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Cane Toad Cannibalism Providing Opportunities for Population Control Strategies

- **Introduction and Related Works:**
  Cane toads are a species of anuran that originated in Latin America, and were originally brought into Australia in an attempt to eliminate the cane beetles. Since its introduction in the 1930s, its numbers have been increasing at an alarming rate, posing threats to numerous native flora and fauna, as the cane toads not only prey on and compete for resources with the native species, but also have no natural predators due to their deadly toxins. Various control measures have been devised, attempting to effectively curb the growth and disperse of cane toads. However, finding ways to eliminate the toads while not disrupting native species sharing the habitat is still an ongoing issue. One phenomenon that caught the attention of researchers is the highly frequent conspecific cannibalism among Australian cane toads developed after their invasion, and is far less common in their native habitat. A study done by DeVore et al. (2021) (2), compared the cannibalism in Australian cane toads and their native relatives in Latin American. They found that cannibalism itself is not rare in anurans, however, it is mostly opportunistic rather than a targeted response as seen in Australia, which has become their major source of mortality. Cane toad tadpoles are able to identify and attack their conspecifics by a maternally-invested toxin chemical contained in the clutches of cane toad eggs, originally used for protecting their young from predators in the early aquatic stages of their life. A study by Crossland et al. (2022) (3) shows that the chemicals carried by the eggs not only attract the cane toads but mainly cane toad tadpoles to a close proximity of the vulnerable hatchings, but also stimulate grazing and biting behavior. Another study by Crossland et al. (2012) (1) explored the possibility of utilizing the chemical cues mentioned in the above study to specifically attract and trap cane toad juveniles, removing them before reaching their terrestrial phase of life, with minimal impact to other native species. One explanation for this behavior is due to the competition for resources within the fast-growing, dense population. It will be interesting to explore its effect on the population over time. As a study points out “This species-specificity of intraspecific communication systems creates opportunities for targeted control of the invader with minimal effects on native taxa”(15) Studies have also suggested that the pheromonal communication between the individuals are sophisticated and complex, and that the population size is affected by many other factors. Our model will only cover selected aspects of them, in an effort to capture the main dynamics relating to the observed cannibalistic behaviors, and explore the question ‘what kind of opportunities can emerge from cane toads’ cannibalism and should humans take to better control their population’.

- **Model Design (ODD Description):**
  - **Purpose and Patterns:**
    The model created is of a small cane toad population that consists of toads, tadpoles, and eggs. The model goes through half a year with this small population and observes their cannibalistic behaviors towards each other when different control variables are changed. The purpose of the model is to observe the effects of cannibalism of cane toads on the cane toad population and to discover if there are aspects from it that can be exploited to control their population. Stochastic elements include movement of tadpoles and toads, number of eggs laid per batch, assigning variables to toad, tadpole, and egg turtles that will define how they interact with other turtles and

the environment (such as the maximum size they can grow to, the length of time it takes for a tadpole to turn into a toad, the probability of toads laying eggs, whether toads or tadpoles eat each other, and many others.

- **Entities, State Variables, and Scales:**
  The model has five kinds of entities, toads, tadpoles, eggs, food, and the environment. Each turtle (toad, tadpole, egg, food) will have an x and y position at all times. Each of the cane toad turtles (toad, tadpole, egg) have a variable, ‘days-alive’, that tells how long they have been alive for.

  Toads have variables **i)** ‘life-span’, which is the maximum number of days the toad can live for before dying of old age, **ii)** ‘max-size’, which is the maximum size in cm that the toad can grow to, **iii)** ‘toad-size’, the current size of the toad in cm, and **iv)** ‘hunger-level’, which indicates how full the toad is [0,1] (the lower the hungrier).

  Tadpoles have variables **i)** ‘tadpole-to-toad-days’, the number of days required for these tadpoles to turn into toads, and also have **ii)** ‘hunger-level’, similarly to the one toads have. Both tadpole and egg turtles have variable ‘num-alive’ which is the number of tadpoles / eggs the turtle represents. This is done instead of creating each one as a turtle to simplify the process of having thousands or even millions of tadpoles / eggs in a simulation at the same time.

  Food turtles only have one other variable, ‘food-level’, which indicates the current food amount stored in the food source. The environment has a discrete representation as a 50x50 grid that wraps around both horizontally and vertically. Each patch in the environment has variables **i)** ‘chemical-level’, the current chemical level amount in this patch, and **ii)** ‘max-chemical-limit’, the current chemical level limit it is able to reach. Every tick will be considered as one hour and these simulations will be run over 183 days (= 4392 ticks, ≈ half a year). Simulations either end when there are no cane toad turtles left alive or when 4392 ticks have been completed.

- **Process Overview and Scheduling:**
  In every tick, multiple processes will occur. These procedures will be divided into four groups; hourly, daily, miscellaneous, and called. The hourly and miscellaneous procedures happen at every tick / hour, while the daily procedures happen every day / every 24 ticks. Called procedures are those that do not appear within the main go procedure but are called by those that are in there. Some called procedures may just be defined within their respective called-from procedure if they are relatively short to describe. Procedures mentioned below are **bolded** for the reader’s convenience.

