SESSION 7A

MATHEMATICAL MODELLING: ITS ROLE IN CROP PRODUCTION

Chairman & Session Organiser: Dr Jon Knight
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Modelling agent's socio-economic and ecological environment: An agent-based approach for developing land use change scenarios

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ABSTRACT

This paper analyses the impacts of future changes in the economic and climatic environment on economically less productive, but culturally very valuable agricultural areas in Europe, in particular the Alentejo, Portugal. An Agent-based model (ABM) is used to generate future projections of land use change from 2000 to 2050. The projections are based on: a) an analysis of economic and ecological constraints to certain land uses, b) the construction of scenarios of future socio-economic and climate change at the regional scale, and c) the application of a rule-based approach to add agent behaviour and local socio-cultural attitudes and perceptions. The ABM uses GIS maps to represent the biophysical characteristics of the study area such as land use patterns, soil type, topography, aspect, road and river networks, farm boundaries and natural protected areas. Through social surveys, information affecting the decisions and actions of farmers resulting from economic opportunities and environmental risks was gathered for use in the analysis. The results of the ABM simulations demonstrate its utility in developing land use change scenarios and evaluating the impacts of policies on land use decisions. Whilst not considered in the current model, the dynamics of vegetation growth can also be captured in agent-based approaches of this form by considering each type of vegetation as an agent in the model. An ABM model that considers the dynamics of vegetation growth would be able to consider the impacts of specific farming techniques such as the application of fertilisers and irrigation.

INTRODUCTION

Rapid technological, economic and social changes have caused major land use changes in traditional landscapes of Europe's 'marginal agricultural areas', resulting in a steep decline in the total area of extensive agro-ecosystems typical of these regions. Agricultural abandonment and reduction of grazing and hay making in semi-natural pastures have transformed landscapes from diverse land use mosaics to coarse mosaics, where large abandoned areas co-exist with widespread intensive use. Remaining open habitats characteristic of traditionally managed land are potentially under further threat from continuing land use change and/or an intrinsic fragility of sparse and disconnected plant and animal populations. Hence many areas have evolved towards less ecologically and culturally valuable vegetation. However, these low intensity farming areas are highly valued within Europe for biodiversity, landscape and cultural reasons. It is thus important to analyse the impacts of future changes in the economic and climatic environment on this economically less productive but culturally very valuable agricultural land. This paper presents the results of the European Commission VISTA[1] project, which aims to assess the vulnerability of ecosystem services to land use change in less productive agricultural areas of Europe including the Alentejo, Portugal. Multiagent-based modelling is one of the tools used in the project to generate future projections of land use change from 2000 to 2050.

Multiagent systems, a concept that originated in the computer sciences (i.e. artificial intelligence research) in the 1970s, have recently gained popularity in the social sciences. Some of the recent applications of ABM include: (a) reproducing spatial and demographic features to understand the evolution of society (e.g. Gilbert and Doran 1994; Kohler and Gumerman 2000; Axtell et al. 2002); (b) evaluating economic systems when rational agents and equilibrium conditions are not limiting assumptions (e.g. Axtell 1999; Duffy 2001; Axtell 2002); (c) simulating of production decisions to assess adoption of new agricultural practices (Balmann 1997; Berger 2001; Polhill et al. 2001; Balmann et al. 2002, as cited in Parker et al. 2003); and (d) linking human and natural systems at both spatial and temporal scales to understand changes in land cover and land use changes (e.g. van der Veen and Rotmans 2001; Parker et al. 2003; Huigen 2004; Evans and Kelley 2004). The growing interest among geographers in considering human decision-making and non-rational decisions may increasingly result in a shift away from other forms of emergent system models such as cellular automata in favour of multi-agent systems (Alcamo *et al.* in press). Whilst the development of ABM is in its infancy in the social sciences, the approach offers new analytical methods for developing land use change scenarios. This is achieved by combining the intuitive appeal of verbal theories with the rigour of analytically tractable mathematical modelling to understand the social processes and dynamics of land use decisions. The novelty of ABM lies in its ability to capture the heterogeneity of agents, the dynamics of their interactions and their behaviour in response to the geography of physical space. In this paper, we link the socio-economic and biophysical environment with the influence of environmental change on land use decisions of the farmers in the village of Amendoeira in Portugal. Section 2 discusses the steps followed to apply the ABM in the development of land use change scenarios and section 3 presents the results of the ABM.

METHODS

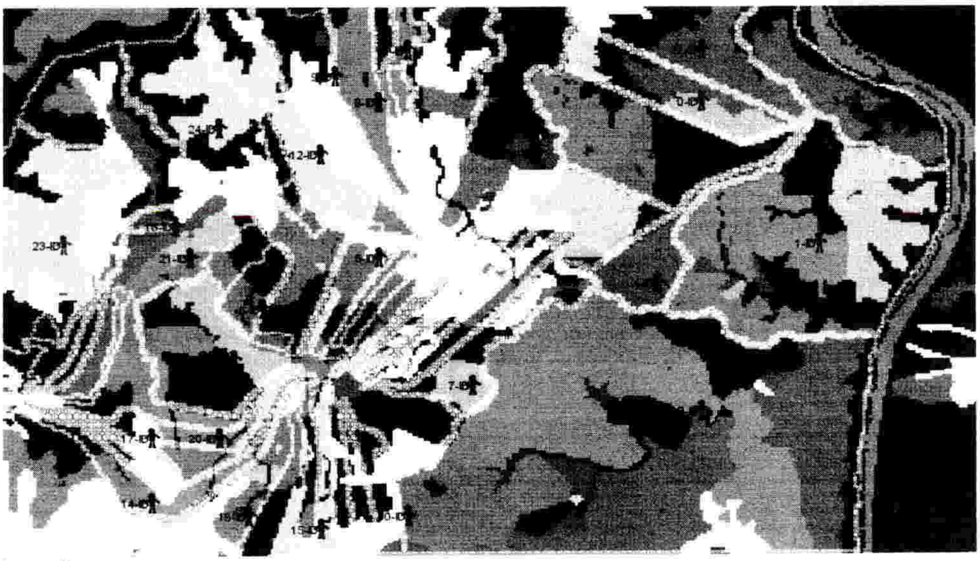
The generation of future projections of land use change from 2000 to 2050 was based on three steps: a) the analysis of economic and ecological constraints to certain land uses based on social survey and historic land use maps, b) the construction of scenarios of future socio-economic and climate change at the regional scale based on an interpretation of the storylines of the Special Report on Emission Scenarios (SRES), and c) the application of a rule-based approach to add agent behaviour and local socio-cultural attitudes and perceptions that cannot be interpreted from the historical record.

[1] Vulnerability of Ecosystem Services to Land Use Change in Traditional Agricultural Landscapes

Modelling agents and their environment

The study area covers approximately 4,400 hectares and has 28 farmers. It is marginal agricultural land, and almost all farmers receive agricultural support ranging from agricultural subsidies provided for forest plantation, cereal and meat products; financial compensation for less favoured areas (LFAs); to agro-environmental measures. For historical reasons, farmers have a very poor social network. However, dependence on agricultural support may also have partly contributed to the continued lack of community reliance. Citing McKnight (1995) and Kretzmann and McKnight (1993), Cavaye (2000) suggests that government technical and financial assistance may limit community mobilisation and social networks because they can disempower local people, create dependency, and suppress local organisation and leadership. Based on the social survey, the farmers were grouped according to particular profiles. The agents' profile included social attributes such as age, gender, education, profession, location of residence, and type of farm acquisition; and economic attributes such as level of income, size of farms, types of cultivated crops, number of workers, and presence of a successor in farming. In the Portuguese case study (Amendoeira village), the farmers were grouped into four categories according to their profiles, which were determined from a social survey: innovative, active, absentee and retiree.

