Introducing a Gestation Period of Time-Delayed Benefit into an Animat-based Artificial Life Model

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Bio-inspired models such as animat agent based artificial life models provide a useful platform for exploring collective and emergent phenomena such as decision making, financial markets and resource management systems. Breeding mechanisms whereby new animat agents are introduced into the system provide an important mechanism for the system as a whole to adapt to new or changing circumstances. We explore the consequences of decoupling individual animat behaviours in time from their effect on the species and system as a whole by incorporating a gestation period of time delay between animat breeding and animat birth. The breeding system incorporated in previous models enabled instant births. This allowed prey animats to propagate with no regard to their own safety. This research introduces a gestation period, thus requiring animats to keep themselves alive long enough to successfully reproduce. We discuss the consequences for large scale animat models with bio-inspired selection mechanisms based on predator-prey cycles and a spatial mixing environment.

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ABSTRACT

Bio-inspired models such as animat agent based artificial life models provide a useful platform for exploring collective and emergent phenomena such as decision making, financial markets and resource management systems. Breeding mechanisms whereby new animat agents are introduced into the system provide an important mechanism for the system as a whole to adapt to new or changing circumstances. We explore the consequences of decoupling individual animat behaviours in time from their effect on the species and system as a whole by incorporating a gestation period of time delay between animat breeding and animat birth. The breeding system incorporated in previous models enabled instant births. This allowed prey animats to propagate with no regard to their own safety. This research introduces a gestation period, thus requiring animats to keep themselves alive long enough to successfully reproduce. We discuss the consequences for large scale animat models with bio-inspired selection mechanisms based on predator-prey cycles and a spatial mixing environment.

KEY WORDS

bio-inspired models; animat, agent-based model, collective behaviour; emergence.

1 Introduction

Artificial life models based on spatial agents or "animats" have experienced a resurgence in interest and reported work in the research literature. This is largely due to the utility of these models in exploring complexity and emergent phenomena arising from collective phenomena in applications such as: financial market systems [1]; crowds and collective decision making [2] and flocking [3]. A sub phenomena of particular interest in how group structure emerges in a large scale system [4] particularly in systems where there is a contin-
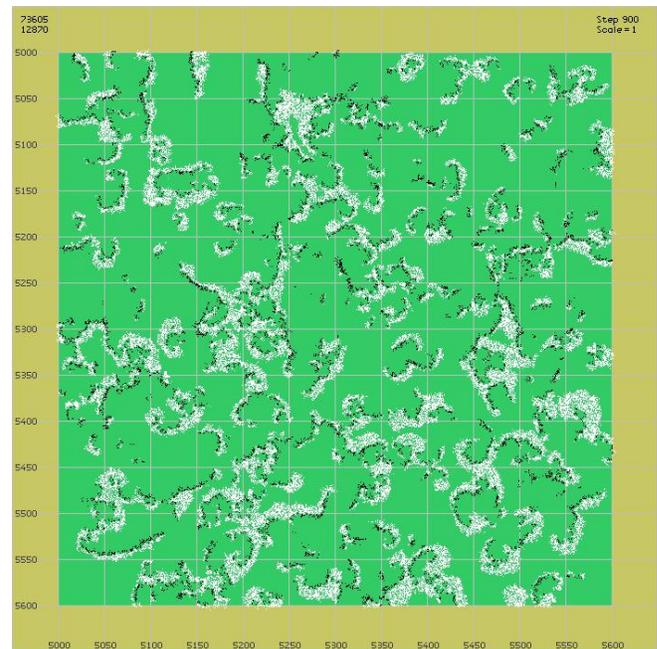

Figure 1: The situation at step 900 of a typical run showing animats on a square grassed area. Predators are black and prey are white. Various macro-clusters, including spiral formations, have emerged. This screen shot contains 12,870 predators and 73,605 prey animats.

ual turnover of agent participants. A key controlling property of such system may be the reproduction mechanism - the means whereby new agents or animats appear, and how they are selected or evolve to meet the needs of their physical or metaphorical landscape. Animat "breeding" [5] or self-reproduction mechanisms [6] appear in a number of artificial life and related models [7, 8]. This and other bio-inspired mechanisms [9] can be incorporated into artificial life models to provide optimisation and other adaptive search mechanisms.

