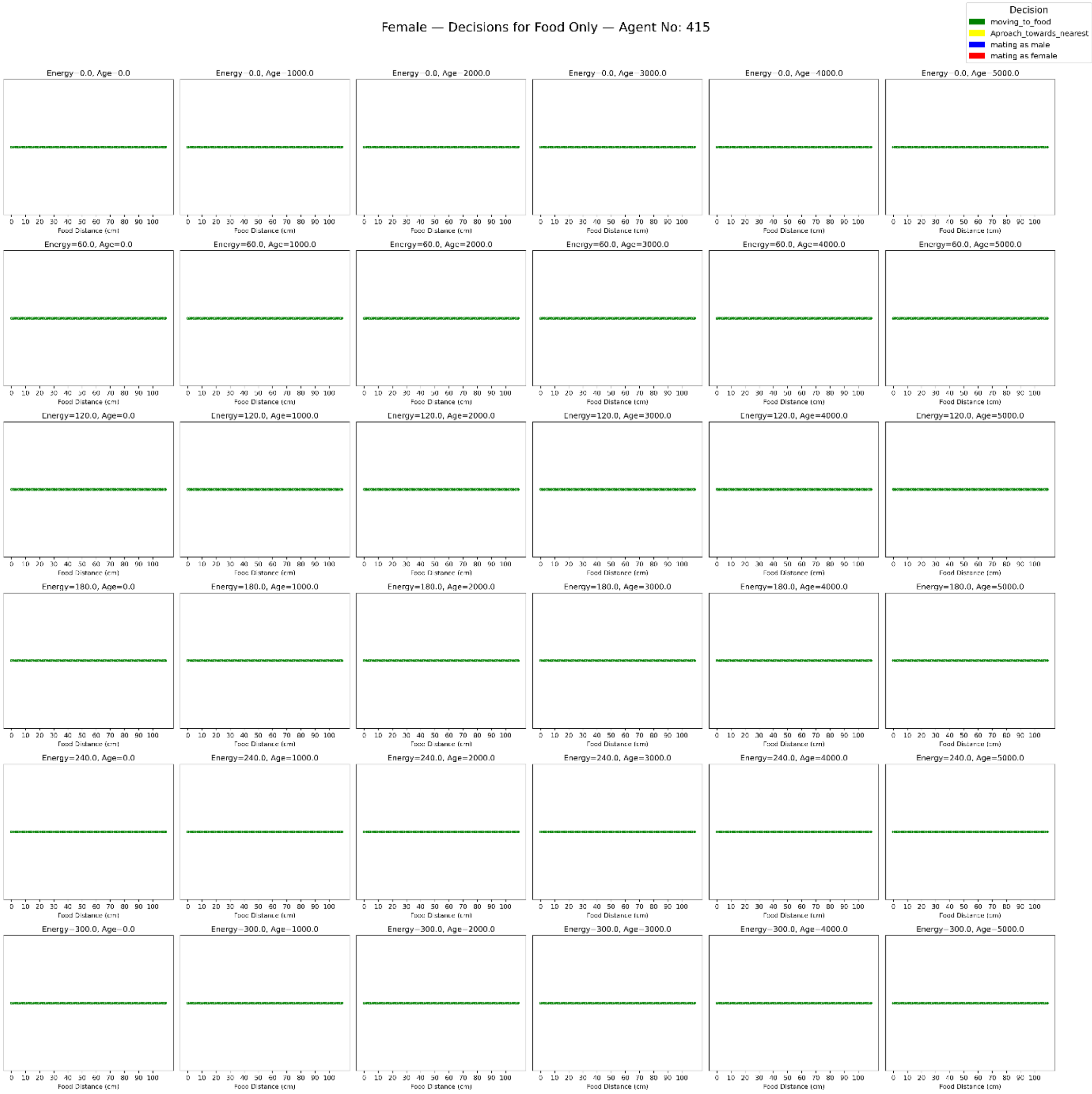


Figure 19: Type1 Female — Decision when only a food is in sight.

We can observe from the fig (19) that when the Type-1 female agent (genome ID: 415) sees only a food in its sight radius, regardless of any age, energy or the distance between food and the type-1 female agent, it chooses “move_to_food”.

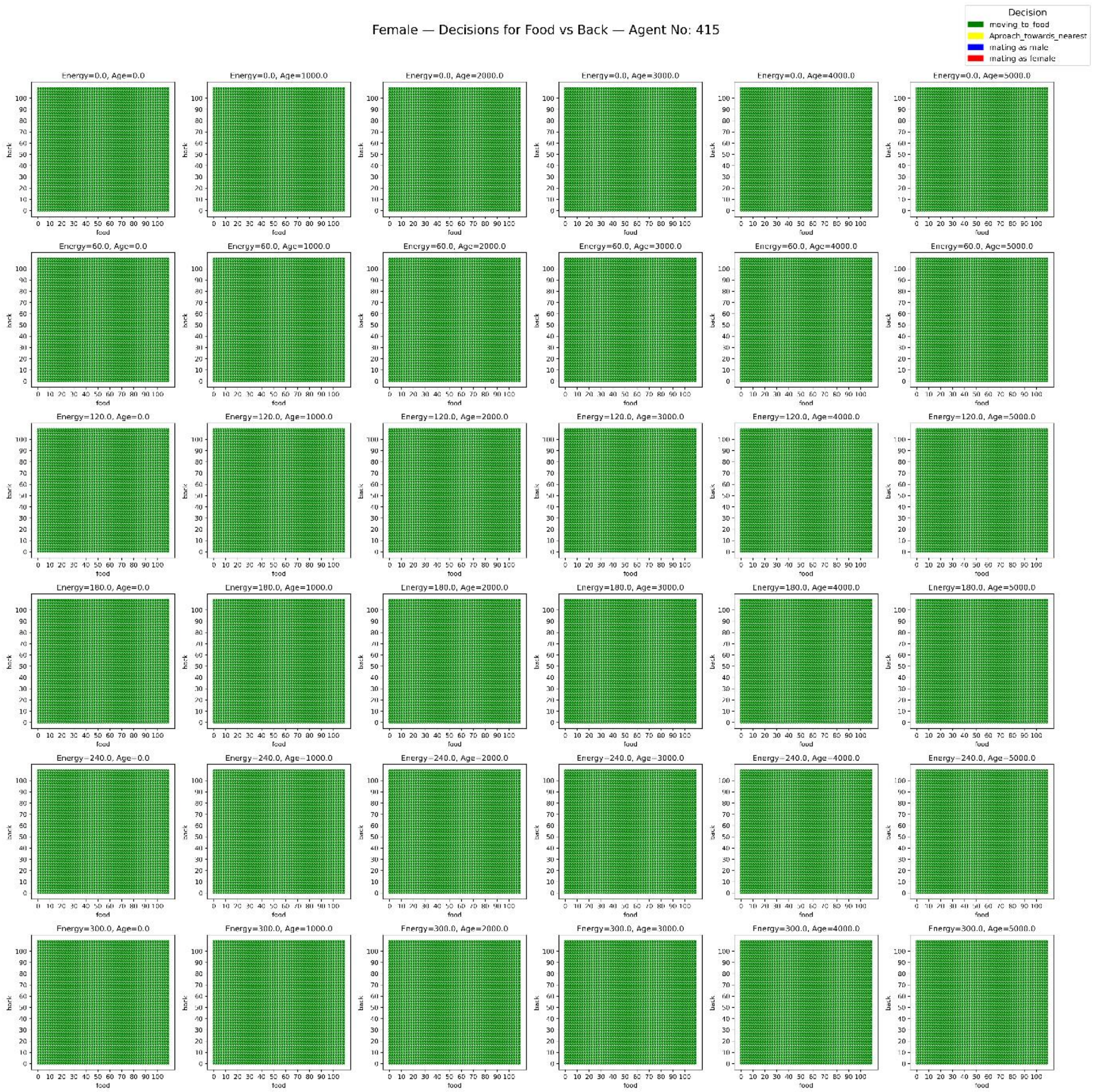


Figure 20: Type1 Female — Decision when a food and another back-facing agent is in sight

We can observe from the fig (20) that when the Type-1 female agent (genome ID: 415) sees only a food and another back-facing agent in its sight radius, regardless of any age, energy or the distance between food and the type-1 female agent, it chooses “move_to_food”.

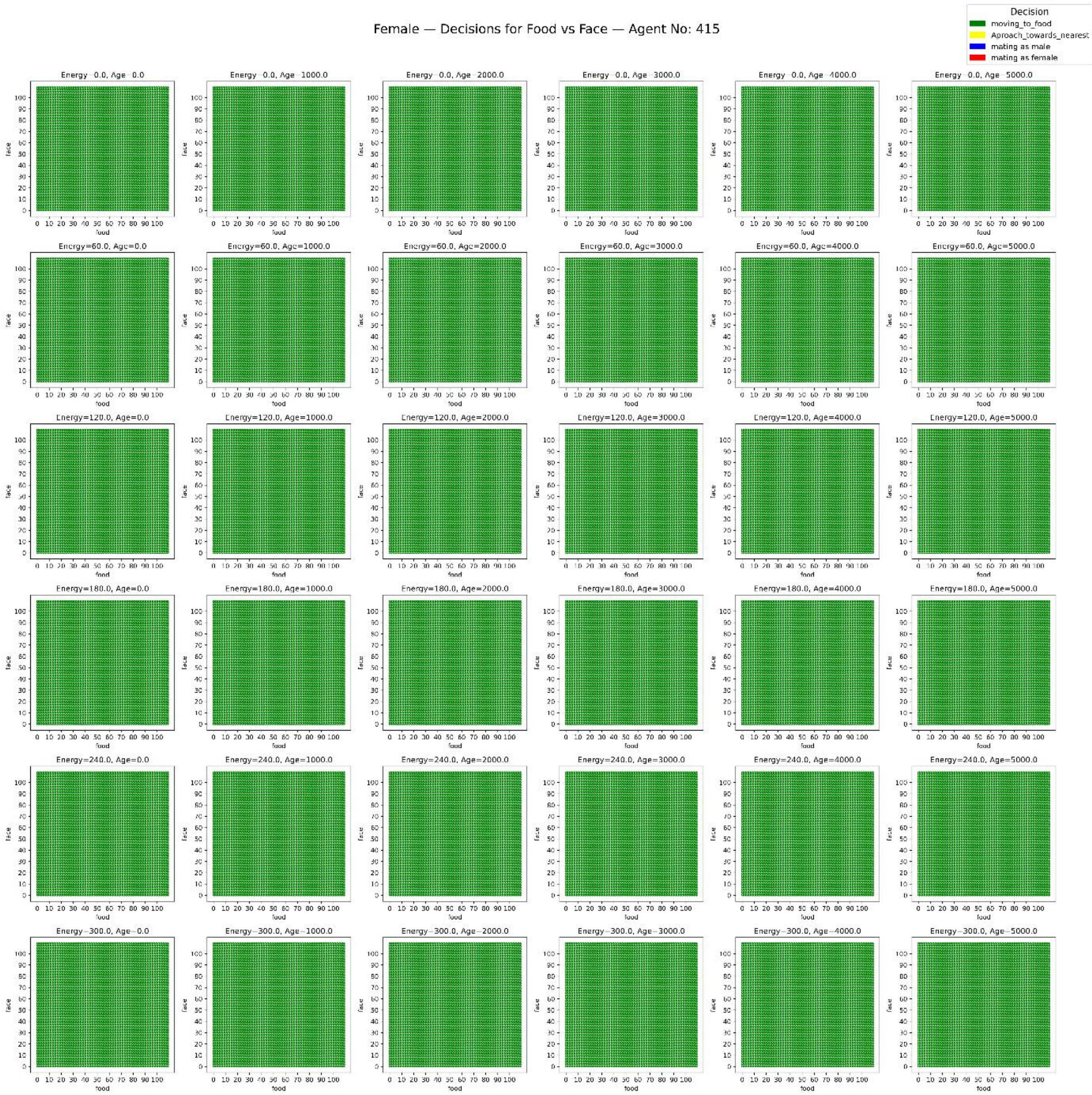


Figure 21: Type1 Female — Decision when a food and another face-facing agent is in sight

We can observe from the fig (21) that when the Type-1 female agent (genome ID: 415) sees only a food and another face-facing agent in its sight radius, regardless of any age, energy or the distance between food and the type-1 female agent, it chooses “move_to_food”.

The Type 1 female agents follow a very stable and very predictable behavioral pattern. When only food was present or food alongside another agent, they prioritized “move_to_food” only which shows they prioritized foraging over anything. They had only engaged or chose to mate_as_female when the mating stimuli were strong and direct, by which it means the presence of a close face-facing agent or a very close back-facing agent at higher energy or age. The Type-1 Female agent chooses to “mate_as_female” always when it saw another face-facing agent at any distance in it sight radius. This behavior shows the direct, fixed reproductive tactics that conserves energy and only would mate or reproduce under optimal conditions. This shows a resource-dependent reproductive strategy.

Type-2 Female Agent:

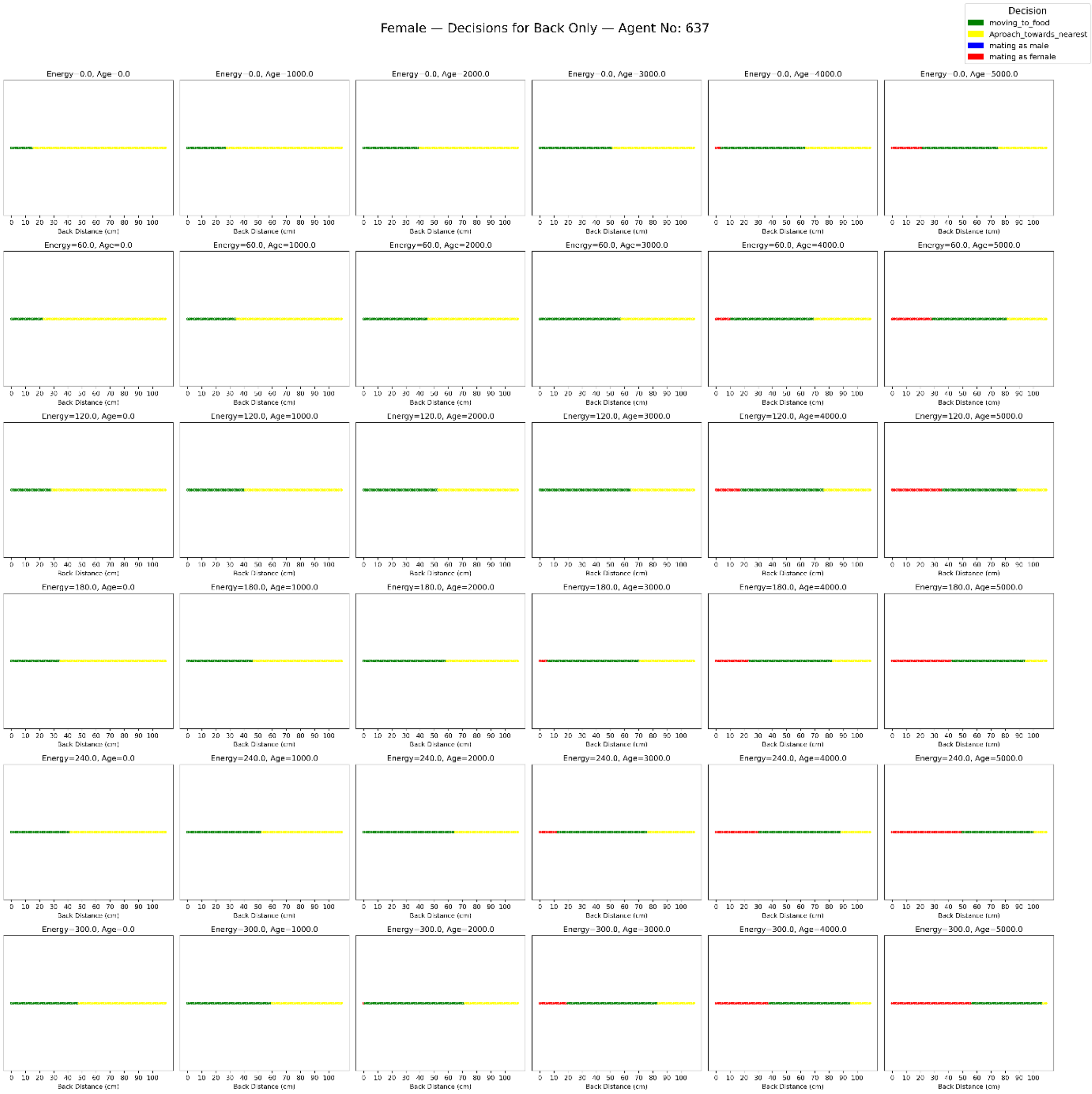


Figure 22: Type 2 Female — Decision when only a back-facing agent is in sight

We can observe from the fig (22) that when the Type-2 female agent (genome ID: 637) at low energy and young age the agent is prioritizing “move_to_food” when it sees only a back-facing agent in its sight radius. As the energy and age increases, the agent begins to choose “move_to_food” at a greater distance threshold followed by “approach_towards_nearerst” at higher distances. At older age and higher energy, the agent chooses “mate_as_female” when the agent is very closer. With the increasing distance between the agent and the back-facing agent it switches to choose “move_to_food” and when the back-facing agent is in the extreme edge of the sight radius, it chooses “approach_towards_nearerst”.