Figure 1. Land use and ownership boundaries in Amendoiera village, 2000

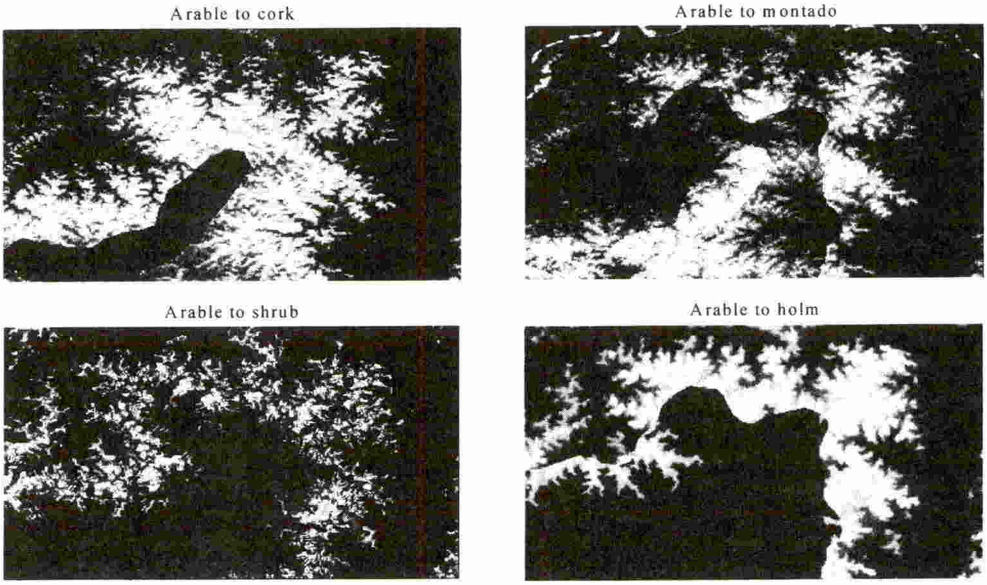


Legend:

- forest plantation such as cork oak, holm e oak, pine or eucalyptus
- arable land that is rotated between cereals and pasture
- "montado" combining trees and arable or grassland use
- dense shrub

The innovative farmers are the least in number, but own the largest properties and have the highest level of education. The activities of these farmers are highly diversified, and include amongst others livestock breeding, hunting, forestry, and nature protection. The social survey revealed that such farmers have the initiative to explore new farming techniques through personal contacts both within and outside of Portugal. However, due to the poor social network in the village, their knowledge is not transferred to other farmers and their actions influence the other farmers only indirectly. Compared to innovative farmers, active farmers are less well educated and somewhat older. Their farming activities are less diversified with livestock breeding and cereal production as the main sources of income. Many active farmers have successors. The use of sustainable farming methods depends on the availability of agricultural support and technological transfer. Unlike the innovative and active farmers, the absentee and retiree farmers are not very responsive to changes in their environment. The absentee farmers, who live far away from the village, usually have their farms managed by neighbouring farmers. Farming is not their main source of income, but they keep their farms for personal reasons (e.g. inheritance) or investment purposes. The oldest farmers with an average age of 76 fall under the category of retiree. The retiree farmers in Amendoiera have the lowest level of education. Although they live close to their properties, they no longer farm actively and, consequently, they are indifferent to the changes in their environment. Their main sources of income are forest subsidies and retirement pensions. In addition to the types of land use, Figure 1 also shows the boundaries of the land ownership of the farmers.

Figure 2. The suitability maps for different land use conversion patterns



An inventory was made of the most important land use changes that have occurred in Amendoeira village in the past. A logistic analysis was carried out to relate these land use changes to landscape attributes (Bakker et. al 2004). The collected landscape attributes are: elevation, slope, south exposition, soil depth, texture and organic carbon. The land use conversions are closely related to at least some of the landscape attributes. Identification of the influence of these attributes on land use change was based on the significance of the coefficients of the logistic regression analysis. The results of the logistic model were used to produce the probability maps of converting arable-to-shrubland, arable-to-montado, arable-to-cork and arable-to-holm. Figure 2 summarises the four most important land use conversions in the past. Areas with lighter colour have higher level of suitability in terms of land conversion, whilst those with darker colour have lower level of suitability. In the case of the arable-to-cork conversion, the most statistically significant attributes are aspect, elevation, silt percentage and clay percentage in the soil. With the exception of clay percentage, the same attributes are important in arable-to-montado conversion. In addition, soil depth is a relevant attribute for converting land use from arable to montado. Slope, elevation and soil depth are the three attributes contributing to arable-to-shrub conversion, whilst only elevation and silt percentage are important for arable-to-holm conversion. The steeper slopes, closer to the river valley have a higher probability of being converted to shrubland. It is assumed that the four land conversion patterns will apply in the future. The maps, which were produced from the logistic regression, provide an empirical basis to construct physical constraints to land use decisions. This implies that although a particular land use conversion can be economically profitable, the farmers' decision to convert is restricted by the suitability of his land.

Developing scenarios

The development of the socio-economic scenarios used in this paper was undertaken within the European Commission funded ACCELERATES[2] project. The scenario construction methodology is described in detail elsewhere (Abildtrup *et al*., in review), but a brief summary follows. The scenarios represent future, plausible changes in a range of socio-economic parameters that are important for the agricultural sector. These parameters include commodity prices and production costs, subsidy levels, quotas and productivity changes due to technological development. Construction of the scenarios was based on an integrated approach that ensured internal consistency between the co-evolution of socio-economics and climate change based on an interpretation of the storylines described in the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emission Scenarios (SRES) (Nakićenović *et al*., 2000).

A stepwise downscaling procedure based on expert-judgement and pair wise comparison was used to obtain quantitative estimates of the socio-economic parameters. First, the global driving forces were identified and quantified for each of the four SRES scenario families (A1, A2, B1 and B2)[3]. Secondly, European agricultural driving forces were derived for each scenario from the global driving forces. Finally, quantitative values of the socio-economic parameters were estimated for the European driving forces. The approach was based on narratives that describe the thinking and interrelationships within each scenario, but also a pair wise comparison approach (Saaty, 1980) that provided a means of converting the qualitative judgements of experts into quantitative parameters in an internally consistent way. The resulting scenarios provide quantitative estimates of divergent futures in the European agricultural sector. These are caricatures of reality, but provide a means of testing the consequences of alternative socio-economic development pathways. For illustration, the pathways for the A1 scenario, which is characterised as a global market scenario, are presented in Figure 3.

Based on the storylines of technology transfer, agriculture, government and non-agricultural livelihoods, a social network scenario was developed for the village of Amendoiera. For the A1 scenario, it was assumed that farmers in highly globalised economies are independent and individualistic, thus the village will continue to be marked by a poor social network in the future. Only large and educated farmers were assumed to have immediate access to new

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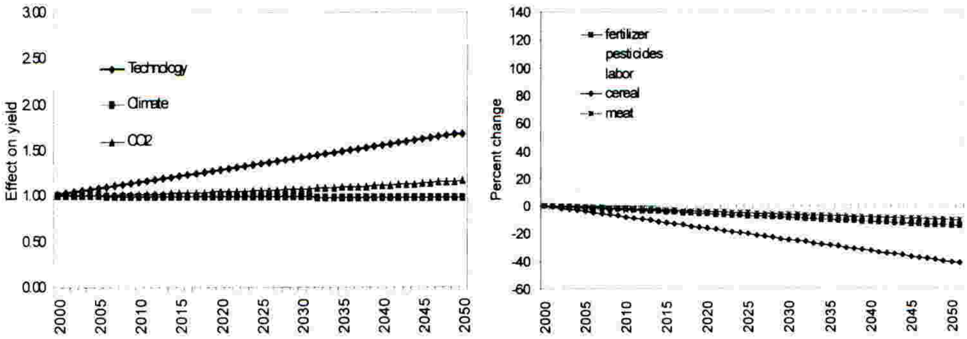
[2] Assessing Climate Change Effects on Land use and Ecosystems: from Regional Analysis to the European Scale (European Commission Framework 5 Programme; contract no. EVK2-CT2000-00061)

[3] The SRES scenarios were based on storylines, which are short narratives of possible future developments during the 21st century including demographic, social, economic, technological and environmental. A1 is a global economic scenario and A2 regional economic scenario. B1 is also global but more environmentally and equity orientated futures, and B2 is regional environmental scenario.

technologies because of their interest and ability to innovate. High investments on technology and high rates of innovation are concentrated on such type of farmers. Their knowledge about technologies is not transferred to other farmers due to a lack of communication in the village. Others access this information through other means (e.g. media), but the application of the technology is based on hierarchal pattern (e.g. size of farms and level of education).