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The notion of artificial Life models is now well established and there are a variety of published approaches such as Avida [10] and others [11–14]. All these models include a process for the creation of new agents (known in Artificial Life as "animats" [15]). This process is often referred to as "breeding". Breeding in Avida, for example, takes the form of a parent program allocating memory and copying some, or all, of itself into this new space. Avida has been used in many ways to investigate propagation, inheritance, mutations, cross-over and evolution [8].

One aspect of the breeding process that is common to all models is that new animats appear immediately. This was not an issue for early abstract models but recent models attempt to simulate far more aspects of biological behaviour. EcoSim [16], for example, is a recent predator-prey model incorporating breeding, movement, vision, energy transfer, adaptation [17] and more. However breeding (and the appearance of new animats) is, as before, instantaneous.

Such instantaneous breeding can have a significant effect on the behaviour of the parent animat. In particular it ensures that animats can successfully propagate without taking any measures to evade predators. Thus the method of reproduction (such as instantaneous breeding) can significantly alter the overall animat behaviours that emerge from the model.

In [18] Martin defines gestation as:

> "In mammals, the interval between fertilization and birth. It covers the total period of development of the offspring, which consists of a pre-implementation phase (from fertilization to implantation in the mother's womb), an embryonic phase (from implantation to the formation of recognizable organs), and a fetal phase (from organ formation to birth)."

The key notion for animat models is that gestation provides a mechanism for time-delay between an animat action and the consequences, either for it as an individual or to its species as a whole. This raises the question as to whether gestation is in fact a mechanism for individuals planning ahead or investing in the future. A species that evolves a significant time delay in this manner, has effectively stock-piled resources against future benefits but has also taken the risk that that benefit may never come to fruition. This risk will then be coupled to the animats' environment and leads to selection of individual trait according to long term benefit and not just short-term single generational benefit.

This present article describes several related experiments in which instantaneous breeding is not used. Instead of new animats appearing immediately, a gestation period of time-delayed birth is introduced. Thus a fixed period elapses between the start of the breeding process and the creation of a new animat. If the parent animat is destroyed during this gestation period, the new animat will not be created and the accrued benefit to the population lost.

These experiments are conducted against the backdrop a well-established spatial predator-prey model [19]. This model consists of a "map" (usually featureless) on which large numbers of agents or "animats" reproduce, feed, flee predators or hunt prey and eventually die. The model reproduces the repetitive cycle of behaviour that is well known with such simulations [13] and from predator-prey equation based models such as the Lotka-Volterra equations [20]. Predators kill prey and, if prey is plentiful, the predator numbers increase, leading to an increased demand for prey which causes the prey population to drop and this in turn causes a drop in the predator population which allows the prey population to recover, and so the cycle continues.

The microscopic behaviour of animats is driven by internal rules. Each animat carries a small set (less than 8) of rules and executes one of the rules every time step. The spatial mix of animats combined with their rule-driven behaviour leads complex and emergent patterns of predators and prey such as the defensive spirals and other features discussed in [21]. Typical emergent clusters and formations can be seen in Figure 1.

In this paper we investigate how the introduction of a gestation period leads to a change in the priorities of the rules for prey animats. It is possible that this change could be evolved over time but such speculation is not part of this work. A brief overview of the predator-prey model is provided in section 2. The effects of the introduction of the gestation period and the new rule priorities are discussed in Section 3. Section 4 investigates the effects of the new rule priorities on population size. Section 5 introduces some alternative length gestation periods. We discuss the effect on gestation as a time delay mechanism in Section 6 and offer some conclusions and ideas for future work in section 7.

2   The Predator-Prey Animat Model

The basic model we use for this work is based on a spatial collection of individual finite state machine animat agents [22]. These agents act as either predators or prey and this adversarial mechanism gives rise to selection and adaptation of individual sub-species according to the prevailing conditions of the model system. Input from its immediate neighbourhood is provided to each animat machine, and a stochastic mechanism is used to deal with tie-breaks or animat rule conflicts.

This predator-prey model [19] has been developed and refined over a number of years and locates hundreds of thousands of animats on a two-dimensional featureless plain. There are two species of animat – the predators that need to eat prey to survive and the prey that "graze" (eat grass). For these experiments, the grass was placed evenly in a large square area covering most of the map. Prey do not survive for long away from the grassed area and hence both prey and predators (that require nearby prey) are effectively restricted to the grassed

2

square, although individual animats do sometimes move outside the area.

