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Aphid Population Dynamics in Agricultural Landscapes: An Agent-based Simulation Model

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Abstract: Presently, there are many population models in existence, but these are often case specific, function at a single spatial scale and fail to tackle the complexity arising from individual actions and interactions that exist in the real-world. A spatially explicit agent-based simulation model has been developed to represent aphid population dynamics in agricultural landscapes. Over time, the aphid agents interact with the landscape and with one another. The construction of the model is detailed, including parameterisation and coupling to a geographical information system (GIS). The results show that a spatial modelling approach that considers both landscape properties and factors such as wind speed and direction provides greater insight into aphid population dynamics both spatially and temporally. This forms the basis for the development of further simulation models that can be used to analyse how changes in landscape structure impact upon important species distributions and population dynamics.

Keywords: Aphids; Agriculture; Agent-based Modelling; Landscape Ecology.

1. INTRODUCTION

Sixty percent of the British landscape is farmland. Most of this has been intensively farmed, which has resulted in wildlife populations being highly fragmented and pest species controlled primarily by pesticides. However, it is quite possible to transform the landscape so that it would be more beneficial to wildlife, and to find alternatives to high levels of chemical usage. The difficulty is to determine what would be the optimal way that would maximize desirable populations but minimize disruption to existing land management practices.

The creation of a generic agent-based insect simulation model for agricultural landscapes will facilitate concurrent examination of the potential impacts of landscape change upon populations of species of both agricultural and ecological interest. In this way more sensitive landscape management can be achieved, through an understanding of the differing implications for a wide range of species of the introduction or removal of landscape features or management regimes [Hunter, 2002].

The final model is still in the development stage, but a single species simulation will be presented that illustrates the usage of the model to study the population dynamics of the bird cherry-oat aphid, *Rhopalosiphum padi* (L.), in a 5 × 5 km region of North Yorkshire. The model is termed ‘agent-based’, as the extent to which the individuals in the model react to their environment and ‘remember’ (physiologically) past events defines them as ‘agents’ [Topping et al., 2003].

2. SIMULATION MODELLING OF SPECIES POPULATION DYNAMICS

2.1 Introduction

There is a tradition in ecology for models that are based upon mathematical ‘top-down’ relationships between variables [Parrott et al., 2001]. This has meant many models prior to the 1990s have focused on populations or species groups, rather than individual animals. However, such models do not take into account the complexity of the multiple concurrent interactions in ecosystems [Laval, 1996]. By ignoring individual behaviour, important factors are not

taken into account, including reproduction and competition between individuals, which may greatly influence general population trends.

A significant need exists for ecological models to address real-world management problems, but the lack of transferability, scalability, complexity and realism in traditional models and their uncertainty is a key issue [Conroy et al., 1995]. In order to produce models that are capable of furthering understanding of the processes that influence population dynamics spatially and temporally, as well as forecasting the effects of management or other human activity on population distributions, it has been necessary to change the way ecological systems are modelled over the last decade or so. Models have become more spatially explicit and attempts have been made to link these to real landscapes via geographical information systems [DeAngelis et al., 1998].

2.2 Agent-based Modelling in Landscape Ecology

In agent-based models, individual insects are modelled as individuals (agents), with a unique history and the ability to interact both with the environment and with other agents. The inherent flexibility of an agent-based, object-oriented approach enables modellers to attempt to create more generic models [Ziv, 1998]. Multi-agent simulation also provides a framework that allows for interactions at different scales and the simulation of emergent ecosystem properties [Ferber, 1999]. The agents, their behaviour and interactions, allow for realistic representation of a phenomenon as the result of the interactions of a group of autonomous agents. Multi-agent systems are also able to consider both quantitative and qualitative parameters, and have the capacity to integrate quantitative variables, differential equations and rule based behaviour into the same model. Modifications to the model are also quite straightforward (such as adding another species). The approach therefore helps in the search for a model, rather than simply model implementation and response analysis.

However, despite the advantages, the use of agent-based modelling techniques in landscape ecology is still a growing trend, with few examples of existing models to date [Mathevet et al., 2003; Parrott et al., 2001; Topping et al., 2003].

3. AGENT-BASED SIMULATION OF BIRD-CHERRY OAT APHID (*Rhopalosiphum padi* (L.))

POPULATION DYNAMICS IN AN AGRICULTURAL LANDSCAPE

3.1 Model Description

The model is written using the object-oriented programming language Java (<http://java.sun.com>) and the Repast agent-based modelling toolkit (<http://repast.sourceforge.net>). It is run in daily time steps. The key inputs are habitat data (derived from raster data of a chosen region, where size and extent are defined by the user), daily minimum, maximum and mean temperature, wind speed and wind direction (the latter are currently single values for prevailing wind). Classes that represent different species of insect structure the model, each hierarchically derived from an 'Insect' superclass. This paper focuses on the use of the model to simulate the spatial population dynamics of the bird cherry-oat aphid (*Rhopalosiphum padi* (L.)) during the autumn and winter. Key information about any Insect agent includes a unique ID tag for the agent, the agent's 'age' (0.00-2.00, becoming adult at 1.00) and the agent's position in three-dimensional space. In addition, for Aphid agents, information on whether or not the agent has undergone migration and the agent's morphology (alate or apterous) is also important.

