Cellular Automata : Modelling and Analyzing Intra-Guild Predation

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***Abstract*— Cellular Automata (CA) is a discrete, abstract computational system, consisting a finite lattice of simple units (atoms or cells), each with some properties and states that evolve in parallel at discrete time-steps, following local evolution rules (which are functions or dynamical transition rules of the states of the cell and its neighbors). [16] Biologically inspired Cellular automata models have been adopted to imitate animal and parasite behaviors in artificial life research. This paper presents a lattice-based model of three populations, two competing predators and one shared prey, to model and analyze Intra-Guild predation (IGP) dynamics and their coexistence. The coexistence space is clearly partitioned into a grid of cells. A single individual of each species can occupy a cell, or it can be unoccupied. The system evolves through time according to collection of probabilistic local rules that explain interactions between species members and imitate the reproduction, death, predation and evasion processes. The results of the experiments indicate prey-predator population dynamics, stability, herding behavior, habitat selection tendencies and intra-guild competition. The goal for this research is to pave the way for subsequent work in the domains of evolutionary and conservation biology, genetics, phylogeny and other similar biological domains using lattice-based cellular automata models of social systems/agents.**

Keywords—Cellular Automata, Prey, Predator, Intra-Guild Predation

I. INTRODUCTION

In systems biology, prey-predator interactions is one of the most important dynamics. The scientific domains of behavioral and conservation ecology, phylogeny, and evolutionary biology are among the many that hold relevance in understanding the dynamics of these interactions. Their infrequent occurrence and the difficulties of observing the animals in their natural habitat are the most significant limitations in understanding prey-predator interactions. However, modelling of prey-predator interaction is gaining traction in domains like conservation ecology as it is far more cost-effective than traditional experimental observation, and it offers no genuine harm to an existing biological system that could become unstable by external factors and influence.

Lotka and Volterra introduced the first formal mathematical model based on differential equations depicting predator-prey interactions in the mid-1920s.[1][2] These models are computationally expensive as they involve numerically solving Partial Differential Equations (PDE) in a spatial domain for different positions and times. An alternative is to utilise a discretely modelled individual with a set of properties, such as age and hunger, and a set of rules that governs their behaviour, i.e. an agent-based approach to simulation. [3] These agent-based approaches have been applied to model various biological and ecological systems [4] [5], including prey-predator systems [6].

Cellular automaton (CA) is another alternative to differential equations that is also closely related to the agent-based approach. CAs have been applied and tested to biological systems as far back as the 1950s [7]. Cellular Automata are widely used in ecosystem modelling, such as vegetation cover dynamics [8, 9], the evolution of urban land-use patterns [10], forest fire spreading [11], marine macrophyte spreading [12], spreading of water plant species [13], and population dynamics of animals [14]. CA has been used to simulate and predict prey-predator population dynamics as well as analyse system stability [15] and harvest techniques [16]. CAs were also used to mimic the competitive growth and colonization and explain the resulting ecosystem succession of two underwater macrophytes [17]. Its application for conservation objectives is not a novel concept; it's been used to investigate the impact of invasive species on an ecosystem [18].

Despite these vast applications in ecological modelling, the availability of commercial engineering software for CA modelling appears to be a long way off. This research project implements a CA-based prey-predator model, and intra-guild predation (IGP) dynamics in two competing predators with one shared prey system are studied. The results of the experiments are relevant to any prey-predator ecosystem (terrestrial, marine, parasitic etc.). The impact of initial population size, density and spatial distribution on the overall interaction dynamics in a Symmetric and Asymmetric IGP system are observed and analysed.

II. BIOLOGICAL BACKGROUND AND MODEL FORMULATION

A. *Intra-Guild predation and characteristics*

The subject of dynamic relationships between two or more interacting populations is not new. The study of the predator-prey system's dynamics has two objectives. The first is an explanation of probable oscillations in the temporal evolution of prey and predator populations, and the second is the correlations between them. Intraguild predation (IGP) is the killing and occasionally eating of a potential competitor of a different species. [19][20][21] This is a combination of predation and competition as both predator species rely on the same prey resources and also gain from feeding on each other. IGP is prevalent in nature and can be asymmetrical, where one predator species feeds on the other, or symmetrical, where both predator species prey on each other. [19] As the dominant intraguild predator has the additional advantage of eating and eliminating potential competition, IGP interactions significantly impact ecological communities. Intraguild predators must share at least one prey species and usually occupy the same trophic guild. The characteristics of size, growth, and population density of the predators, as well as the population density and behaviour of their shared prey, determine the degree of IGP. [19] In theory, IGP is most stable if the top predator benefits significantly from killing or eating on the intermediate predator, and the intermediate predator is a better competitor for the shared prey resource. [21]

