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Resource Scarcity Effects on Spatial Species Distribution in Animat Agent Models

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Modelling multiple species spatial distribution patterns and the consequent effects on land resources is a complex problem. We have developed an animat model based on spatial agents that predate on one another and which interact with spatially distributed resources such as vegetation. We show how a model based on relatively simple microscopic interactions can be used to analyse spatial species distribution effects and explore some implications of this class of resource consumption model. We find that animats will exhibit migratory herding behaviour when resources are scarce.

Keywords: species distribution; land use; animat agents; ecosystem

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Technical Report CSTN-059

Resource Scarcity Effects on Spatial Species Distribution in Animat Agent Models

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Abstract

Modelling multiple species spatial distribution patterns and the consequent effects on land resources is a complex problem. We have developed an animat model based on spatial agents that predate on one another and which interact with spatially distributed resources such as vegetation. We show how a model based on relatively simple microscopic interactions can be used to analyse spatial species distribution effects and explore some implications of this class of resource consumption model. We find that animats will exhibit migratory herding behaviour when resources are scarce.

Keywords: species distribution; land use; animat agents; ecosystem.

1 Introduction

Modelling resource utilisation and its effect on the distribution of species is an important problem for ecology and environmental conservation. Constructing accurate applicable models is non-trivial when a number of different species are involved in a food chain/predation hierarchy. Some ecological modelling problems such as the famous Canadian Lynx/Arctic Hare system [1] are amenable to classical predator prey models such as partial differential equations based on the Lotka-Volterra equations [2, 3]. However when spatial species variations are incorporated into Lotka-Volterra systems, the problem becomes significantly more complex [4]. It is however notoriously difficult to incorporate spatial effects directly into the equations in a practical way.

An alternative approach is to work at the level of microscopic constituent agents or spatial animats, and conduct numerical experiments to investigate emergent macroscopic behaviours. Our particular approach is based on a simulated spatial environment (in 2-dimensions) with around $10^5 - 10^6$ individual microscopic animats representing predators and prey. This "artificial life" approach has been successfully employed for studying a number of emergent species behaviours.

Many such models [5–7] concentrate predominantly on the study of emergent macro behaviours and are not particularly concerned with the details of microscopic "animat" [8] existence. One interesting exception is [9] where a hierarchy of animats is established in which beetles need to eat worms and worms need to eat grass, although this model focuses on energy conservation and transfer rather than on macroscopic emergent behaviour.

Our predator prey model [10, 11] has been been developed over the past four years and we have concentrated on making small, well-defined changes to the microscopic details of the animats and then analysing new emergent behaviours. This is contrast to other models described in the literature whereby a evolutionary approach is employed. We have documented the unexpected emergence of spatial clusters such as the defensive spirals and other features discussed in [12]. Figure 1 shows some common emergent formations from our model.

In earlier versions of our model, predators were required to eat prey to survive but prey did not have to eat. This initially led to situations in which the prey population exploded in areas of the model where predators were not present. We were able to control the prey population by the introduction of a "crowding factor" which limits the number of immediate neighbours that any animat can have before it becomes "overcrowded" which in turn reduces the chances of the animat to breed and survive. Overcrowded prey animats will tend to move apart [13], to relieve the overcrowding, thus spreading over a greater area and providing isolated communities of predators with improved chances of survival.