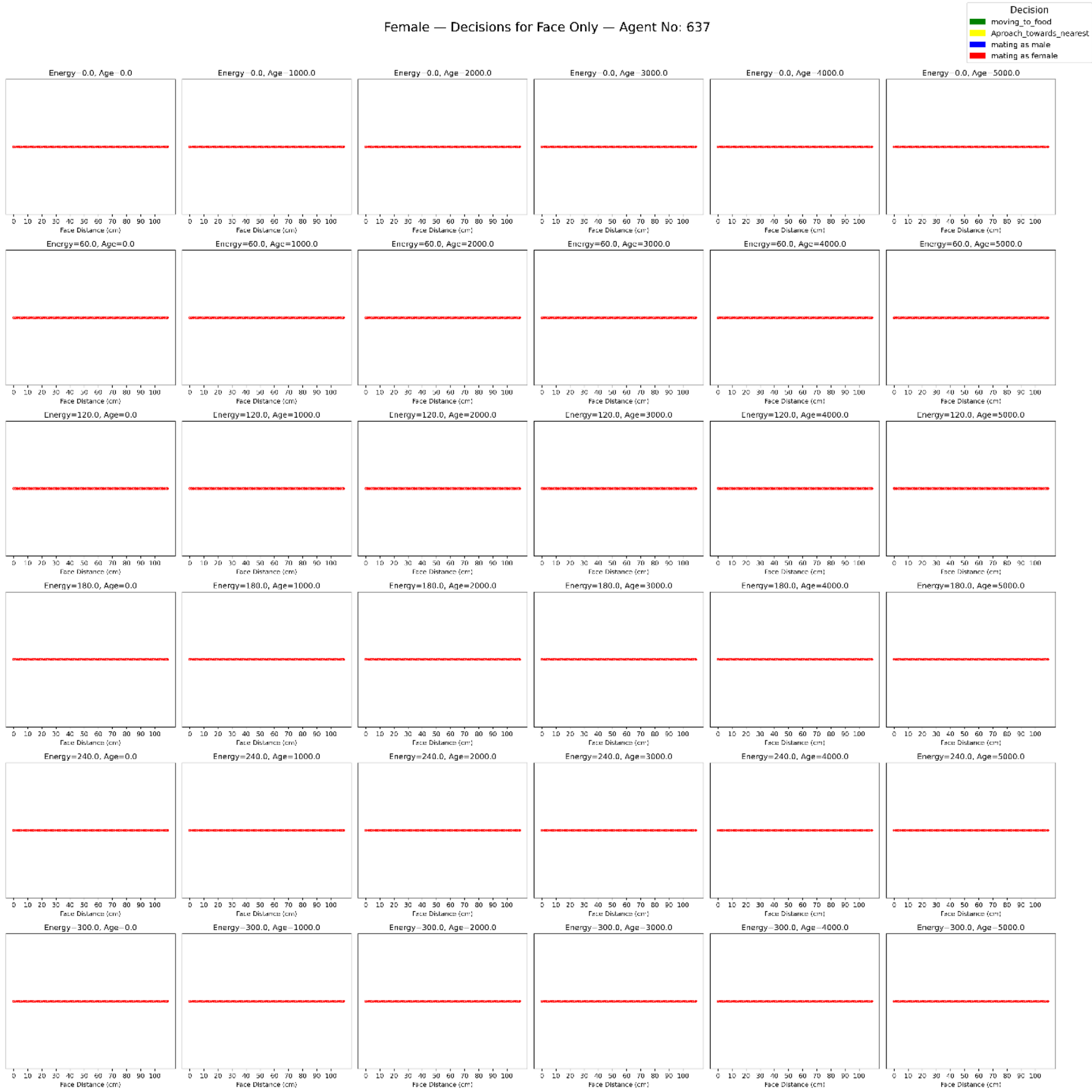


Figure 23: Type 2 Female — Decision when only a face-facing agent is in sight

We can observe in fig (23) that when the type 2 female agent (genome ID: 637) has only a face-facing agent in its sight radius, it always chooses “mate_as_female” regardless of age, energy, distance between the agents.

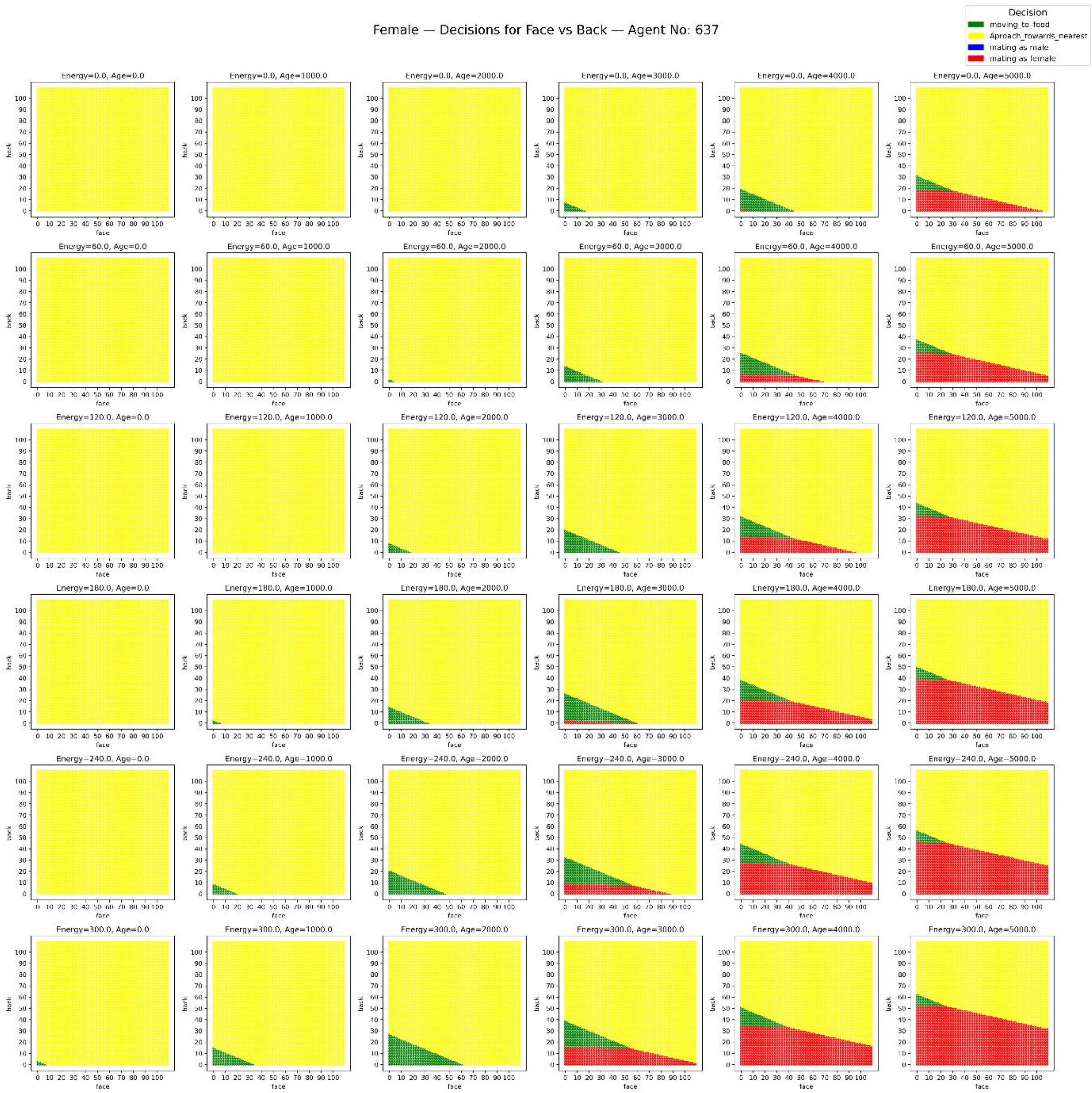


Figure 24: Type 2 Female — Decision when only a face-facing and back-facing agent is in sight.

We can observe in fig (24) that when the type 2 female agent (genome ID: 637) exhibits context-dependent behavior based on the presence of face-facing and back-facing agent in its sight radius. At low energy and a younger age, the type 2 female agent always chooses to "approach_towards_nearest". At younger age and higher energy, the agent chooses "move_to_food" when the face-facing agent is closer and back-facing agent is very closer otherwise they choose approach_towards_nearest". At higher energy and higher age, the threshold for distance of face-facing agent increases to full sight distance and higher back-facing distance they choose mate_as_female. As age and energy increases, the type 2 female agent chooses "move_to_food" at higher distance from back facing but comparatively lower distance to face-facing agent, otherwise chooses "approach_towards_nearest".

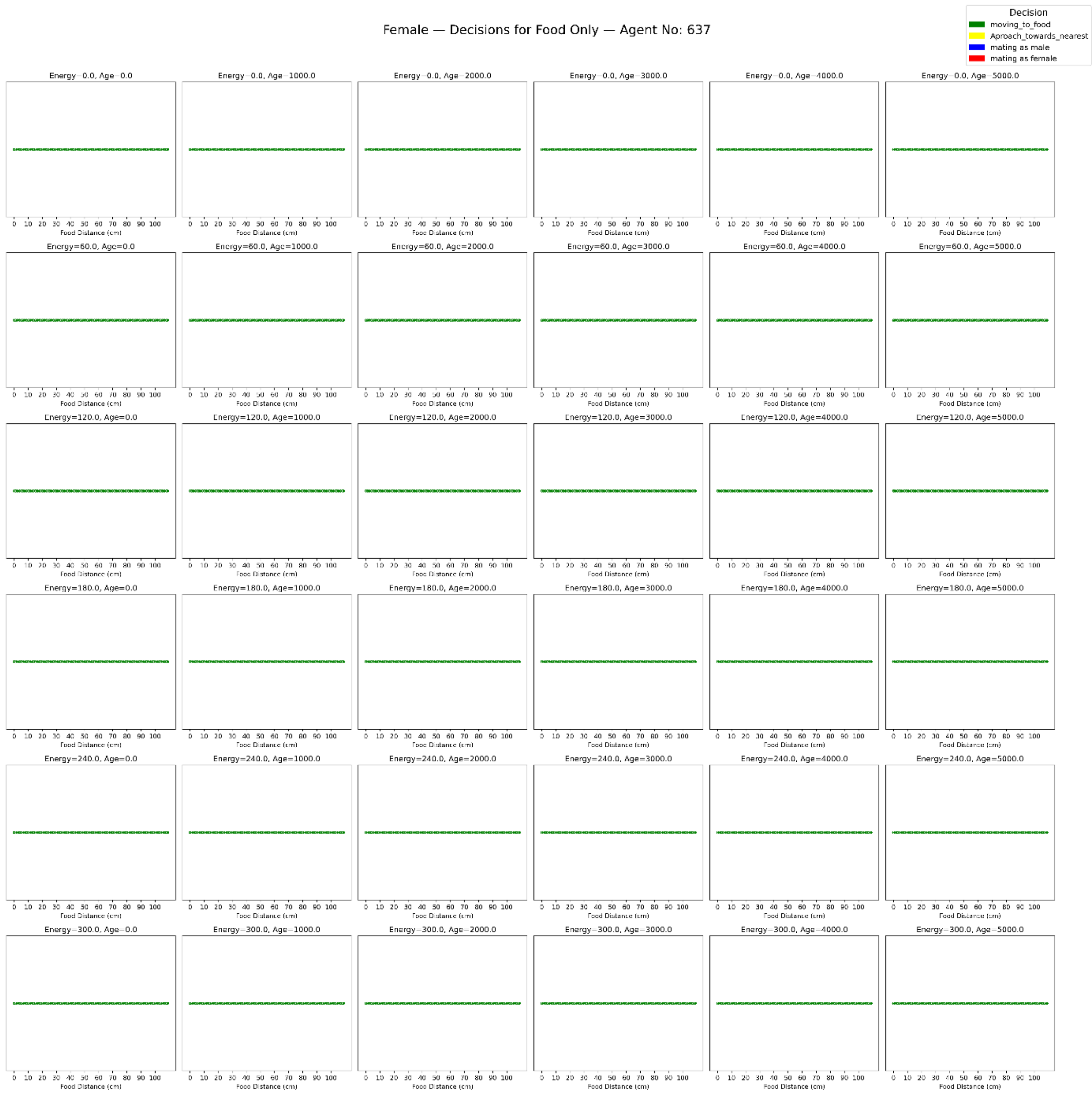


Figure 25: Type 2 Female — Decision when only food is in sight

We can observe in fig (25) that when the type 2 female agent (genome ID: 637) sees only a food in its sight radius, regardless of any age, energy, and distance between food and the type-2 agent, it always chooses “move_to_food”.

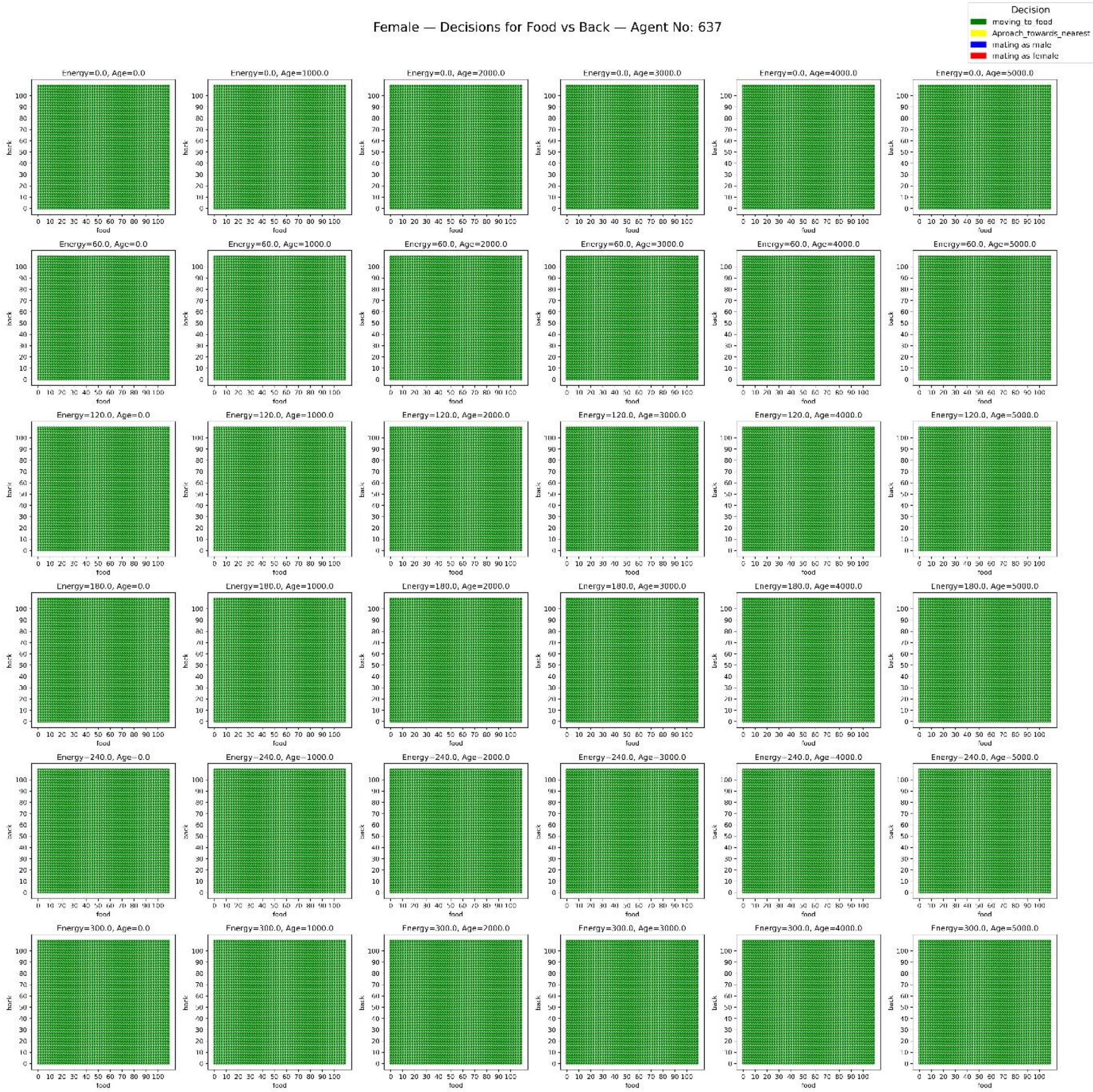


Figure 26: Type 2 Female — Decision when only food and back-facing agent is in sight radius

We can observe in fig (26) that when the type 2 female agent (genome ID: 637) sees only a food and back-facing agent in its sight radius, regardless of any age, energy, and distance between food and the type-2 agent, the type-2 agent and the back-facing agent, it always chooses "move_to_food".