IGP has a direct ecological impact on competing predators' survival and distribution and an indirect impact on prey species' and other species' population and distribution within the community. IGP interactions are important in community structuring as they're so common.[20] IGP may assist shared prey species by reducing total predation pressure, especially if the intermediate predator consumes more of the shared prey. [22] Asymmetrical IGP can have a big impact on habitat selection, as the intermediate predators often avoid otherwise ideal habitats due to the presence of the top predator.[25] Changes in intermediate predator distribution as a result of increased predation risk can have a greater impact on community structure than direct mortality caused by top predators. [26] Symmetric IGP is common among social insects [27][28] and carnivores [29][30] where group size plays an important role. Groups of the IG prey can kill and eat an individual IG predator. Symmetric IGP may lead to a development bottleneck if the intra-guild prey is a better competitor. Predation by adult IG prey on the young predator population might decrease the overall growth and survival of the predator, in turn reducing the predator population. [31][32]

B. *Cellular Automata*

Cellular automata (CA) was discovered and proposed by Von Neumann [33] in the 1940s, and Wolfram established the computational theory of CA in the 1980s. [34] A CA is made up of an n-dimensional grid of cells, each of which can be in one of a limited number of defined states. Each cell has a definite neighbourhood of surrounding cells. [39] The Von Neumann type and the Moore type [33], as shown in Fig. 1, are two typical neighbourhood definitions.

Each cell in a CA is set to a starting state when it is first initialized. The cell's state is updated simultaneously (asynchronous) or sequentially (synchronous) throughout each time step, according to a function or rule relating to the cell's prior state and that of its defined neighbours. The user is needed to provide no input other than initialization, making it a genuine automaton or "zero-player game." [39]

The geometry and rules are the two most significant factors to consider when modelling a CA. Toroidal and non-toroidal are two basic categories of CA geometries. Toroidal geometry is characterised by the connection of the top and bottom, left and right boundaries, resulting in the formation of a torus, which can be considered periodic. Anything that crosses an edge of a rectangular plane appears on the other side of the plane and continues in its original direction of travel. In contrast, the boundary of a non-toroidal geometry is fixed. The defined rules are what allow a CA to operate autonomously. Rules can be deterministic, probabilistic, or a mix of both. [39]

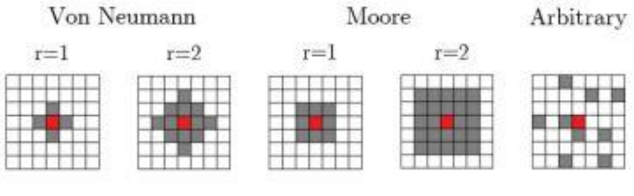


Fig. 1. Different neighbourhoods for a 2D cellular automaton, (radii 1 and 2). The red cell indicates the current cell and the grey cells indicate the cell neighbourhood. [39]

C. *Modelling the Cellular Automata system for Intra-Guild predation*

Consider a finite-sized habitat containing three species, competing predators 1 and 2, and a shared prey 3. The competing species are divided into 'top predator' 1 and 'intermediate predator' 2 (the species more likely to be preyed upon). Assume that the prey's energy supply is plentiful, and predators rely only on prey for energy. Predators will actively feed on the prey to reproduce, while prey groups will naturally try to reproduce while avoiding predation. It's reasonable to assume that a predator must be physically close to prey in order to catch and consume it and that reproduction can only take place in the presence of other individuals. A CA can be used to model such a scenario as follows:

- Define a two-dimensional array as grid G with m × n cells.
- Define toroidal / non-toroidal boundary conditions.
- Each cell $x \in$ G can be in one of four states: empty (0), top-predator (1), intermediate-predator (2) or prey (3). Let the states be a set S= {0, 1, 2, 3}.
- Define set of rules R that governs the behavior of the cells.

1 Assumptions and geometry:

The model's relative simplicity entails several assumptions about the environment and the species' behavior. All individuals of the relevant populations/species are homogenous, which means that no two members of the same species are alike. Prey are vulnerable to loneliness and overcrowding, and may die of it. Prey can also be killed by predators. In the absence of predators, this will result in complete prey saturation of the cell space. Predators die from hunger, which is caused by a lack of prey nearby and is age-independent, with each member having an equal chance of dying at each time step. The predators' only energy source is prey, whereas the prey's food supply is plentiful. The environment is assumed to be homogeneous, i.e. every cell is the same and equally accessible, and there are no barriers or obstacles. Individual members of the species cannot survey their neighborhood and are given no explicit orders to move. This simulates mobility by breeding in more attractive and desirable spaces. Every time-step follows the same set of rules, disregarding any time-related cycles like day/night or seasonal cycles. [39]

The geometry of the formulated CA model is as follows:

- The lattice cell space is a square grid of n x n cells (100 x 100 units).
- The boundary condition is toroidal, implying an open or periodic system.
- The cell neighborhood is Moore of radius 1, with each cell having eight neighbors.