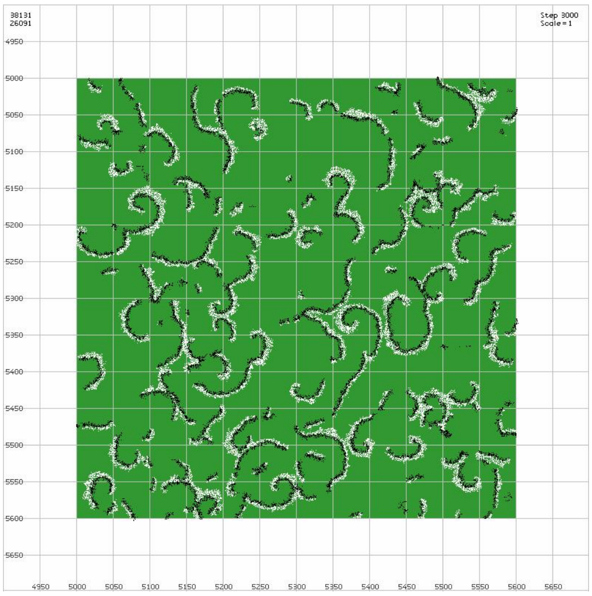

Figure 1: Animats on a square grassed area with a grass value of 35. This is a lower value than Usual and animats are therefore more diffuse. Predators are black and prey are white. Various macro-clusters have emerged. Note how the animats stay almost exclusively on the grassed area.

In the latest version of our model we have followed the lead established in [9] and introduced "grass" which prey animats must eat to survive. Predators remain unchanged and continue to require a steady supply of prey to survive. We then varied the pattern and type of grass to see what effect this had on emergent macro behaviours.

A brief overview of the model is provided in section 2. We present: some species-distribution and spatial "herding" results in section 3; some ideas and possible explanations for the behaviours in section 4; and offer a summary and some conclusions in section 5

2 The Animat Model

Our model is comprised of two species of "animat" – the predators and the prey. Each animat has its own set of rules and at every time-step it executes **one** of these rules. A rule typically has conditions that must be satisfied before the rule can be executed. Some examples of rules are: *Move away IF a predator is adjacent. (Prey rule)*; *Eat prey IF a prey animat is adjacent AND current health is below a certain value. (Predator rule.)*

The rules are consulted in an order of priority. The animat always executes the first rule in its list for which the conditions are satisfied. The "Breed Rule" regulates the production of new animats and when an animat is "born" it inherits the rules of its parents. This inheritance could include mutation operators to produce genetic effects. However, in keeping with our philosophy of making very small changes to the model in order to be able to measure the effects, such mutations have not yet been studied. We have experimented with changing the order of priority of the rules and thus produced different sub-groups of animats where each sub-group has the same set of rules but with a different priority order. This work was first published in [10] and different aspects are still under investigation. The model has evolved over the last two years with rules being edited, inserted or deleted in order to achieve maximum localisation.

The interaction of the animats as they follow their rules has produced interesting emergent features in the form of macro-clusters often containing many hundreds of animats. We have analysed and documented these emergent clusters in [12]. The most fascinating cluster that consistently appears is a spiral and several spirals are visible in the various figures in this article.

Predators need to eat prey to survive. In early versions of the model, prey animats did not need to eat. We have now introduced a "Graze Rule" for prey animats that means that prey also need to eat to survive. Initially we assumed that adequate "grass" was available at all points in the model. At this stage, the Graze Rule was implemented as follows: *IF the animat is overcrowded THEN grazing is not successful.*

At this stage we did not explicitly include "grass" in the model. It was simply assumed that grass was always available but that an animat was not able to graze if it was overcrowded. An animat became overcrowded if the number of adjacent neighbours was greater than some predetermined value (usually 10). Thus if an animat had too many neighbours, "grazing" would fail and the animat would soon starve. We then decided to introduce a map into the model and locate "grass" in specific areas on the map and the Graze Rule has now been modified to: *IF the animat is located at a point on the map containing grass THEN grazing is successful.*

In this paper we have experimented with various spatial grass patterns, which are set once at the beginning of a model run. We generally study the average behaviour over 10 or 100 separate runs. Animats are initialised randomly but in the same grass environment and we run the model to see what collective animat behaviour arises. We typically find remarkable stability of the model and that despite having very different microscopic starting configurations of animats, statistically similar patterns invariably emerge and a characteristic macroscopic behaviour can be identified.