Each animat is implemented as an instance of the animat class which maintains a set of state variables (location, health, age) and a set of rules – see Figure 2.
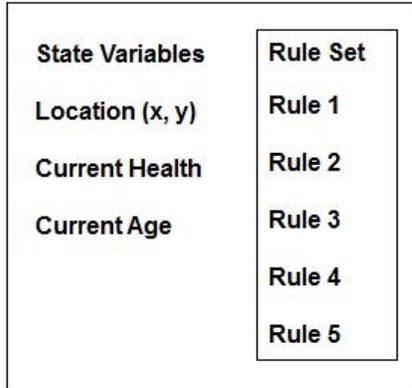

Figure 2: Each animat maintains state variables along with a set of rules. The rules differ depending on species (prey or predator) and sometimes differ within a species, e.g. different prey animats may give a different priority to the "flee" rule.

Every time step the age is incremented and if it reaches the pre-defined maximum for the species the animat "dies of old age" and is removed. Each time step the health is reduced and if it reaches zero the animat "starves to death". Health can be increased by eating (predators eat prey and prey eat "grass"). However health may not be increased above a pre-defined maximum for each species.

Every animat carries a small set of rules that direct its behaviour and at each time-step of the simulation, each animat executes one of its rules, causing it to move, eat or breed. The interacting directed movements of thousands of animats produces emergent clusters and formations that have been previously analysed [23]. The rule sets differ for each species (predator and prey) and can be set up to differ within species, if required. Section 3 describes a set of experiments in which groups of prey animats have different rule sets. If it is not stated otherwise, each animat is identical to all other animats of its species. In the experiments outlined in this article, all predators are identical and have unchanged rule sets.

The rule set of every animat lists the rules in *priority order*. Thus every animat, at every time-step, always attempts to execute rule 1. However, most rules are conditional on certain requirements being met, for example a certain rule may only be executed if another animat is adjacent. If the conditions for a rule can not be met, then that rule is ignored and the animat will attempt to execute the next rule in the set. The rule sets for both species are listed in Table 1.

The "breed" rule is used to create new animats. For these experiments, a new animat is always a clone of its parent (iden-

Table 1: Animat Rule Sets in Priority Order

Rules for predator animats:	Rules for prey animats:
1. breed if health $> 50\%$ and mate adjacent	1. graze (eat grass) if health $< 50\%$
2. eat prey if health $< 50\%$ and prey adjacent	2. breed if health $> 50\%$ and mate adjacent
3. seek mate if health $> 50\%$	3. randomly move to any adjacent position (50% chance of success)
4. seek prey if health $< 50\%$	4. seek mate if health $> 50\%$
5. randomly move to any adjacent position (50% chance of success)	5. flee from predator if predator is adjacent

tical rule set) and is placed adjacent to the parent when it appears. In previous versions of the model the new animat was created at the time of execution of the breed rule. This is consistent with other Artificial Life models as discussed above.

In the following sections, we alter the breeding rule mechanism to incorporate a time delay - or gestation period between an animat breeding and giving birth to a new animat. This can be done in a number of ways, as described below.

3   Experiment 1 – Rule Priorities

Previous work on the model [24] allowed animats to evolve the most efficient rule sets. Note that this evolution involved changing the position (priority) of each rule within the rule set and did not involve changing the rules themselves. It should also be noted that in the final evolved rule set for prey (see Table 1) the "flee" rule was positioned at the end of the set, i.e. it had the lowest priority.

Experiment 1 was conducted in order to investigate the effect that a gestation period would have on rule priority. A gestation period was introduced into the model and this means that when an animat executes the "breed" rule, a new animat is not immediately created. Instead the animat is deemed to be "pregnant" for a fixed period of time steps.

This fixed period is pre-defined (and different) for each species – predator and prey. For this experiment the gestation period for predators was set to 12 time steps and the gestation period for prey was set to 6 time steps.