2 Rules:

The world is grid of cells, with 4 possibilities: Predator (1), Intermediate-Predator (2), Prey (3), or Empty (0). All predator, intermediate-predator and prey have a defined initial population probability, and a set health that changes over time. The rules of the CA model are applied in a single step, executing every rule applicable to a cell's state once before going on to the next cell. [39]

Algorithm for Asymmetric IGP involves initializing grid space randomly with Predator, Intermediate-predator and Prey with defined population probabilities and health values. For each cell, evaluate the state of cell {0, 1, 2, 3} and the Moore neighborhood, and apply the rules synchronously.

If cell is Predator (1):

- Check if no prey nor intermediate-predator in the neighborhood, reduce health by 1, and move to a random empty cell in the neighborhood.
- Else If prey in the neighborhood, target a random prey, and if target prey health less than predator health, eat the target prey.
- Else if intermediate-predator in the neighborhood, target random intermediate-predator, and if target intermediate-predator health less than predator, eat the target intermediate-predator.
- Else reduce predator health. If predator health reaches zero, predator dies of hunger.

If cell is Intermediate-Predator (2):

- Check if no prey in the neighborhood, reduce health by 1, and move to a random empty cell in the neighborhood.
- Else If prey in the neighborhood, target a random prey, and if target prey health less than intermediate-predator health, eat the target prey.
- Else reduce intermediate-predator health. If health reaches zero, intermediate-predator dies of hunger.

If cell is Prey (3):

- Increase health by 1 every time-step
- Check If empty cells in the neighborhood greater than equal to 7 (loneliness) or less than 1 (overpopulation), reduce health by 2. If health reaches zero, prey dies of overpopulation/loneliness.
- If prey health reaches value greater than 6, prey reproduces into empty cell in the neighborhood.

Algorithm for Symmetric IGP involves minor variation to the characteristics of intermediate-predator. The intermediate-predator can eat the top-predator under certain conditions based on group size. In absence of a prey, the intermediate-predator may consume a top-predator if there are more than 4 fellow intermediate-predators in the neighbourhood. The full set of rules for Asymmetric and Symmetric IGP is set out in Algorithm 1 & 2 respectively in Appendix A.

D. Experiment Hypothesis

Based on the above discussion, the following hypotheses are proposed for the prey-predator Intra-guild interactions and population dynamics, and are simulated in the experiments:

H1: Agents of each species will form clusters or herds in the lattice space.

H2: As the population size and density of the "top predator" increases, the intra-guild predation (IGP) pressure on the "intermediate predator" increases i.e. more "intermediate predators" are killed by the "top predator".

H3: Compared to one prey-predator system, in Intra-guild predation (IGP), the predation pressure on the prey species is lower i.e. less prey species are killed by the predator species in IGP.

H4: In Symmetrical IGP, if the intra-guild prey is a better competitor, this may lead to development bottleneck, reducing the population size of the top-predator.

III. SIMULATION AND EXPERIMENTS

Experiments are performed in a one prey-predator system and both Asymmetric and Symmetric Intra-guild predation (two competing predator and one shared prey) system to test the proposed hypothesis.

A. Simulation environment setup

The experiments have been done using custom written python program and the PyGame library is used for graphical simulations (extended on "PreyPredator" program by Ryan Whytsell [35]). The reference program simulates interaction between one prey-predator system. The same was used and extended to incorporate Intra-Guild predation dynamics. The main program and the custom modifications are highlighted in Appendix B. The modified program follows the above discussed algorithm and rules to simulate IGP prey-predator behaviour. As shown in Fig. 2, the CA model is a 2-Dimensional 100 x 100 unit square cell space with periodical boundary conditions i.e. toroidal geometry. The cells can have four possible states: empty (Black), prey (Blue), top-predator (Red) and intermediate-predator (Yellow). The neighbourhood configuration is Moore.

B. Experiment methodology

The cell space is initialized randomly with top-predator, intermediate-predator, prey and empty cell with equally defined population probability ($P_{predator}$, $P_{int\text{-}predator}$, P_{prey}, P_{empty}) of 0.25 each. Population probability P is the probability of a cell initialized as a particular cell type (Predator, Intermediate-Predator, Prey, and Empty).