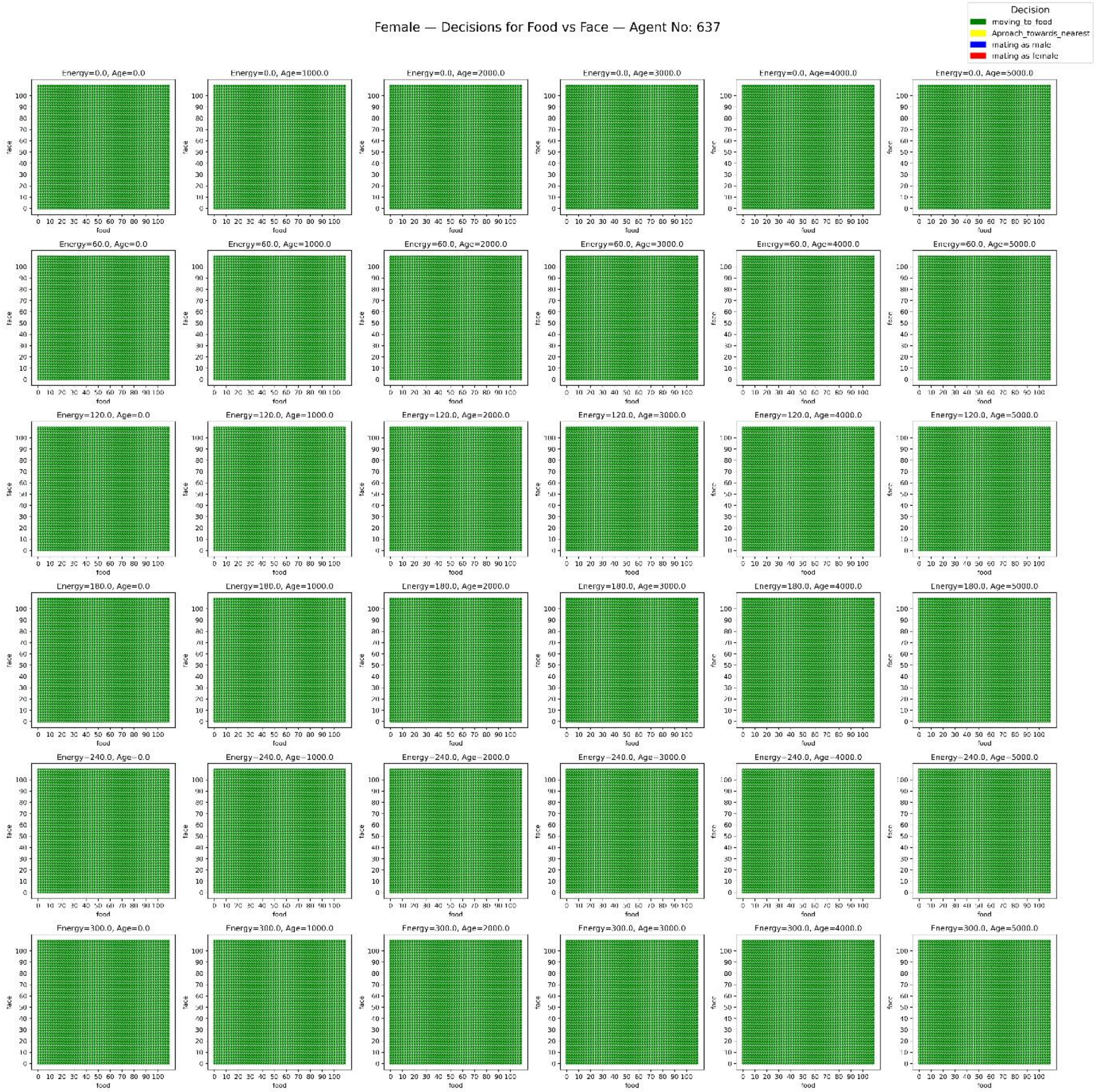


Figure 27: Type 2 Female — Decision when only food and face-facing agent is in sight radius

We can observe in fig (27) that when the type 2 female agent (genome ID: 637) sees only a food and face-facing agent in its sight radius, regardless of any age, energy, and distance between food and the type-2 agent, the type-2 agent and the face-facing agent, it always chooses “move_to_food”.

The type 2 female agent shows the behavior that changes according to their internal physiological state. The type 2 female agents at low energy and young age would avoid reproduction and would prioritize move_to_food(foraging) or approach to the nearest agent(aproach_towards_nearest). As the age and energy increased, they sifted this behavior and began reproducing more frequently even in complex even in complex or ambiguous stimulus combinations. This means as age increases (at the end of their lifetime) they choose more to reproduce before dying. Here for them it's more important for them to reproduce and send their genome more for the next generation. When they are young or low in energy, they often choose safer options like move_to_food, or approach_towards_nearest, but when older or energetic, they override the ambiguity and choose to initiate mating, which shows the shift towards prioritizing reproduction. This suggests the "condition-dependent reproductive tactics" where the decisions to reproduce are made dynamically based on the agent's readiness and context. This closely mirrors the conditional ARTs in real animals, where females chose to reproduce based on their health, condition and opportunity.

- Female lizards show exactly this kind of behavior, they choose to reproduce when they reach a threshold body condition, otherwise they prioritize survival and. growth.
- Fishes show the same energy dependent mating decisions, with older or well-fed ones are more likely to mate early and frequently.

This behavior is referred to as "phenotypic plasticity" in evolutionary biology, which means the ability of one genotype to show different behaviors based on conditions.

Type 1 females show energy-conservative selectivity, while Type 2 females show adaptive flexibility, a hallmark of evolved biological intelligence.

Stimulus Condition	**Type-1 Female Behavior**	**Type-2 Female Behavior**
Only Food	Always chooses move_to_food.	Always chooses move_to_food
Only Back-Facing Agent	**Agent nearer**: mate_as_female. **Agent further away**: move_to_food	• **Low energy**: close → move_to_food, far → approach_towards_nearest • **High age:** close → mate_as_female, moderate → move_to_food, far → approach_towards_nearest
Only Face-Facing Agent	Always chooses mate_as_female	Always chooses mate_as_female
Food + Face-Facing Agent.	Always chooses move_to_food.	Always chooses move_to_food
Food + Back-Facing Agent	Always chooses move_to_food.	Always chooses move_to_food
Face-Facing Agent+ Back-Facing Agent	With the increase of age and energy, the minimum distance threshold for the female to choose mate_as_female increases. If the back-facing agent is far away, the female opts to move_to_food instead.	• **Low age + low energy**: approach_towards_nearest • **Low age + high energy**: close back & front → move_to_food, else approach_towards_nearest • **High age + high energy**: back closer → mate_as_female, back far & face closer → move_to_food, both far → approach_towards_nearest

Table 1**.** The analysis of both the type of female agents

3.3.2. **Male**:

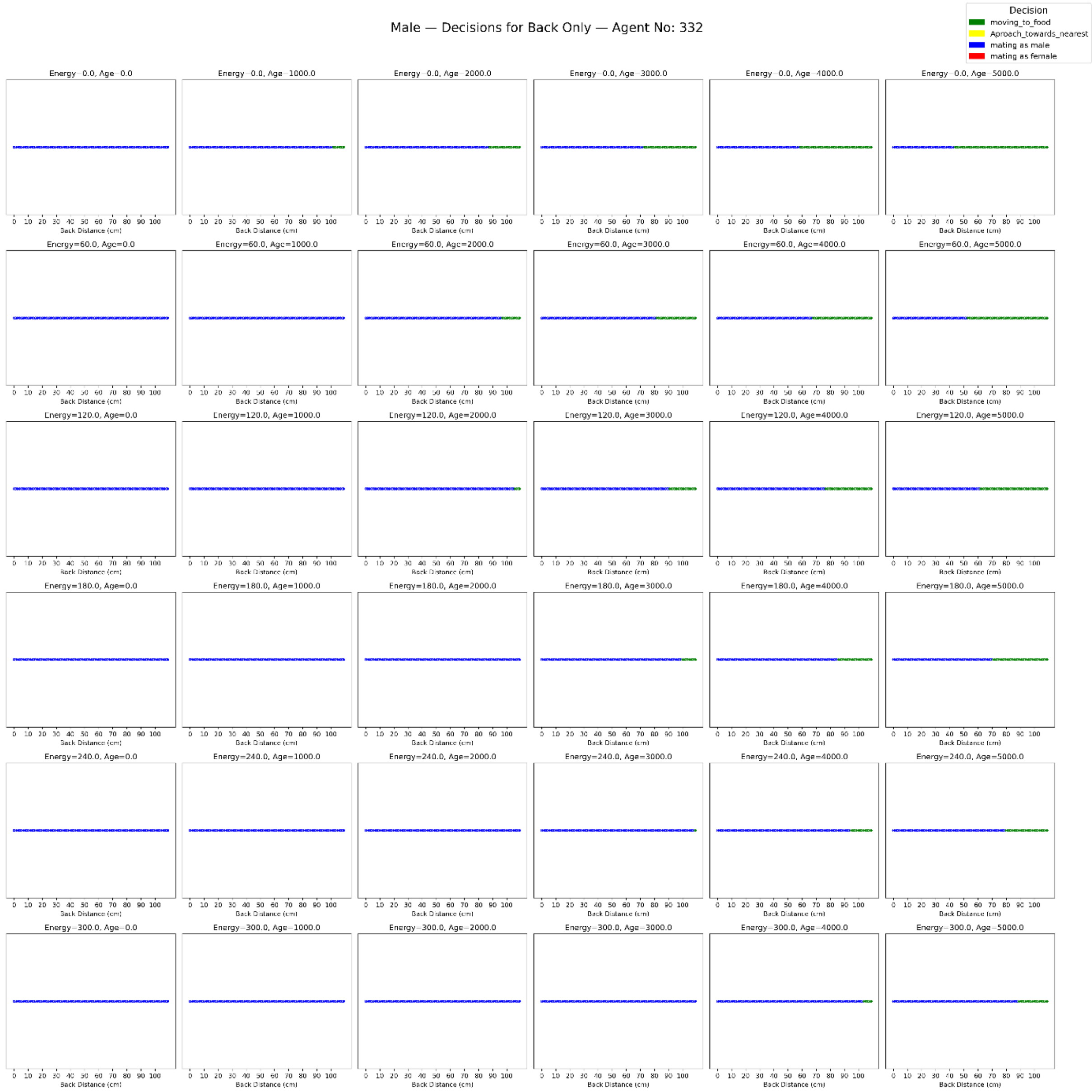


Figure 28: Male — Decision when only back-facing agent is in sight radius

We can observe in fig (28) that when the Male agent (genome ID: 332) sees only a back-facing agent in its sight radius, at low age and energy the male agent always chose “mate_as_male”. As the age and energy increases the male agent continues to choose “mate_as_male” unless the distance between the back-facing agent becomes too big, that is when the agent chooses “move_to_food” when the agent back-facing is far away.

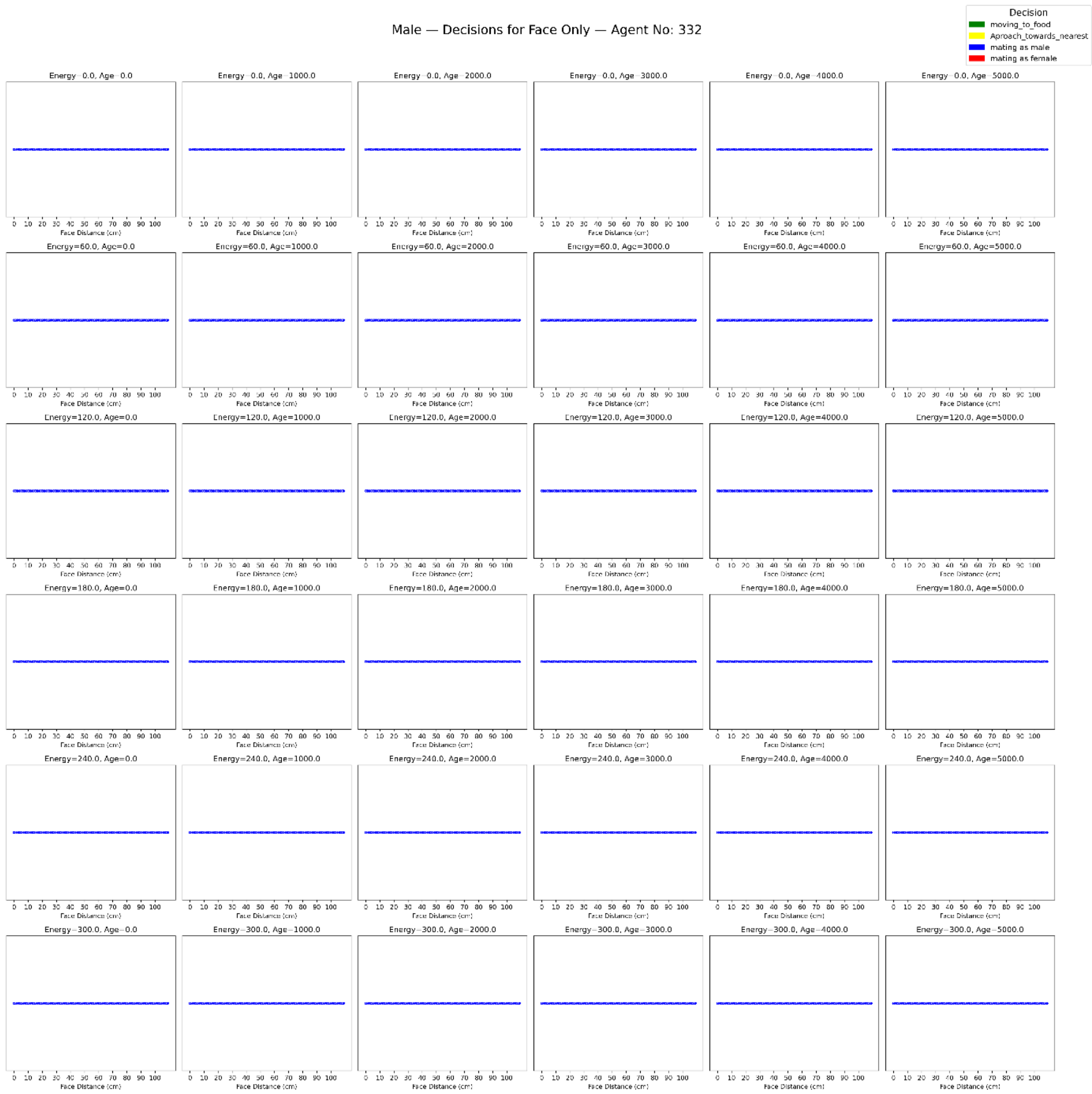


Figure 29: Male — Decision when only face-facing agent is in sight radius

We can observe in fig (29) that when the male agent (genome ID: 332) sees only a face-facing agent in its sight radius, regardless of any age, energy, and distance between food and the male agent always chooses “mate_as_male”.