Five rule sets were defined for prey – see Table 2 . The sets are all the same except for the position (priority) of the "flee" rule in the set. The conditions for each rule remain unchanged, e.g. the condition for the "seek mate" rule remains "if health $> 50\%$".
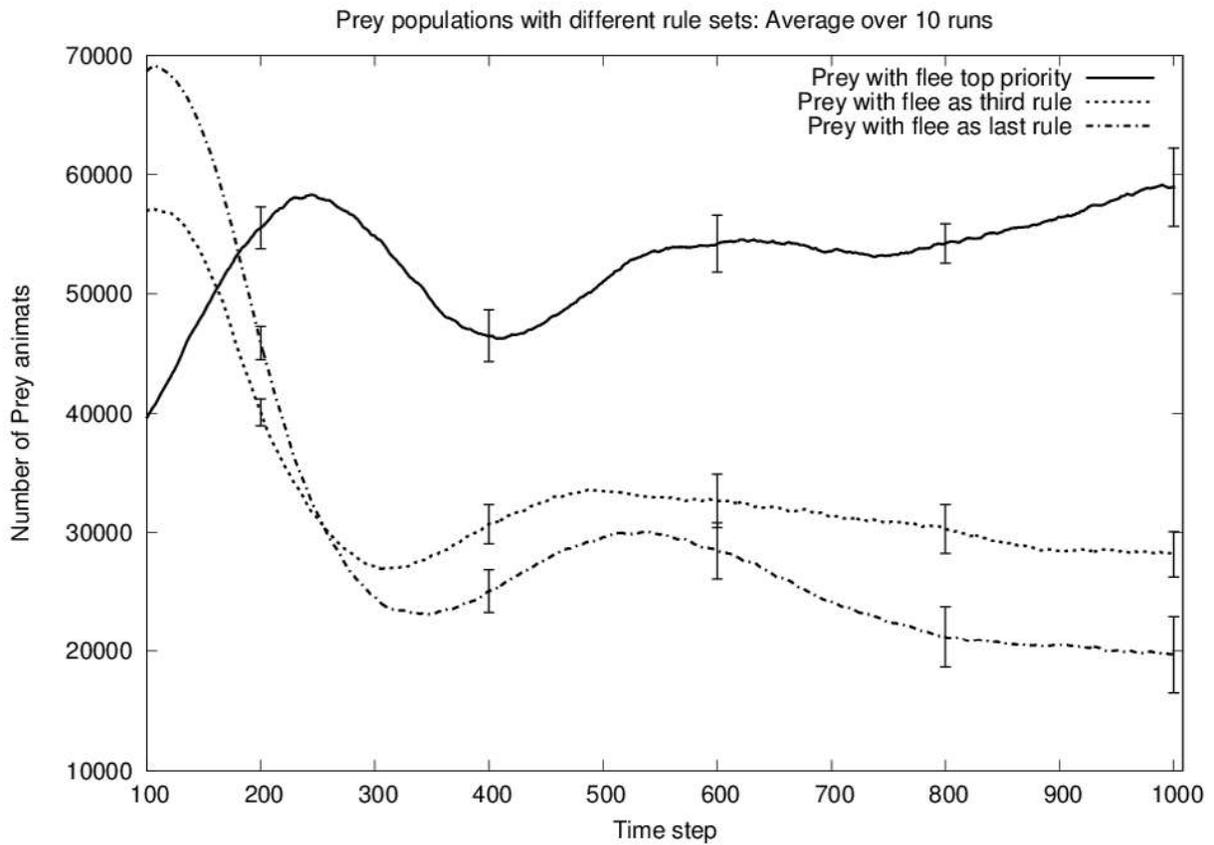
Figure 3: Plot showing the effects of changing the position (priority) of the "flee" rule in prey animat rule sets. Prey are most numerous when the flee rule is the top priority and the population declines as the "flee" rule is placed further down the priority list. The plot shows the averages over ten runs with different random number seeds.

Table 2: Rule sets for prey, showing subspecies-defining sets A,B,...,E with priority orders 1,2,...,5

Set	1	2	3	4	5
A	flee	graze	breed	random	seek mate
B	graze	flee	breed	random	seek mate
C	graze	breed	flee	random	seek mate
D	graze	breed	random	flee	seek mate
E	graze	breed	random	seek mate	flee

Table 3: Number of prey at time step 1000 with each rule set.

Rule set A	14,990
Rule set B	5,085
Rule set C	5,647
Rule set D	1,932
Rule set E	3,381

These rule sets were distributed equally (but randomly) to the initial group of 40,000 prey animats. Thus each rule group consisted of representative animats scattered randomly across the map. Any prey animat was free to breed with any other prey animat irrespective of rule set. For this experiment, each animat was a clone of its "mother" and the rule set is passed unchanged from parent to offspring.

There is no cross-over or mutation of rule sets and thus there is no evolution of rule sets. However natural selection [25] will ensure that the group with the "best" rule set will gradually dominate. The rule set for predators remained unchanged – thus all predators contained identical rule sets as outlined in section 2.