  Hourly Processes:

  i. **‘death’**: Simply checks if a cane toad turtle either dies of old age (has ‘days-alive’ = ‘life-span’) or starves to death (has ‘hunger-level’ <= 0).
  ii. **‘move’**: The movement of toad and tadpole turtles (1 unit forward per tick). First, if the ‘chemical-level’ of the patch the turtle is on is a positive number the turtle will move one unit uphill towards any neighboring patches with higher chemical levels and call the **‘eat-toad**’ procedure either if the turtle is starving (has ‘hunger-level’ < 0.05) or if there are eggs in the patch the turtle just moved to. But, if the patch has a ‘chemical-level’ of 0, if it is full

('hunger-level' >= 0.7) it will move 1 unit in a random direction and try to '**eat-food**'. If it is hungry (else) it will try to find a target to eat with '**turn-to-target**'.

iii. The 'hunger-level' toad and tadpole turtles are reduced by 0.01.

iv. Patches with 'chemical-level' > 0 reduce their chemical levels by 0.7. If by doing so their chemical level returns to 0, so does their 'max-chemical-limit' as well as the patch color to black (an increase in chemical level in '**eat-toad'** causes change in patch color**).**

<u>Daily Processes:</u>

v. '**replenish-food'**: Simply replenishes all food turtles' food levels by 50 units with a cap of 1000 units.

vi. '**grow**': All cane toad turtles will increment their 'days-alive' by 1. **a)** <u>Egg</u> turtles will hatch if they been alive for 3 days (average hatching time) (has 'days-alive' = 3) by creating int ('num-alive' / 100) tadpole turtles in the same position with each representing 100 tadpoles and having 'tadpole-to-toad-days' ~ N(42,10) and 'hunger-level' = 0.8.
b) <u>Tadpole</u> turtles will grow into toads if they have been alive for 'tadpole-to-toad-days' days. This creates 'num-alive' toad turtles in the same position, each with 'life-span' ~ N(6000,400), 'max-size' ~ N(12.5,1), 'toad-size' ~ N(0.75,0.05), and half hunger.
c) <u>Toad</u> turtles that have not reached their 'max-size' grow by N(0.035,0.005) cm with a cap.

vii. '**reproduce**': The population has (count toads) / 4 chances to hatch eggs at a 0.01 rate. The count toads part scales the amount of egg batches according to the number of toads alive. Each successful reproduction creates an egg turtle at a random location in the environment with N(12500,2000) eggs ('num-alive') and starts the count on their 'days-alive'.

<u>Miscellaneous Processes:</u>

viii. '**assign-color-toad**': Simply assigns colors to toad and tadpole turtles according to their hunger levels; [0.8,1] - green, [0.5,0.8) - yellow, [0.3,0.5) - orange, [0,0.3) - red.

ix. '**assign-color-food**': Very similar to '**assign-color-toad**' for food sources according to their food levels except multiply the percentages with 1000 (maximum food level) and (0,0.3) - red, 0 - black.

x. For patches with a positive chemical level, set its color to a scale of blue using the scale-color function.

<u>Called Processes:</u>

xi. '**eat-toad**': If local variable 'increase-hunger-level' (initialised to 0) becomes a positive number, increase the hunger level of the eating toad by that amount (capped at 1). If it remains at 0, call '**eat-food**'. **a)** <u>Toads</u> will prioritise eating eggs, so if there is an egg turtle in the same patch the toad will eat int ('toad-size' * 2.5) eggs or the remainder if the egg turtle's 'num-alive' is smaller ('increase-hunger-level' = num-eggs-eaten * 0.2 / 'toad-size'). This calls '**release-chemical**'. If there are no eggs in the same patch, check for tadpoles next. If there is a tadpole turtle, the toad will eat int ('toad-size' * 1.25) tadpoles or the remainder if the tadpole turtle's 'num-alive' is smaller ('increase-hunger-level' = num-tadpoles-eaten * 0.4 / 'toad-size'). If there are no tadpoles either, the toad will eat another toad that is less or equal to a fifth of its size ('increase-hunger-level' = eaten toad's size / 'toad-size'). **b)** <u>Tadpoles</u> will prioritise eggs if there are any egg turtles in the same patch. If any, the tadpoles will eat about [1.25,2.25] eggs each ('num-alive') or share the remaining eggs ('increase-hunger-level' = num-eggs-eaten * 0.65 / 'num-alive'), which also calls '**release-chemical**'. Else, they will eat other [1.25,2] tadpoles each from another tadpole turtle or share the remaining tadpoles from (‘increase-hunger-level’ = num-tadpoles-eaten / (‘num-alive’ * 8) (‘increase-hunger-level’ = num-eggs-eaten * 0.2 / ‘toad-size’). If all else fails and there are at least 2 tadpoles within the turtle, multiply ‘num-alive’ by max(‘hunger-level’, 0.5) (‘increase-hunger-level’ = max(‘hunger-level’, 0.5) / 4).

xii. ‘**eat-food**’: If there is a food source in the same patch that still has food: **a)** <u>Toads</u> will eat (‘toad-size’ * 2) units or the remainder if it’s smaller (‘increase-hunger-level’ = amount-eaten * 0.05 / ‘toad-size’). **b)** <u>Tadpoles</u> will eat (‘num-alive’ * 0.25) units or the remainder if it’s smaller (‘increase-hunger-level’ = amount-eaten * 0.4 / ‘num-alive’).

xiii. ‘**turn-to-target**’: First the nearest food, egg, tadpole, and toad <= ‘toad-size’ / 5 (only for toads) turtles are located within a radius of 15 if any. Toads and tadpoles have a probability of ((1 - ‘hunger-level’) + (‘chemical-level’ of patch / 5)) for a chance of 30% to eat its own kind. If it does, ignore the targeted toad (if any) by 90%, ignore the targeted tadpoles (if any) by 50% if the chemical level here is 0, and ignore the food target if there is at least one cane toad target, This increases the chances of targeting an egg. But if it doesn’t get the 30% cannibal chance, ignore all cane toad targets if any. After all that, if there are no targets, move one unit in a random direction. If there are target/s, move towards the nearest one.

xiv. ‘**release-chemical**’: Increase the patch’s chemical level by 1 unit, with a cap at 5 units. From this ‘centre’ patch, further increase the chemical level by 2 and increase the chemical levels of other patches within a 6 unit radius by (2 * 1 / (distance to centre patch + 1)). Set the centre patch’s ‘max-chemical-limit’ to 5 and the neighbors within 6 radial units to (5 * 1 / (distance to centre patch + 1)).

