ASTROMOD: a computer program integrating vegetation dynamics modelling, environmental modelling and spatial data visualisation in Microsoft Excel

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Abstract This paper describes the development of a software framework for predicting vegetation change within the Astroni crater, a state nature reserve near Naples, Italy. ASTROMOD (ASTROni MODel), is designed to allow the analysis of environmental and management scenarios in the crater, thus aiding the reserve's manager in effective decision making. ASTROMOD comprises a vegetation dynamics model developed for forest ecosystems, combined with models of environmental determinants. It integrates a user-friendly interface for visualising spatial data, a parameter database and a series of programming modules within Microsoft Excel. This approach is a significant departure from other spatial biophysical modelling approaches which require costly and complex software tools.

Keywords: Vegetation dynamics; Environmental modelling; Spatial data visualisation; Microsoft Excel

Software availability

Program title: ASTROMOD DTM.xls

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Year first available: 2001

Hardware require: IBM compatible PC.

Software required: Microsoft Excel 7 or later version.

Program size: 1.2 Mb.

Availability and cost: freely downloadable from http://www2.rhbnc.ac.uk/~vhfa011/astromod/.

1. Introduction

Advances in ecological understanding and the requirements for land managers to deal with increasingly complex scenarios justifies the adoption of powerful technological tools to aid management decisions. Developments in computer technology are providing nature reserve managers with an expanded suite of tools, including computer modelling for predicting ecosystem change, expert systems to aid in the decision making process, and Geographical Information Systems for the analysis of spatial information. These tools can be integrated to create Decision Support Systems (DSS). DSS have been developed for ecosystem management, specifically in the field of forest pest control (Moore, 1989; Loh and Rykiel, 1992; Power and Saarenmaa, 1994), forest wildfire behaviour (Zack and Minnick, 1991), rangeland management (Ludwig, 1991) and catchment management (Richardson et al., 1994). The great difficulty with these tools is their relative complexity and limited life span as technology advances. This paper presents a framework for the development of a computer-based tool for biophysical modelling and spatial data representation that is inexpensive and user-friendly.

2. The software

The main concern for environmental and ecological modellers is speed of calculation, and thus most models are either developed using advanced modelling software and/or are run on powerful machines such as Unix workstations. The objective of this research was to develop a tool using a software framework that was familiar to most people. Microsoft Excel is one of the most common software packages currently found on personal computers. Excel provides user-friendly interfaces through the “Dialog” format, programming in Visual BASIC through the “Module” format and database capabilities within the “Worksheet” format. Probably the most significant breakthrough was the ability to represent spatial data within the “Worksheet” format. For mapping, a programme was written in Visual BASIC that reduces the worksheet cells to a 1.4 by 1.4 mm size and changes the colour of each cell according to the value present within the database (Fig. 1). There are three choices for determining the colour of the mapped values. The first choice involves calculating the minima and maxima from the values to be mapped which are then used to assign different tones of a single colour to the values. The second choice also involves using maxima and minima values but two colours can be selected. The third choice allows the user to assign the colour to individual values. This is particularly useful when mapping different vegetation types. The database includes x and y spatial co-ordinates for each cell which allows detailed mapping of all the spatial data sets (e.g. elevation above sea level). ASTROMOD’s simulation outputs are also linked to the x and y coordinates, thus allowing the mapping of results onto the modified spreadsheets.

Within an Excel file one can therefore have a simulation model, a spatial data visualisation facility, a parameter database, and a user-friendly interface. Saving ASTROMOD as a single Excel file greatly simplifies the process of saving, copying and sending different versions of the tool. ASTROMOD was developed in Microsoft Excel 7, although significantly newer versions of Excel are now available (e.g. Microsoft Excel 2002). So far, all the tools developed in Excel 7 have continued to operate without any problems in later versions. One of the components of the ASTROMOD tool, the Digital Terrain Model (D.T.M.), is freely available from the following web-site: http://www2.rhbnc.ac.uk/~vhfa011/astromod/. ASTROMOD DTM.xls allows the user to calculate the average slope and aspect of 25 m by 25 m plots within the crater from a grid of spot heights. The height, slope and aspect can then be mapped. This tool is readily adapted to calculate and map slope and aspect from any gridded elevation data.