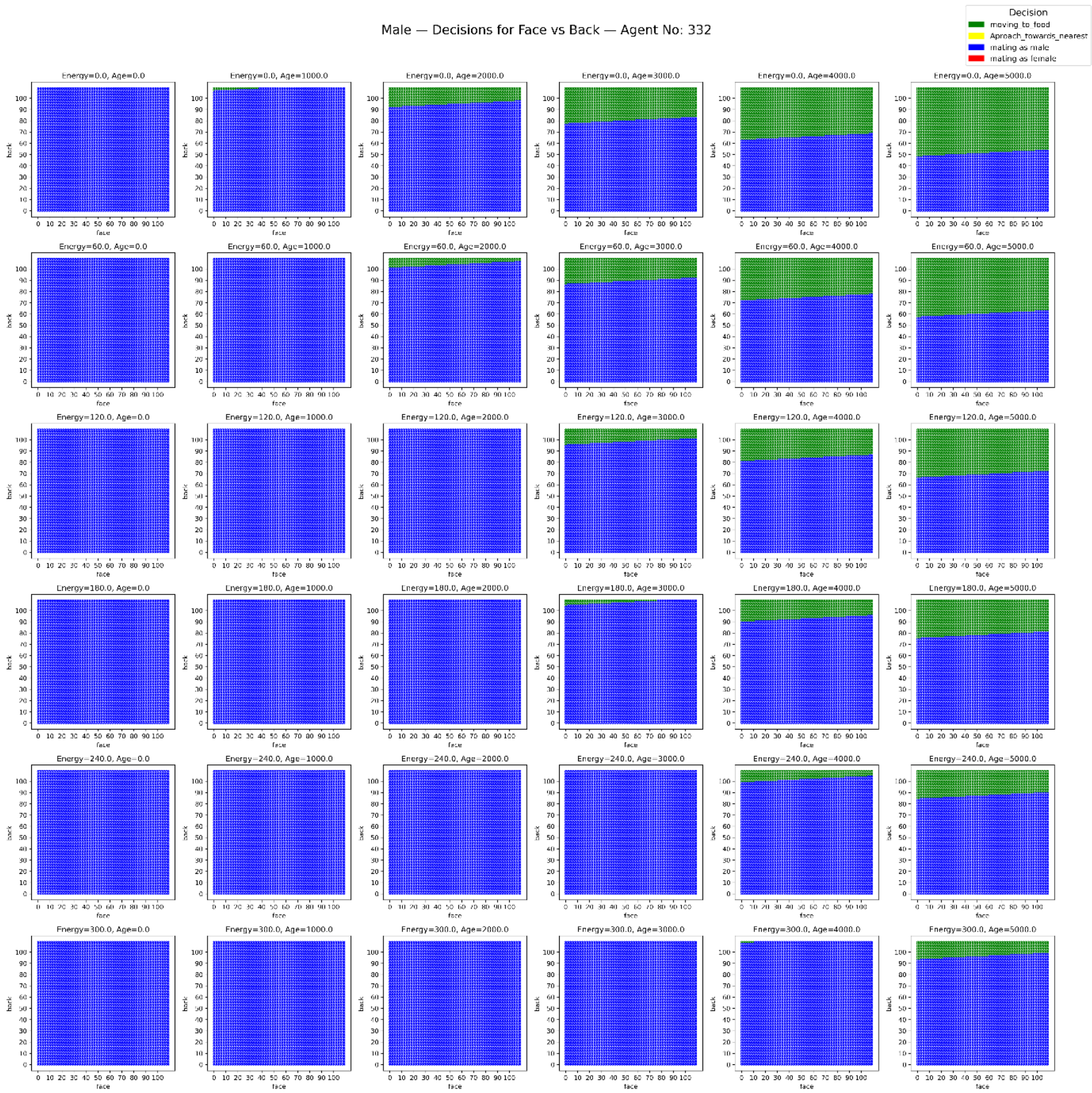


Figure 30: Male — Decision when only food and face-facing agent is in sight radius

We can observe in fig (30) that when the male agent (genome ID: 332) sees only a food and face-facing agent in its sight radius, at low energy and low age it always chooses to “mate_as_male”. At higher age, the agent chooses “mate_as_male” for all distance between the male agent and the face-facing agent, this happens until the distance between the male agent and the back-facing agent goes large, and the back-facing is closer to the sight radius boundary, the agent chooses to “move_to_food”.

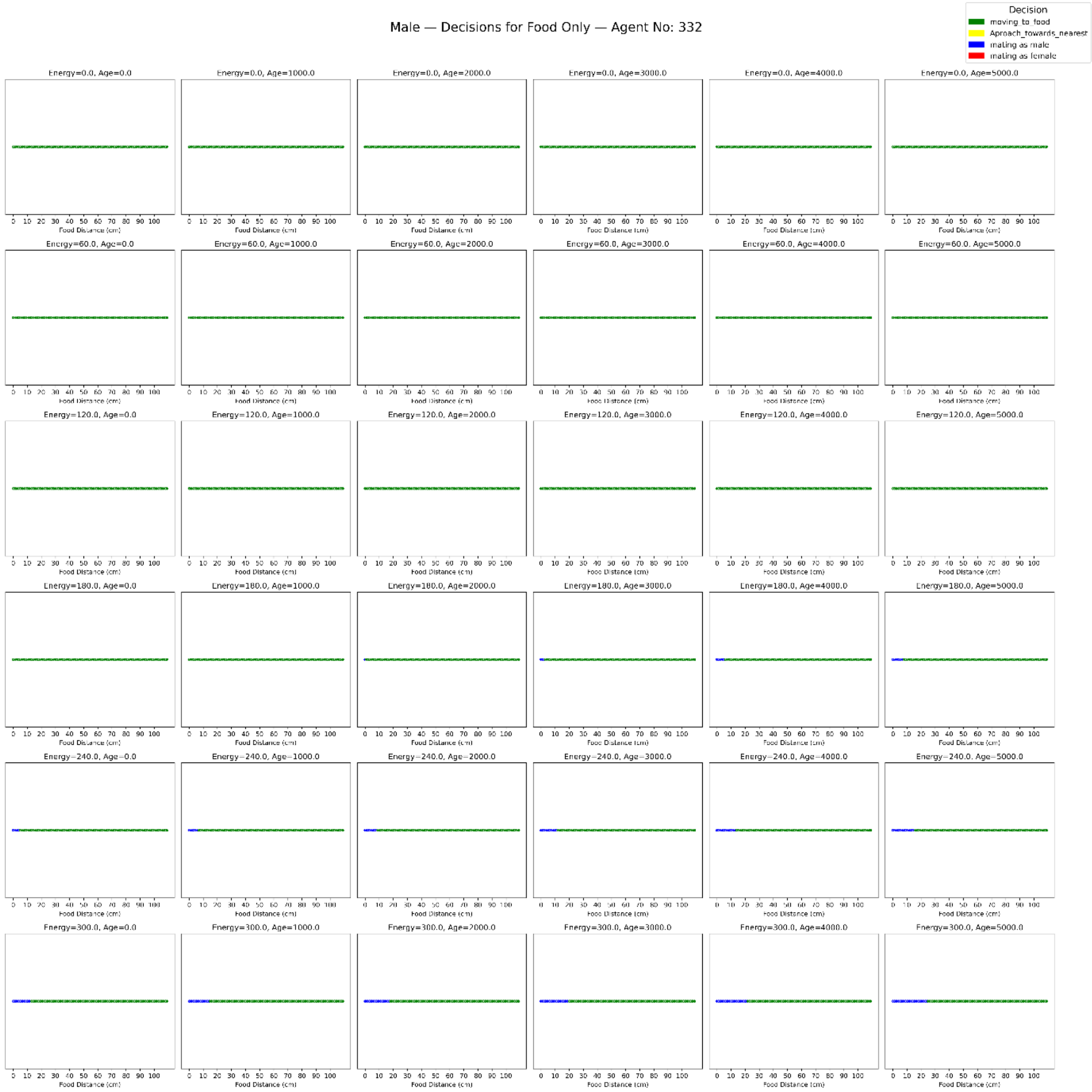


Figure 31: Male — Decision when only food is in sight radius

We can observe in fig (31) that when the male agent (genome ID: 332) sees only a food in its sight radius, at low energy and low age it always chooses to “move_to_food”. At lower energy and higher age, the agent chooses “move_to_food”. As the older age and higher energy, the agent chooses “mate_as_male” when the food is very close, otherwise “move_to_food”.

Figure 32: Male — Decision when only food and back-facing agent is in sight radius

We can observe in fig (32) that when the male agent (genome ID: 332) sees only a food and back-facing agent in its sight radius, regardless of age, energy, or distance between the male agent and the food, or the male agent and the other back-facing agent, the male agent chooses “move_to_food”.

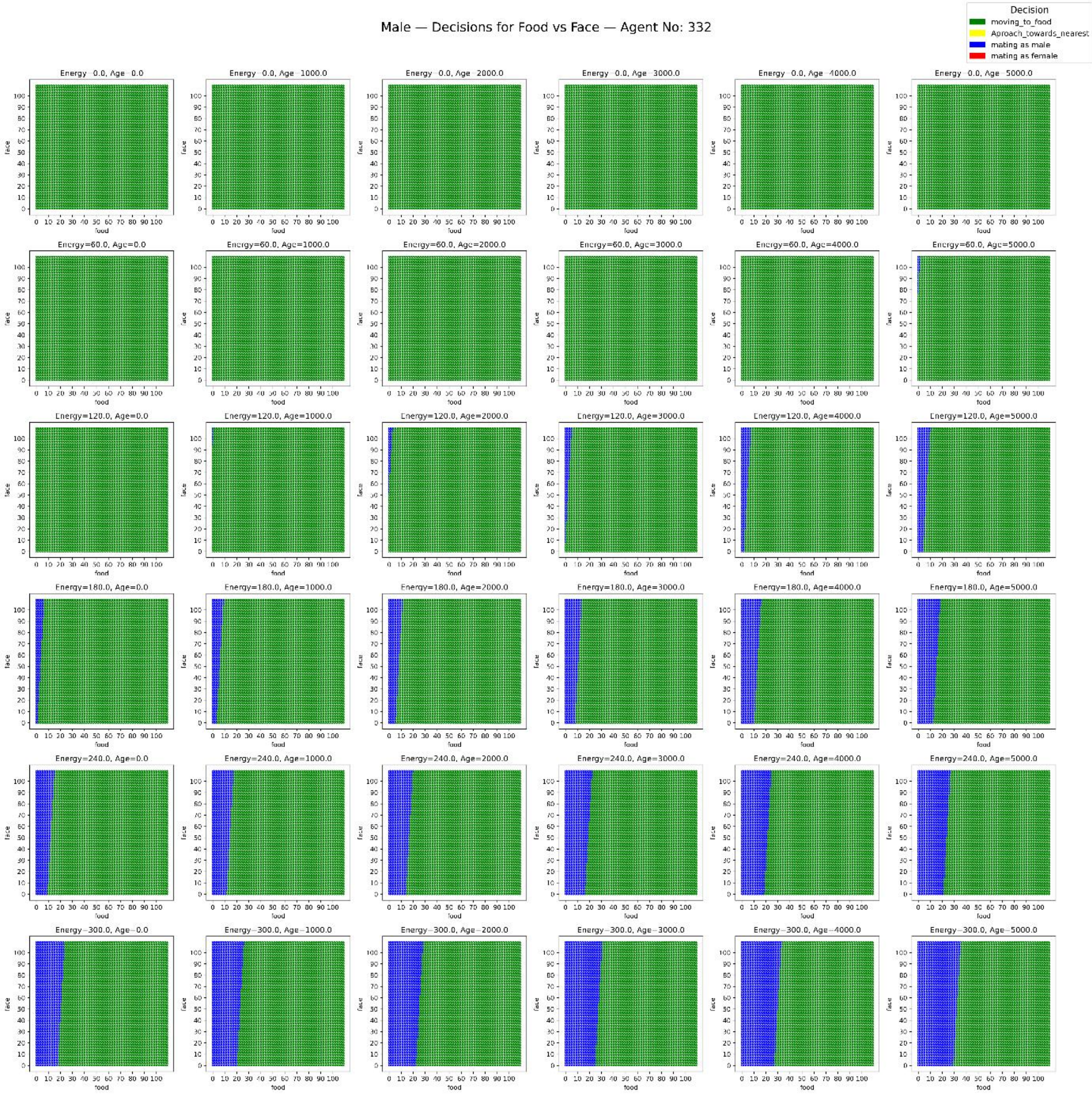


Figure 33: Male — Decision when only food and face-facing agent is in sight radius.

We can observe in fig (33) that when the male agent (genome ID: 332) sees only a food and face-facing agent in its sight radius, at low energy and age, it always chooses "mate_as_male". As energy and age increases, it always chooses "mate_as_male" until the energy is higher and food is very close.

The male agents demonstrated a single dominant behavioral profile, with little to no variations across the male categorized gender. The males' reproductive tactics can more be described as a "proactive matter", that is it wants to initiate mating whenever it can, especially if face-facing agents were present.

In complex scenarios, male agents prioritized mating as long as energy and proximity thresholds were satisfied. It can be seen that even at a young age when the back-facing agent and front-facing agent is present the males chose to mate_as_male. This shows how strong the mating drive is. When both food and an agent was available it prioritized move_to_food more, but when the agent was face-facing at high age it chose to mate_as_male when the food was near.

It can be concluded that the males are fixed and energetically dependent agents.

3.3.3. **Hermaphrodites**:

<u>Type-1 Hermaphrodite Agent:</u>

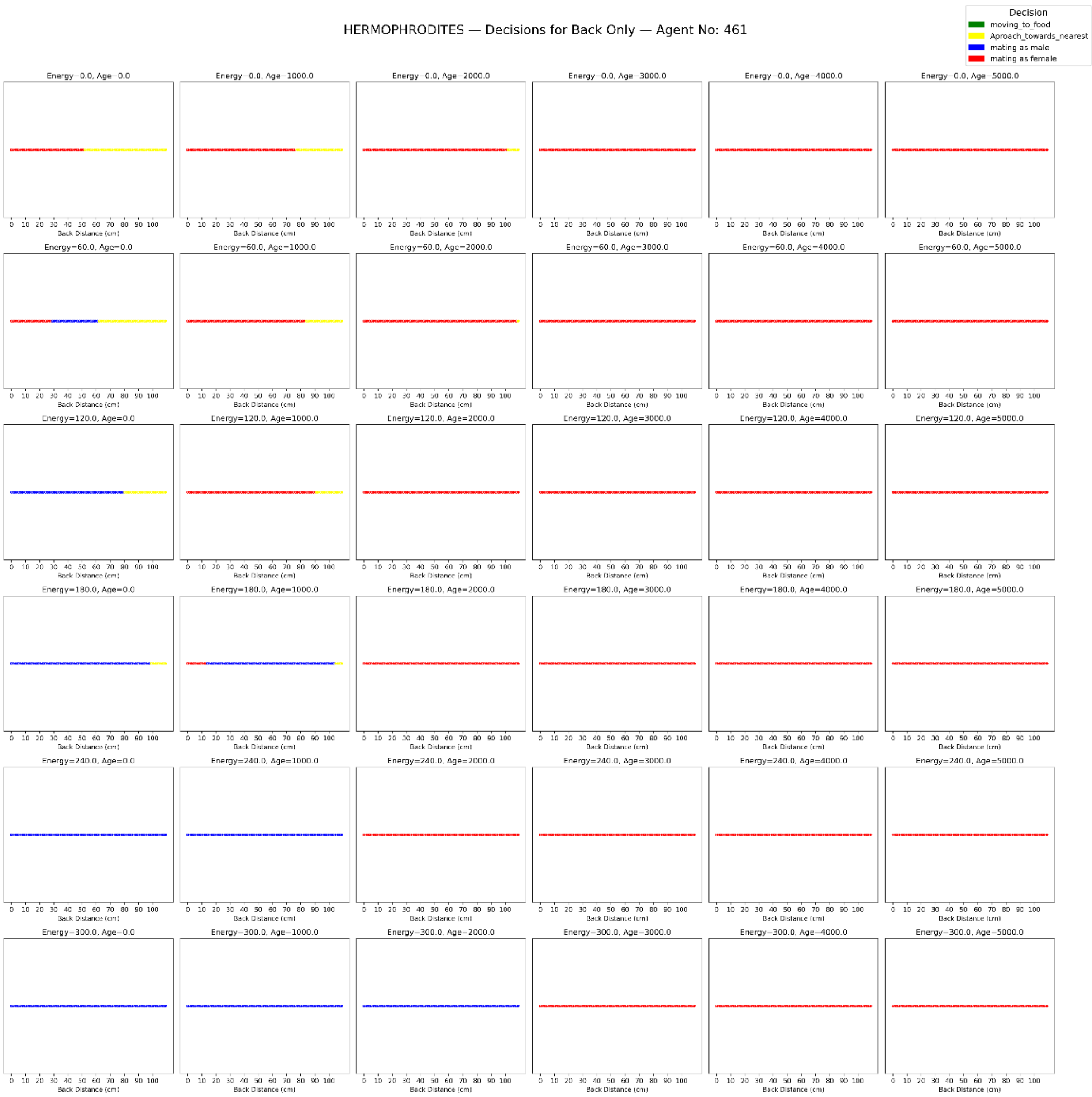


Figure 34: Type 1 Hermaphrodite — Decision when only back-facing agent is in sight radius

We can observe in fig (34) that when the Hermaphrodite agent (genome ID: 461) sees only a back-facing agent in its sight radius, at very low energy and age, it always chooses "mate_as_female" when the back-facing agent is closer and as the distance between them increases the type 1 Hermaphrodite chooses "approach_towards_nearest". At younger age and higher energy type 1 Hermaphrodite chooses to "mate_as_male". At older age, the type 1 Hermaphrodite chooses "mate_as_female".