- <u>**Design Concepts:**</u>

  The main driving principle the model addresses is that the cannibalistic aspect of cane toads is infact a big contributor in controlling the cane toad population. This can be demonstrated by observing the population number overtime as food starts to become more scarce and their numbers keep escalating. This is mainly based on their interactions with each other which is affected by their hunger, the area’s chemical levels, and the amount of food in the area. This observation cannot be made based on a single individual toad nor confidently concluded with a few observations, therefore, this behavior is emergent on the entire population. The model assumes that all cane toads have the potential to become cannibals so it is not something that they are ‘born with’ but it is something that depends on the competition for scarce resources and their high numbers when each of them have the objective to survive.

  The model also assumes that cane toads and cane toad tadpoles are attracted to the chemicals that are released when their eggs are eaten, and that they move towards areas with high intensities of it. Toads and tadpoles are also expected to prefer eating eggs than tadpoles / toads. The effects of removing a number of toads / tadpoles / food sources cannot be observed through a single individual toad / tadpole / egg and cannot be confidently concluded within a few simulations. This behavior is, therefore, emergent on the population system.

  There are multiple stochastic aspects in this model as not all egg batches will have the same number of eggs, not all toads will have the same size nor maximum size, or not all toads or tadpoles will experience cannibalistic urges at the same time. However, there are surely many other stochastic aspects that are actually part of this ‘model’ in the real world such as weather and season impacting the mobility and activeness of the cane toads, the distance cane toads can actually travel in a day instead of one ‘unit’ per hour, the defensive adaptation to how they would react to niche predators that can eat / kill them, the pregnancy cycle to determine where the eggs will be laid and which features and eggs may get from which parent, etc.

For ease of observation, a graphical display is used for **i)** the turtle’s locations, **ii)** the toad and tadpole turtles’ hunger levels according to color as previously mentioned ([0.8,1] - green, [0.5,0.8) - yellow, [0.3,0.5) - orange, [0,0.3) - red), and the food turtle’s food levels ([0.8,1] - green, [0.5,0.8) - yellow, [0.3,0.5) - orange, (0,0.3) - red, 0 - black), and **iii)** different icons to indicate the differentiate each turtle type {egg: ‘egg’, tadpole: ‘exclamation’, toad: ‘frog top’, food: ‘plant’}. **iv)** Furthermore, plots of **a), b) c) d)** population of eggs, tadpoles, toads, and all of them, **e)** food availability (total food levels / num food sources), **f), g), h), i)** number of cannibalistic death for eggs, tadpoles, toads, and all of them, **j)** hunger percentage (total hunger levels / population of toads and tadpoles), **k)** number of deaths from starvation, and **l)** number of deaths from old age (though for every simulation ran it ends up empty so it can be ignored).

- **<u>Initialisation:</u>**
  A specified number of toads and tadpoles are initialised onto the landscape, each at random coordinates. The toad and tadpole turtles have an appropriate number of days alive (toad ~ N(3650,2) and tadpole turtles ~ N(12.5,2), and both with hunger levels of 0.8. Toads start with a ‘life span’ of ~ N(6000,400) days, a ‘max-size’ of ~ N(12.5,1), and a ‘toad-size’ of ~ N(‘max-size’ - 3, 1). The number of initial tadpoles / 100 is the number of tadpole turtles to be created, each representing 100 ‘num-alive’ tadpoles, and starting with tadpole-to-toad-days' ~ N(42,10). All patches in the environment are initialised with ‘chemical-level’ and ‘max-chemical-limit’ of 0 and a color of black. A specified number of food turtles are created and placed at the centre of a random patch and are initialised with food levels of 500 (half the maximum, 1000 units) units.

  There are a lot of fixed parameters. Each of these have been directly referred to by their values in the sections above. This section acts as a reference for those parameter values:

  - ‘max-iterations’ = 183 days / 4392 hours (ticks)
  - ‘food-radius’ = 15 units
  - ‘max-food’ = 1000 units
  - ‘min-food’ = 0 units
  - ‘initial-food-levels’ ~ ‘max-food’ / 2
  - ‘food-replenishment-rate’ = 50 units / day
  - ‘reproduction-prob’ = 0.01% per chance
  - ‘eggs-laid’ ~ N(12,500, 20000)
  - ‘initial-toad-days-alive’ ~ N(3650, 2)
  - ‘toad-life-span’ ~ N(6000,2)
  - ‘max-toad-size’ ~ N(12.5, 1)
  - ‘initial-toad-size’ ~ N(‘max-size’- 3, 1)
  - ‘toad-growth-rate’ ~ N(0.035,0.005) cm / day
  - ‘initial-tadpole-num-alive’ = 100 tadpoles
  - ‘new-toad-size-from-tadpole’ ~ N(0.75, 0.05)
  - ‘initial-tadpole-days-alive’ ~ N(12.5, 2)
  - ‘tadpole-to-toad-days’ ~ N(42, 10)
  - ‘max-hunger-level’ = 1.0
  - ‘min-hunger-level’ = 0.0
  - ‘initial-hunger-level’ = 0.8
  - ‘hunger-deduction-rate’ = 0.01 / hour
  - ‘initial-chemical-level’ = 0
  - ‘initial-max-chemical-limit’ = 0
  - ‘chemical-level-deduction-rate’ = 0.7 / hour
  - ‘chemical-level-release-rate’ = 1 / egg eaten

- ‘chemical-level-radius-spread’ = 6 patches
- ‘max-chemical-limit’ = 5
- ‘min-chemical-limit’ = 0

- **Input Data:**
  The model only requires the number of initial toads, tadpoles, and food sources.