Also, cells of each species are initialized with health $H_{predator}$, $H_{int\text{-}predator}$, H_{prey} of 2, 2, & 4 units respectively which are fixed throughout all the experiments. The health of the competing predator species are initialized equally to not give any unfair advantage to a particular species, and the top-predator dominance in Asymmetric IGP and the top and intermediate predator competition in Symmetric IGP will be governed by the CA rules and algorithm defined.

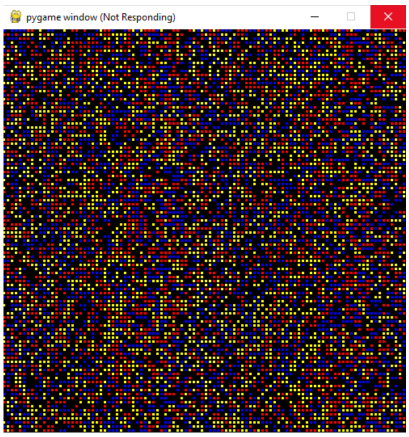


Fig. 2 Simulation Environment

1 Asymmetric IGP system experiments:

Experiments were carried out to observe the behavior of the two competing predator – one shared prey system (the top-predator also preys over the intermediate-predator) for different initial population probabilities and spatial distribution configurations. The results from the experiments will be used to study the habitat formation, and clustering tendency of the prey-predators and the overall intra-guild predation pressure by top-predator on the intermediate-predator.

a) Experiment A: Fixed initial population probability of the IGP prey-predator system, with variation in the initial spacial distribution of the preys and predators.

In this experiment, the initial population probabilities of the prey-predator system i.e. ($P_{predator,}$ $P_{int\text{-}predator}$, P_{prey}) is maintained at 0.25, and the initial spatial distribution of the prey and predators is varied to imitate various habitat of the system. *Random* spatial distribution where the prey and predator species are initialized randomly all over the cell space, and *Clustered* spatial distribution where there are two separate 50 x 50 unit cells of top-predator-prey, and intermediate-predator-prey clusters. The population dynamics of the prey-predator system over 1000 experiment time steps are measured and observed. Also, the CA graphical simulation snapshots of the system at 0 (initial), 200 and 500 experimental time-step are captured to visually analyze the spatial distribution of the system.

b) Experiment B: Fixed spatial distribution of the IGP prey-predator system, with variation in the initial population probabilities of the prey and predators.

The initial population size and density of the top-predator is varied to mimic increased Intra-Guild predation pressure on the intermediate-predator. The initial spatial distribution is kept *Random*. Experiments with various initial population probabilities of the prey-predator system i.e. ($P_{predator,}$ $P_{int\text{-}predator}$, P_{prey}) of 0.25 each, (0.3, 0.25, 0.25) and (0.35, 0.25, 0.25) are carried out. The population dynamics of the prey-predator system over 1000 experiment time steps are measured and observed. The Intra-Guild predation pressure on the intermediate predator is calculated as the total number of intermediate-predators that are killed by the top-predator excluding death by hunger (this is quantified as *Predator Kill Count*) divided by the total number of intermediate-predators that have existed throughout the simulation (1000 simulation time-step). This gives us the average rate of intermediate-predators killed by the top-predator.

2 One prey-predator system vs Asymmetric IGP system experiments

Experiments were carried out to observe the behavior of the one prey-predator system as compared to the two competing predator – one shared prey system (the top-predator also preys over the intermediate-predator) for comparable initial population probabilities (0.25 each) and spatial distribution configurations (Random). The results from the experiments will be useful to study and compare the overall predation pressure on the prey by the predators.

a) Experiment C: Fixed initial population probabilities and spacial distribution of the One prey-predator system and the Asymmetric IGP prey-predator system.

In this experiment, the initial population probabilities of the prey-predator system is maintained at 0.5 each ($P_{predator,}$ $P_{prey)}$ for one prey-predator system and 0.20, 0.20, 0.20 ($P_{predator:}$ $P_{int\text{-}predator}$: P_{prey}) for Asymmetric IGP prey-predator system, and the initial spatial distribution of the prey and predators is maintained *Random*. The prey-predator population dynamics over 1000 experimental time-steps is observed and analyzed for both the systems. Also, the predation pressure on the prey is calculated as the total number of prey that are killed by the predators (this is quantified as *Prey Kill Count*) divided by the total number of prey that have existed throughout the simulation (1000 simulation time-step). This gives us the average rate of prey killed by the predators.

3 Symmetric IGP system experiments

Experiments were carried out to observe the behavior of the two competing predator – one shared prey system in Symmetric (both predators prey on each other) mode for fixed initial population probability and spatial distribution configurations. The intermediate-predator is made to compete and eat the top-predator in accordance with the CA rules and algorithm discussed in *Section 2.C*. The results from the experiments will be useful to study and compare the overall population dynamics and stability of the prey-predator system.

a) Experiment D: Fixed initial population ratio and spacial distribution of Symmetric IGP prey-predator system.