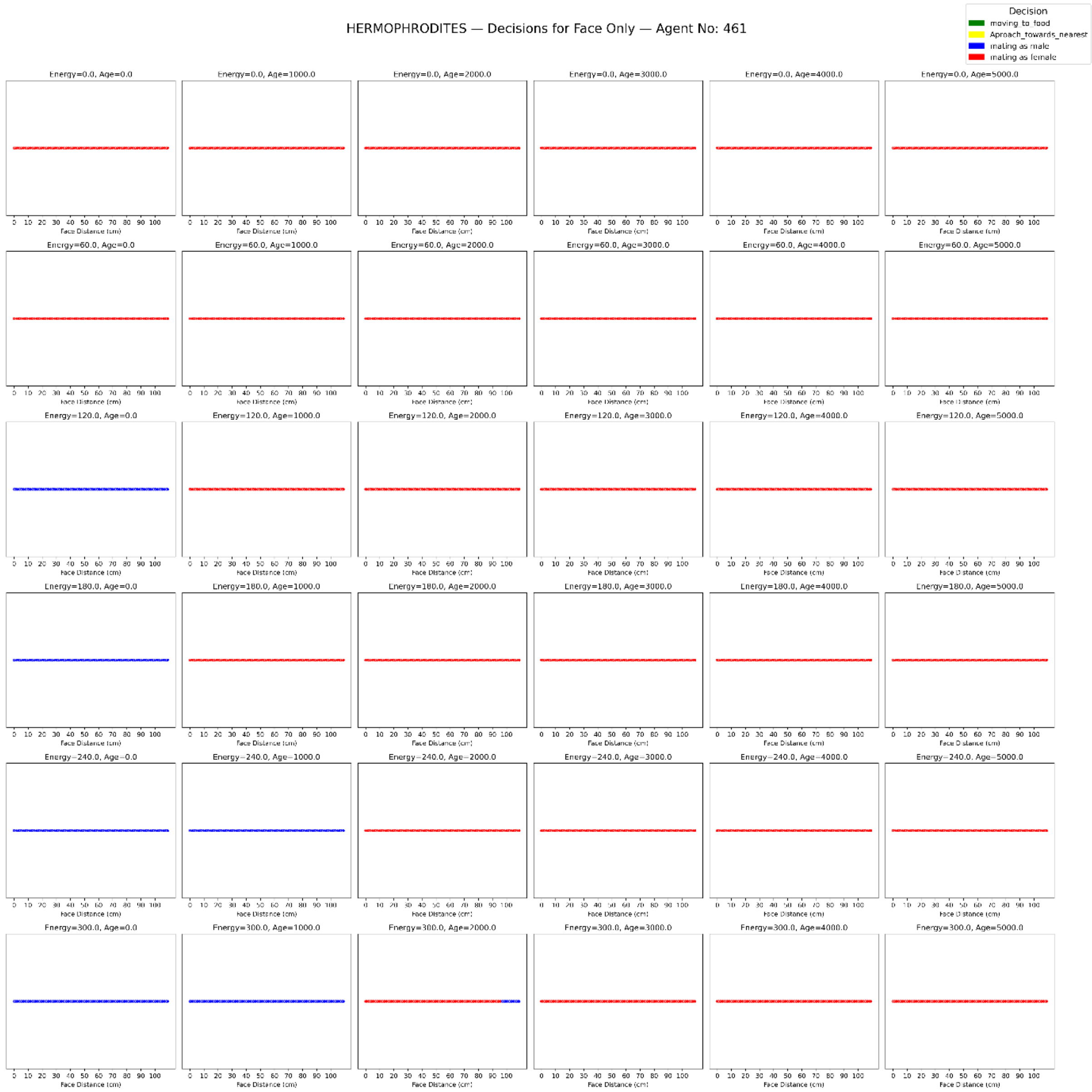


Figure 35: Type 1 Hermaphrodite — Decision when only face-facing agent is in sight radius

We can observe in fig (35) that when the Hermaphrodite agent (genome ID: 461) sees only a face-facing agent in its sight radius, at higher energy and younger age, the Type 1 Hermaphrodite agent choose "mate_as_male". At all other instances the type 1 hermaphrodite chose "mate_as_female".

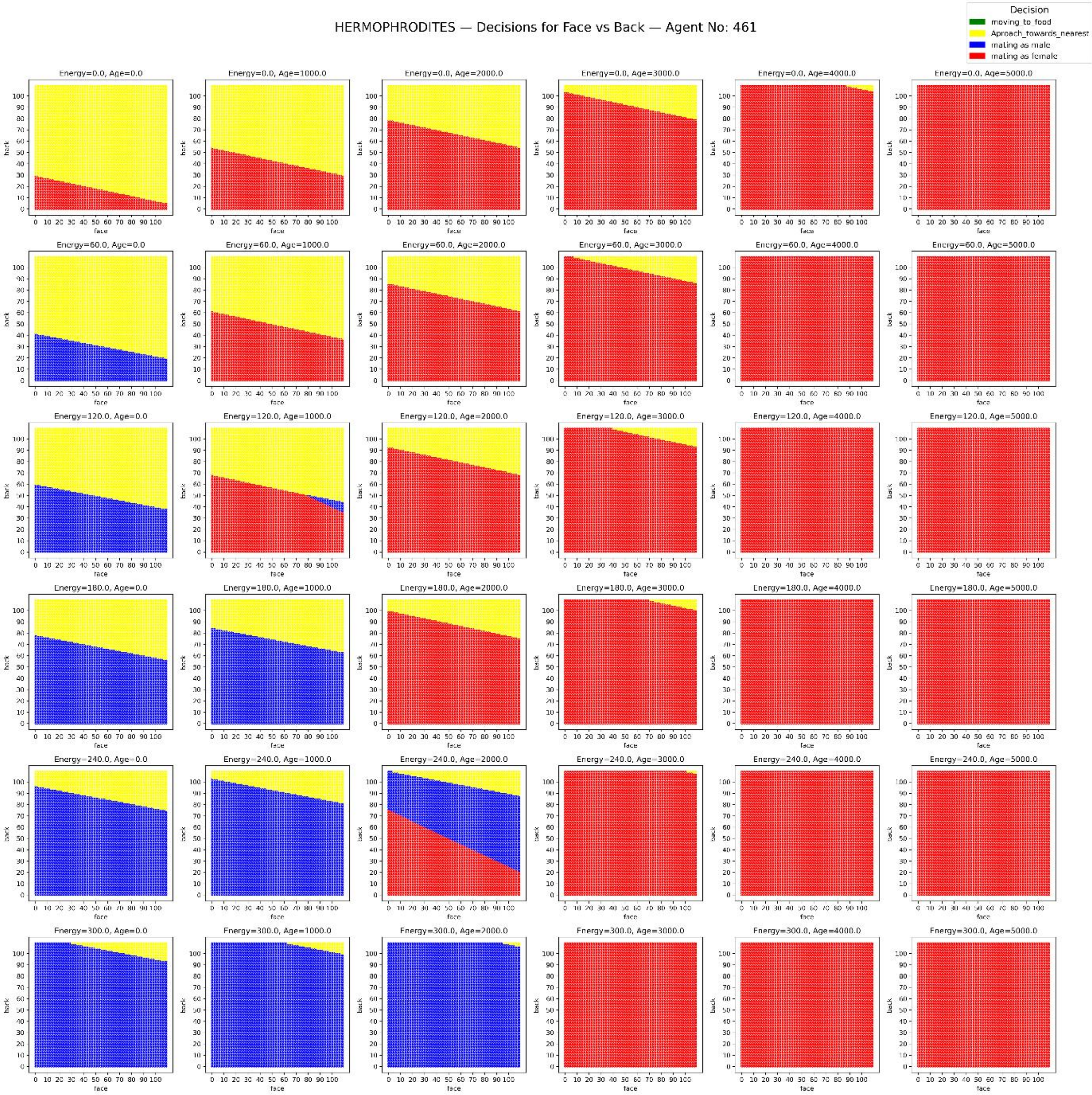


Figure 36: Type 1 Hermaphrodite — Decision when only face-facing and back-facing agent is in sight radius.

We can observe in fig (36) that when the Hermaphrodite agent (genome ID: 461) sees only a face-facing and back-facing agent in its sight radius, at lower energy and younger age, the Type 1 Hermaphrodite agent choose “mate_as_male” with face-facing agent at any distance but back-facing agent being closer to the type 1 Hermaphrodite otherwise “approach_towards_nearest”. At higher energy and younger age, the Type 1 Hermaphrodite chooses “mate_as_male” when the face-facing agent at any distance and the back-facing agent a bit closer than the face-facing agent, when the back-facing is further away it chooses “approach_to_nearest”. With older age agent always chose to “mate_as_female”.

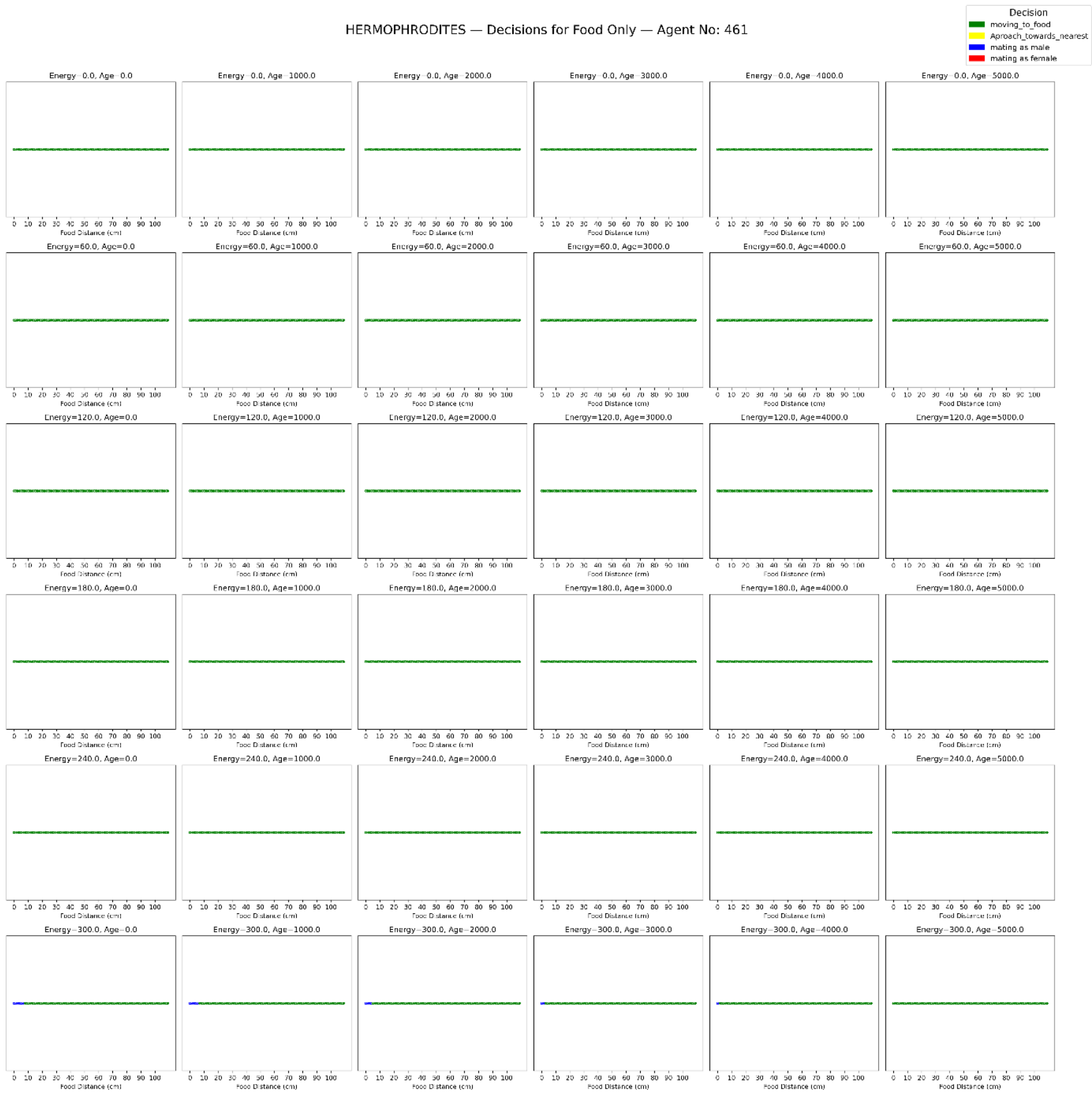


Figure 37: Type 1 Hermaphrodite — Decision when only food is in sight radius

We can observe in fig (37) that when the Hermaphrodite agent (genome ID: 461) sees only a food in its sight radius, it always chooses "move_to_food", regardless of age, energy and distance in between.

Figure 38: Type 1 Hermaphrodite — Decision when only food and a back-facing agent is in sight radius

We can observe in fig (38) that when the Hermaphrodite agent (genome ID: 461) sees only a food and a back-facing agent in its sight radius, it always chooses “move_to_food”, regardless of age, energy and distance in between each other.

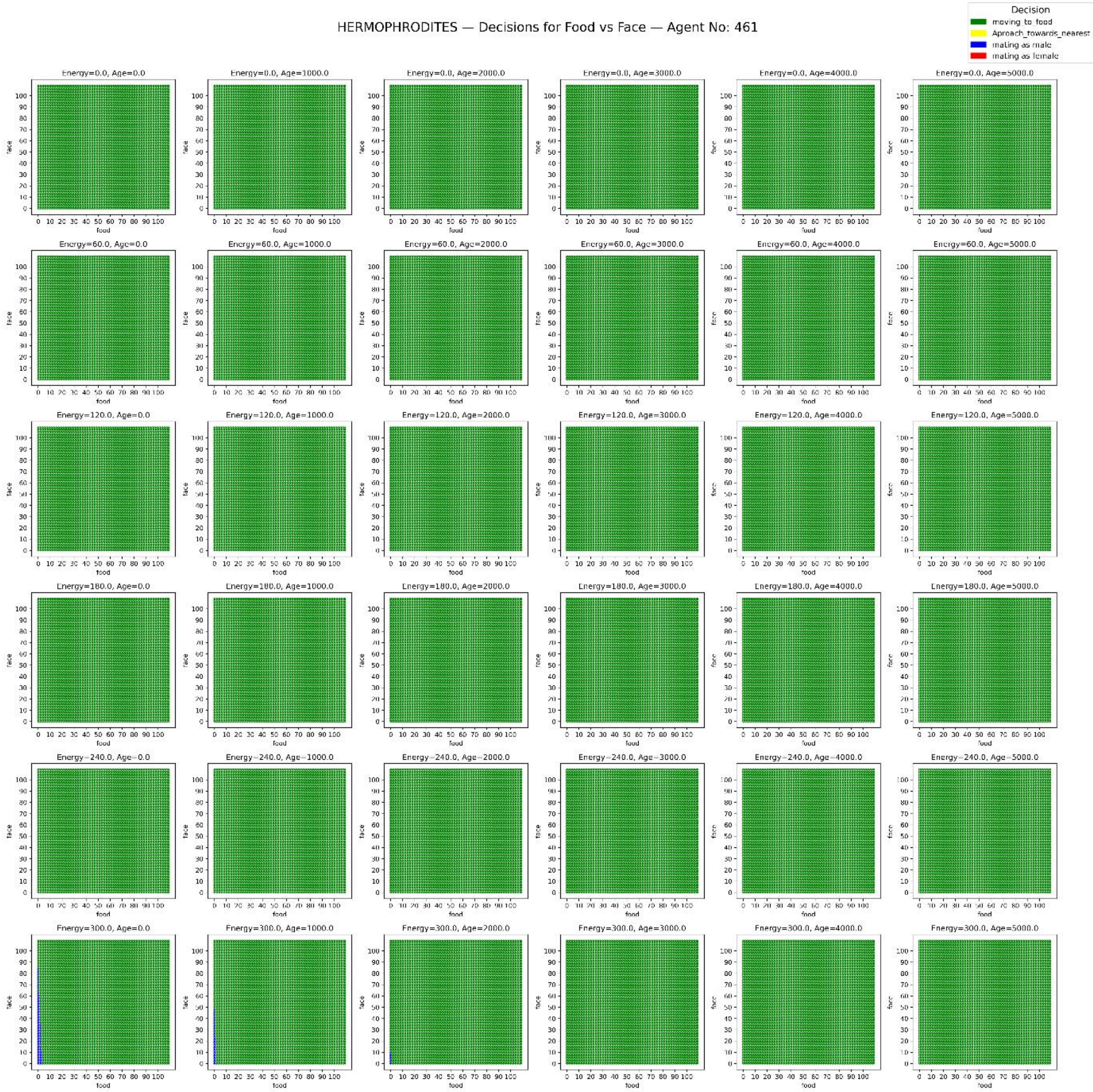


Figure 39: Type 1 Hermaphrodite — Decision when only food and a face-facing agent is in sight radius.