Figure 3. Trends in socio-economic and climate-related variables in the A1 scenario, 2000-2050 (after Ewert et al 2005, Rounsevell *et al.* 2005)

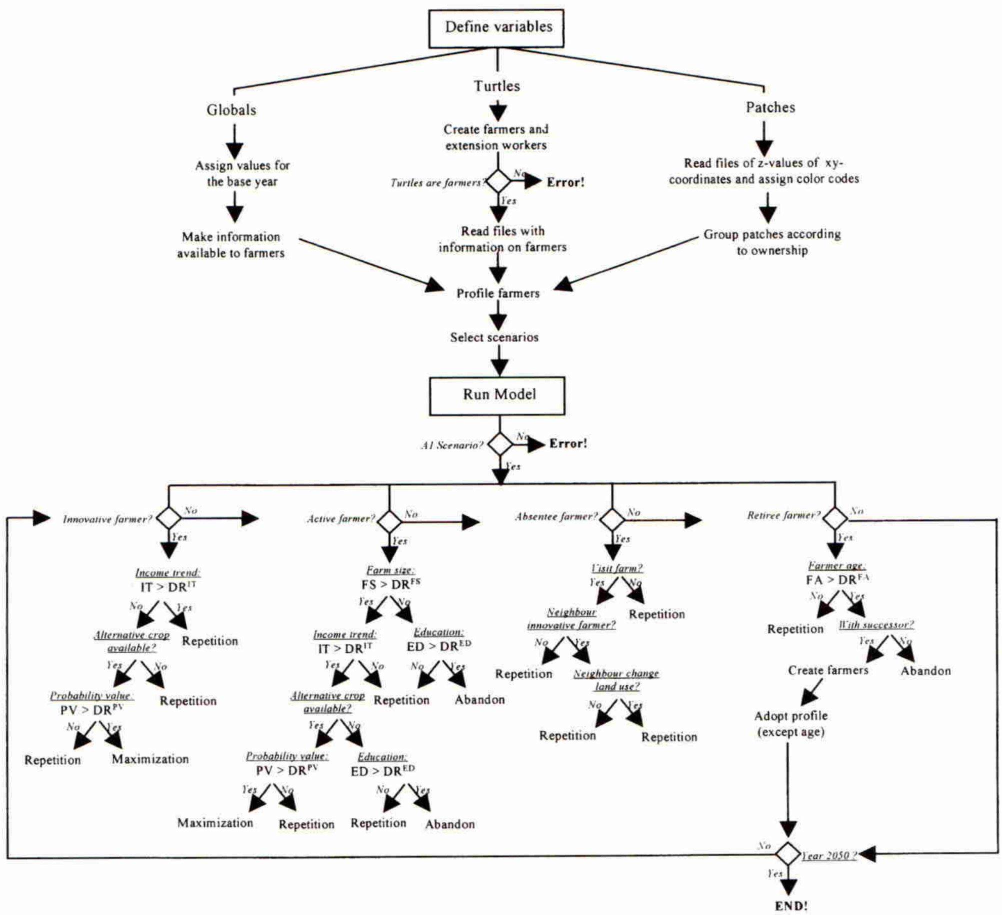


ABM rule-based approach

Each of these farmers has cognitive abilities, which enable the processing of information and which are influenced by the agent's profile. Four spatial allocation rules relevant to adaptive land use decisions of the farmers were included in the model: (1) maximization, (2) repetition, (3) comparison, and (4) imitation. These strategies are based on various economic, social and behavioural theories (Jager *et al.* 2000). Whilst maximization strategy is guided by economic decisions, comparison and imitation strategies are influenced by the social relationship of the farmers. Farmer adaptive behaviour to the changes in the environment, specifically with respect to the A1 global market scenario, is summarized using decision trees (Figure 4), which serve as schematic flows when running the ABM using the NetLogo software (Wilensky 1999). The model consists of three groups of variables – "globals", "patches" and "turtles". In the model, farmers are the turtles, the biophysical characteristics of their farms are the patches, and the changing circumstances in their climatic and economic environment are the globals. In technical terms, the globals define the information that is accessible to both patches and turtles, which analytically means defining the current and future economic and climatic environments of both patches and turtles. Values are assigned to global variables such as prices, subsidies and yield for the base year 2000, and are changed over time using different downscaled economic and climatic scenarios. The globals are thus responsible for the temporal dynamics in the model. The patches create the spatial character of the model. These are represented by the GIS maps that contain the biophysical properties of the region. Whilst globals are dynamic in time and patches in space, turtles are adaptive to these changes over time and across space. Their adaptive decisions depend on certain rules derived from the social survey, for example: (1) farmers remember their past income and change crop if their income drops in the last three years; (2) farmers with higher education, but whose farm income is decreasing, look for employment outside agriculture; (3) farmers who reach a certain age abandon their land if they do not have a successor; and (4) farmers change land use only if their land is suitable for another crop.

The innovative farmers with their large farm ownership and high educational attainment are more responsive to economic opportunities or risks. The model assumes that the main strategy of the innovative farmers to respond to changes in their environment is maximization.[4] To maximize income, the innovative farmers regularly update their income to check opportunities to increase income by cultivating alternative crops. Moreover, if their income drops below the minimum income level in the last three consecutive years, they look for alternative crops. They always appraise the suitability of their land to alternative crops. If suitability is low (i.e. probability value less than 50%), they continue to cultivate the same crops (i.e. repetition). In the model the suitability check is done using the probability maps.

Figure 4. Agents' decision trees for the agent-based model



Legend:
$IT < DR^{IT}$ – current income is less than the income for the number of years identified in the decision rule (e.g. 3 years)
$PV > DR^{PV}$ – land suitability is greater than the decision rule on land suitability requirement (e.g. 50%)
$ED > DR^{ED}$ – education is greater than the decision rule on the minimum level of education (e.g. 6 years of school)
$FS > DR^{FS}$ – farm size is greater than the decision rule on the minimum size of large farms (e.g. 100 hectares)
$FA > DR^{FA}$ – farmer's age is greater than the decision rule on the age of the farmer to transfer land ownership (e.g. 75 years)

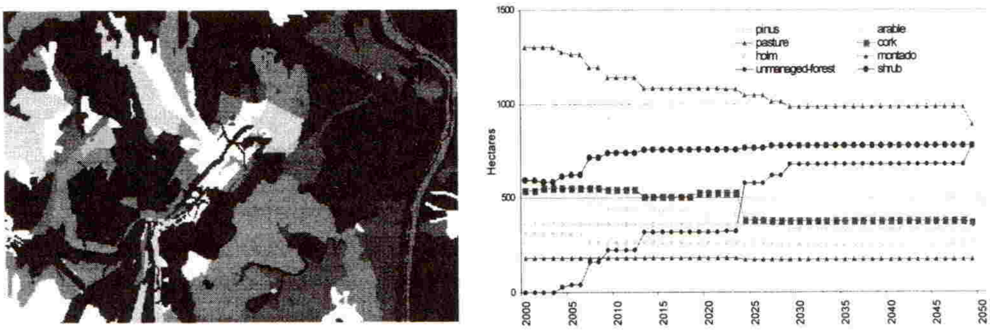
[4] Whilst they use social relationships to collect information through comparison or imitation, this is not visible in the model because their social network extends beyond the case study area.

Although active farmers are not are not as explorative as innovative farmers, they are assumed to have overt attributes that enable them to receive and respond to available information. In the A1 scenario, globalisation enhances the transfer of information, for example, through the media. However, the rate of transfer of information to the active farmers is not as fast as the innovative farmers. Access to information enables some active farmers to carry out maximization in the A1 scenario (Figure 1a), particularly those with larger land properties. However, if their land is not suitable for conversion to other crops, then active farmers engage in repetition. Regardless of their farm size, active farmers with a higher level of education and whose farms are not economically viable abandon their land. High rates of land abandonment result from low profitability in farming and the availability of alternative non-farming activities in a fast growing global economy. The retiree farmers, who reach a certain age and do not have a successor, also abandon their land due to the absence of a land market in the village. In contrast, the absentee farmers do not abandon their land even if farm income drops for personal reasons or future investment purposes. As the absentee farmers prefer to maintain the existing land use, they often engage in repetition.

RESULTS AND DISCUSSION

Figure 5 shows the spatial (2050) and temporal dynamics (2000-2050) of land use change under a global market scenario (A1). In comparison to the reference year 2000 (Figure 1), the landscape in Amendoiera village is characterised by an increase in shrubland. Moreover, many forest plantations will turn into unmanaged forest (dark shades). Both shrubs and unmanaged forests represent abandoned land from previously arable and forest plantations, respectively. Because the government is assumed to be weak in the A1 scenario, farmers do not received technical advice from agricultural extension services. Moreover, in this scenario agricultural subsidies decline so the large farmers do not buy land from small farmers, whose farms are not economically viable, or old farmers, who do not have families or relatives to take over their land. In the absence of buyers and successors, these farmers abandon their land. The lack of agricultural support to marginal agricultural areas such as Amendoiera results in out-migration of farmers, particularly those who have high education and can find alternative jobs outside agriculture. The trend in land use change reveals that the increase in unmanaged forests will be higher than for shrubs. The changes in land use before 2020 were attributed to the decreasing trend in the prices of cereals and livestock products. The reduction in area allocated for forest products, in particular cork, is attributed to the decline in forest subsidies.