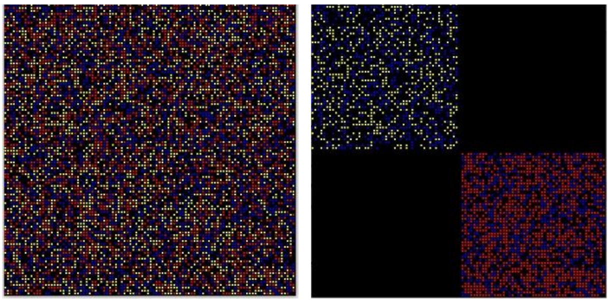
In this experiment, the initial population probabilities of the prey-predator system is maintained at 0.25:0.25:0.25 ($P_{predator,}$ $P_{int\text{-}predator}$, P_{prey}) for Symmetric IGP prey-predator system, and the initial spatial distribution of the prey and predators is maintained *Random*. The prey-predator population dynamics over 1000 experimental time-steps is observed and analyzed.

IV. RESULTS AND DISCUSSION

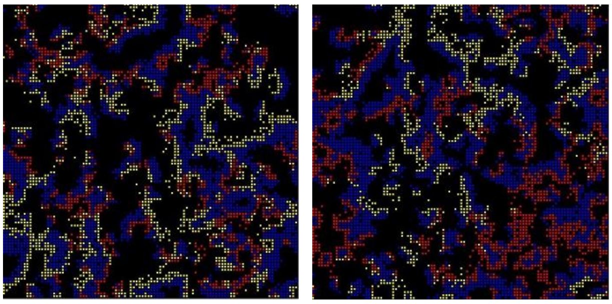
The section discusses the experimental results and analysis, and their relevance to the biological intra-guild prey-predator behaviour.

A. Experimental results and their relevance to biological intra-guild prey-predator behaviour

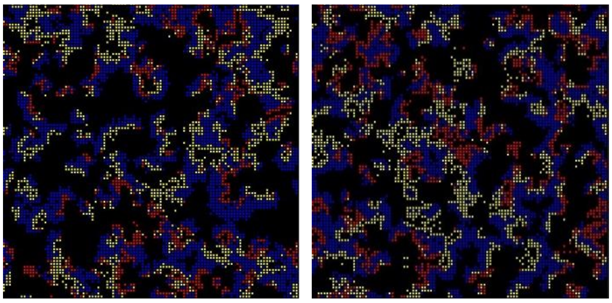
Fig. 3 shows the simulation snapshots of the IGP prey-predator system for *Random* and *Clustered* initial spatial distribution at 0, 200 and 500 experimental time-steps. We see that despite the different intial spatial distributions, the system same. At 200 time-steps, there tends to be top-prey dominance in the *Clustered* initial distribution as compared to the *Random* where the predator-prey populations are uniformly distributed. Whereas at 500 time-steps, both the systems show uniform distribution of the prey-predator species. We observe separate patches dominated by top-predators and intermediate-predators which are mutually exclusive. The patch formation of the species corresponds to the herding behavior of the organisms where they tend to stay together to either corresponds to the herding behaviour of the organisms where they tend to stay together to either prey or evade predators as a group. Also, the mutually exclusive patches are analogous to habitat formation of the top-predator-prey and intermediate-predator-prey systems. Asymmetrical IGP impacts habitat selection where the presence of the top-predator often causes the intermediate-predators to avoid otherwise ideal habitat. [25] These observations prove hypothesis **H1** which can be claimed true. Also, from Fig. 4 (a) and (b) which shows the prey-predator



time-step 0 (initial)



time-step 200



time-step 500

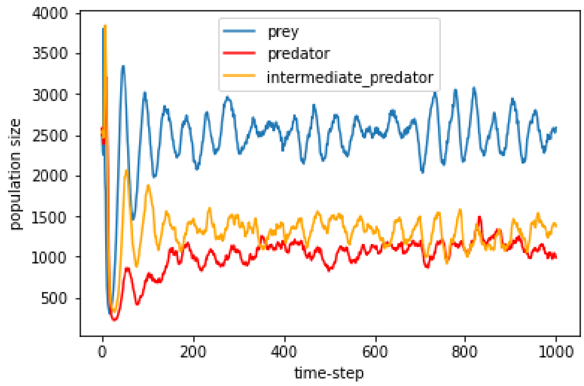
IGP system with (a) *Random* (b) *Clustered* spatial distribution

Fig. 3 Simulation snapshots of the IGP prey-predator system with fixed initial population probabilities (($P_{predator}$, $P_{int\text{-}predator}$, P_{prey}) at 0.25, 0.25, 0.25 with different initial spatial distribution at time-steps 0, 200 and 500, from observations of experiment A.