We can observe in fig (39) that when the Hermaphrodite agent (genome ID: 461) sees only a food and a face-facing agent in its sight radius, it always chooses “move_to_food”, regardless of age, energy and distance in between each other.

Type-2 Hermaphrodite Agent:

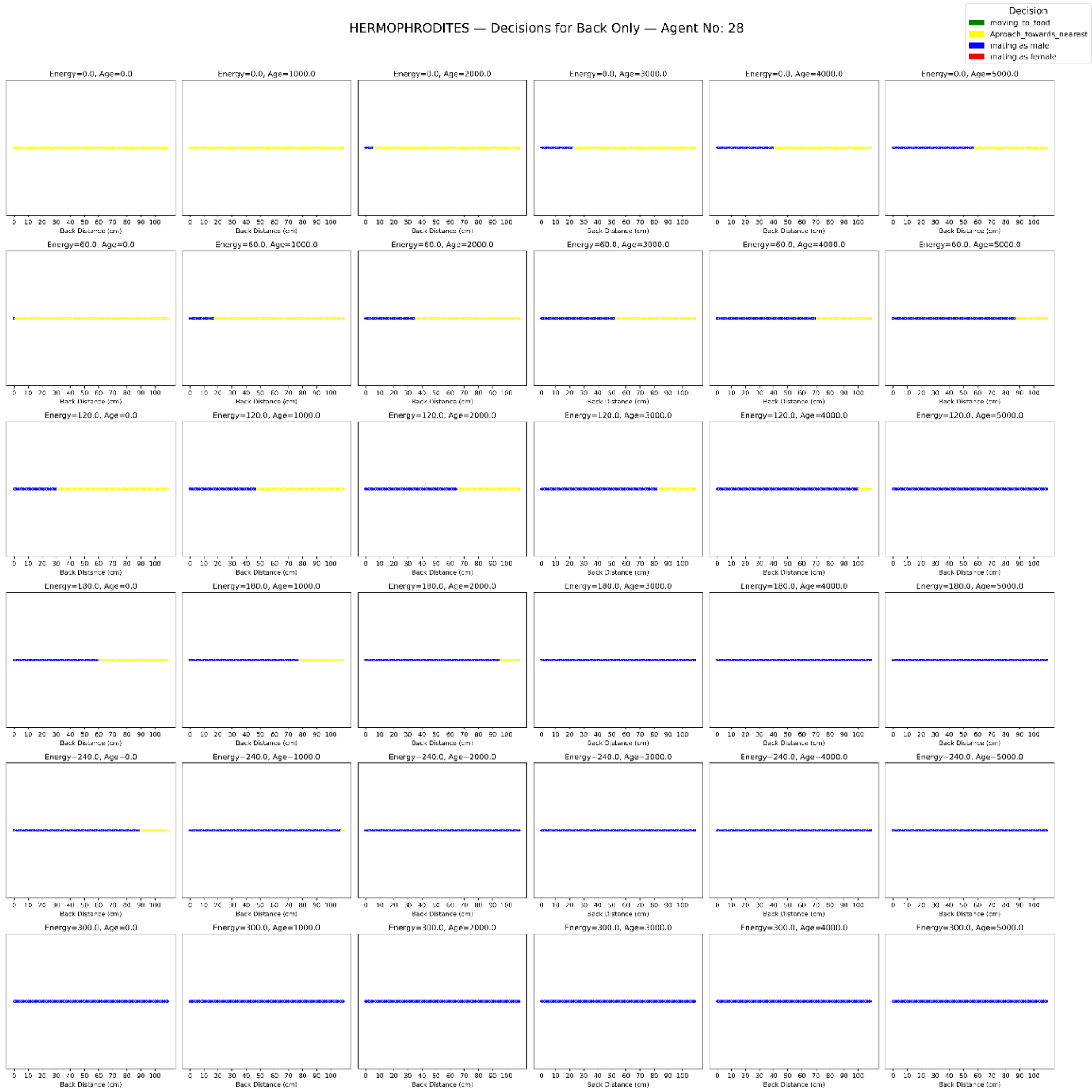


Figure 40: Type 2 Hermaphrodite — Decision when only back-facing agent is in sight radius

We can observe in fig (40) that when the Hermaphrodite agent (genome ID: 28) sees only a back-facing agent in its sight radius, at very low energy and age, it chooses “approach_to_nearest”. With the increasing age and energy, the type 2 agent chooses “mate_as_male” with the threshold distance increasing with the increase of the age and energy. At high energy and older age, it always chooses “mate_as_male”.

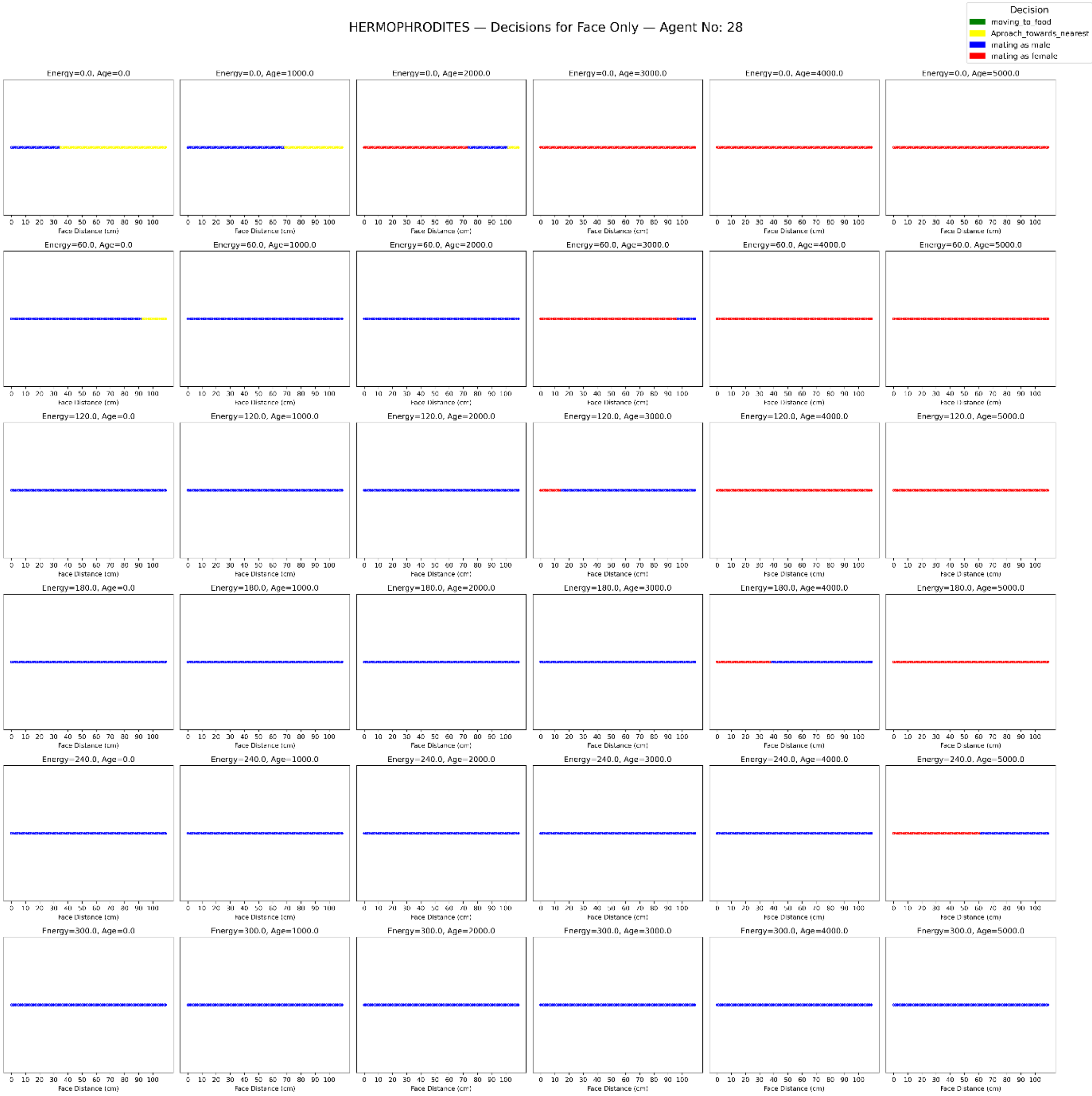


Figure 41: Type 2 Hermaphrodite — Decision when only face-facing agent is in sight radius

We can observe in fig (41) that when the Hermaphrodite agent (genome ID: 28) sees only a face-facing agent in its sight radius, at young age and low energy the type 2 Hermaphrodite chooses to "mate_as_male" when the face-facing agent is very close otherwise "approach_towards_nearest". At high energy, the agent always choses to "mate_as_male". At lower energy and older age always choose "mate_as_female".

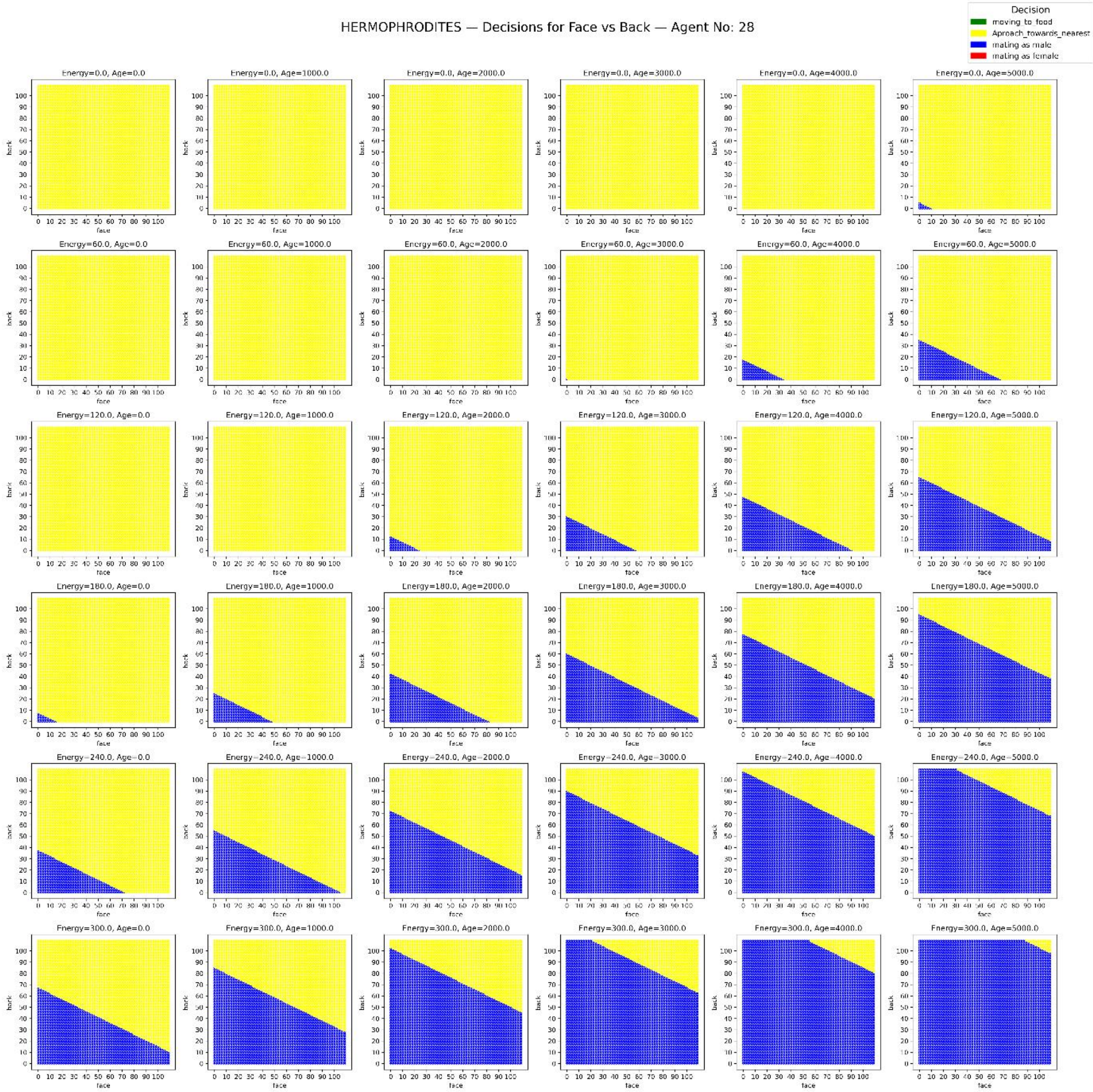


Figure 42: Type 2 Hermaphrodite — Decision when only face-facing and back-facing agent is in sight radius

We can observe in fig (42) that when the Hermaphrodite agent (genome ID: 439) sees only a face-facing agent and back-facing agent in its sight radius, at low energy it always chooses “approach_towards_nearest”. As the energy and age increases the distance threshold for the face and back-facing agent to choose “mate_as_male” increases of the type 2 Hermaphrodite agent.