Figure 5. Spatial and temporal dynamics of land use change in Amendoiera village, 2000-2050



The above illustrative results show the useful application of ABM in developing land use scenarios and evaluating the impacts of policies on land use decisions. Whilst not considered in the current model, the dynamics of vegetation growth can also be captured in agent-based approaches of this form by considering each type of vegetation as an agent. This is a future research direction to improve the current model. An ABM model that considers the dynamics of vegetation growth will be able to consider the impacts of specific farming techniques such as the application of fertilisers and irrigation.

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Use of risk prediction models for integrated control of diseases of oilseed rape in the UK

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ABSTRACT

To reduce reliance on fungicides for control of oilseed rape diseases, Decision Support Systems (DSS) are being developed to improve targeting of spray applications as part of an integrated disease management strategy. This paper reports on the development and use of an empirical risk prediction model and mechanistic disease progress models for light leaf spot and phoma stem canker. Delivery of the light leaf spot forecast is currently Internet-based, but a PC-based version is being developed as part of the PASSWORD project, which will produce a pest and disease module of the ArableDS system. Uptake of the Internet forecast by target end users (mainly growers and advisors) has been encouraging, with approximately 1000+ visitors and 2500 page visits during the past 2004/5 season, with 51% of these being made within two periods crucial to light leaf spot spray decisions.

INTRODUCTION

Light leaf spot (*Pyrenopeziza brassicae*) and phoma stem canker (*Leptosphaeria maculans*) are damaging diseases of winter (autumn-sown) oilseed rape in the UK (Fitt *et al.*, 1997). For both diseases, control can be achieved by fungicides but the timing of applications is critical for sprays to be economically effective (Gladders *et al.*, 2004). However, the risk of severe epidemics of both diseases differs between regions of the UK, with the most damaging light leaf spot epidemics in northern England and Scotland and the most damaging phoma stem canker epidemics in eastern England (Fitt *et al.*, 1996; cropmonitor.co.uk/ commercialsurvey/csosr/riskmaps.cfm). Severity of light leaf spot and phoma stem canker epidemics also differs between seasons and between crops within a region (Fitt *et al.*, 1996). There is therefore a need for accurate predictions of the risk of severe epidemics to guide decisions about fungicide applications.

MATERIALS AND METHODS

Light leaf spot – regional forecast (empirical model)

A regional light leaf spot forecast was developed using empirical models (Welham *et al.*, 2004). The models were developed using data from the Defra-funded Oilseed rape Pest and Disease survey (cropmonitor.co.uk). Initial regional forecasts have been published in autumn via traditional grower/industry publications since 1996 and on the Internet since 1998 as a simple map-based forecast (www3.res.bbsrc.ac.uk/leafspot/). The preliminary forecasts released each autumn were produced using 30 year mean meteorological data for each region, and then updated each March using actual winter weather data.

Validation of the light leaf spot forecast was done by comparing the regional observed percentage of plants with light leaf spot for a region (using data from the spring Defra Oilseed Rape Pest and Disease survey; cropmonitor.co.uk) against the predicted percentage of plants affected from the model (Figure 1). Figure 1 shows the observed regional mean % plants affected with light leaf spot for seasons with harvest years 2000 to 2003 with regional means predicted from the model. Generally, predictions were good. However, the prediction of the model for individual crops could be improved by including crop-specific information (Welham *et al.*, 2004).

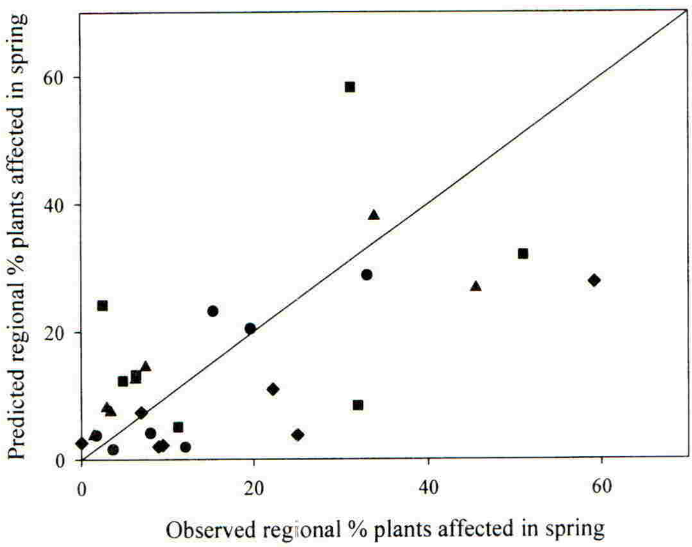

Figure 1. Observed and predicted regional mean incidence (% plants affected) of light leaf spot (*P. brassicae*) in March/April for light leaf spot regions for seasons with harvest years 2000 (●), 2001 (■), 2002 (♦) and 2003 (▲). The 1:1 line representing exact prediction is also shown

Light leaf spot – crop-specific forecast (empirical model)

The regional forecast was extended to include crop-specific information, as analysis showed that the resistance of the cultivar and date of sowing both affected the %plants affected with light leaf spot. These models can be used to a limited extent to produce interim forecasts, based on current weather, but are not designed to produce a "real time" description of epidemic progress (Welham *et al.*, 2004).

In 2000, interactive web pages were developed using Active Server Page (ASP) technology. This allowed users to specify a cultivar (to take account of host resistance) and sowing date so that growers can input information about their own cultivars and sowing date to produce a forecast specific to their crop, or to assess the impact of different cultivars and sowing dates on disease risk

(Evans *et al.*, 2002).. Initial forecasts made in autumn using 30 year mean meteorological data for each region are updated in early March by including observed winter weather.

The light leaf spot forecast is currently being incorporated into an oilseed rape pest and disease DSS (the PASSWORD project [password.csl.gov.uk/]) which will form a module of the ArableDS system. ArableDS aims to integrate farm decisions on disease and weed control.

Light leaf spot development (mechanistic model)

A structured population model with four compartments was developed to investigate the effects of the presence of *P. brassicae* inoculum (ascospores and conidiospores) and weather factors on the progress of light leaf spot on winter oilseed rape leaves (Papastamati *et al.*, 2002). Input data for this model included detailed local weather data, information on initial inoculum (ascospore) sources and concentrations and leaf wetness observations, and the model produced daily predictions of epidemic progress. Although the model predicted light leaf spot progress well, the use of the model is currently limited by the availability, at the farm/field level, of ascospore data and the detailed meteorological data required to run the model. However, the incorporation of the mechanistic model into a decision support system would provide the potential for a "real time" forecast that could be updated on a daily basis.

Phoma stem canker –regional forecast (empirical model)

As a component of the PASSWORD project, a regional phoma stem canker risk forecast has been developed (Sutherland *et al.*, 2002). The models were developed using data from the Defra-funded Oilseed Rape Pest and Disease survey (cropmonitor.co.uk). Similar in basis to the light leaf spot forecast, the model has provided users, in the autumn, with forecasts of incidence and severity of phoma stem canker for the following summer (phoma.csl.gov.uk/).

Phoma stem canker - crop-specific forecast (empirical model)

A crop-specific phoma stem canker progress model has been developed (Baierl, unpublished data), with epidemic progress divided into four stages over the season (Figure 2). Random effects models were applied to predict the start of phoma leaf spotting. The effect of resistance rating on the thermal time elapsed between 10% phoma leaf spotting and onset of stem canker was estimated by analysis of variance. Increase in stem canker severity with thermal time (degree-days) was analysed using random coefficient regression models to account for repeated assessments on the same crop. Finally, the relationship between yield and stem canker severity was investigated using linear regression. Inputs to the model are standard meteorological data (rainfall, maximum and minimum temperature). This model has considerable economic value because it can predict yield loss at harvest when the crop has 10% plants affected in autumn. Farmers can therefore adjust their expenditure on fungicide at the time when first decisions are made (Current advice is to apply fungicide when 10-20% plants have phoma leaf spot).