At each daily time step in a model run for the region the following events take place:

- Adult alate aphid agents may immigrate into the region.
- Alate aphids may move according to the wind speed, wind direction, habitat, and their development stage. This movement may be local foraging, or long distance migration.
- Aphid agents age.
- Aphid agents may die.
- Adult aphid agents may reproduce and new agents may be born.

3.2 Initial Immigration

Before the simulation is started, initial immigration is input as a number of immigrants, which are then randomly distributed across the region. For aphids, the immigrants are assumed to be reproductive alate adults, of uniform age. They are also assumed to have undergone 'migration', thus will probably not have a desire to migrate long distances again [Kennedy et al., 1963].

3.3 Reproduction

Aphid agents become reproductive once the agent achieves the appropriate age for reproduction, for alate aphids this is 0.9522, for apterous this is 0.9463. The birthrate depends on the morphology of the reproductive aphid, and the daily minimum, maximum and mean temperatures (for equations see [Morgan, 2000]).

Nymphs are then located at the same location as their parent. The stimulus to produce alates capable of dispersal is related to crowding and/or tactile responses to the nutrient quality of the host [Loxdale et al., 1999]. The aphid density per m² at the location nymphs are born therefore determines the morphology of the nymphs created (for equation see [Morgan, 2000]).

3.4 Ageing and Mortality

Aphid agents at any life-stage may die depending on a survival rate affected by the number of day-degrees below 2.8⁰C for the day. The survival rates of the aphid agents are calculated from the daily minimum, maximum and mean temperatures (for equation see [Morgan, 2000]).

Other abiotic factors such as rainfall may be relevant [Morgan, 2000] as well as the effects of predation and parasites or fungi, but these are not included in the model as yet. Mortality also occurs when the aphid agents reach maximum age 2.00 (the number of days that this will take depends again on temperatures, see below), and when they remain on unfavourable habitat for more than three days (at present the absence of research in this area makes this an estimate of the agent's ability to survive poor conditions). The age of the aphid agent increases each day, at a rate determined by the daily temperatures (see [Morgan, 2000]).

3.5 Movement

The flight of alate aphids can be separated into two phases. The first is a migratory phase followed by a foraging phase [Kennedy et al., 1963; Moericke, 1955; Ward et al., 1998].

The rules of migratory flight used in this model (Figure 1) follow four principles: firstly, alate aphids will all attempt to migrate voluntarily if wind speed is not above 8km/hr [Haine, 1955; Johnson, 1962; Kennedy et al., 1963]. Second, aphid migration will take place within a day and during daylight hours (thus a migration event will complete within a single run of the model, as this

functions on a daily basis) [Loxdale et al., 1993]. Thirdly, an individual can only migrate a distance of several kilometres once (if at all) during its lifetime [Ward et al., 1998]. Finally, migration will last for a random duration of between 2.5 and 6.5 hours [Loxdale et al., 1993] during which time the aphid will be carried by the wind a distance determined by the flight duration multiplied by the wind speed, in the direction of the wind's movement [Haine, 1955; Loxdale et al., 1993]. It is also assumed that a 'boundary layer' at a height of 1m exists, below which the aphid is unaffected by the wind and free to move at will and above which the aphid's movement is controlled by the wind [Taylor, 1974].