- **Submodels:**
  This section will refer to processes in the ‘Process Overview and Scheduling' section.

  For process **x)** the following Netlogo code was used to color the patches to scale:
  set pcolor scale-color blue ‘chemical-level’ ‘min-chemical-level’ ‘max-chemical-level’

  For process **xi)** here are the equations for a clearer view:
  - Toads Eating Eggs:
    ‘num-eggs-eaten’ = min(int(‘toad-size’ * 2.5), ‘num-eggs-left’)
    ‘increase-hunger-level’ = (‘num-eggs-eaten’ * 0.2 / ‘toad-size’)
  - Toads Eating Tadpoles:
    ‘num-tadpoles-eaten’ = min(int(‘toad-size’ * 1.25), ‘num-tadpoles-left’)
    ‘increase-hunger-level’ = (‘num-tadpoles-eaten’ * 0.4 / ‘toad-size’)
  - Toads Eating Toads:
    ‘increase-hunger-level’ = (([‘toad-size’] of eaten-toad) / ‘toad-size’)
  - Tadpoles Eating Eggs:
    ‘num-eggs-eaten’ = min(int(‘num-alive’ * (1.25 + random [0,1])), ‘num-eggs-left’)
    ‘increase-hunger-level’ = (‘num-eggs-eaten’ * 0.65 / ‘num-alive’)
  - Tadpoles Eating Tadpoles (different turtle):
    ‘num-tadpoles-eaten’ = int(1.25 + random [0,0.75]) * ‘tadpole-num-alive’)
    ‘num-tadpoles-eaten’ = min(‘num-tadpoles-eaten’, ([num-alive] of eaten-tadpoles))
    ‘increase-hunger-level’ = ‘num-tadpoles-eaten’ / (‘num-alive’ * 8)
  - Tadpoles Eating Tadpoles (same turtle):
    ‘increase-hunger-level’ = max(‘hunger-level’, 0.5) / 4
    ‘num-alive’ = int(‘num-alive’ * (max(‘hunger-level’, 0.5))

  Similarly for process **xii)**:
  - Toads Eating Food:
    ‘num-food-eaten’ = min(‘toad-size’ * 2, ‘food-level’)
    ‘increase-hunger-level’ = 0.05 *‘num-food-eaten’ / ‘toad-size’
  - Tadpoles Eating Food:
    ‘num-food-eaten’ = min(‘num-alive’ * 0.25, ‘food-level’)
    ‘increase-hunger-level’ = 0.4 * ‘num-food-eaten’ / ‘num-alive’

  And process **xiv)**:
  - Chemical Level Increase for Patches within Radius of 6:
    ‘chemical-level’ = ‘chemical-level’ + (2 * (1 / (distance to center + 1)))

- **Methods:**
  The experiments conducted were designed to observe the effects of different scenarios on the cane toad population and their cannibalistic behaviors, where each scenario differs by having changes made to it during initialisation with different values for the experimental variables; initial number of toads, tadpoles, and food sources. The scenarios carried out are as follows:

  - A. Default:
    1. {‘num=initial-toads’ = 250, ‘num-initial-tadpoles’ = 25000, ‘num-food’ = 250}
  - B. Less Food Sources:
    1. {‘num=initial-toads’ = 250, ‘num-initial-tadpoles’ = 25000, ‘num-food’ = 50}
    2. {‘num=initial-toads’ = 250, ‘num-initial-tadpoles’ = 25000, ‘num-food’ = 100}
  - C. Less Initial Toads:
    1. {‘num=initial-toads’ = 0, ‘num-initial-tadpoles’ = 25000, ‘num-food’ = 250}
    2. {‘num=initial-toads’ = 100, ‘num-initial-tadpoles’ = 25000, ‘num-food’ = 250}
  - D. Less Initial Tadpoles:
    1. {‘num=initial-toads’ = 250, ‘num-initial-tadpoles’ = 0, ‘num-food’ = 250}
    2. {‘num=initial-toads’ = 250, ‘num-initial-tadpoles’ = 10000, ‘num-food’ = 250}

  Aside from the default scenario, there are two other scenarios when investigating changes in the three experimental variables. Each of these scenarios were run three times and their plots were recorded as below in the results section.