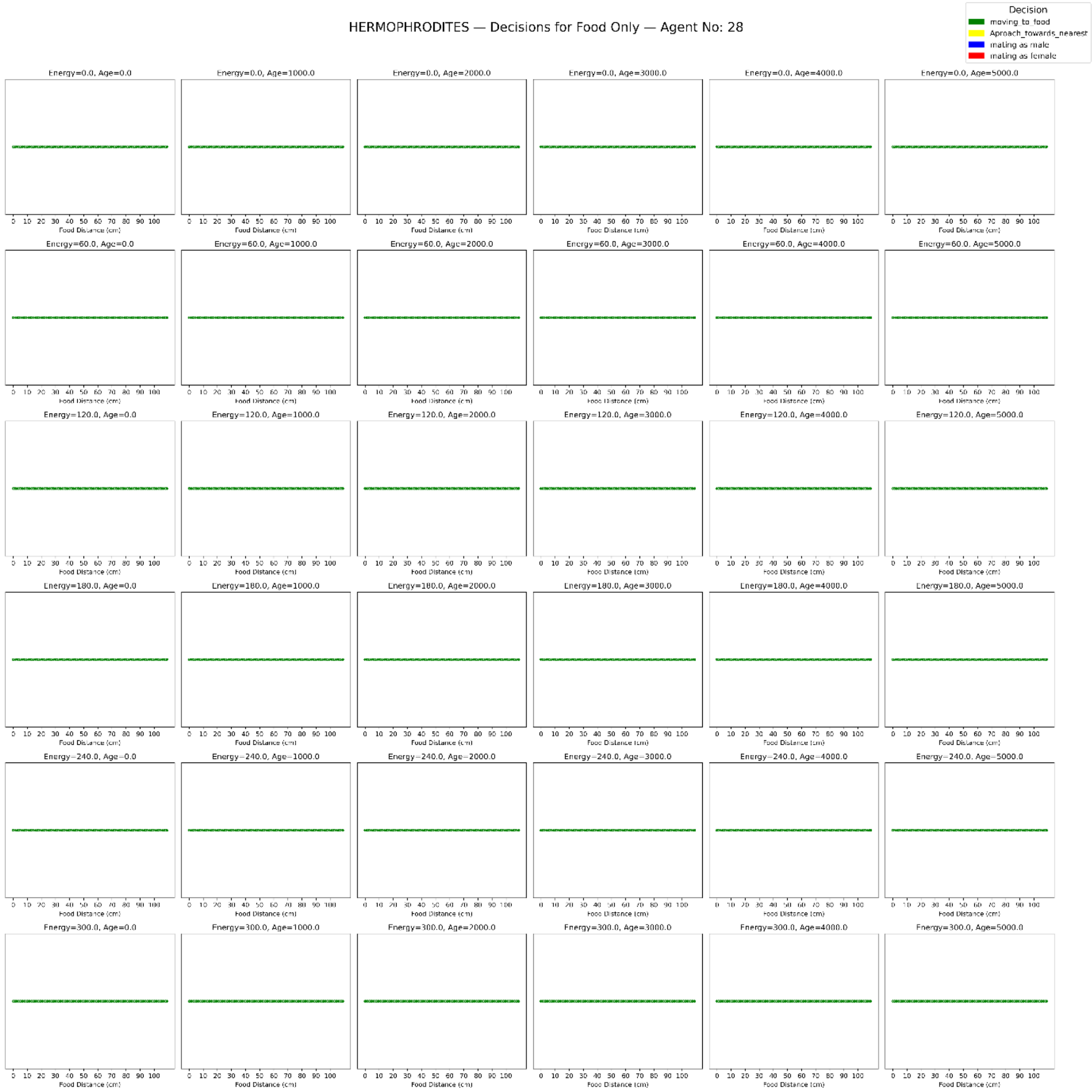


Figure 43: Type 2 Hermaphrodite — Decision when only food is in sight radius

We can observe in fig (43) that when the Hermaphrodite agent (genome ID: 439) sees only a food in its sight radius, regardless of age, energy and distance between, the type 2 hermaphrodite always chooses "move_to_food".

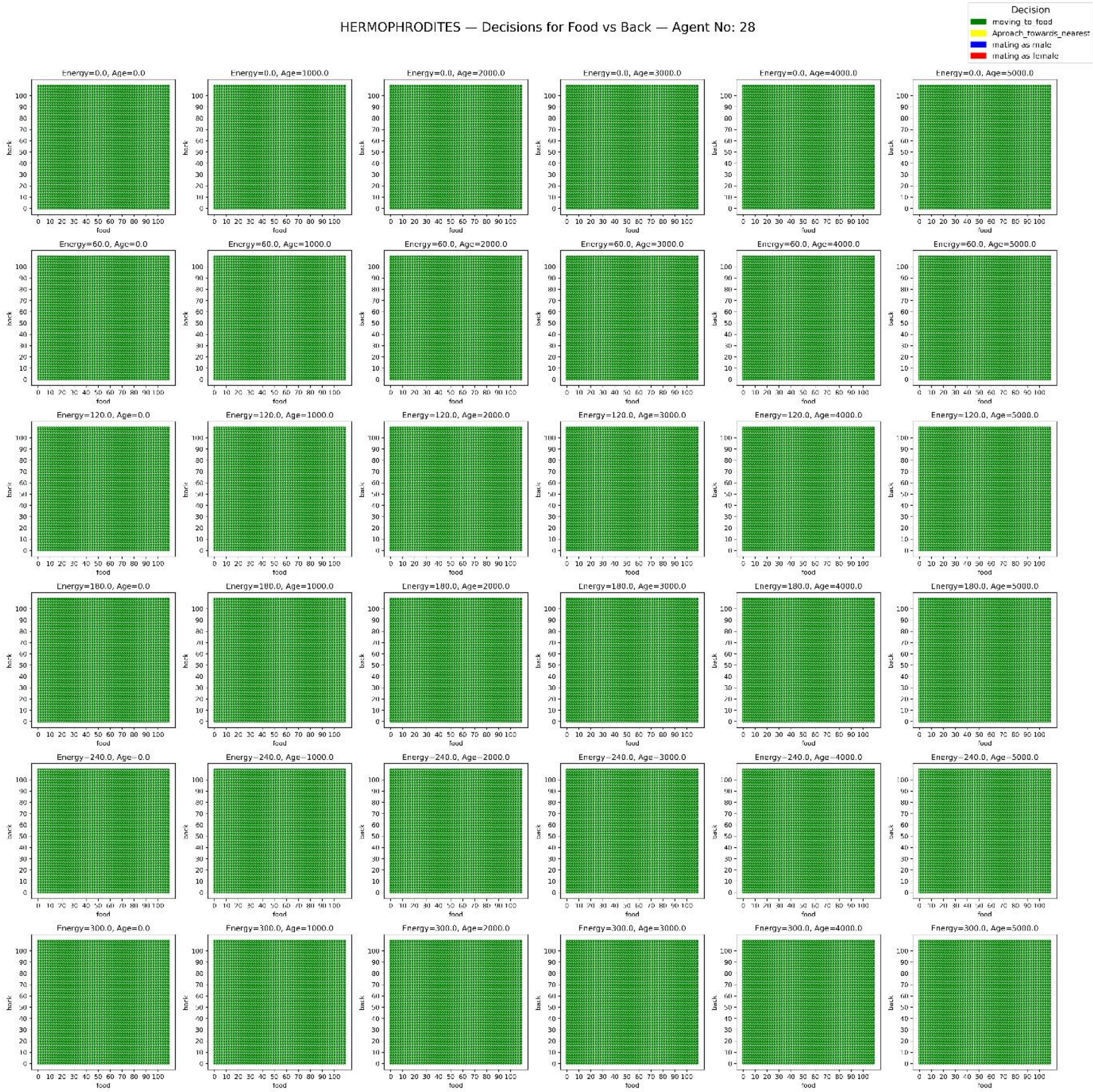


Figure 44: Type 2 Hermaphrodite — Decision when only food and back-facing agent is in sight radius

We can observe in fig (44) that when the Hermaphrodite agent (genome ID: 439) sees only a food and back-facing agent in its sight radius, regardless of age, energy and distance between, the type 2 hermaphrodite always chooses “move_to_food”.

Figure 45: Type 2 Hermaphrodite — Decision when only food and face-facing agent is in sight radius

We can observe in fig (45) that when the Hermaphrodite agent (genome ID: 439) sees only a food and face-facing agent in its sight radius, regardless of age, energy and distance between, the type 2 hermaphrodite always chooses “move_to_food”.

Stimulus Condition	Type 1 Hermaphrodite Behavior	Type 2 Hermaphrodite Behavior
Only Food	Always chooses move_to_food	Always chooses move_to_food
Only Back-Facing Agent	o **Low energy + low age**: back close → mate_as_female, back far → approach_towards_nearest o **High energy + low age**: back close → mate_as_male, back far → approach_towards_nearest o **Low age + highest energy**: mate_as_male o High age: mate_as_female	o **Low energy**: back close → mate_as_male, back far → approach_towards_nearest o The threshold distance to choose mate_as_male increases with age and energy o **High energy**: always mate_as_male o Type 2 hermaphrodite with only back-facing agent: always acts as male, never female
Only Face-Facing Agent	o **Low age + low energy**: mate_as_female o **Low age + high energy**: mate_as_male o **High age(>2000):** always mate_as_female	o **0 energy + 0 age**: face close → mate_as_male, else → approach_towards_nearest o **Low age**: mate_as_male o **Low energy + high age:** mate_as_female o **High energy + high age:** face close → mate_as_female, face far → mate_as_female o **Highest energy + age:** always mate_as_male
Food + Face-Facing Agent	Always chooses move_to_food	Always chooses move_to_food
Food + Back-Facing Agent	Always chooses move_to_food	Always chooses move_to_food
Face-Facing Agent + Back-Facing Agent	o **Lowest age + lowest energy**: back close → mate_as_female, back far → approach_towards_nearest o **Low age + increasing energy**: back closer than face → mate_as_male, back very far → approach_towards_nearest o **Low energy + mid age**: back closer than face → mate_as_female, back very far → approach_towards_nearest o **High energy**: mate_as_female	o **Low energy + low age**: always → approach_towards_nearest o **Increasing age and energy**: back closer than threshold → mate_as_male, back far → approach_towards_nearest

Table 2: The analysis of both the type of hermaphrodite agents

Agents labelled as the hermaphrodites are capable of mate_as_female and mate_as_male too. The analysis showed that the hermaphrodite had two distinct behavioral subtypes.

Emergent ART in Type 1 Female:

- **Strategy**: "Choosy, Resource dependent reproductive tactic." Reproduction occurs only under conditions that are favorable in terms of age, energy and the proximity of potential mating partners.
- **Tactics**:
  - Prioritizes survival and foraging(move_to_food)
  - Initiates mating (mate_as_female) only when the potential partner is sufficiently close.
  - Avoids reproduction when the food is available in sight or the conditions are suboptimal.
- **The Biological analogy**: This type of female mirrors the female lizards, fish or birds that only mate under optimal environmental and internal conditions, prioritizing their survival over risky reproduction.

Emergent ART in Type 2 Female:

- **Strategy**: "Opportunistic, Condition-dependent reproductive tactic with sneaky tendencies." The reproduction is conditional on the potential partner's orientation the distance, age and energy.
- **Tactics**:
  - Prioritizes survival and foraging(move_to_food).
  - Approaches the Back-Facing agents without immediate mating by choosing (Approach_towards_nearest). These shows the sneaky behavior.
  - Chooses mate_as_female if sees, face-facing or energy/age threshold is met.
  - Use orientation cues to optimize the mating opportunities and minimize risk.
- **The biological Analogy**: The type 2 female are similar to the sneaky females or conditional ARTs in birds' fish and insects, that wait for opportunities, avoid direct competition and mate opportunistically.

Emergent ART in Type 1 Hermaphrodites:

- **Strategy**: "Sequential hermaphroditism with energy and age dependent role switching." The young agents act as male or female depending on the energy, while the older agents predominantly act as females.
- **Tactics:**
  - Prioritizes survival and foraging(move_to_food).
  - Young and high-energy agents adopt male role ear partners; the low energy ones adopt female role.
  - Older agents always adopt female role or selectively approach mating partners.

- The role choice Is mainly governed by age here

- **The Biological Analogy**: This mirrors the sequential hermaphroditism in nature, which is seen in fishes Clownfish.

Emergent ART in Type 2 Hermaphrodites:

- **Strategy**: "Male-biased opportunist hermaphrodites with context-dependent female function." The mating decisions depend on the partner's orientation, distance, age and energy.
- **Tactics**:
  - Prioritizes survival and foraging(move_to_food).
  - Acts as male mostly.
  - Act as female later in life when older. (they accept the cost when the survival is less critical) and sees face-facing agent.
- The Biological **analogy**: This mirrors the flatworms and self-fertilizing fish that are male-biased but are conditionally flexible.

Type 1 Female ART:

The ART in the type 1 females show Choosy, Resource dependent reproductive tactic.

Type 2 Female ART:

The ART in the type 2 Female show Opportunistic, Condition-dependent reproductive tactic with sneaky tendencies.

Type 1 Hermaphrodites ART:

The ART in the type 1 hermaphrodites show Sequential hermaphroditism with energy and age dependent role switching.

Type 2 Hermaphrodites ART:

The ART in the type 2 hermaphrodites show Male-biased opportunist hermaphrodites with context-dependent female function.

Male agents have no ART

3.4. Emergent Phenotype in $Em_{reproduction}$

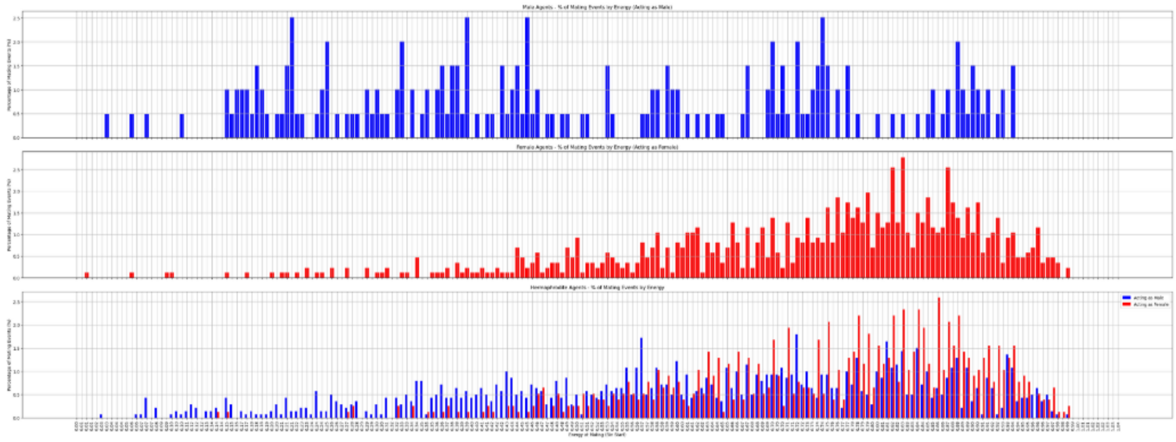


Figure 46: Percentage of male, female, hermaphrodites by Emreproduction graph

For **male** we can see, the mating occurs for a broad range of energy, with very few events at very low Ems and increase towards higher Em bins. This shows that males do not have the energy cost for reproduction to deal with, so they have a spreader Ems.

For **females** we see a strong skewed distribution. Almost no reproduction occurs at low energy thresholds. The frequency rises at the upper end of the energy threshold which shows females mate at higher energy. Which goes right, as they need to compensate for the reproduction cost, they need to beer.

For **hermaphrodites**, we see the mix of both the strategies. They combine both roles, when they act as female, they follow the female trend and when as male they follow the male trend.

3.5. Reproduction Trends Across Generations

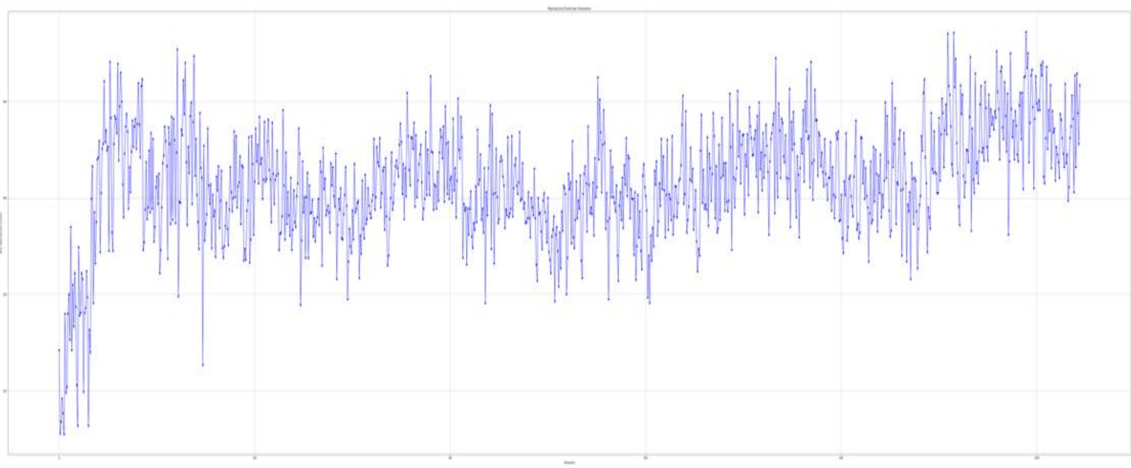
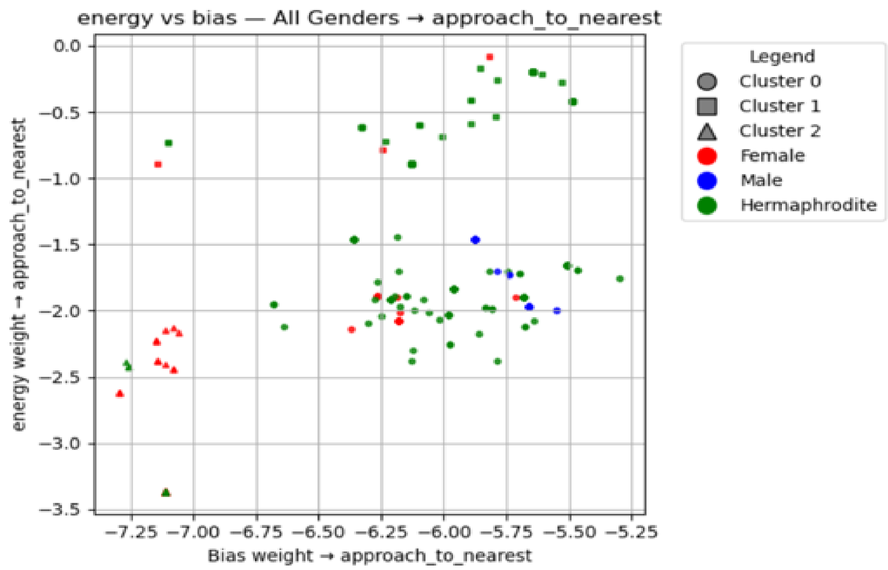


Figure 47: Total Reproduction per generation against generation graph

Across all 1000+ generations we have tracked the total successful reproduction of each generation and have plotted the graph of successful reproduction count against generation number. The graph shows that the reproduction rate increased during early generations. As agents adapted and evolved, eventually stabilizing around a plateau, which suggests an evolutionary convergence.