3 Some Experiments

We have formulated a number of special environmental for the spatial distribution of resources (grass) which lead to some definite animat collective behaviours. The model in its most general form can be started from almost any random mix of predators and prey which over a few generations will organise themselves spontaneously into spatial clusters with a sustainable average animat density. There must be enough resource to sustain prey and consequently enough prey to support predators up the food chain. Figure 1 shows a typical emergent mix after the model has been initialised randomly. A confrontational wave like structure often emerges as interacting groups of predators and prey animats interact. Although these clumps or clusters vary rapidly in detail, the statistical distribution of such patterns becomes very stable. The mean density of animats will typically converge to a mean value dependent upon the overall resource availability - the amount of "grass" available, but with a slowly varying boom-bust behaviour superposed on the stable envelope function. The boom-bust behaviour with a phase delay between booms in numbers of prey and numbers of predators is a well known consequence of the Lotka-Volterra equations. It is of course interesting and important that this mean behaviour persists despite spatial fluctuations.

In contrast to the open model of Figure 1, we have devised various spatial resource patterns to encourage the animats in particular directions. In the discussion below we refer to normalised values for the grass - essentially in terms of percentages. These govern the relative value of grass to a typical prey animat.

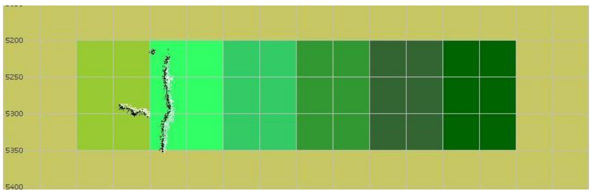

Figure 2: Animats on a strip of grass with varying nutritional values that increase from 25 on the left to 80 on the right. Predators are black and prey are white. This is the situation at time step 200.

In the first experiment animats were placed at the left hand side of a broad horizontal strip of grass. The strip consisted of grass with varying nutritional values from 25 on the left to 80 on the right. As time progressed the animats spread across the available area. Figures 2 and 3 show animat progression over time. It is clear from the figures that there are more animats on the areas with high nutritional value. However typical formations, including spirals, continue to form across almost all areas. Also a trail of communities or "herds" is left behind the travelling wave-front of animats that explore the grassed corridor. We have measured the animat density as it varies along the grass gradient and this is discussed in section 4.

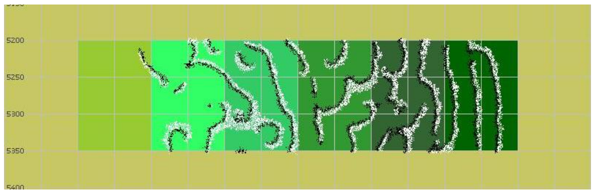

Figure 3: Animats on a strip of grass with varying nutritional values that increase from 25 on the left to 80 on the right. Predators are black and prey are white. The usual formations, including spirals, continue to emerge. This is the situation at time step 2600.

A second set of experiments concerned animat behaviour along the "corridor" when grass is eaten up and not replenished. In these experiments the nutritional value of the grass was set to an initial uniform value of 80. However, when grass was consumed it was not replenished. Thus as animats progressed, the area behind them became devoid of grass.

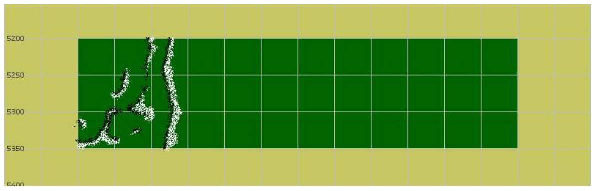

Figure 4: Animats on a strip of grass with a uniform nutritional value of 80. Predators are black and prey are white. This is the situation at time step 200.

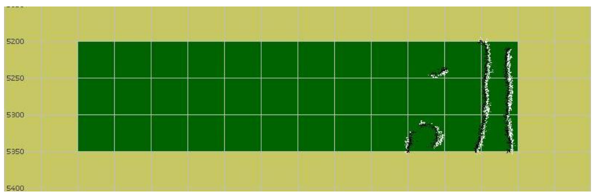

Figure 5: Animats on a strip of grass with a uniform nutritional value of 80. Predators are black and prey are white. Grass is being consumed and not replenished and animats can therefore not exist on areas where the grass has previously been consumed. This is the situation at time step 2600.