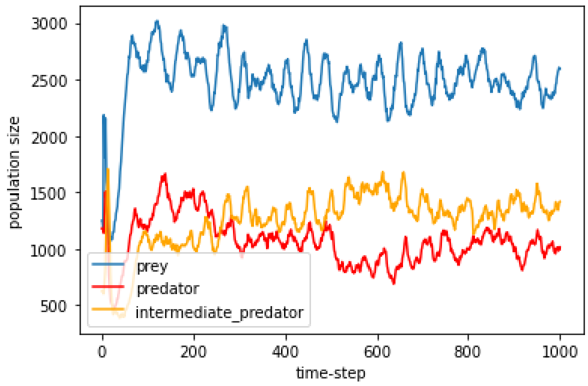
population dynamics for the Random and Clustered initial spatial distribution of the system respectively, we see that the overall system attains stability (the population varies around a mean) where the prey population is the largest, followed by intermediate predator, and then the top-predator. We also see competition between the two intra-guild predator species. This proves that the simulated CA model is biologically relevant and effectively mimics the prey-predator behaviour and characteristics. The Random spatial distribution attains stability quickly at around 200 time-steps whereas there are initial fluctuations in the Clustered spatial distribution which takes longer to stabilize.

Random initialization is a better way to model biological systems as that correctly imitates the natural selection, reproduction and evolution of species and their habitat, and doesn't give any unfair advantage to a particular species at the beginning.

Table I shows the predation pressure on the intermediate-predator by the top-predator with increasing initial population probability (and hence the size and density) of the top-predator, from the observations of experiment B. We see that with increasing initial



(a) Random



(b) Clustered

Fig 4. Prey-predator population dynamics over 1000 experimental time-steps for different initial spatial distribution with fixed initial population probabilities (($P_{predator}$, $P_{int\text{-}predator}$, P_{prey}) at 0.25, 0.25, 0.25, from observations of experiment A.

population probability, the average intermediate-predator population size, the predator kill count (the number of intermediate-predators killed by the top-predator), and the predation pressure on the intermediate-predator remains more or less same i.e. fluctuates within a negligibly small margin. We can infer that, despite the increasing initial population size/probabilities of the top-predator, the overall system always stabilizes to the same ratio of the species population. The CA model, though is highly stable, doesn't effectively manifest the effect of population size and density of a particular species on the overall population dynamics, and hence hypothesis **H2** cannot be effectively proven true. A possible reason might be the limited cell space (100 x 100 cell units) of the CA, despite the toroidal geometry, the average population of the species saturates at a point, not allowing for further increase or decrease. Also, as almost all CA evolutions are

TABLE I. OBSERVATIONS FROM EXPERIMENT B

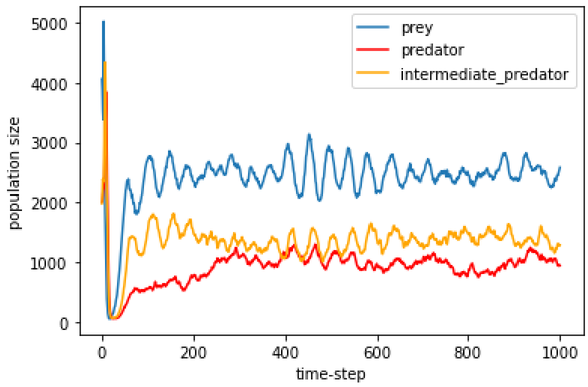
Initial spatial distribution = Random , Prey population probability = 0.25, Intermediate-Predator population probability = 0.25, Experimental time-step = 1000			
Predator Population Probability	***Average intermediate-predator population size***	***Predator Kill Count***	***Predation Pressure (percentage)***
0.25	1352.333666	36362	2.6
0.3	1431.906094	36537	2.5
0.35	1278.208791	38593	3.0
0.45	1318.770230	37266	2.8
0.5	extinct	extinct	extinct