- **Results:**

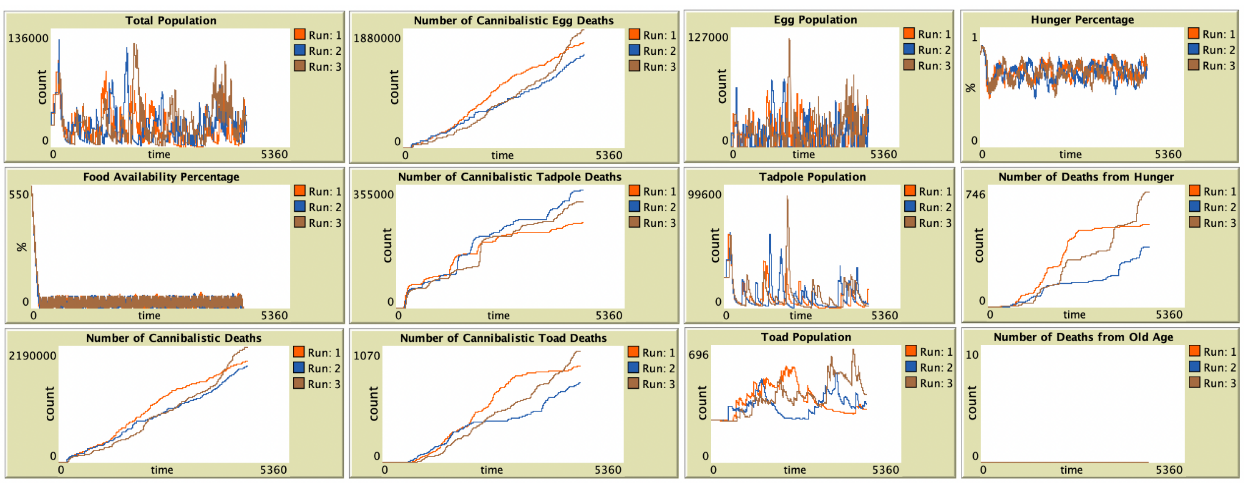

Figure 1: Scenario A.1. {‘num=initial-toads’ = 250, ‘num-initial-tadpoles’ = 25000, ‘num-food’ = 250}.

In the default scenario, the total population size quickly reached its max of 136,000 but just as quickly decreased shortly after. The total population size fluctuated mostly between a few thousand and 90,000 throughout. The hunger percentage of the population (toads and tadpoles) was consistently between 55-75%, excluding the initial drop at the start when all initial toads and tadpoles have hunger levels of 0.8. The cannibalistic deaths across eggs, tadpoles, and toads all seem to be in proportion with one another.

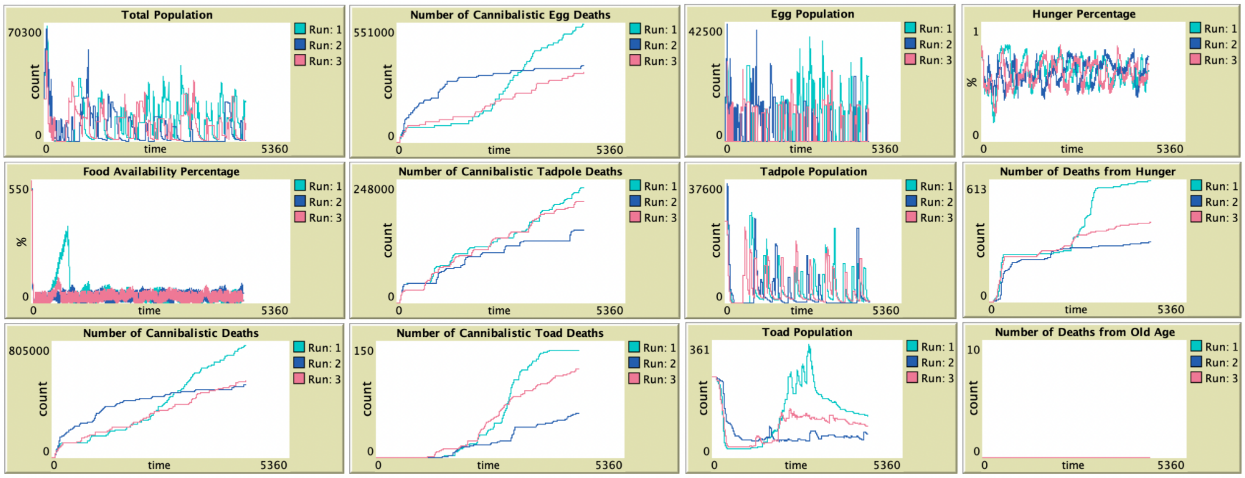

Figure 2: Scenario B.1. {‘num=initial-toads’ = 250, ‘num-initial-tadpoles’ = 25000, ‘num-food’ = 50}.

When there were 50 food sources, after the initial max total population (around 70,300), the total population mainly fluctuated between thousands and 35,000, which is significantly lower than the default. In the first run where the egg population grew immensely, the larger egg population together with the lack of food sources induced much higher egg and toad deaths caused by cannibalism and by starvation respectively. The number of toads and tadpoles consistently decreased steeply at the start of the simulations due to the lack of food and it was likely that the toads competed against each other to eat the tadpoles. The overall numbers in all three populations decreased by more than half than that in ***Figure 1***. For a brief moment in the first run there was a spike in food availability, likely because there were little to no toads or tadpoles at the time.