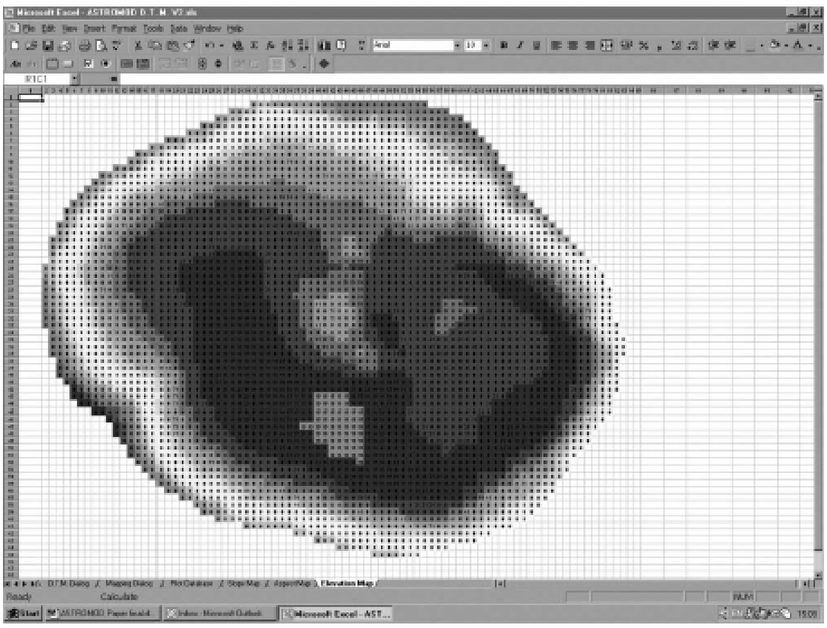

Fig. 1. the transformed Excel “Worksheet” showing the spatial data visualisation.

3. The site to be modelled

The Astroni Crater State Nature Reserve, Naples, Italy, was selected as the case study site. The Astroni crater is an extinct volcano, located within the Campi Flegrei, Campania region, southern Italy. The Astroni crater's nature reserve occupies the inner slopes of the crater and covers an area of 247 hectares. The reserve's vegetation presents a complex zonation system characterised by a temperate deciduous community at the base of the crater and a Mediterranean evergreen community on the slopes. The communities are further sub-divided into natural and planted. Disturbances at various temporal and spatial scales present a further differentiation, with the invasion of alien species, particularly *Robinia pseudoacacia* and *Ailanthus altissima*, adding a final level of complexity. The crater's high ornithological diversity (over 120 bird species have been recorded within the crater), strategic importance (20 km north of Naples, the largest city in southern Italy), impressive volcanic landscape and fascinating history makes it a major focus of conservation interest.

The Astroni Crater State Nature Reserve has a significant challenge that faces it in the immediate future. Concomitant with the internal changes of the crater, the surrounding landscape has also experienced a fundamental transformation. In the last decades, especially after the devastating earthquake of 1980 and the construction of the "Tangenziale di Napoli", an eight lane motorway linking the Campi Flegrei to Naples, the area has been subject to a phenomenal increase in urbanisation, not all legal. This has significant implications for the region's hydrological balance as the land surface is sealed off and run-off is channelled into the sewage system which is then directly discharged into the nearby sea. It is therefore evident that composition and distribution of plant communities now present is going to change signifi- cantly within the next century. A tool is required that can predict these changes. Thus, this imminent threat and the crater's small size and easy accessibility, makes it an excellent site for the development of a predictive tool for vegetation change. The presence within the crater of both temperate and Mediterranean communities also implies that the software structure and formulae may have applications within a considerable range of European ecosystems.

4. The Models

What follows is an overview of the assumptions involved in developing ASTROMOD. A complete description of the algorithms and tests are available in Berardi (1999).

4.1. The environmental models

The simulation of vegetation distribution, composition and change over time involves the use of environmental models which control these processes. The nature of, and interactions between water, radiation, nutrient and disturbance regimes are critical in determining the composition, productivity and persistence of biotic assemblages in forests. At the micro-scale, combinations of these regimes may influence the types of plants that occupy a site, and their rate of growth and phenology. At the meso-scale, these regimes can markedly influence the floristic composition and structure of a forest. An ability to characterise such regimes accurately is an important prerequisite for developing a predictive understanding of the relationship between environmental heterogeneity, and ecological patterns and processes.

Significant progress has been made in the development of computer-based mathematical and computational techniques to model a number of climatological, hydrological, geomorphological and biological processes at various scales of analysis in terrestrial landscapes (Davis and Dozier, 1990; Quinn et al., 1991; Hutchinson et al., 1992; Band et al., 1993; Moore et al., 1993). The techniques developed allow the characterisation of environmental spatial variation with a precision and resolution previously unattainable, and have enormous potential application to the study and predictive modelling of ecological phenomena (Leibhold et al., 1993). This is particularly the case in complex terrain where relatively small changes in slope, aspect and catchment area can markedly influence local variation in the environment (Moore et al., 1993; Wigmosta et al., 1994).