TABLE II. OBSERVATIONS FROM EXPERIMENT C

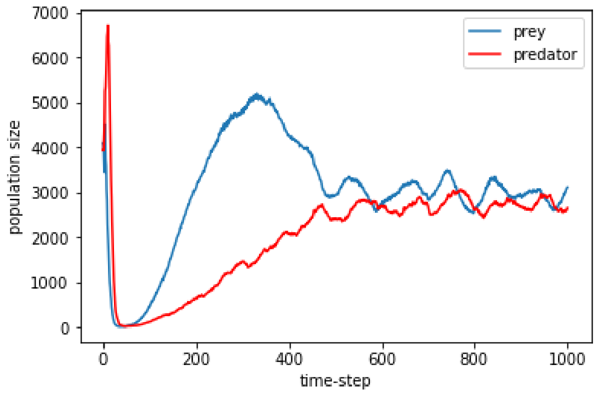
Initial spatial distribution = Random , Prey population probability = 0.4, Predator population probability=0.2, Intermediate-Predator population probability = 0.2, Experimental time-step = 1000			
Prey-Predator system type	***Average prey population size***	***Prey Kill Count***	***Predation Pressure (percentage)***
1prey-1predator	2987.560440	128030	4.2
Asymmetric IGP	2408.550450	217318	9.01

locally irreversible, initial conditions (in this case population size) will gradually be forgotten as time progresses in the experiment and will not have major impact on the overall system dynamics. [15] An interesting observation here is on increasing the population probability of the predator beyond a certain threshold (in this case 0.5), the intermediate predators get extinct, followed by the prey, and finally the top-predator (as there is no energy source), i.e. the system collapses. In biological systems, if the predation component is severe enough, it reduces drastically or even eliminate (locally) the prey population. [27]

The observations of experiment C, where 1prey-1predator system and the Asymmetric IGP system are compared based on their respective predation pressure on the prey, are shown in Table II. We see that 1prey-1predator system has a higher average prey population size and a correspondingly lower prey kill count (number of preys killed by the predators) and predation pressure on



(a) Asymmetric IGP system



(b) 1prey-1predator system

Fig 5. Prey-predator population dynamics over 1000 experimental time-steps for Random initial spatial distribution with fixed initial population probabilities ($P_{predator}$, $P_{int\text{-}predator}$, Pprey) at 0.2, 0.2, 0.4 for Asymmetric IGP and ($P_{predator}$, P_{prey}) of 0.2, 0.4 for 1prey-1predator system, from observations of experiment C

prey, when compared to the Asymmetric IGP system. Also from Fig. 5 (a) and (b) showing the prey-predator population dynamics for Asymmetric IGP and 1prey-1predator system respectively, from observations of experiment C, we see that despite a healthy competition between the top and intermediate predator species in the Asymmetric IGP, the average prey population remains relatively higher in 1prey-1predator system than Asymmetric IGP system. In the context of the CA model, this can be justified as there are two predators preying on the shared prey in Asymmetric IGP when compared to one predator in the 1prey-1predator system. However, this contradicts the hypothesis **H3** where the predation pressure on the shared prey species is expected to be lower in IGP. Biologically, there is no exclusive 1-predator-1prey systems nor 2 competing predator-1shared prey systems. Each predator will be preying on multiple prey species and each prey will be predated by various predator species which are conveniently neglected in the CA model for the sake of simplicity. The CA model needs to account for these multi-level prey-predator interactions to effectively portray the predation pressure on the species. However, modelling multi- level prey-predator system in a finite lattice space CA model would not be practical and could be exponentially difficult. Also, comparison with 1prey-predator system might not be right benchmark, and the Asymmetric IGP system should be compared with other multi-predator with shared prey systems to rightly judge the predation pressure on the shared prey.

Fig. 6 shows the prey-predator population dynamics in a Symmetric IGP system, from the observations of experiment D. We see that the average population difference between the intermediate and top predator has widened as the top-predator population size has reduced. Also, Fig. 7 shows the comparison between the average species population size for Asymmetric and Symmetric IGP, from observations of experiment D and A. The average intermediate-predator population is higher with a correspondingly lower top-predator population in Symmetric IGP than in Asymmetric IGP. Here the intermediate-predator is a better competitor to the top-predator. Also, the health of the species in the CA model can be interpreted as the size and age of the species, and the CA rules are defined in such a way that Intra-guild predation will only happen when the health of the predator is more than the other intra-guild predator. In biological systems, symmetric IGP may lead to development bottleneck if the intermediate-predator is a better competitor. Adult

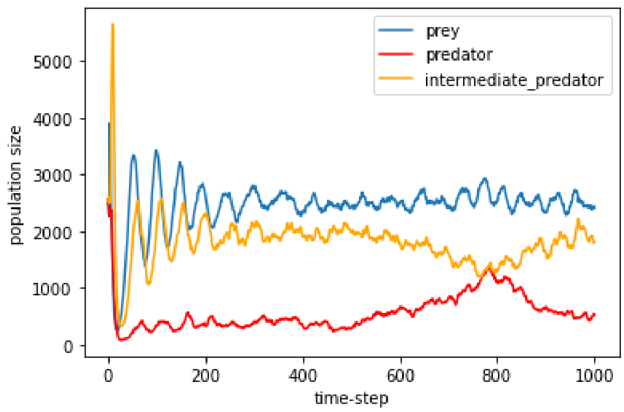


Fig 6. Prey-predator population dynamics over 1000 experimental time-steps for Random initial spatial distribution with fixed initial population probabilities ($P_{predator}$, $P_{int\text{-}predator}$, P_{prey}) at 0.2 each for Symmetric IGP system, from observations of experiment D