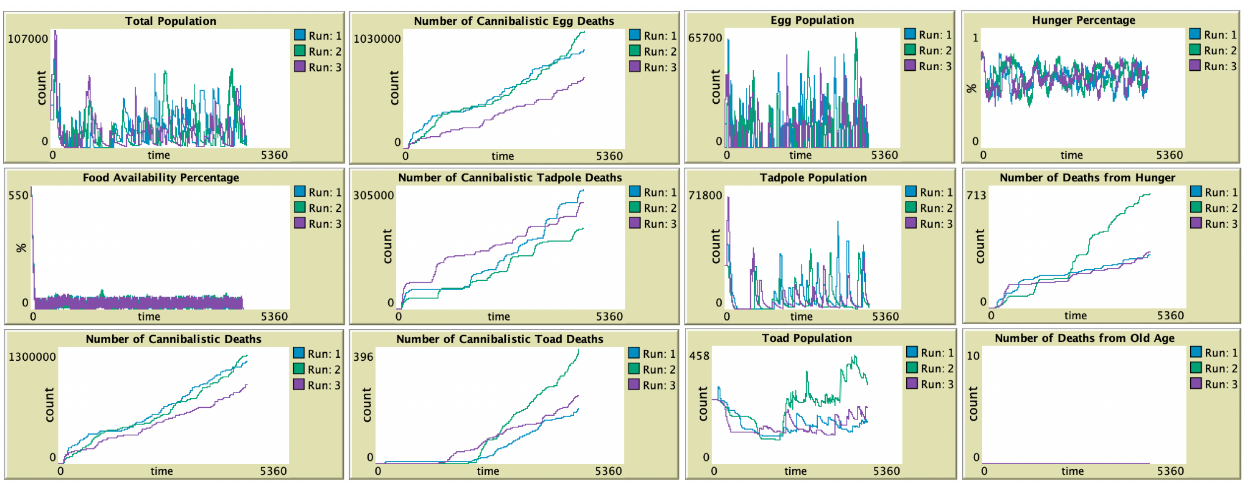

Figure 3: Scenario B.2. {‘num=initial-toads’ = 250, ‘num-initial-tadpoles’ = 25000, ‘num-food’ = 125}.

With 125 food sources, the patterns seen in the figures portray similar behaviors and effects to those in ***Figure 2*** in comparison to the default scenario. However, because of there being more food than ***Figure 2*** those effects were not as strong. While there were more cannibalistic deaths the populations did not suffer as much. This is likely due to the overall number of toads throughout the simulations, as more toads means more eggs being laid.

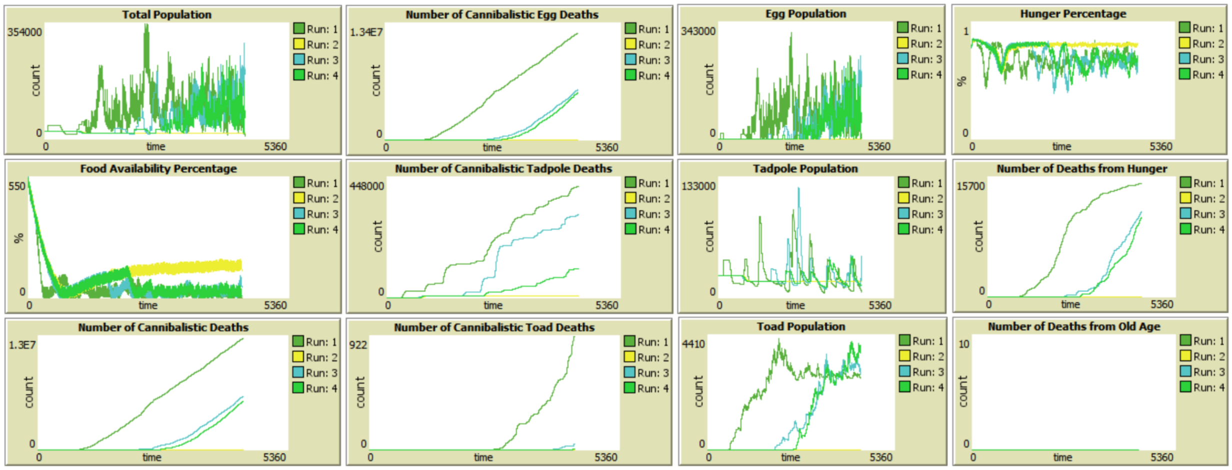

Figure 4: Scenario C.1. {'num=initial-toads' = 0, 'num-initial-tadpoles' = 25000, 'num-food' = 250}.

When there are no toads at the start of the simulations, there is no initial boost of population as seen in other scenarios as again, no means = no eggs. However, the population exponentially picks up the speed and far surpasses all previous scenarios. The toad population at the end of the simulations consistently stood at around an alarming number of 4,000 with no sign of stopping. The number of cannibalistic deaths is higher but at around the same ratio of the population size, however, deaths caused by hunger skyrockets to about 10,000-15,000. Though the first run does seem to be an outlier as it is significantly different from the other runs in almost all aspects, especially cannibalistic deaths and hunger deaths. For the two inlier runs, there are almost no cannibalistic toad deaths, this is probably because they die of hunger before they are even able to find another toad to eat, which would already be rare at the rate that they are starving at.

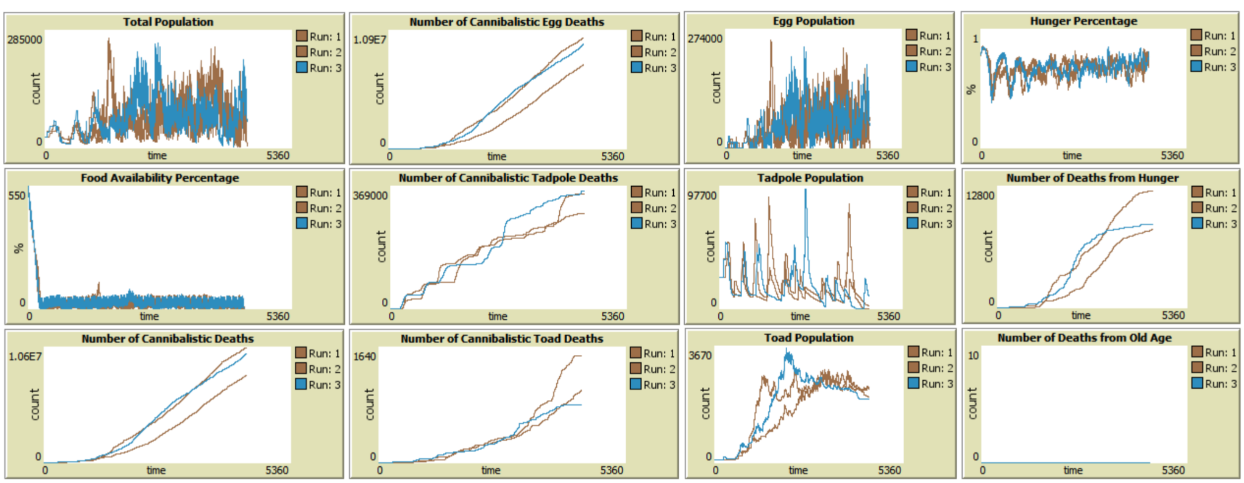

Figure 5: Scenario C.2. {'num=initial-toads' = 100, 'num-initial-tadpoles' = 25000, 'num-food' = 250}.