Prediction of the onset of phoma leaf spotting (10% plants affected) for each season is made at the end of September, based on local temperature and rainfall data in summer (from 15 July up to 26 September). At this stage, scenarios for the further progress of the disease can be run using expected values for daily temperature in winter and spring (i.e. 30 year mean data for a given location) and information about the stem canker resistance rating of the cultivar sown. The predicted disease progress can be updated with observed records as new information becomes available during the season. This applies both to temperature data and to disease assessments. If phoma leaf spot or stem canker symptoms are observed earlier than predicted, the prediction can be adjusted. Similarly, as only simple meteorological data are required, the model can be used to investigate stem canker development in Scotland. For example, phoma leaf spotting occurs annually in Scottish crops, but damaging stem cankers fail to develop. Data from Aberdeen indicate cankers do not develop there because average temperatures are lower, and there is insufficient thermal time for severe stem canker development by comparison to south-east England (Figure 3).

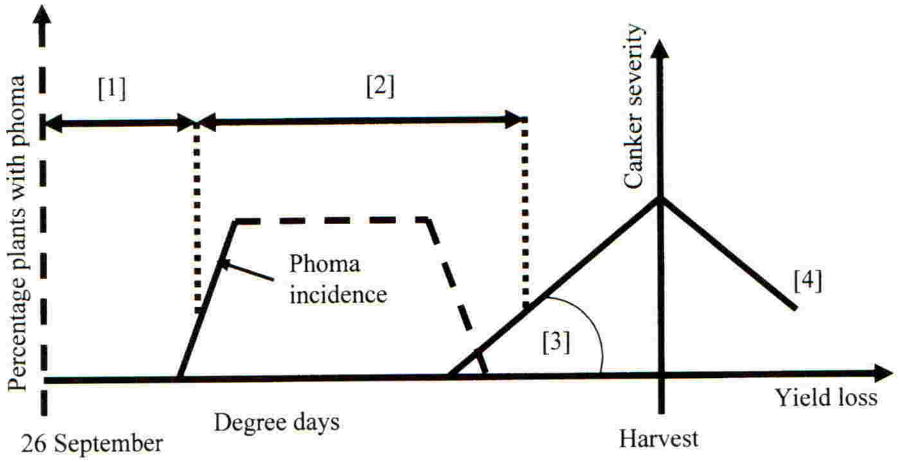

Figure 2. Schematic summary of the empirical phoma stem canker progress model. Numbers in brackets indicate stages 1 to 4: [1] Prediction of the onset of phoma leaf spotting (in autumn, 10% plants affected), [2] Time between onset of phoma leaf spotting and onset of stem canker development, [3] Increase in stem canker severity until harvest, [4] Relationship between stem canker severity and yield loss

Phoma stem canker development – (mechanistic model)

A mechanistic model of progress of phoma leaf spotting and stem canker on winter oilseed rape has been constructed, and values of the parameters estimated from published and archival data sets (Papastamati, 2005). The model is based on the important stages in the life cycle of *L. maculans* on winter oilseed rape; (i) ascospore production, (ii) leaf infection, (iii) phoma leaf spot development, (iv) growth of the pathogen down the leaf petiole and (v) stem canker development. The model incorporates the effects of meteorological variables (leaf wetness duration, temperature) on the various stages of the life cycle. The mechanistic model uses structured population modelling techniques to produce a series of ordinary and delay-differential equations describing the developmental stage of every infection as a function of age of that infection event. Outputs are the number of phoma leaf spots per plant and the incidence (% plants affected) of stem canker at the end of the season. Data from 2000/01, 2001/02 and 2002/03 seasons have been used for parameter estimation. As with the mechanistic light leaf spot model, the use of the model is currently limited by the availability, at the farm/field level, of ascospore data and the detailed meteorological data required to run the model. However, both mechanistic models could be easily updated as new information becomes available. Sub-models could be incorporated instead of actual data; for example, in the absence of ascospore data, it may be possible to use a model that predicts ascospore release.

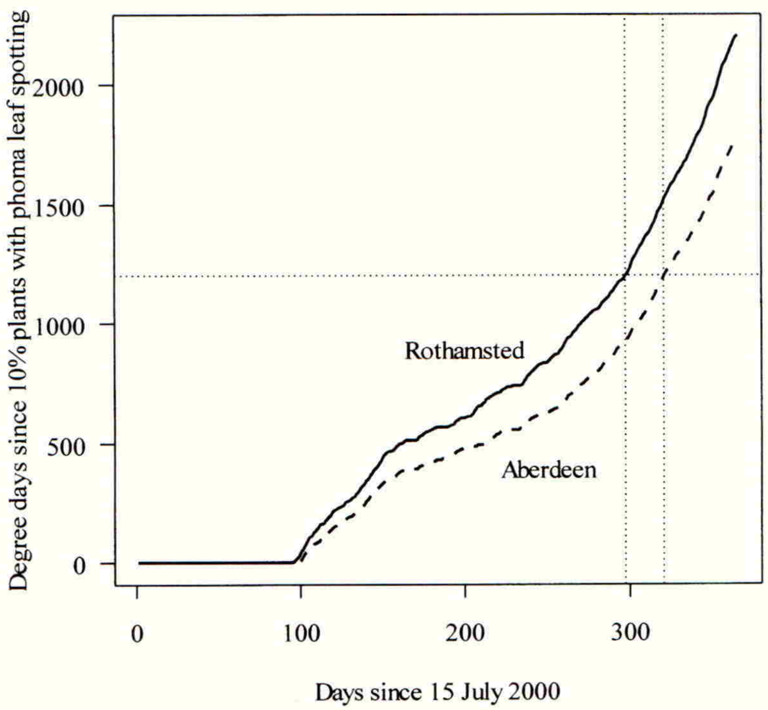

Figure 3 Predicted phoma stem canker development at Rothamsted and Aberdeen based on meteorological data for 2000/2001. The dotted line (1200 degree-days) indicates the predicted date for onset of canker development and suggests that, at Aberdeen, onset is too late for damaging cankers to develop before harvest (320 degree days; 31 May 2000) in contrast to the earlier onset at Rothamsted (297 Degree days; 8 May 2001)

DISCUSSION

Decision support systems can help to guide decision making by growers and advisors and systems have been used successfully for several years in a number of countries (e.g. Denmark; Rydahl, 2004). However, in the UK, the uptake of such systems by farmers and advisors remains surprisingly low (Parker, 2004). Parker suggests that one of the major barriers to uptake is the complexity of the systems which were first made available to UK users (e.g. DESSAC) and the perceived amount of time required to upload field and/or meteorological data to the DSS. From a scientific stand-point, complexity can also affect the robustness of the model and the predictions that are produced. On both of these points, it is interesting that, although the mechanistic models predict disease progress well, neither can currently be used at the field level, as ascospore data are not available. The empirical forecast models, although simple by comparison, are more flexible with respect to input data and lend themselves to easy use *via* the Internet. Although the recently developed empirical phoma stem canker forecast has not as yet been used, the web-based light leaf spot forecast, simple to use and simple at the point of delivery, has been useful to UK oilseed rape growers. Of the 1078 visitors since 1 October 2004 (when the forecast was released for the current season), 51% of the 2401 page visits were made during October/November and March/April, the two key periods when fungicide spray decisions are made with respect to light leaf spot.

ACKNOWLEDGEMENTS

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Integration of probabilistic modelling within consumer and environmental risk assessments: reporting, communicating and contextualising the risks

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ABSTRACT

The use of probabilistic exposure assessment and risk analysis leads to the corollary that there needs to be sufficient confidence in the outputs for their effective integration into regulatory decision making. This paper will present the current status of probabilistic tools as used within consumer and environmental risk assessments in the EU. It will also provide examples of reporting styles and insights into risk communication, particularly for context setting of risk outputs against the problem formulation. Using worked examples to illustrate deterministic risk endpoints and how they match to probabilistic outputs, the coherence of the probabilistic risk approach is maintained thereby increasing confidence in its use. The paper will also identify where such approaches have limited relevance.

INTRODUCTION

Probabilistic techniques within consumer and environmental risk assessments in the EU are a developing discipline. There needs to be sufficient confidence in the risk analysis outputs for their effective integration and use in regulatory decision making. This paper aims to provide worked examples to illustrate the coherence of the probabilistic risk approach within decision making and in communicating the outputs to the target audience.