Regular grid or raster Digital Elevation Models (DEMs) have become the basis for recent approaches to modelling earth surface processes (Moore et al., 1991). A DEM is defined as a regular gridded matrix representation of the continuous variation of relief over space (Burrough, 1986). The value of DEMs derive from the information regarding terrain and its attributes, which can provide direct input to a range of environmental models. The extraction of information from DEMs can be divided into two classes of analysis. The first class of analysis, primary analysis, involves direct calculation from DEM raw elevation data, and includes the estimation of slope, aspect, profile and plain curvature, flow path-length and specific catchment area (Burrough, 1986). Secondary analysis involves calculation from a combination of first class analysis results, and can be used to characterise the spatial variability of specific processes occurring in the landscape. For example, the amount of incident solar energy can be estimated from the elevation, slope, aspect and shadowing of a surface (Dubayah and Rich, 1995).

The primary data for ASTROMOD's DEM was first produced in ArcView 3.0 from digitised contours and exported as an elevation matrix structure. The elevation matrix or rectangular grid is the most commonly used modelling construct for a DEM (Moore et al., 1991). Once again, this data structure was highly suited for Microsoft Excel, in that elevation can be stored as a three-dimensional array. In ASTROMOD, a 25 m grid DEM was produced so that the environmental data could be directly linked to the vegetation dynamics model's gap unit of 25 m by 25 m. This grid size has implications for the environmental modelling. The grid size of a DEM has been shown to affect the topographic attributes of a landscape (Hutchinson and Dowling, 1991; Jenson, 1991; Quinn et al., 1991; Zhang and Montgomery, 1994). Zhang and Montgomery (1994) found that grid sizes of 30 m and 90 m did not accurately depict hillslope and runoff generation processes in moderately to steep gradient topography. A 10 m grid-size was found to show significant improvements over 30 m or coarser grid sizes, while finer grid sizes provide relatively little additional resolution. The spacing of the original data used to construct a DEM also limits the resolution of the DEM. Decreasing the grid size beyond the resolution of the original survey data does not increase the accuracy of the land surface representation of the DEM, and potentially introduces interpolation errors (Zhang and Montgomery, 1994). A 25 m grid was therefore deemed to be a good compromise.

Four fundamental environmental variables needed to be calculated in order to simulate vegetation change: irradiation flux, air temperature, soil-water saturation and evapotranspiration deficit. Botkin (1993) gives an overview of the need for these parameters in gap modelling. Each of these variables were calculated at the resolution of the gap area i.e. averaging the values for 25 by 25 m units.

Incident solar radiation on the surface of a plant may change significantly depending on whether the site is south or north facing, shaded by the surrounding relief, and whether the sky is overcast or not. For example, in a study comparing north and south slopes, Running et al. (1987) found that radiation was 8 to 34 % higher on southern slopes than on northern slopes. This factor is also significant when calculating potential evapotranspiration, where incident irradiation can affect plant temperatures either directly or indirectly by influencing air temperature and movement. For realistic simulation of vegetation dynamics it was therefore necessary to estimate the variations in incident irradiation across the Astroni crater.

The availability of actual irradiation measurements from the study site is perhaps the most important issue determining whether the model will produce actual solar radiation fluxes for a given time and location, or some type of potential or relative radiation (Dubayah and Rich, 1995). For obtaining actual fluxes, some field data must be available, such as from solar pyranometer data, atmospheric optical data, or atmospheric profile (sounding) data. For ASTROMOD, equipment was not available for monitoring actual irradiation fluxes within the crater, so relative radiation values were estimated instead. There are three sources of illumination on a slope in the solar spectrum: direct irradiance; diffuse sky irradiance; and irradiance reflected by nearby terrain towards the point of interest. Reflected irradiation was not calculated because it is a small fraction of total irradiation and of little use in photosynthesis since it is mostly in the short wave-bands (Linacre, 1992). Direct and diffuse irradiance were calculated hourly from sunrise to sunset, every day of the month. These hourly values were then used to calculate a monthly index of light intensity. The algorithms were mostly adapted from Dubayah and Rich (1995).