3.6. Neural Weight Clustering

Clustering of the weights of the inputs to the outputs and the weight to the respected output bias is plotted in the graph using KMeans clustering. Each output has 7 inputs so there is a total of 6 clustering graphs per output excluding bias, as bias is the value against which all input clustering is done. Not all plots have a good clustering, here the plots that have a good clustering will be discussed.



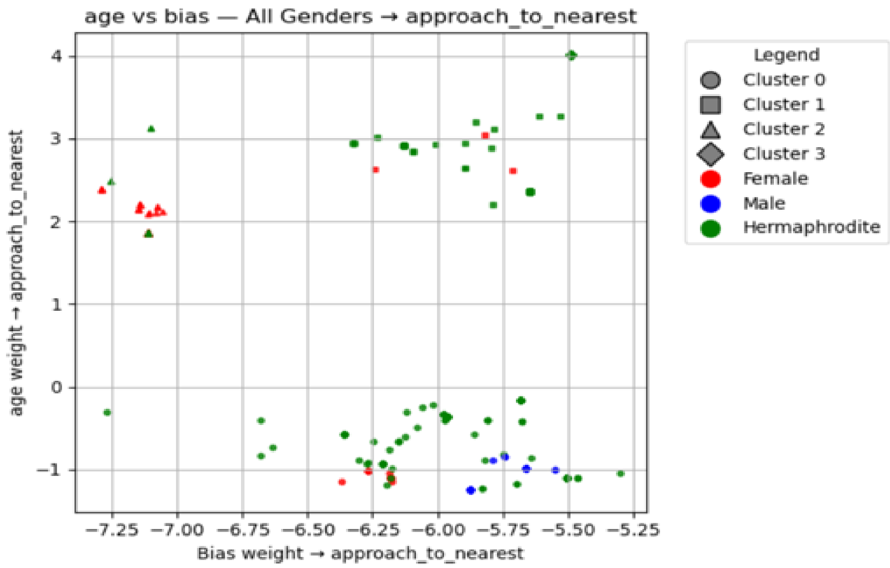


Figure 48: Input Weight Cluster graph to approach_to_nearest

Here we can see these cluster perfectly defines whatever we have undergone during the Stimulus-Driven Behavioral Patterns analysis. In the type 2 female we see at lower energy and at lower age and they choose the following module approach_to_nearest. Here we see at the weight of energy against weight of bias graph the squares (Cluster 1) full fills these. The agent in this cluster is the type 2 because these group agents female and hermaphrodites both have a higher weight of bias and energy so a smaller input value would bring a higher result in for choosing this module. So, the cluster 1 females and hermaphrodites are the type 2 agents. And cluster 3(triangle) cluster has a very low (larger negative) weights which ceases these agents from choosing this module. So, this cluster agents are type 1. Same in the weight of age against weight of bias graph, the cluster 1(square) represents the type2 agents and the cluster 2(triangle) represents the type 1.

4. Discussion:

4.1. Summary of the main finding:

An embodied evolution framework is developed, where the agents are given ecological features such as age, energy, body size, face, back. The agents in the simulations have no inbuilt genders. They can choose to act as male by choosing to mate_as_male or female by choosing to mate_as_female. The system is run for 1000+ generations to study their evolutionary development and ARTs in the agents and study how and what they develop to.

Prior to this set up a lot of work has been done where models were run with prior known discrete phenotypes and the work was done on the frequencies of the tactics used in different situations. The models have very low agent-environment and agent-agent sensory interactions, which lacks the essence of real life. (TABORSKY, n.d.). Many researchers then developed a broader model next where heir models the number of environmental sensory inputs and it investigates whether a simple physical difference between the sexes – the females have a non-reproductive period after mating, while males do not— is enough to have the male and female gender evolve behavioral differences between male and female robots. (Rold, n.d.). Further more sophisticated models were next developed where rich sensory environments and social interactions in evolving robotic colonies are developed. This research showed how the Alternative mating strategy evolves and stably co-exists in small robot colonies. This study shows how the robots develop Behavioral strategy to coexist. (Elfwing, n.d.).

This new system not only deals with much closer to real-life scenarios with the agents having more broader environmental and self-physiological sensory data; this enables the agents to have agent-agent and agent-environment interaction much more profoundly. The system has been helping us to see how if an generation with no built-in, hardcoded gender initially agents can evolve to self-determine gender roles and develop alternative reproductive tactics (ARTs).

The analysis shows that the last 10 generations have had a clean distribution based on the gender roles they evolved to adopt. It shows that after the final classification of agents on lifetime behavior (choosing of mate_as_male or mate_as_female as output) and different testing stimulus proximities yielded 8.6% males, 29.6% females, and 62.4% hermaphrodites. Furthermore, diving into the depths to analyze each gender separately, it is found that though all males had uniform behavioral pattern with no signs of alternative reproductive tactics (ARTs), but the females and the hermaphrodites have developed a profoundly two types (two distinct behavioral subtypes) of female and hermaphrodites that perfectly shows the system has evolved to develop ARTs for these two genders.

Lek Mating Strategy

Figure 49: Sage-grouse at a lek, with multiple males displaying for the less conspicuous females (Lek Mating, n.d.)

Lek mating is a reproductive strategy where males congregate in designated areas, which are called leks, to perform competitive displays and courtship rituals. The female visits these lek to evaluate the males and select a partner to mate from among the displaying males.

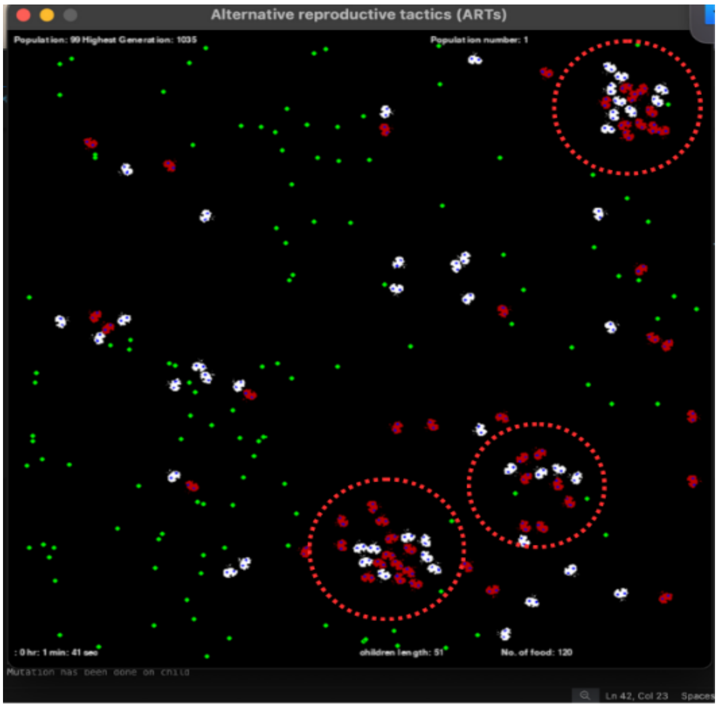


Figure 50: Snapshot of the simulation showing formation of Lek

The red dotted circle highlights the region where a lek is formed—where males are waiting, females arrive, and all individuals remain stationary for a while, indicating that mating is occurring.

Male.

The male follows a fixed proactive reproductive strategy. Whenever they see a face-facing agent inside their sight radius they choose to mate_as_male. When they choose mate_as_male or female they don't move and stay still. A tactic is noticed among the males that they never use the approach_towards_nearest module, which shows that they do not approach another agent for mating rather stay put in its position.

Agents have 4 modules to choose from, move_to_food, approach _towards_nearest, mate_as_male, mate_as_female. The outputs move_to_food, approach _towards_nearest makes the agent move, only the mating modules cause the agent to cease its movement and wait, so if an agent is waiting, having no movement it means it is in mating state.

Males have evolved to mimic and adopt lek mating as their primary reproductive strategy. In this system, the 'lek' is represented by the males remaining stationary- this is the signal showing their readiness to mate. The female acting agents evaluate their potential mates based on proximity, as they select the nearest stationary agent as the preferred partner. This behavior strongly replicates the lek mating, where the competitive positioning is playing a key role in mate selection.

Female.

The Type-1 female agents show a choosy, resource-dependent reproductive strategy". Reproduction occurs only under favorable conditions of age, energy, and proximity of potential mates. The agent are choosy, they mate_as_female directly when they see a face-facing agent. And if they see a back facing agent, they would only mate, if it is closer or otherwise, they would choose move_to_food. They prioritize foraging and only mate if conditions are suboptimal. When they see a back and a face facing agent they choose to mate_as_female only if the back-facing agent is closer and have age and energy a bit higher. Their behavior replicates the selective female lizards or birds, who mate only under optimal environmental and internal conditions.

The Type-2 female agents have demonstrated opportunistic, sneaky and condition-dependent reproduction tactics. The agents prioritize survival and foraging. when the agent sees that another back facing agent is their only, it acts as sneaky approach, rather than to activate to mating module(mate_as_female), it uses approach towards it, if it is at a distance and if a front-facing agent is in it sight radius only, it always chooses mate_as_female. When it sees a face and back-facing gent it always chooses to be nearer to it, and chooses to approach towards the nearest one, and at older age chooses to mate_as_female. It replicates the sneaky female birds and fishes and insects that wait opportunity and right conditions and avoid direct competitions to mate.

Hermaphrodites.

Type-1 Hermaphrodites agents follow a Sequential hermaphroditism reproduction tactics, switching between male and female roles depending on their internal state. These type-1 hermaphrodites, when they are young and energetic they act as male agents to maximize reproduction with minimum cost. As their age increases or energy decreases, they shift to acting as female agents, accepting to bear the cost of reproduction, just to ensure genetic continuity before death. This mimics the sequential hermaphroditism, which is observed in fish species, where reproductive roles are adjusted according to age and condition. Ex: Clownfish.

Type-2 Hermaphrodites agent shows a Male-biased opportunistic hermaphroditism with context-dependent female function reproductive strategy. The type-2 hermaphrodites' agent mostly takes the role as male, engaging in no-cost reproduction (as a male), and shift to act as female later in their life (older age) where only they see a face-facing agent in their sight radius, and accept to bear the reproduction cost. This strategy is similar to the flatworms or self-fertilizing fish that are male biased but conditionally flexible using the orientation to optimize reproductive outcomes,

Type 1 Female ART:
The ART in the type 1 females show Choosy, Resource dependent reproductive tactic.

Type 2 Female ART:
The ART in the type 2 Female show Opportunistic, Condition-dependent reproductive tactic with sneaky tendencies.

Type 1 Hermaphrodites ART:
The ART in the type 1 hermaphrodites show Sequential hermaphroditism with energy and age dependent role switching.

Type 2 Hermaphrodites ART:
The ART in the type 2 hermaphrodites show Male-biased opportunist hermaphrodites with context-dependent female function.

Male agents have no ART

4.2. Limitations and Challenges

Data such as energy, decision taken, input to the neural network list, etc. of every agent at every timestep are stored for analysis. This rises a severe memory management issue. A large memory is required to store the data.

The simulation cannot be run continuously for large generations together as the data file becomes too large, so it creates a huge issue during analysis, because the system's RAM becomes insufficient to load and process such high-volume data efficiently.

At the moment the system stores the reproduced offsprings in a list and after the generation is complete, it selects 100 offsprings randomly from the pool of offsprings and repopulate the simulation for further generations in the simulation. This doesn't mimic the real-life scenario. We cannot mimic the real-life situation where the children's born will be sharing the same environment together with parent as this will overwhelm the preset systems computation power.

We could add numerous numbers of sensory data as inputs but this would introduce significant computational overhead and likely create bottleneck the system's performance.

4.3. Future works

The sensory data that the neural network of the agents uses has magnitude but no direction, that is, the agent gets the data of how far the food, back-facing, front-facing agents are but not which direction it is, relative to their own orientation. are they aligned together or which side of the agent are there, so we can introduce few more inputs corresponding to each distance inputs which will be normalized angle representing the relative position of the food or agent in sight radius.

Now the agent only knows if it is seeing a back facing or front facing agent. But doesn't know if the agent is acting as a male female at that instant. We can add another input for the corresponding distance of the agent input too.

We can use this system in a swarm of drawn, giving the drones ability of think. Where the gender will be the roles that the drone will take. This will help us to build an intelligent drone swarm which can evolve with time.

4.4. Future Industrial Applications

The model we worked on in this project is quite special; this is because we had not given the agent any predefined gender or role, the agents just did not evolve as "male", "female" or "hermaphrodite" roles – they rather spontaneously developed subtypes with in genders (type-1 and type-2 Females and Hermaphrodites). Though we have not defined any hardcoded fitness function, rather the no of reproductive success acts as the fitness for the system, which shows that the natural selection happens organically, where only the best genes get the chance to pass on to the next generation.

The emergence of the tactical diversity (ARTs) without being programmed is a big finding and a huge leap, showing true self-organization in artificial systems.

The system uses to build its own intelligence over time using sensory inputs of the surrounding; thus, this model can be mimic to develop autonomous swarms of robots and drones.

The model can be used in numerous industrial domains to utilize the principle of role emergence, adaptive decision making, and decentralized coordination:

1. Robotics and swarm intelligence:
    a. The autonomous robots/ drones can dynamically assign themselves roles (scouting, transporting, etc..) depending on their physiological and environmental state.
    b. In search and rescue mission, where the swarm of robots can decide themselves to be "explorer" or "rescuer" in real-time.
2. Manufacturing plants:
    a. Smart factories can employee agents that naturally shifts between production, quality assurance and logistics roles adapting to fluctuating workloads.
    b. The robotic assembly line could evolve task allocation strategies, minimizing the downtime and energy waste.

5. Conclusion

In the study, it is seen that the embodied evolution simulation has evolved its agents who were initially no genders act as male female and hermaphrodites in the later generations. Upon further analysis it was seen there were subtypes of genders. The males having no sub types, but the females and the hermaphrodites had two types. All of this ad purely emerged from decentralized neural decision-making, sensory interaction and natural selection.

The males are found mimicking the Lek Mating Strategy for reproduction. The type 2 female acts as the female partner of the reproduction system of the Lek Mating Strategy. Type 2 females have the "condition-dependent reproductive tactics" where the decisions to reproduce are made dynamically based on the agent's readiness and context.

The type 1 females show a resource dependent reproductive strategy.

The type 1 hermaphrodites choose to act as male at high energy and younger age, as the age increases the agent is more prone to act as female(mate_as_female). Their gender roles are condition driven.

The type 2 hermaphrodites act as male at male at younger age, and as they grow old and energy increases, they shift roles as female.

These findings demonstrate that an asymmetric reproduction cost and environmental mixing can alone be enough to drive complementary, biologically realistic alternative reproductive tactics (ARTs). The system connects the evolutionary biology principles and multiagent systems, offering a unified framework to explore how the life-history strategy emerges and organize themselves across both biological and artificial domains.

Though there are several limitations and challenges but looking at this simple environment with fixed sized population and a shallow neural network architecture, which has limited the complexity of the emerged behaviors. Future work with a deeper neural network and adding more sensory data inputs will evolve the ARTs to a much brighter level.

We can further have our ART-inspired controller offer promising applications in robotic swarms. Finally, this study shows how simple, local applied neural network decision rules can give rise to a complex, adaptive strategies found in nature.

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