PROBABILISTIC TECHNIQUES

Consumer

Probabilistic modelling of consumer exposure is defined here as the combination of distributions of individual data or on consumption patterns, body weights and pesticide residue concentrations to give a cumulative consumer intake estimate. This allows a fuller utilisation of the available data – often using the hundreds or thousands of data points available rather than the single data point as in deterministic calculations. Probabilistic modelling of dietary exposure has been used in various countries in Europe but has not reached the stage where it is accepted as a routine higher tier exposure refinement mechanism for regulatory purposes. This appears to be mainly due to the perceived lack of transparency in the modelling which is characterised by the phrase 'black-box' technique. However, this is not the situation in the US where the technique is considered to be acceptable and is used on a routine basis – in many cases even where higher tier refinements to risk assessments are not required. The acceptability is helped by the plethora of publicly available models which appears to break down the barriers on regulatory acceptability of the outputs. Examples include DEEM (Exponent Inc), CARES (CropLife America) and Lifeline (The LifeLine Group).

Developments in Europe have been hindered in many cases by the lack of available consumption data. Whilst many European countries publish these data in summary form e.g. mean consumption, 97.5th centile consumption, it is really only in the Netherlands and the UK that data for individual consumers are available in the public domain and therefore can be used for this type of exposure prediction.

In the UK, the variability of organophosphorus residues in individual carrot roots was the 'trigger' for the UK's Pesticide Safety Directorate to start exploring the possibilities for this technique (Harris, 2000). As the work progressed and more individual unit residues data became available, it was possible to construct diets containing a wide range of fruit and vegetables (Hamey and Harris, 1999). The deterministic models gave intakes exceeding acute reference doses (RfD) which would have required regulatory intervention to reduce acute consumer exposure but through the use of these models, registrations were allowed to continue whilst further work continued. The models showed that an occasional exceedance of the acute RfD may occur but that this would not be such a frequent event as to result in ill health. This showed that probabilistic modelling could be used as a highly effective 'aid to decision making'.

Environmental

The use of probabilistic modelling within environmental risk assessment is considered here as the use of distributions of data (exposure and/or predicted exposure and/or effects) to provide a greater insight into the realistic environmental risk. Probabilistic tools can be applied either to exposure assessment, or effects assessment, or both. This allows a fuller utilisation of all of the available data rather than the single data point as in deterministic assessments. Probabilistic modelling can increase realism by incorporating risk mitigation measures (e.g. typical agronomic practice), landscape features (e.g. crop specific habitats) and ecological considerations (e.g. behavioural knowledge).

Probabilistic risk assessment techniques have been used in various countries in Europe, but have not reached the stage where it is accepted as a routine higher tier risk refinement mechanism for regulatory purposes. Like consumer risk, this appears to be mainly due to the perceived lack of transparency and confidence in the modelling outputs. The future acceptability of these approaches will be helped with wider experience in the techniques and better communication of the outputs and their implications.

Developments in Europe have gathered momentum since the influential EURPA workshop (Hart, 2001) and most recent developments are as a result of a collaborative project EUFRAM funded by the European Commission incorporating probabilistic approaches into the environmental risk assessment of pesticides (www.euframcom).

For example within aquatic risk assessments under Directive 91/414 the deterministic models compare worst case exposure and lowest available laboratory toxicity endpoint. For spray drift to surface waters this assumes:

- A spray application 1 m away from a static ditch with vertical sides in which the water column is 1 m wide and 30 cm deep;
- the wind during application is blowing towards the ditch and at right angles to it at a constant 2-5 m/s;

- a 90th percentile drift deposition (Rautmann *et al.*, 2001) over the entire width of the ditch;
- no vegetation in the zone between the application area and the ditch.

This current deterministic scenario is considered to represent a reasonable worst-case in agricultural landscapes within the EU and should be viewed as worst-case and protective, but not as unrealistic. However, there are also many circumstances under which such conditions do not occur, and where exposure is much less (e.g. in citrus crops). Similarly for products where dissipation in the aquatic environment is rapid, endpoints based solely on toxicity studies performed under laboratory conditions of continuous exposure may overestimate realistic population impacts. Probabilistic models refining these assumptions could be used as a highly effective 'aid to decision making'.

The outputs from probabilistic environmental risks assessments should be considered together with the standard deterministic regulatory assessments (including field studies) to assist with risk mitigation and overall decision making.

WORKED EXAMPLES

Consumer example 1 - Triazophos and carbaryl

Hamey and Harris (1999) used triazophos and carbaryl residues in apples, pears, peaches and nectarine and/or carrot containing either of these residues. Deterministic acute estimates (24 hour intakes; 97.5th centile) were calculated for UK toddlers (children aged 1½ to 4½ years) and then the probability of exceeding the acute reference dose was also calculated.

Table 1: A comparison of intakes calculated deterministically and expressed probabilistically for carbaryl or triazophos in apples, pears, peaches and nectarine and/or carrot (adapted from Hamey and Harris, 1999)

Residue and fruit/carrot assumed to be eaten by all	Reduction due to peeling apples	97.5th centile intake – deterministic mg/kg bw/day	Maximum intake – probabilistic mg/kg bw/day	% probability intake > acute RfD	% probability intake > acute 10x RfD
Carbaryl					
Apple*	No peeling	0.0624	0.058	0.006	-
Apple*	With peeling		0.049	0.001	-
Triazophos					
Apple	No peeling	0.00175	0.019	3.0	0.235
Apple	With peeling		0.017	2.9	0.146
Carrot	No peeling	0.00294	0.018	1.7	0.039
Carrot	With peeling		0.015	1.7	0.025

* plus nectarine, peach and pear

In this example, the uses of carbaryl were allowed to continue whereas the uses of triazophos on carrots were withdrawn.

Consumer example 2 - Compound A and B

Two theoretical pesticide residues were used to calculate intakes from a wide range of fruit and vegetables for Dutch consumers (general) (Boon *et al.*, 2004). Traditionally, European deterministic estimates of acute consumer exposure are based on high level intakes of a single crop in isolation. This is because the assumptions used in the calculation are very conservative in nature and it is generally believed that the probability of these extreme events for the complete diet is highly unlikely to occur (PSD, 2002).

Table 2: Comparison of the point estimate and the probabilistic approach for compound A and B for the total population (consumers and non-consumers) in µg/kg bw/day, using Swedish food consumption data (adapted from Boon *et al.*, 2004)

	Deterministic estimate	Probabilistic approach		
		99.9th centile	99.99th centile	maximum
<u>Compound A</u>				
Apple/pear	4.1	2.9	4.7	9.7
Kiwi	2.8	1.0	2.3	4.8
Orange/small citrus/grapefruit	67	42	81	121
All foods together	-	48	85	170
<u>Compound B</u>				
Carrot	16	8.0	22	48
Cauliflower/Brussels sprouts/broccoli	32	8.7	22	28
Peach/nectarine	81	24	63	123
tomato	43	37	64	104
All foods together	-	44	80	126

When calculating the acute consumer exposure to compound A or B for all foods that could simultaneously contain one of these residues, the 99.9^{th} centile intake was between the lowest and highest calculated deterministic estimates. If the acute RfD for either compound was 65 µg/kg bw/day then the uses of compound A on citrus and compound B on peaches/nectarines would have been prohibited. However when the full range of data was taken into account, the intake at the 99.9^{th} centile for all foods were below this level. This demonstrates a further feature of probabilistic modelling where it allows the estimate of intake of pesticide residues in multiple foods to be carried out. However, it indicates another challenge to regulators in the question of which percentile represents 'safe' exposure. In the US, the EPA routinely use the 99.9^{th} centile (Chaisson *et al.*, 1999) but as yet, there is no consensus on this point in Europe.

Environmental example - Compound A

An avian assessment for Compound A indicated an unacceptable risk to insectivorous birds from foliar applications according to the current SANCO Guidance document for Birds and Mammals (European Commission, 2002). The risk assessment was based on toxicity data from standard laboratory species and the predicted insect residues following spray application were based on an unpublished data base as per SANCO Guidance. The risk assessment assumed that the insectivorous bird eats a diet consisting wholly of exposed foliar insects.

A probabilistic model was prepared that utilised detailed ecological information on the diet of the chosen focal species. The dietary data indicated that the insect diet was composed of both foliar, and soil insects and earthworms. Predicted worst case pesticide residues in soil insects and in earthworms were calculated using standard interception factors. By incorporating predicted pesticide residues in the other food types (e.g. soil insects and earthworms) it was possible to model a more realistic dietary exposure. The model produced a distribution of dietary residues based on iterations of daily diets that reflected the detailed ecological knowledge of the focal species. These were compared with the lowest toxicity endpoint from the standard laboratory species to indicate a lower risk when using more realistic exposure.