The spatial distribution of minimum, maximum and average air temperature is computed using a modifi- cation of the simple approach proposed by Running et al. (1987). It corrects for elevation via a lapse rate, for slope-aspect via the ratio of short-wave radiation on a sloping surface to that on an unobstructed horizontal surface, and for vegetative effects via a leaf area index. For the Astroni crater, this approach increases temperatures on south-facing slopes and decreases temperatures on north-facing slopes. This approach also increases temperatures on plants that are on the exposed unvegetated slopes. The effect of cold air drainage (katabatic winds) are also included with the lapse rate. In the Astroni crater, cold air drainage into the caldera can have a significant impact on temperatures over relatively small distances. This generally occurs between midnight and sunrise, and thus contributes more significantly to the minimum temperatures reached just before sunrise (Linacre, 1992).

In creating ASTROMOD, formulae for estimating drought-stress were derived from Botkin and Levitan (1977). Drought stress is considered to be the single most important environmental determinant of Mediterranean ecosystems (De Lillis and Fontanella, 1992). The water content of the rooting zone is used to model the effect of drought stress, assuming that it is indicative of the water availability for plants (Cramer and Prentice, 1988). In the model, the depth of the soil is defined as the depth to which tree roots can penetrate or that material can be transported directly to tree roots. Below is a subsoil that may be bedrock or unconsolidated particles where chemicals are not available to the roots. The model assumes that at some depth of soil, the watersaturated zone begins, in which all capillary pore spaces between soil particles are filled with water, and there is essentially no gaseous atmosphere. The top of this saturated zone is defined as the water table. The relationship between depth to the soil base and depth to the water table is used in the model to distinguish trees adapted to wet ground and those adapted to dry areas.

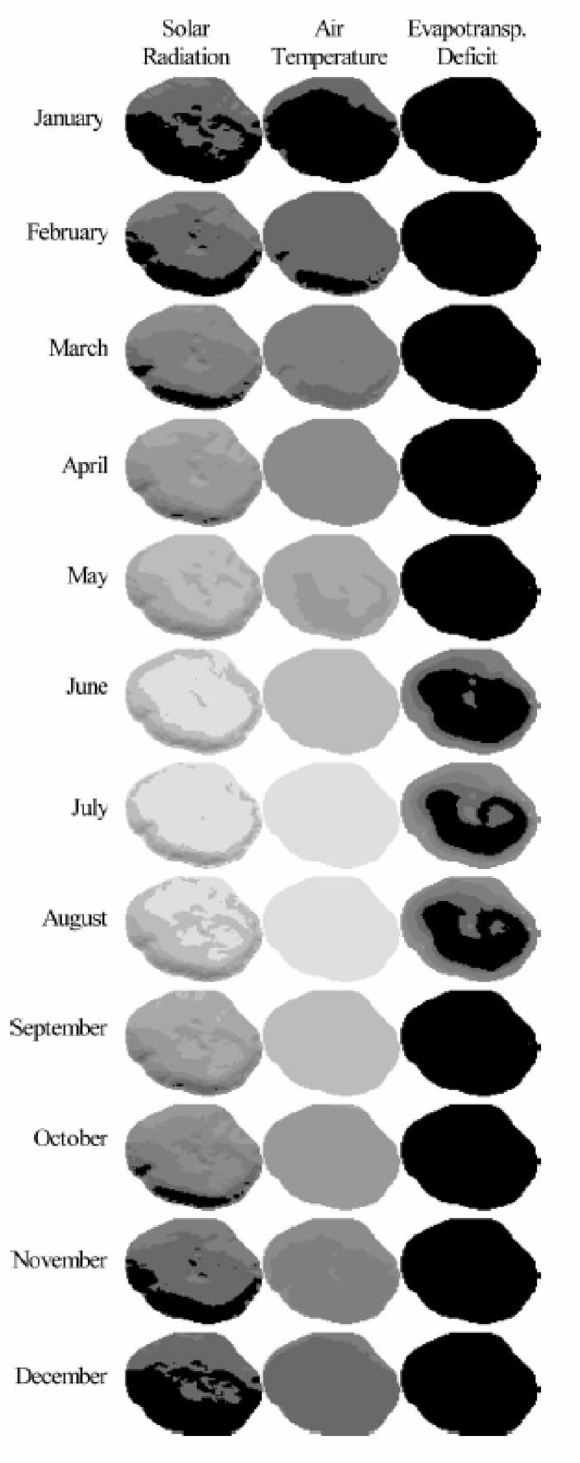

Fig. 2. Modelled environmental characteristics within the Astroni crater from January to December. The maps show tone variations with respect to yearly maxima and minima. For solar radiation, light tones signify high radiation intensities and dark tones signify low radiation intensities. For temperature, light tones signify high temperatures and dark tones signify low temperatures. For evapotranspiration deficit, light tones signify high evapotranspiration deficit and dark tones signify low deficit.