With 100 toads at the start, similarly as scenario B.2. was to B.1 the same patterns and effects are happening at weaker intensities. Though when compared to the default scenario, just by removing 150 toads at the start of the simulations it still makes a huge impact on the overall cane toad population.

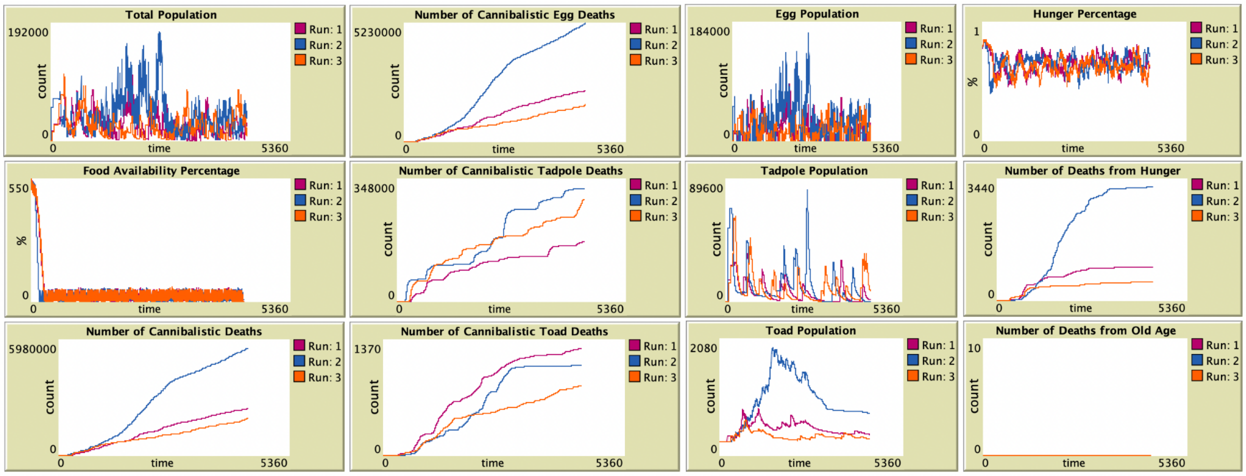

Figure 6: Scenario D.1. {'num=initial-toads' = 250, 'num-initial-tadpoles' = 0, 'num-food' = 250}.

It is immediately clear that the second run is an outlier compared to the other two as it has much higher cannibalistic egg death, higher overall population, and much higher hunger deaths. However, by looking at just the inliers, there does not seem to be any obvious effects when there are no initial tadpoles. Everything seems quite inline with the results of ***Figure 1***. However, it can be concluded that the reduction of the number of initial tadpoles does not have as big of an impact on the overall cane toad population as the reduction of initial toads as shown in ***Figure 4*** and ***Figure 5***.

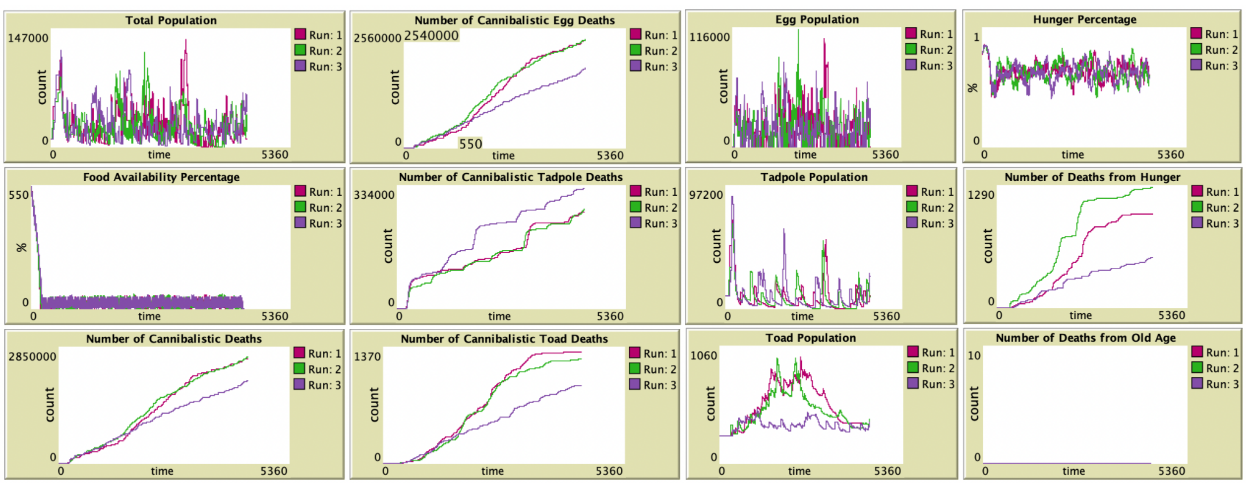

Figure 7: Scenario D.2. {'num=initial-toads' = 250, 'num-initial-tadpoles' = 10000, 'num-food' = 250}.