This data, when used in conjunction with other ecological data foraging behaviour, was able to assist in a better understanding of the realistic risk. Qualitative extrapolation of the results to other species and use of further ecological (e.g. foraging behaviour) and agronomic data was also conducted.

Currently, this type of modelling approach , along with others are undergoing evaluation and with more experience and confidence in their use it is considered that these approaches will prove to be a valuable addition to regulatory decision making for environmental risk.

DISCUSSION

Exposure estimations and risk analysis should be a decision focussed task (i.e. conducted to facilitate and aid decision making) and probabilistic techniques can be applied to varying degrees within discrete parts of the risk assessment. Where uncertainty (i.e. lack of knowledge) is large, this should be highlighted and the impact of this on the risk should be estimated.

Exposure estimations and risk assessment needs to be rational and utilise decision-focused thinking while making maximum use of the available data. In an ideal situation, it is an iterative and continuous process whereby the risk assessment process undergoes review with the availability of new data. This can be accomplished with continuous evaluation of fitness-for-purpose and continuous communication with all stakeholders.

In the real world, risk assessment is a decision tool, however there is also a need to define an acceptable level of risk, as without a threshold, any risk can be considered "unacceptable" and therefore present a threat to the transparency of regulatory decision making.

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Mite movement and biocontrol: A virtual approach

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ABSTRACT

A combined experimental and modelling framework has been produced to allow rapid development of stochastic, spatially explicit models for biological control in ornamental crops. Application of this framework to the simulation of the dynamics of spider mites, *Tetranychus urticae*, and predatory mites, *Phytoseiulus persimilis*, have shown that the movement and dispersal of mites are crucial to the success of biological control. This paper describes the application of the novel technology of virtual plants to modelling of mite movement within the complex plant canopies associated with ornamental crops.

INTRODUCTION

Due to increasing pressure to reduce pesticide inputs, ornamental growers in the UK are increasingly turning to the use of biological control to reduce pest damage. Biological control has been used successfully on protected edibles in the UK (Hussey, Parr & Gould 1965, Nachman 1981, Kropczynska and Tomczyk, 1996). However, due to the low tolerance to pest damage, diversity of crops grown, often in close proximity, and the range of different growing practices used, the approach to biological control taken in edible crops cannot be transferred directly to ornamental crops.

For biological control to succeed on ornamental crops in the UK, it will be necessary to focus on preventing pest establishment, through the use of prophylactic releases of natural enemies. For this strategy to work, it is necessary to have a detailed understanding of the tritrophic interactions involved in biological control, particularly in relation to the movement of natural enemies and pests within and between crops.

Initial modelling work has identified the movement of natural enemies as a crucial factor in determining the success of a prophylactic release programme for biological control in ornamental crops. Experimental work on the movement of *P. persimilis* on *Choisya ternata* has shown that the number of connections between plants has a significant impact on the dispersal of natural enemies, which is in agreement with the work of Zemek and Nachman (1998, 1999).

In order to implement prophylactic releases of natural enemies for biological control, it is therefore extremely important to have a good understanding of the number of connections between and within plants in a canopy, and this will depend upon the structure of the crop plant. The novel technology of virtual plants (Room *et al.* 1996, Hanan 1997, Prusinckiewicz *et al.* 1997) provides a useful tool for gaining this understanding. This paper presents a brief overview of virtual plant technology, and the way in which it may be utilised to aid biological control in ornamental crops.

VIRTUAL PLANTS

What are virtual plants?

Virtual plants are computer-generated models of the three-dimensional structure and growth of plants, based on the mathematical concept of Lindenmeyer systems (L-systems). L-systems are essentially a mapping that describes how a structure changes from one time step to the next. L-systems can also include time delays, so that one structure, e.g. a bud, may transform into a new structure, e.g. a flower, after a set time interval. Plant parts in a given state are represented by symbols, and the way in which they change over time is defined by a set of rules, known as productions. For example, the growth of a simple flower can be represented as follows, where A represents an apical bud, I an internode, L a leaf, B a flower bud, F a flower, and [] encloses a branch.

Starting with an apical bud, A, the following rules are implemented in each time step:

A → IL[B]A	(each apical bud becomes an internode + branch with apical bud + leaf + flower bud)
I → I I	(each internode doubles in length)
B → F	(flower bud becomes a flower)

In successive time steps, the virtual plant is represented as:

Step 0:	A
Step 1:	IL[B]A
Step 2:	IIL[F]IL[B]A
Step 3:	IIIIL[F]IIL[F]IL[B]A
Step 4:	IIIIIIIIL[F]IIIIL[F]IIL[F]IL[B]A

The angles of branching for branches, and leaves, and the width of lines are represented by other symbols, and these have been omitted from this example for ease of illustration.
A graphical representation of the plant at time step 4 is shown in Figure 1 below.

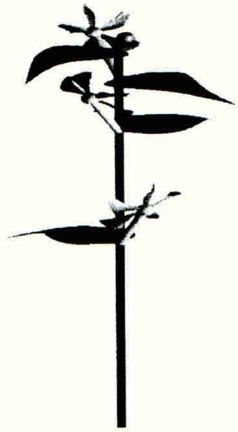

Figure 1 Graphical representation of the virtual plant from time step 4.

Creating a virtual plant

For the work on ornamental crops, the virtual plants are being created through the digitisation of real plants using a sonic digitiser and the Floradig software from the Centre for Plant Architecture and Informatics (CPAI), Brisbane, Australia. The sonic digitiser consists of a triangular array with a microphone at each apex, a probe which has two miniature electrodes which emit a sound milliseconds apart and a metal tip, and a box of electronics that calculates the three dimensional point at the end of the tip. To digitise a point, the tip of the probe is placed on the point and a trigger pressed to fire the electrodes, and the co-ordinates of the point are returned to the computer. These points are then passed to the Floradig software, and defined as a node, leaf point, bud or flower. Leaves are digitised as a set of points defining the main edges of the leaves.

Once all the plant structures have been digitised, the software is able to calculate the branching angle, internode length, leaf size and other related information that is necessary to create the virtual plant model as an L-system. At present this information can only be converted into an L-system manually, although CPAI are currently developing software to automate the generation of L-systems rules from Floradig information. Having developed the L-system, the virtual plant can then be visualised, using the L-studio software from the University of Calgary, Canada, on a PC.

Virtual crop canopies: creating and analysing

For the current project on canopy structure, 16 *C. ternata* and 16 Chrysanthemum plants have been digitised, and the information on branching angles, internode lengths, leaf angles, lengths and widths exported into a Microsoft Access database. These data are currently being analysed to determine the relationship between the position of the structures on the plant and the mean angle, length or width. Once this has been done, a stochastic L-system will be created to grow the plants, with the internode lengths and branching angles being chosen from fitted statistical distributions.

Having developed an L-system for a single plant, the stochasticity of the L-system will enable multiple plants, each with a slightly different structure, to be created to form a model of a crop canopy. Having created a model of the crop canopy, it can then be analysed to determine the number of connections between leaves, both within and between plants. This is done using a simple collision detection (CD) algorithm. The leaves are represented as a set of triangles, and then the co-ordinates of the apices of the triangles are passed into the CD algorithm for each leaf, which then tests each of the triangles in different leaves for collisions with triangles from other leaves. If a collision is detected, the leaf with which a collision is detected is returned back to the L-system. A list of leaves that are touching is then stored in an array defined within the L-system, along with the plant to which the touching leaves belong. In this way, all the touches within and between plants can then be calculated, and related back to the structure of the individual plants.

SIMULATION EXPERIMENT

The experiment was designed to investigate how the time to location of a static prey by a randomly foraging predator was influenced by two aspects of canopy structure: connectedness and canopy complexity.

The virtual plant models described in Skirvin (2004) were used as the basis for the experiments. The models simulate plants that have 4 leaves, set at right angles to each other. There are 3 levels of spatial complexity: all 4 leaves attached to a single node, 2 leaves attached to a node, or a single leaf attached to a node; so that the plants have either 1, 2 or 4 nodes, which are separated vertically on the plants. Connectedness of the plants is varied by simulating two types of grids: a regular grid, where each plant is connected to 4 others, and an offset grid, where each plant is connected to 8 other plants.