Figures 4 and 5 show the animat progression over time. In these cases the travelling wave of animats still progresses down the corridor at the same average speed as before, but leaves a wake of devastated grass behind it that can no longer support any animat population.

Inspired by the effects of these experiments we contrived a way for the animat herd to permanently migrate. One approach would be to incorporate seasonal variations into the grass abundance. Another is to set up a slow time envelope of grass renewal around a loop shape as shown in the figures 6 and 7.

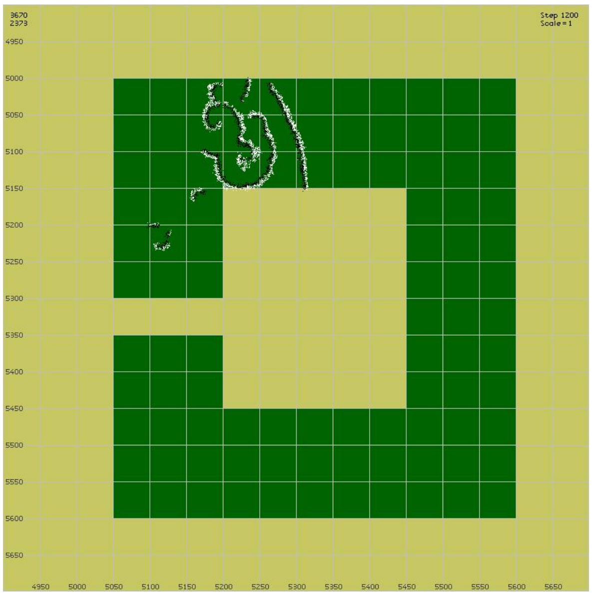

Figure 6: Animats on a loop of grass with a uniform nutritional value of 80. Predators are black and prey are white. Grass is consumed forcing animats to move clockwise around the loop. Small populations sometimes lag behind and are able to exist on patches of grass that were not consumed by the main body. This is the situation at time step 1200.

The grass is still set at a uniform initial value of 80 but is now arranged in a loop. Animats start on the upper left-hand-side and are forced into a clockwise direction of movement by a narrow strip of “desert” across the grass. Grass is still being consumed but is also “growing” again (albeit very slowly). Since the animats move in formations, there are small areas of unconsumed grass sufficient to sustain small populations that lag behind the main movement. This is shown in Figure 6.

Sometimes the small populations survive long enough to be able to be sustained by the grass that is “growing” all around them. Figure 7 shows a population of only prey animats that has survived and is now increasing in numbers as it moves in the reverse direction to take full advantage of newly grown grass in areas that were previously denuded.

There some notable effects that result from the model geometry. These are important artifacts, but they can be compensated for by more elaborate choices of geometry. For example an anti-aliased rounded corners corridor can be constructed to alleviate this effect.

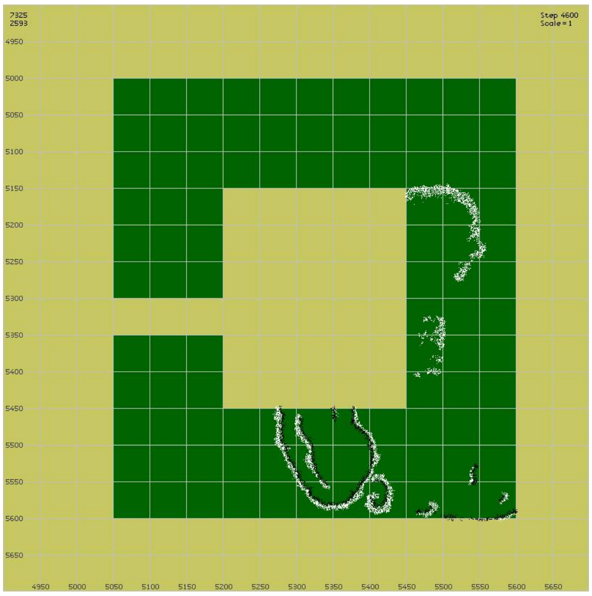

Figure 7: Animats on a loop of grass with a uniform nutritional value of 80. Predators are black and prey are white. Grass is consumed forcing animats to move clockwise around the loop. A group of prey animats has survived behind the main formations and is increasing and moving in the reverse direction as grass is replenished around them. This is the situation at time step 4600.