The amount of water available to a tree for growth is the amount stored in the soil, not the amount simply received from rainfall. Water may become available when transferred from other areas by subsurface runoff or through upward capillary action (Moore et al., 1993). Some rain that falls evaporates immediately or runs off the soil surface and is never available to the trees. Once in the soil, water can be lost through downward percolation, horizontal runoff, or evaporation from the soil being raised to the top by capillary action. The water taken up by trees is eventually transferred to the atmosphere by transpiration from the tree leaves.

In the model, the water balance is calculated monthly. Although daily calculations would have been preferable to increase realism, and therefore accuracy, the monthly time interval was chosen principally because monthly weather records are common, and a daily calculation would have significantly increased computational time. The modelled environmental characteristics were stored on the spread sheet and subsequently mapped (Fig. 2). The maps show that during the winter months there is a significant difference in solar radiation between the south and north facing slopes of the crater, with the central parts showing intermediate values. As one moves into the summer season, the higher solar angles result in the flatter areas of the crater (principally the crater's base) receiving the highest irradiation. This distinction in solar radiation is reflected in temperature variations during the winter period, with the lowest temperatures apparent on the north facing slope: these slopes effectively do not receive any direct radiation during this time and thus are not heated by the sun's rays.

The effects of katabatic air mass movements seem to have a far greater significance in the summer period, where they over-ride the effects of higher radiation at the base of the crater, thus making the latter cooler than the slopes. Both radiation and temperature seem to have a limited effect on evapotranspiration deficit within the crater, with slope and depth to the water table the overwhelming factors in controlling drought stress. The modelling results imply that the lowest parts of the crater are never subject to drought stress, while from May until October, most of the higher and sloping parts of the crater are subject to intense stress. It is probable that although slope and depth to the water table are the controlling factors in the crater's drought stress distribution, the lower temperatures at the base of the crater may also contribute to lower evapotranspiration rates.

4.2. The vegetation dynamics model

ASTROMOD uses a type of vegetation dynamics modelling commonly termed "gap modelling", first proposed by Botkin et al. (1972). Probably the strongest justification for using the gap modelling approach in ASTROMOD is its landscape unit characteristic. The discrete spatial unit enables the identification of a location within the hierarchical gradient from the plant individual to forest ecosystem, while enabling a straightforward link to environmental models of the landscape. Gap models dynamically simulate particular attributes of each individual tree on a spatial unit of relatively small size, usually either a gap in the forest canopy or a sample quadrat. In gap modelling, gaps can be defined according to several different criteria. For example, the scale could be determined by sampling considerations (e.g. the pixel sampled by a LANDSAT satellite) or, ideally, by the scale of the natural pattern of disturbance in the landscape (Shugart and West, 1980).

The majority of gap models simulate changes in forest landscapes by defining the gap created by the death of a dominant canopy tree as the principal unit of forest stand dynamics . This unit is assumed to be of constant size, and its estimation is based on the average area occupied by dominant canopy individuals of the ecosystem in question. Within this unit, one assumes that the location of the remaining live trees can be ignored without incurring a significant loss in reliability, avoiding the need to use a distance-dependent approach (Botkin et al., 1992).

The basic structure of gap models has rarely been modified from the initial gap model, JABOWA, proposed by Botkin et al. (1972). Each tree's diameter increment is computed annually as a function both of species attributes (e.g. maximum growth rate), and of the individual tree's environment (e.g. shading by other trees). Each tree is subjected to a probability of annual mortality that is determined by the species' longevity and by the level of stress the tree is subjected to. The slower a tree grows compared to its optimal growth rate, the higher the intrinsic mortality rate. Regeneration is determined by a combination of conditions on the forest floor and the species' ability to cope with these conditions. The model output resembles a stand tally sheet, listing the species and diameter of each tree on the model stand. With allometric formulae, these values can then be processed further to produce data such as species biomass, basal area, density and productivity. An excellent description of the algorithms and assumptions of gap models can be found in Botkin (1993).

These characteristics make gap models ideal for development within Microsoft Excel. The model outputs can be shown on the spreadsheet and Excel's Chart functions can be used to graphically represent changes in species composition over time for individual plots. Changes in species composition within the gap unit across a landscape can be represented within the spatial data visualisation worksheet.