Even with 10,000 initial tadpoles, not much can be said in terms of effects on the population in any aspect. The toad population can be seen as marginally larger than that of the default scenario, however, it cannot be said with confidence that it is because of the decrease in initial tadpoles.

- **<u>Discussion:</u>**
  One thing that can be observed from the results is that in our current setup of the environment, the cane toad population size seems to settle eventually, likely to the point where the amount of food in the environment is able to sustain the population alongside their cannibalism. This explains why the egg and tadpole population and food availability keep oscillating up and down, cannibalism mainly occurs when food has run out.

By observing the results of the different scenario types with their different sets of variable value between initial number of toads, tadpoles and food sources, the total population size fluctuates between a very large spectrum range. This suggests that the presence of cannibalism somewhat controls the population size due to cannibalism being the driving factor for most of the numbers. Cannibalism on its own is unlikely to be a solution at all to the cane toad problem as all the results of each scenario show the presence of a self-sustaining population, even though its methods are by turning on each other. Instead the results have proven that that is how their population is able to survive and grow while eating their young at the same time.

Other strategies must be implemented and explored on top of the cannibalistic environment in order to reduce or eliminate the population. For example, the manual removal of cane toads or the use of cane toad egg chemicals to trap other toads have been popular strategies over the past few years (4)(5). While the removal of toads obviously sounds like a way of fighting the cane toad population one toad at a time, the results tell a different story. When the initial number of toads is set to zero (but with tadpoles present), the population grows exponentially larger throughout the simulations in comparison to the scenarios where there are 100 or 250 initial toads. Even in the scenario with 100 initial toads, it makes a huge difference compared to the default. The overall number of deaths by cannibalism seem to decrease with a higher initial number of toads. This is probably due to the lack of toads at the start of the simulations with there being nothing else to control the egg and tadpole populations which allow a good majority of the initial ones to survive. This goes against the ideals of manual removal or capturing of cane toads and perhaps suggests that it is better to not remove them from their population habitats as they really do seem to be their own worst enemy.

While little to no effects were observed in the decrease of initial tadpoles, the decrease of food sources largely impacted the overall total population compared to the default scenario. With less food more competition and cannibalism occurs within the populations of eggs, tadpoles, and toads. The simulations in ***Figure 2*** and ***Figure 3*** show that the toad population usually ended with less toads than when the simulations first started. Perhaps, if more ticks were considered the simulations would have shown that the toads would die out. This suggests that removing food sources from cane toad populations is a good opportunity to lower their numbers and force them to eat each other more. Though this does not affect the toads directly like manual removal, which was discussed above as not being an ideal solution, ‘food source removal’ can be thought of as a catalyst that induces more cannibalism forcing them to eat each other and as an effective method of cane toad control. Whereas in the other scenarios, where they always have the options to choose to eat from a food source or their young, their population will always flourish.

These are some of the examples that can be observed from the results, but whether they are realistic enough to mimic the population lifestyle and behavior is one important thing that needs to be considered. The model presented consists of a high number of calculations and each key process such as movement, reproduction, target finding, and eating rely heavily on them. The calculations themselves are not very complex, however, the relationships between the processes are, affecting each other in subtle ways which can give rise to many different patterns of behavior. The observations mentioned earlier may all just be caused by the scheme of the current setup, so they may not currently reflect what happens in the real world. However, the model effectively represents estimations of these processes of what is actually happening in the cane toad population, with implementations such as the reproduction of eggs and opportunistic consuming of eggs leading to the release of chemicals which attract and encourage more cannibalistic behavior. With these modelled processes, a set of better curated constant values for their calculations from proper research and field studies can better improve the realistic aspect of the simulations and results.

One interesting observation from the experimentation phase of the model was about the egg hatching time. In an earlier version of the model where each tick represented one day, since cane toad eggs take two to three days to hatch, the hatching time was implemented as two ticks. But due to the movement and eating process that also happened on every tick, not many toads were able to eat any of the eggs, which did not accurately depict that lifestyle in real life. Which is why a decision was made to change each tick to represent an hour, making the number of eggs consumed much more realistic. In this model, cane toads are simplified into three stages, with the egg stage being the most vulnerable. The above scenario shows that the length of the vulnerable stage is critical to the effect of cannibalism with the results from the figures having high cannibalistic egg deaths, which is the main source of food for tadpoles and toads when there is low food availability due to the number of eggs cane toads can lay at a time. This is one thing that can be considered for future directions for the model where some attributes of the process may be changed overtime in response to the environment.

One limitation of the model is the capability of the Netlogo program in handling large numbers of entities (eggs and tadpoles). Tadpoles and eggs are two of the main subjects of the model. So because they are naturally large in numbers, improvisations of a one-to-represent-all were used for them (many to be represented by one turtle). This may lose some individualities of each individual a turtle represents, such as not being able to have tadpole sizes or individual hunger levels for each tadpole. Another limitation of this model is the scaling of number and time. As each tick represents an hour, half a year already consists of 4392 ticks. With the 4392 ticks, some of our simulations could take up to 30 minutes to complete, just to model a simulation for half a year. This makes it difficult and unsuitable to observe results and behaviors in the long run.

The model implementation is very good but more time needs to be spent actually investigating and researching the cane toad population because there are a lot of variables and interactions between them that need to be considered to realistically portray them and may uncover even more hidden behaviors that this model was not able to. In carrying out this assginment, Netlogo familiarity and fluency has been established within the group, who have collectively learned that difficulty and complications that can arise when handling models with large amounts of detail and the amount of effort required to make sure every process works together in unison.

- **References:**

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