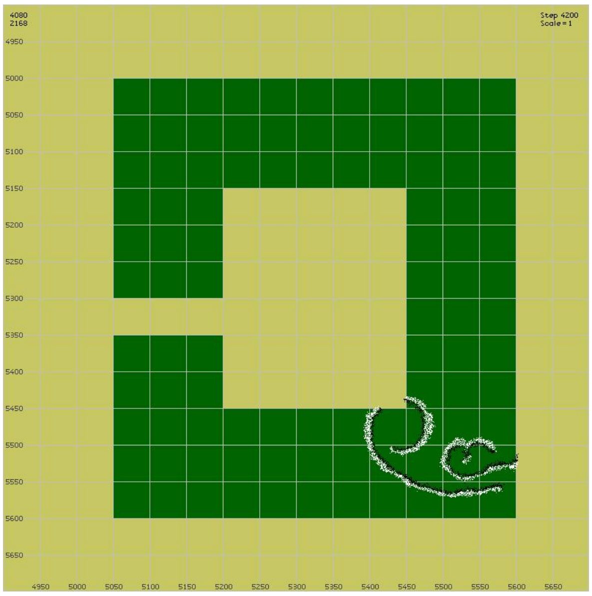

Figure 8: Animats on a loop of grass with a uniform nutritional value of 80. Predators are black and prey are white. A spiral formation has emerged in the bottom right-hand-corner and then spiraled outward. When the spiral meets the non-grassed area a slice is taken out of it.

Figure 8 shows that as a spiral forms and moves it encounters the "sharp corner" of the non-grassed area. Animats that are forced onto the desert area rapidly starve and disappear. However, because all activity is highly local, animats in the parts of the spiral still within the grassed area continue as before, resulting in a perfect spiral with a slice taken out of it.

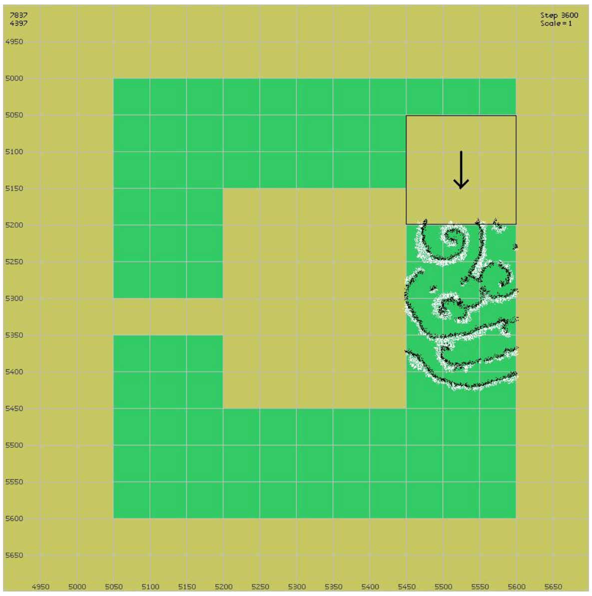

Figure 9: Animats on a loop of grass with a uniform nutritional value of 45. Predators are black and prey are white. Grass is neither consumed nor replenished. A "travelling desert" moves around behind the animats forcing them to move onwards. This is the situation at time step 3600.

A final experiment we set up was to contrive some deliberate obstacle to the animat herds. A slow moving region of famine could be emulated. Replenishing the loop of grass led to problems of small groups of animats becoming separated and moving in the reverse direction (discussed above). In order to avoid this problem, the loop was constructed with a uniform grass value with neither consumption nor re-growth of grass. However, a block of "desert" (grass value of zero) travelled around just behind the animats forcing them to move continually onwards. Figure 9 shows the situation at step 3600 for a lower uniform grass value of 45.