5. Application of model to Astroni Crater

5.1. Example of an ASTROMOD simulation

This section presents the results of an ASTROMOD simulation involving all the 3,949 Astroni 25 m by 25 m plots. Primary succession was simulated for 1,000 years and a simple management routine was simulated between 1,000 and 1,150 years. 1,000 years of simulation would allow the species composition to reach an advanced stage of succession, similar to the state the vegetation within the crater would have been previous to any intervention by humans. The forest within the crater has been extensively managed for at least the last two centuries, with the removal of timber and planting of native and alien species. Thus, ASTROMOD simulations from the 1,000 year mark allowed the testing of a simple management scenario. This scenario mimicked the crater's management history so as to result in a similar simulated vegetation distribution and composition to that present in the Astroni crater today. From 1,050 years, the simulation was continued until the 1,300 year mark without any management intervention to investigate the impacts of the current management policy of non-intervention.

Testing of ASTROMOD simulations against observations within the Astroni crater involved a simple comparison of the distribution of the dominant species within each simulated plot with the vegetation map of the reserve. Between 1,000 and 1,050 years, ASTROMOD was programmed to simulate the establishment of the tree plantations, and the extraction of wood via coppicing and logging. This was carried out by the establishment of a determined number of planted species saplings (estimated to be 100 per plot), and preventing any other species from establishing in these plots. When the planted trees reached a certain size (e.g. 20 cm in DBH for *Castanea sativa* plantation) the plots were coppiced. The surviving tree stumps would then produce multiple shoots (the exact number determined stochastically). In the plots that were not coppiced, trees that had achieved a diameter greater than 70 cm were logged. It was assumed that the alien invasive species *Robinia pseudoacacia* and *Ailanthus altissima* were controlled. From year 1,050 onwards, non-intervention was simulated (equivalent to the management strategy since 1987). All species were allowed to establish themselves throughout the crater and no coppicing or logging took place. The subsequent 100 years were simulated to give some sort of prediction for the future i.e. what would the result of 100 years of non-intervention be?

5.2. Comparison of simulated and actual tree species distribution

Particular attention should be given to the location of the ecotonal boundary between the deciduous forest principally dominated by *Quercus robur* and *Quercus petraea*, and the evergreen forest dominated by *Quercus ilex*. When the mapped distribution of the dominant tree species at simulation year 1,050 (Fig. 3. (b)) is compared to the vegetation map (Fig. 3. (e)), one can see that the two maps have similar species distributions. Slight variations occur on the southern side of the crater where the simulated results show that *Quercus ilex* is able to dominate in the lower elevations compared to the actual distribution. The pattern of *Quercus ilex* distribution around the central lava and ash domes is also slightly different, with *Quercus ilex* domination displaced towards a more northerly location (further away from the lake). This anomaly could be attributed to a slightly more xeric simulated environment. A more accurate estimation of soil and water table depth may improve the accuracy of the ecotonal boundary positioning.

The distribution of the simulated planted stands is also relatively similar to the actual distributions. All introduced species are able to successfully establish themselves within the prescribed plantation zones, and survive repeated logging and coppicing cycles. What none of the simulated maps show are the location of the macchia, garrigue and ruderal vegetation communities. Simulation of these vegetation communities would require a different vegetation dynamics model operating on a significantly larger scale.