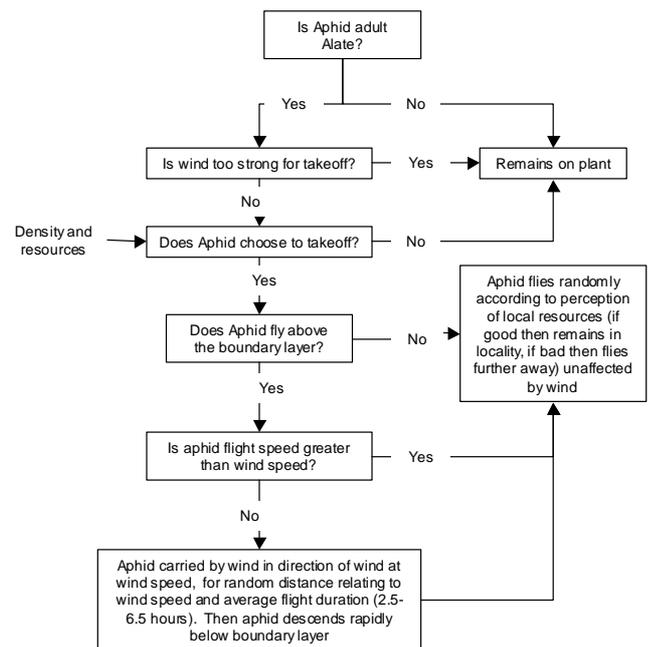


Figure 1: Flow diagram of movement rules

Aphids lose control of their flight at wind speeds of around 2km/hr [Haine, 1955; Loxdale et al., 1993]. Thus it can be inferred that foraging flight may occur at low wind speeds (2km/hr or less), taking the form of increasingly 'random movement' as wind speeds lower, and short flights tend to be concentrated around host plants [Kennedy et al., 1959]. The speed of these movements is set to be the aphid maximum flight speed of 0.9m/s (3.24km/hr) [Compton, 2002]. To obtain the distance flown this is then multiplied by the average flight time of an aphid, which is about 100-200 minutes [Lewis et al., 1965].

4. SIMULATION RESULTS

A simulation was run for the autumn and winter of 1985/86. An initial population of 10,000 alate aphids were distributed across a grid of 25m cells, in a region 5 km × 5 km. This grid was derived from an ASCII raster taken from a LCM2000 dataset of Hertfordshire, England (origin 51°51'12"N, 0°19'37"W), with data on land cover used in a GIS to identify areas of favourable and unfavourable habitat. The population levels over time for the region are shown in Figure 2, and the spatial pattern of dispersal was observed (Figure 3, and to be presented at the conference). There are two major population peaks, at day 313 and day 357. Numbers reach their peak in early autumn due to the influx of alate immigrants. The second peak is lower due to lower temperatures as well as a lack of immigrants.

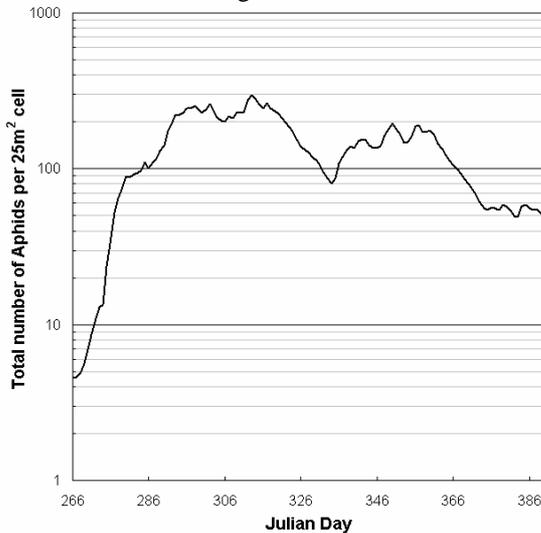
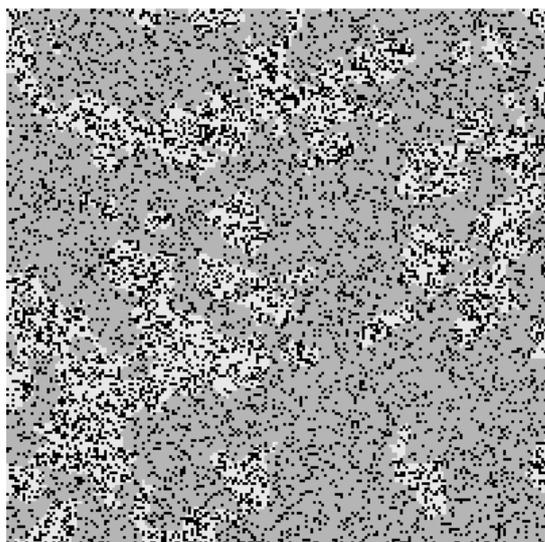
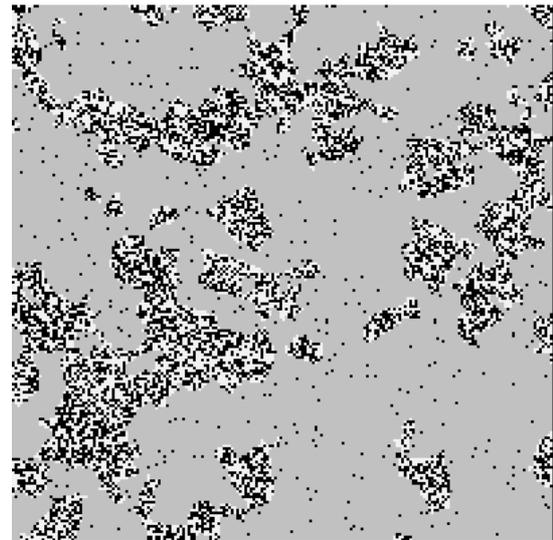