This experiment was conducted ten times with the same configuration but different random number seeds. The results are presented in Table 3. The figures shown are averages across the ten runs. It is clear that Rule Set A is significantly more successful than any other rule set.

Thus it is important for the "flee" rule to be ranked highly by prey now that the model contains a gestation period as part of the breeding process. In previous versions of the model, Rule Set E was most successful because offspring animats were instantly created and there was no gestation period and hence no need for the "flee" rule to have a high priority.
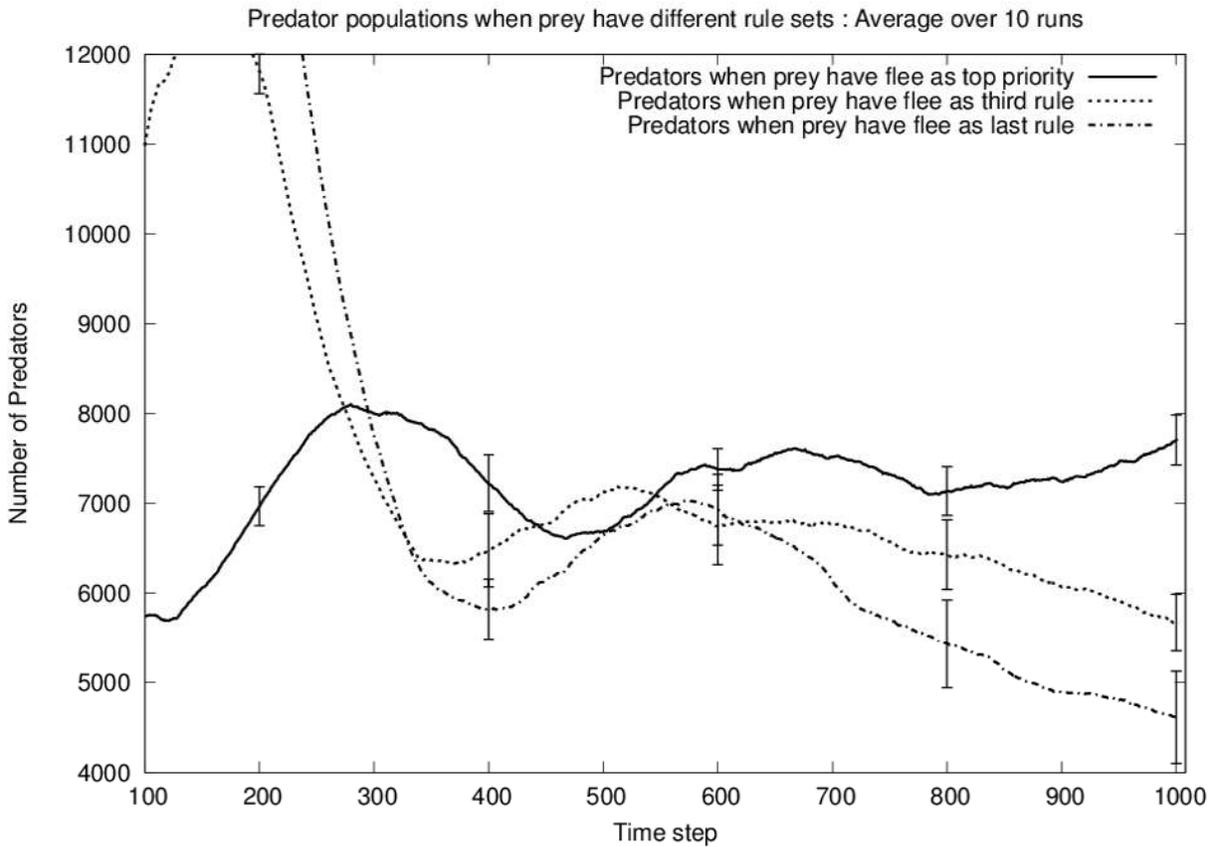
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Figure 4: Plot showing how predator populations are affected by changing the position (priority) of the "flee" rule in prey animat rule sets. Predators initially do well when prey rank the "flee" rule as a low priority but the resulting increase in predators leads to a scarcity of prey and a crash in the predator population. The plot shows the averages over ten runs with different random number seeds.