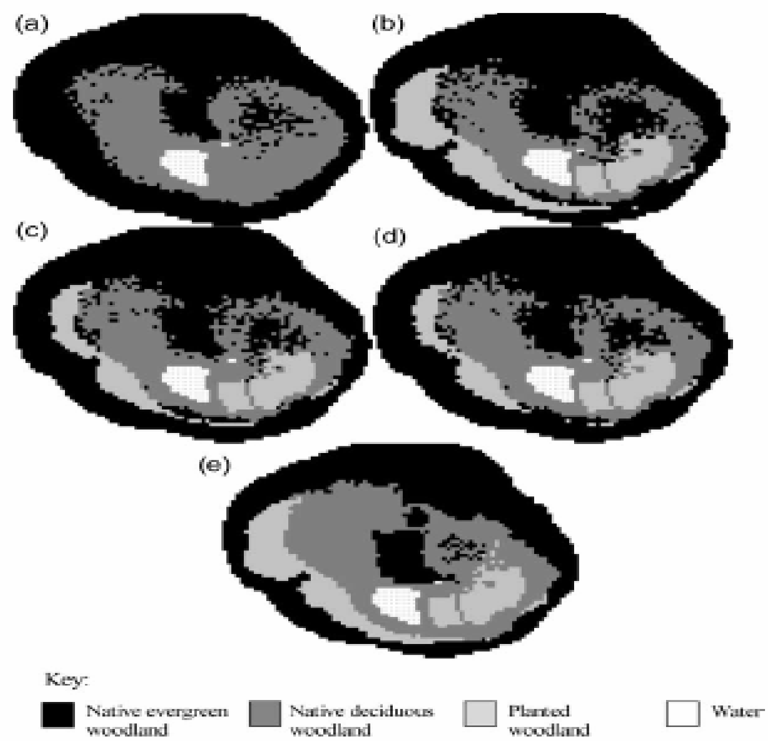

Fig. 3. Simulated dominant species distribution within the Astroni crater (a) before human-intervention; (b) after human intervention; (c) after 50 years of non-intervention; and (d) after 100 years of non-intervention. (e) Present dominant species distribution with the Astroni crater.

When comparing the simulated dominant species distribution at year 1,000 i.e. before human intervention (Fig. 3. (a)) with the year 1,050 (Fig. 3. (b)), one can see that, during the human intervention phase, there is a significant increase in domination by *Populus tremula* within the deciduous oak forest and a slight expansion by *Salix caprea* in the wetter sites. *Fraxinus ornus* is also more prominent both on the lower slopes and the base of the crater. The boundary between the deciduous oaks and *Quercus ilex* also undergoes changes, with the deciduous oaks losing ground, especially to the north and east of the central ash and lava domes. The opening up of the canopy over the 50 year simulation period would have certainly favoured the more r-selected *Populus tremula*, *Salix caprea* and *Fraxinus ornus*. *Quercus ilex* may have been favoured over the deciduous oaks on the evergreen/deciduous boundary because of its capacity to tolerate xeric conditions.

During the “non-intervention” phase (Fig. 3.(c) and 3. (d)), one can see that the deciduous oaks are able to regain dominance in the non-planted areas at the base of the Astroni crater, but they are not able to displace the planted species there. However, *Quercus ilex* is able to occupy a large proportion of the *Ostrya carpinifolia* plantation. This confirms the field survey results (Berardi, 1999) which noted the absence of *Ostrya carpinifolia* saplings in the shrub layer, while *Quercus ilex* saplings where able to establish themselves successfully.

Further analysis of ASTROMOD simulations were carried out by comparing the simulations and the actual survey data of 46 plots within the Astroni crater. This involved a more detailed analysis of species composition, demography and influence of environmental determinants. The tests showed that ASTROMOD was not able to realistically simulate the demography of smaller, sub-canopy plant individuals. Apart from coppiced plots where the canopy was opened artificially, small trees were consistently under-represented in the simulated plots. This result can be attributed to the homogeneity in simulated light intensities below the canopy, which reduced the survivorship of sub-canopy trees. Where the canopy is more regularly opened, for example, in the *Quercus ilex* plots where mortality rates are higher (higher environmental stress / lower maximum age of species), more sub-canopy individuals were able to persist and therefore simulations were more realistic.

6. Improving the modelling

The environmental and vegetation dynamics models were integrated into ASTROMOD over the 1994 to 1997 period. Considerable improvements have since been implemented in all aspects of the modelling. The most significant development that is relevant to ASTROMOD has been PICUS, a spatially explicit 3D-gap model by Lexer and Hönninger (2001). The modelling of the radiation regime is especially advanced, especially in calculating direct and diffuse radiation thought the canopy. This would contribute to more realistic modelling of the sub-canopy layer, and would allow the incorporation of the shrub and herb layer. Improvements in this area could also be achieved by having a nested hierarchy of gap sizes: 4 m^2 for the herbaceous layer; 25 m^2 for the shrub layer; and 625 m^2 for the tree layer. One would use exactly the same growth and environmental algorithms for each layer, with the achievement of a certain plant size allowing shrub and tree species from the herbaceous into the shrub layer, and tree species from the shrub into the tree layer. This method would allow the positioning of tree individuals to be known at a resolution of 4 m^2, and therefore a significantly more realistic simulation of the heterogeneous distribution of light intensities and nutrient concentrations.

Significant improvements in modelling the effects of drought and temperature stress in Mediterranean ecosystems have been made in regional models (e.g. Osborne et al., 2000), but there still considerable deficits in conventional gap models (Bugmann and Cramer, 1998). Similar questions have been raised on modelling the effect of site nutrient status (Lexer and Hönninger, 2001). Chertov et al. (2001) present a promising approach to resolving this issue. They present a model of soil organic matter dynamics determined by three communities of organic-destructors: fungi, actinomicetes and bacteria. This method is appealing since it mirrors the "plant functional type" approach of vegetation dynamics modelling which has had considerable success in modelling systems with limited auto-ecological data (e.g. Pausas, 1999).