4 Directed Diffusion and Animat Flux

There are a number of approaches to analysing these collective behaviours. One of particular interest is to relate the macroscopic movements of animat wavefronts to a predictive equation.

Fick's first law of diffusion states that for a steady state situation:

$$J = -D\frac{\partial \rho}{\partial x} \quad (1)$$

where J is animat flux in terms of animats per unit length, per unit time, D is the diffusion coefficient in units of length per unit time for our 2-dimensional model, and ρ is the animat density function as it varies spatially along the horizontal axis as indicated in figure 10. This is one useful predictive approach. The diffusion coefficient can be related to the various microscopic properties of the animat model [14], but what is most interesting is that a stable statistical average behaviour of the animats emerges consistently, regardless of microscopic noise and details.

As reported in [14] we have established that a typical animat density profile across a grass/no-grass edge can be modelled by:

$$\rho(x) = \rho_0 \operatorname{erfc}(\frac{x}{\sqrt{4Dt}}) \quad (2)$$

where the length $\sqrt(4Dt)$ is the diffusion length and can be fitted experimentally.

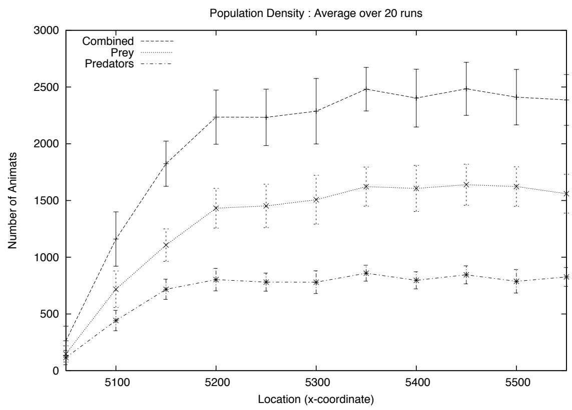

Figure 10: Mean Animat density as a function of spatial distance x, "along the corridor"

Figure 10 shows how the (total and individual species) animat density varies spatially along the herding corridor. As shown, the animat density profile builds up slowly and reaches a flat value consistent with the supporting capacity of the land resources - ie the grass value chosen. There are of course periodic boom-bust cycles due to the predator-prey effects but these are typically washed out over many runs and we see the stable envelope value.

5 Summary and Conclusions

In the experiments reported in this paper, we have introduced a resource gradient so that the "grass density" varies linearly. As we might hope, we therefore obtain a general flow of animats up the resource density gradient and we have recovered a sensible macroscopic behaviour from our microscopic constituent animats.

We have shown that an animat model such as ours displays highly localised behaviours that persist even in the presence of slowly changing global resources. In a sense, the spatially localised population of animats acts as an an emergent collective (herd) and moves on and adapts its behaviour to changed circumstances.

Drastic changes to the available resources, such as encountering a desert devoid of vegetation, do cause the food chain of animats to collapse, but this effect can be used to steer the herd spatially along a corridor of resources.

We have shown how the herd of prey animats along with their accompanying predators will migrate along a preferred route of abundant vegetation. This has been accomplished with only very minimal prescribed microscopic behaviours. The herding and migration are effectively emergent responses to changing environmental circumstances.

What appears important in models like this, is that there is time for the collective herd to respond. Although individual animats are unaware of the macroscopic effects and do not change their local rules, the herd itself reorganises its spatial density and directions of preferential growth. Individual animats die off, but new animats take over and the emergent collective diffuses preferentially along the resource abundance gradient.

We believe this general sort of microscopic animat approach may be useful in exploring realistic and specific application-oriented problems in ecology and species distribution and migration. The animat approach allows investigation of specific scenarios when a more mathematical approach based on sets of partial differential equations might be impractical.

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