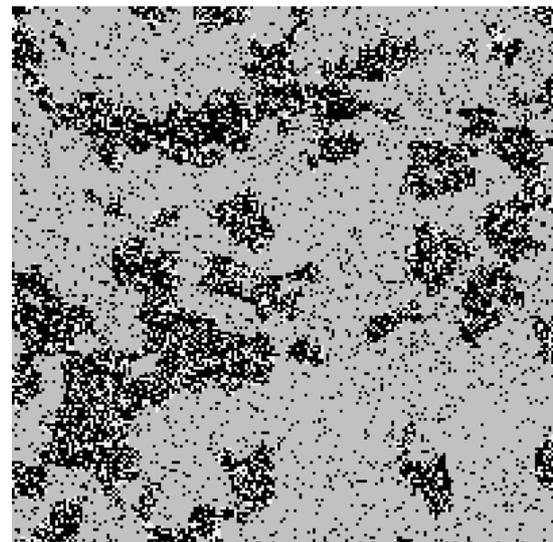
Figure 2: Mean density of aphids per occupied 25m grid cell.



a



b



c

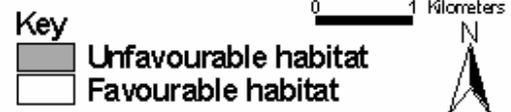


Figure 3: Spatial distribution of *R. padi* at a) Julian day 0, b) Julian day 10 and c) Julian day 50 showing the population dynamics as alates first move into favourable habitat, populations increase and then alates diffuse across the landscape.

4.1 Validation and Sensitivity Analysis

The model is validated against independent field data collected at plant scale (scaled to 1m², assuming 300 plants per m²), Figure 4. Aphid densities are slightly over-predicted by the model, but follow a very similar trend; populations increased rapidly from very low numbers and

peaked around 40 days later. Thereafter numbers declined gradually, although aphids were present throughout the winter, albeit at low density. As the model presented here is developed further, more comprehensive, landscape scale validation shall also be used.

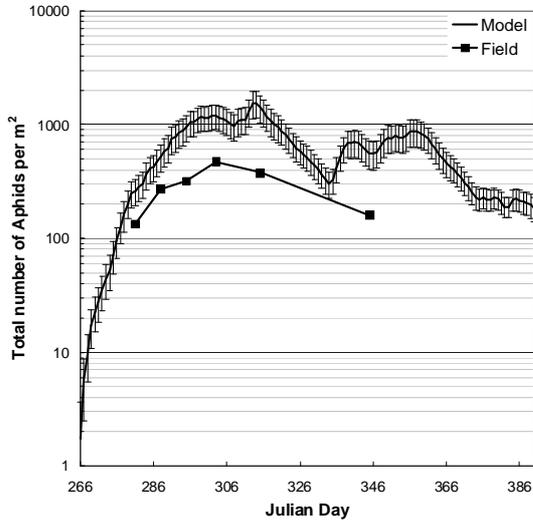


Figure 4: Simulation for single 1m² crop cell (solid line, with StDev) and observed (■) *R. padi* populations in 1985 at Rothampsted (data from Morgan, *pers. comm.*)

Simple tests of the sensitivity of the model to several population processes were carried out. These were found to be similar to the sensitivity of the model developed by Morgan [2000], where mortality rates are a key influence on the population density and structure. For example, an increase in mortality of only 5% suppresses peak densities by at least five-fold.

5. CONCLUSIONS

Three major challenges for the model now exist. The model will need to handle realistic aphid densities across larger regions, which will increase run-time and computational power required. Millions of aphids may come from heavily infested crops [Johnson, 1962]. One solution is to parallelise the model, or to implement scaling solutions such as 'super-individuals' [Scheffer et al., 1995].

The second challenge is to add more insect species. This includes the addition of predators or parasites to control aphid populations, as well as the introduction of insects of conservation value.

The third is to more tightly couple the model to the GIS in order to examine the impacts of landscape change upon the insect populations,

which could include hedgerow removal, land use change or climate change amongst others. The use of an underlying cellular automata model or Monte Carlo simulation to represent this change may be necessary to model gradual spatial changes over time.

It can be concluded from this study that significant progress has been made to establish an extendable and powerful landscape model of insect population dynamics using agent-based simulation. Much work is still required to provide a tool that examines the effects of landscape change on more than one species, but this study shows that useful insights into spatial and temporal dynamics across spatial scales can be gained by the use of this model. It may eventually be possible to adapt this flexible model to simulate broader ecosystems including, for example, mammals or birds.

6. ACKNOWLEDGEMENTS

This work is part of a PhD funded by the Central Science Laboratory. Thanks to Daniel Parry for his advice on Java programming.

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