Future developments of ASTROMOD will also concentrate on the modelling of contagion. This was not possible in the present study because of limitations in the computing capacity. Contagion can be defined as the influence of a gap unit on its neighbours. The less the dynamics of the modelled forest landscape are a consequence of contagion among the mosaic elements, the more easily the computations of the model are performed (Weinstein and Shugart, 1983). This is the main reason why the majority of gap models avoid the incorporation of contagion, although this is a fundamental aspect of forest dynamics, from seed dispersal to disease and pest distribution, to the spread of fire (Forman and Gordon, 1986).

Several attempts have been made to incorporate spatial interactions within gap models (Smith and Urban, 1988; Urban et al., 1989; Van Voris et al., 1990; Woodby, 1991; Lexer and Hönninger, 2001). The most widely cited spatial gap model, ZELIG (Urban et al., 1989) has a grid of 10 by 10 m plots interacting with each neighbour, while the edge effects of the external plots are eliminated by creating a torus. The principal element of contagion in ZELIG is light, where the reduction in light levels are calculated by taking into account different proportions of leaf weights from neighbouring plots. 50% from the four adjacent grid units and 25% from the four grid units situated in the corners.

An example of contagion functions which could be incorporated into ASTROMOD include regeneration, which is spatially dependent i.e. a species has a higher chance to regenerate in a plot the closer a seed-bearing tree of the same species is to that plot (Chave, 1999). Simulation of fire behaviour is also an important potential component, since there is evidence that fire has determined the state of some vegetation communities in the Astroni crater e.g. the garrigue. A realistic threedimensional description of vegetation is essential for accurate simulation of fire behaviour (Perry, 1998). Thus, linking high-resolution models of vegetation dynamics and environmental conditions with a model of fire behaviour seems to be a promising technique for fire regime simulations. By combining ASTROMOD's capacity to generate detailed vegetation and environmental data with a model of fire behaviour, it would be possible to simulate fire spread patterns and the effects this would have on the vegetation.

Since there are many spatial variables that influence fire regime, attempts have been made to link fire models with spatial data stored in GIS (Perry, 1998). One of the most recent GIS-based developments of fire behaviour models is FARSITE (Fire Area Simulator), a model which spatially and temporally simulates the spread and behaviour of fires under conditions of heterogeneous terrain, fuels, and weather (Finney, 1997). FARSITE enables the user to examine the effects of ignition locations, weather patterns, fuel distribution and type on the spread of fire, and experiment with different crew in fire fighting operations. The GIS raster data required to run simulations within FARSITE include elevation, aspect, slope, fuel type, canopy cover, crown height, crown bulk density, temperature, humidity, precipitation, and wind characteristics. Except wind characteristics, all the raster data can be generated within ASTROMOD, and it would be a straightforward step to link the two models together.

A key factor necessary for improving the reliability of both the environmental and vegetation dynamics modelling is the availability of long-term monitoring data for comparison with the simulated results. Botkin (1993) compared a JABOWA simulation with actual tree allo- metric data from the Hubbard Brook Experimental Forest. Every tree was identified and its DBH measured in 208 10 m by 10 m plots in 1965, 1977, 1982 and 1987. A JABOWA simulation was carried out starting with the 1965 tree measurements, replicating each plots' environmental conditions (including meteorological variations) over the 1965-87 period. The only significant unknown parameter was soil available nitrogen concentration. When 63 kg ha^{-1} to 64 kg ha^{-1} available nitrogen were used in the simulation, modelled and observed total biomass for all plots differed by an average value of only 0.9 %. A benefit of ASTROMOD development is that key elements which determine ecosystem functioning have been identified, allowing the establishment of an appropriate field research strategy in the Astroni crater for long-term monitoring. This includes measuring solar radiation, air temperatures, and soil water content, and how these influence tree species distribution, establishment, growth and mortality. Sixty plots have been established within the crater where long-term monitoring of these variables is occurring.

7. Conclusion

Progress in ecosystem management depends upon the evaluation, diffusion and adaptation of innovative modelling techniques to help us understand the implications of the assumptions we make about ecosystems and the effects of our actions on them. This research has developed complex environmental and ecological models within a cost-effective, user-friendly data handling and visualisation system using Microsoft Excel. Although improvements must be made before practical applications of the model are made, it has been shown that there is no need to use expensive and complex software to develop modelling systems for ecosystem management.

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