4 Experiment 2 – Different Rule Sets

Experiment 1 (see section 3) established that the best rule set to use for prey is one where the "flee" rule is at the top of the priority list. This section investigates the effects on population when the "flee" rule is fixed in a specified position (priority) within the rule set.

Table 4: Fixed rule sets for prey, showing 3 fixed sets (vertically) with priority orders 1,2,...,5 shown horizontally.

Set	1	2	3	4	5
1	flee	graze	breed	random	seek mate
2	graze	breed	flee	random	seek mate
3	graze	breed	random	seek mate	flee

Three simulations were conducted. In each simulation, the prey were all given the same, fixed rule set. These rule sets are defined in Table 4.

The first rule set ranks the "flee" rule as top priority, the second rule set places it as the third rule and the final set ranks it as the lowest priority. The resulting populations are shown in

Figure 3 (prey) and Figure 4 (predators). The conditions for each rule remain unchanged.

Each simulation was conducted ten times with the same configuration and different random number seeds. The results clearly show the correlation between the priority of the "flee" rule and the prey populations. When the "flee" rule is the top priority, the prey population stabilizes at a high level. When the "flee" rule is a lower priority, the prey population drops accordingly.

The predator populations are initially the inverse of the prey populations, i.e. when the prey rank the "flee" rule as top priority, then the predators are least successful and vice versa. This phase relationship is complicated by the spatial pockets of animats and the spatial fluctuations effectively add noise to what would otherwise be a smooth relationship for a large population.

However if the predators become too successful, the predator population increases dramatically leading to a shortage of prey. This shortage, in turn, leads to a crash in the predator populations which never fully recover. Thus, in the long-term, predators benefit more from prey with a highly-ranked

"flee" rule than was initially predicted.

5 Experiment 3 – Period Duration

Experiments 1 and 2 (see sections 3 and 4) established that the best rule set to use for prey is one where the "flee" rule is at the top of the priority list. However it was still not clear what the relative effects of gestation periods were for both predators and prey. This section describes the results of trying a number of different gestation periods to see what effect they would have on animat populations.
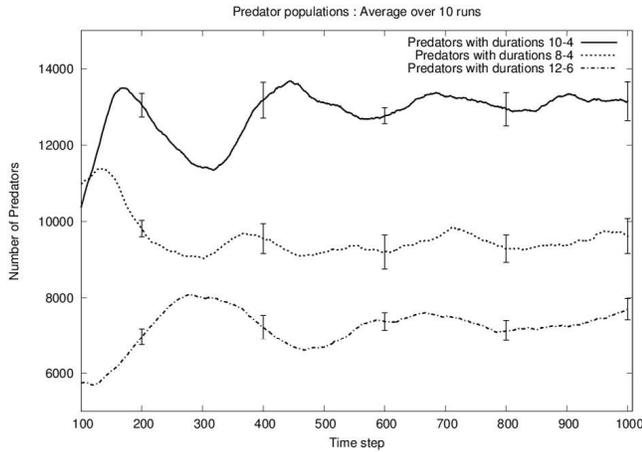

Figure 6: Plot showing the effects of duration periods on the predator population. Predators do best when their gestation period is more than double that of their prey. The plot shows the averages over ten runs with different random number seeds.

The resulting populations are shown in Figure 5 (prey) and Figure 6 (predators). It is clear that prey are most numerous when the predator gestation period is 10 (time steps) and the prey gestation period is 4, i.e. the prey gestation period is less than half that of the predators. It is interesting to note that predators are also most numerous with the same set of gestation periods, confirming that long-term predator success is based on prey numbers.

Other results were less sustainable – the populations for predator = 8 and prey = 4 gestation periods as well as predator = 12 and prey = 6 gestation periods are also shown. A number of other combinations were tried, many of which led to an extinction of one or both species of animat. This of course indicates that the system is unable to sustain animat populations of these parameter values – although it is possible that larger systems might allow spatial pockets of animats with those parameters to survive long enough to establish and maintain themselves.