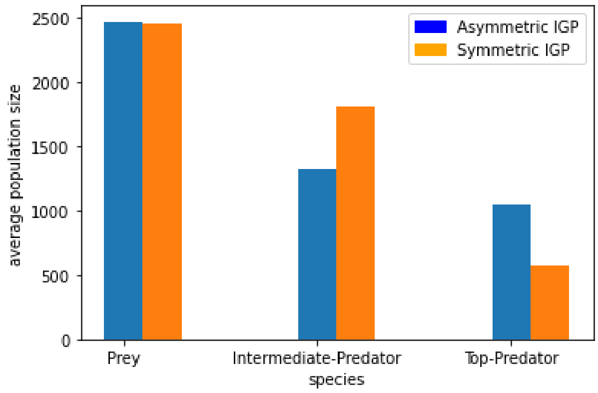


Fig 7. Comparison of average population size of prey-predator species in Asymmetric and Symmetric IGP with same initial population probabilities and spatial distribution, from observations of experiment D and A.

Intermediate-predator may prey on young top-predator population, and decrease the overall growth and survival of the predator, consequently reducing the overall predator population. [31][32] Thus, hypothesis **H4** can be considered true.

The calculation methodology for predation pressure, average population size, and prey and predator kill count for the experiments discussed above are detailed in Appendix C. Also, the population size data from the experiments are provided in Appendix D.

V. Critical Evaluation and Future Work

This study had a more exploratory approach, owing to a lack of previous research in the area of lattice-based systems modelling Intra-Guild predation. The results of experiment A can be useful in conservation biology to learn more about prey-predator herding behavior and habitat development in a multi-agent setting, as well as their habitat selection tendency and intra-guild predator avoidance techniques. The observations and learnings from experiment B and C can be looked upon together to infer that simplistic modelling of complex biological systems may not be able to effectively capture the nuanced aspects like predation pressure. The finite space lattice based model attains saturation after certain time-steps and no minor variation in population size and density will have an impact on the overall system population dynamic. However, the results from experiment B can be useful to determine the population size threshold beyond which the predation becomes excessive leading to prey extinction and subsequent system collapse. Intra-guild predation competition between the predators can be analyzed using the observations from experiment D. This can be useful to conservation biologists regarding moderating prey-predator population and considerations before introducing a top or intermediate predator in the local ecosystem. Further, the formulated bio-based CA model can be utilized to simulate and examine related concepts in evolutionary and conservation biology. These can be useful for studying indirect interaction between prey species that share a common predator, or predator species that share a common prey. [36] [37]

The focus of this project is restricted to the investigation of intra-guild predation behavior in terms of population size, density, spatial distribution, and interaction dynamics. However, consideration of further adaptations and modifications in prey-predator systems, such as size, age, speed etc., can increase the project's biological relevance. Moreover, the formulated CA model did not effectively mimic the variation in predation pressure corresponding to changes in species population. An improved rule base and cell space geometry can be formulated and implemented to test these hypothesis. Also, the CA model considers the prey, predator, and their environment as homogeneous. Adding heterogeneous characteristics like gender, fitness etc. and subsequently roles to individuals may improve the biological relevance of the model. Including environment and terrain variations, as well as their effect on species relationships, can help the model appear more realistic.

Further, to simulate and study intra-guild coexistence and coevolution, the formulated intra-guild predation CA model can be extended by incorporating cell states and update rules that evolve over time with metaheuristic optimization methods such as Prey-Predator Algorithm (PPA) [38] or Genetic Algorithm (GA).

VI. Conclusion

Biologically inspired Cellular Automata based models can be formulated to study and analyze the prey-predator system interactions and population dynamics. The CA model described in the paper mimic the intra-guild predation between two competing predators and their interaction with the shared prey with different population size, densities and spatial distribution. In Asymmetric IGP system, the observation from the experiments show herding behavior and habitat selection tendencies of different prey-predator species. Also, the experiments were indicative of the optimal initial population size and spatial distribution for system stability and the threshold beyond which the system might collapse. In Symmetric IGP system, the experimental results showed interesting emergent behavior of development bottleneck in top-predators, and how intermediate-predators becoming better competitors reduce the overall population of the top-predators. Further, the formulated CA models can be extended to simulate intra-guild coexistence and coevolution using optimization algorithms.

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