Simulations were run for a range of three grid sizes, 5 x 5, 10 x 10 and 20 x 20. For each set of simulations, three prey locations were simulated: in one of the four corner plants, on an edge plant, or on any of the plants not on the edge of the grid. For each prey location, the model was run 2500 times for the 5 x 5 grid, 10000 for the 10 x10 grid and 40000 times for the 20 x 20, with the predator start point being chosen at random for each run of the model.

The time for the predator to locate the prey was output for each run of the model along with the starting location of the predator, and the location of the prey. If the prey was not found within 1 million time steps, then it was assumed that the predator did not find the prey.

Analysis of the model output

For each run, the starting location of the predator and location of the prey were used to calculate the initial distance of the predator from the prey, in terms of concentric neighbourhoods around the prey location, according to the following equations:

Regular grid: $X + Y + Z$

Offset grid: $X/2 + Y/2 + Z$

where: X, Y, and Z are the distances between the x, y and z co-ordinates of the prey and predator locations. The division by 2 in the offset grid accounts for the larger size of the neighbourhood of a single plant (8 plants touched instead of 4).

Having determined the neighbourhood distance between predator and prey, the mean time to prey location for each distance was then calculated for each of the grid sizes, plant canopy complexities and connectedness.

RESULTS

The results show that the time to prey location is related to distance in a non-linear way and that it increases with the distance of the predator from the prey (Figure 2). As the connectedness of the plants is increased, then the time to prey location is shorter (compare regular and offset grids in Figure 2). As the complexity of the plant canopy is increased, then the time to prey location increases as illustrated in Figure 3 for the 20 x 20 regular and offset grids.

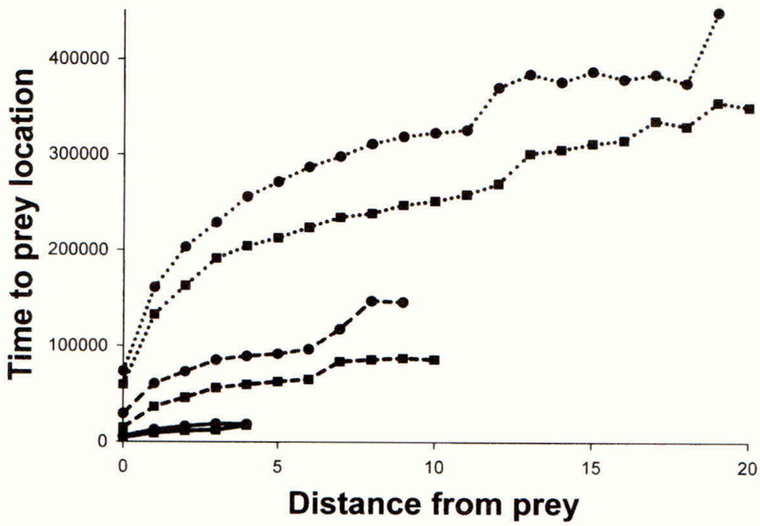

Figure 2. Graph showing the effect of plant connectedness [●- touching 4 plants; ■- touching 8 plants] on the relationship between distance from prey and time taken to locate prey for the three grid sizes [▪▪▪▪ - 20x20 grid; — — - 10x10 grid; —— - 5x5 grid]

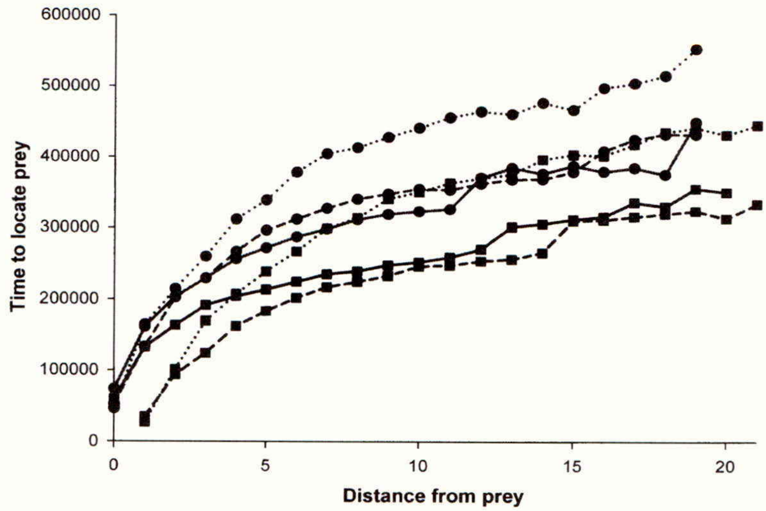

Figure 3. Graph showing the effect of plant canopy complexity [▪▪▪▪ - 4 nodes (1 leaf per node); — — - 2 nodes (2 leave per node); —— - 1 node (4 leaves per node)]on the relationship between distance from prey and time taken to locate prey for the 2 levels of plant connectedness [●- touching 4 plants; ■- touching 8 plants]

There is also an effect of the prey being on the corner, edge or middle of the grid, with times to prey location being shortest when the prey is in the middle of the grid, and longest when it is in the corner (Figure 4).

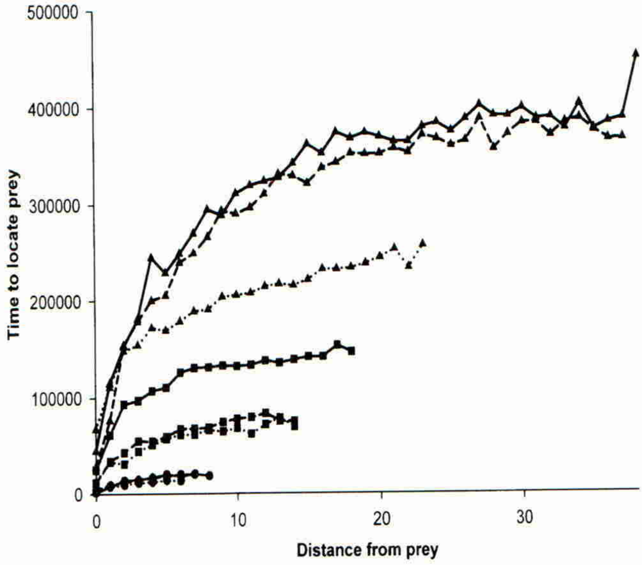

Figure 4. The relationship between distance from prey and time to locate prey, when prey are on Middle [▪▪▪], Edge [▬ ▬] and Corner [▬▬] plants in the grid, for the three grid sizes [● - 5x5 grid; ■ - 10x10 grid; ▲ - 20x20 grid] when each plant touches 4 others, and the plants have a single node with 4 leaves.

DISCUSSION

The results from the simulation experiment demonstrate the importance of canopy structure in determining the ability of a predator to locate its prey. The fact that a more connected canopy leads to a shorter time to prey location is unsurprising, as there is a greater number of ways of moving from one plant to another, but it is the first time it has been demonstrated through simulation. The fact that a more complex canopy leads to a longer prey location time is mainly driven by the separation of the leaves in the vertical plane. This means that the predator has to spend more time moving up and down a plant, rather than being able to move horizontally through the canopy. However, this is more likely to mimic the natural situation in crops.

This work has major importance for biological control, since it shows that canopy structure needs to be taken into account when deciding on strategies for the introduction of biological control agents, as the distance of the predator from the prey is not a linear relationship, and the further away the predator is, the longer it takes to locate the prey. This would support the use of dispersed predator introductions rather than point introductions, however economic factors and the biological features of the predator will affect the most suitable introduction strategy.

There is a need to now extend this work to look at the case of a predator that has a more directed movement, rather than the random movement used in these simulations. This would indicate whether predators using semiochemicals to locate their prey are more effective than randomly searching predators.

The model also has applications for other areas of ecology, where there is an interest in linking canopy structure to the movement of organisms. For example, Finke and Denno (2002) showed that complex vegetation structure led to lower intraguild predation between a mirid bug and wolf spider in a salt marsh, and proposed that this was due to there being greater refuges for the mirid bug when thatch was present. This theory could be tested quite easily using the modelling approach presented here. Also, the searching behaviour of pests in the selection of their food could be examined. Neuvonen (1999) re-examined data about the selection of leaf whorls on the shrub *Daphne laureola* by noctuid larvae (Alonso and Herrera, 1996), but was unable to determine whether the pattern of selection was due to selective foraging behaviour or random behaviour. The virtual plant model could be adapted to answer this question without difficulty, allowing a comparison between random behaviour and more selective searching strategies.

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