The system as a whole benefits from a balance between plentiful prey and successful predators. Although predators do benefit from an increased prey population, this deepens the
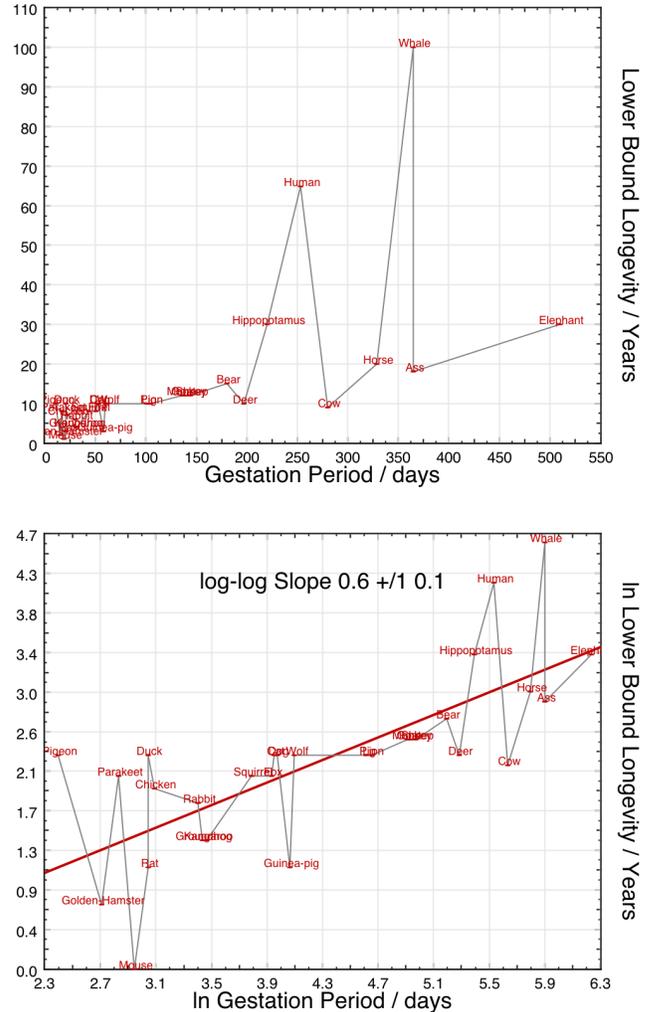

Figure 7: Plot of Longevity (lower bounds used) vs gestation period of a range of real mammals, using data from [26].

amplitude of the boom-bust cycles and can lead to a species dying out which causes the system to crash. This confirms the existence of a sustainable population level that is large enough to support fluctuations up to a certain size without system crashes occurring.

6 Discussion

We have seen that introducing and altering gestation period does not affect the fundamental boom-bust cyclic behaviour that arises from the coupled populations of prey and predators. However the gestation period does affect the stable mean population values that the environment can sustain. This suggests that gestation period might well usefully adapt over generations in response to a changing environment - richer grass, climate change and so forth.
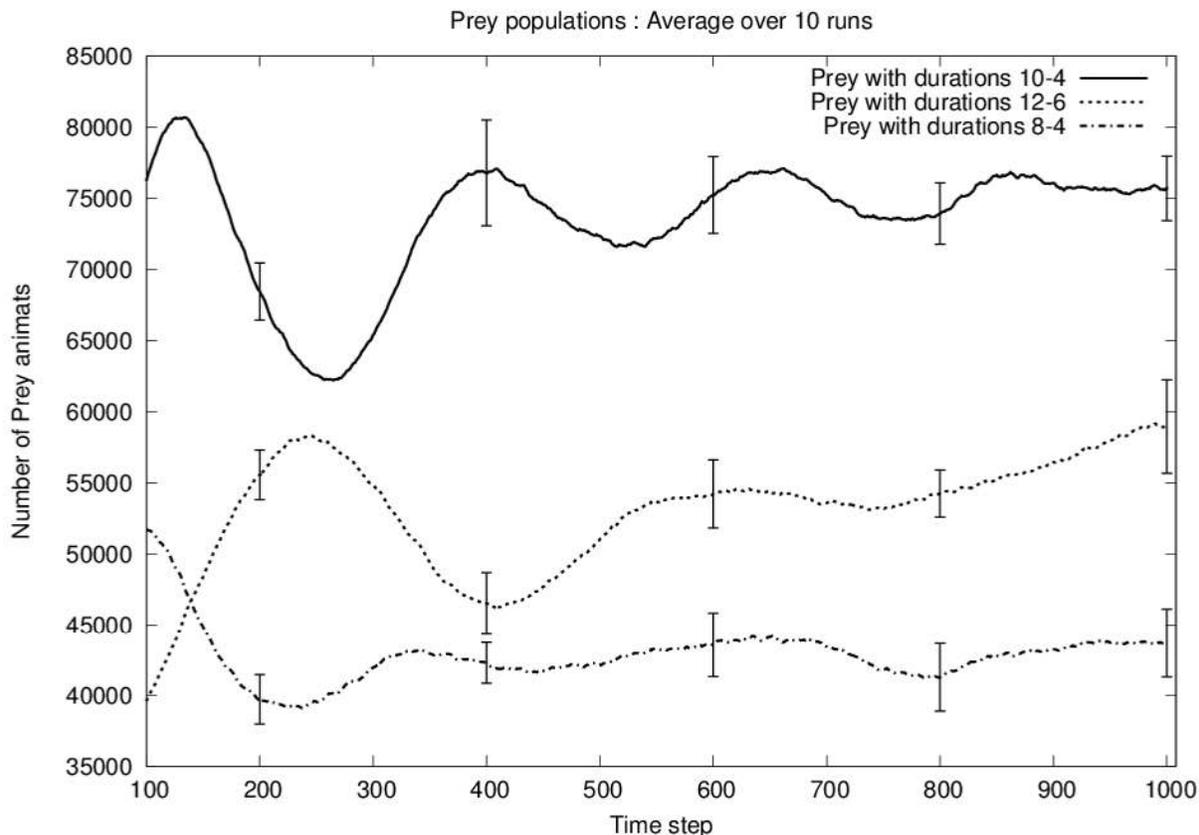
Figure 5: Plot showing the effects of duration periods on the prey population. Prey do best when their gestation period is less than half that of the predators. The plot shows the averages over ten runs with different random number seeds.

The simulations indicate that the individual prey have an even greater species advantage in fleeing predators since there is a multiplier effect of both the pregnant animat and its offspring both dying when eaten. This has a more dramatic effect on the prey population size which in turn has a more marked effect on the predator population in the usual cyclic manner.

Gao et. al. note that gestation period is likely coupled to changes in external environment [27] and we also observe that the gestation times of real animals has a marked correlation with the longevity or typical lifespan of individual species. A simple plot of the data from [26] is shown in Figure 7. Interestingly, there appears to be a systemic relationship between gestation period and longevity in the form of an approximate power law. The two obvious outliers are humans and whales - both known to have significant higher order intelligence than the other species plotted.

Gestation period therefore gives a mechanism for incorporating delayed benefit or effect on the population that is thus separated out from the direct effect on an individual animal or animat. It would seem therefore a good candidate mechanism to explore further as a means of testing effects on the species or population as a whole, as against instant gratification effects on individuals.

One must be careful not to over interpret bio-inspired algorithms or metaphors in other systems [28] but the gestation period does appear to be an interesting bio-mechanism that can be usefully incorporated into an artificial life model. The gestation period does seem to be closely linked to the time-scale over which individual animats operate. It thus provides a means of exploring the temporal fitness as well as the normal species trait landscape.

An interesting open question is to what extent the animat collectives must cooperate to make the gestation investment work well for the species. If animats interact in a way to protect or at least not immediately sacrifice pregnant animats of their same species, then the gestation time period of investment pays off.

7   Conclusion

We have introduced a time-delayed gestation period into a spatial animat model with predator-prey selection and adaptation mechanisms. We find the temporal behaviour of individual animats is affected by the gestation period parameter and hence that the macroscopic behaviours of the species is

also affected.

We have shown that animat behaviour cannot be analysed out of context. Animat behaviour is governed by the priority order of the rules within the rule set and one particular rule may be extremely useful in one context but useless in another. The "flee" rule for prey was found to be useless (evolved to the lowest priority) in the context where new animats were created instantaneously.

This was because the prey population could thrive even if parent animats were consumed by predators immediately after breeding. However, these experiments have demonstrated that the introduction of a gestation period changes the "flee" rule to a high-priority rule because it is now important for prey animats to avoid being consumed during the gestation period.

At a time when societal concerns are growing that political and managerial decision making is often geared to short term and often near-instant gratification criteria this is an interesting area of collective emergence to study further.

There is scope for further in-depth studies on a wider range of gestation periods used here. Larger systems and systems with other encoded behaviours such as sentinel or protection-of-pregnant animats are likely to couple to the gestation period property and are therefore worth investigating together.

There is an interesting relationship between gestation and longevity for real animats. We also believe that the trade-off space of shorter gestation duration time resulting in helpless offspring that require nurturing longer as born animats is also worth exploring and would likely relate further to actual bio-animal data.

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