A Study of Review on GIS-based Modelling Methods with Relation of Ecology

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Abstract:

Geographical information systems (GIS) are computer-based systems designed specifically to facilitate the digital storage, retrieval, and analysis of spatially referenced environmental data. Coupled with ecological modelling, GIS can provide significantly increased opportunities for detailed environmental resource inventory and analysis and show considerate promise for extensive use in nature conservation. The paper introduces these two concepts and discusses the role of GIS-based modelling in nature conservation focusing on the predictive models for species occurrence, plant community occurrence and habitat suitability. The importance of Digital Elevation Models and their derived properties in these ecological studies is explained. Emphasis is placed on empirical or inductive modelling based on field observations. The generic steps of empirical modelling are described and demonstrated by a case study in Lefka Ori, Crete, Greece. Tools such as fuzzy mapping and geo-statistics have a potential role to play in improving the level of information and therefore in the understanding of species and plant community distribution.

The present review paper is based on the various ecological studies completed on the GIS based modelling methods in the field of changing scenario of geographical structure.

Keywords: DEM, Empirical Modelling, Habitat, Predictive mapping

Introduction:

Maps have always been invaluable tools in ecological studies, providing spatial as well as attribute information, e.g. maps showing species distribution, extent and distribution of reserves, or the distribution of vegetation communities (Wadsworth and Treweek, 1999). The complexity of ecological problems, however, requires a diversity of information from a range of sources as well as analytical techniques that cannot be applied to conventional maps. Until recently the traditional means used for storing spatial information, i.e. the paper map, had to deal with storage limitations and restricted capabilities for updating and analysing spatial data. Those limitations have only recently been overcome with the evolution of computer-aided cartography. Computers have provided the capacity and the speed for the analysis of large and complex databases (Bernhardsen, 2002). Moreover, parallel developments in spatial data processing disciplines, such as topography, photogrammetry, remote sensing and geography, provided the opportunity for different sets of spatial data as well as techniques to be linked together, leading to the final "shaping" of Geographical Information Systems (GIS) (Burrough and McDonnell, 1998).

Ecological data sets have two distinct characteristics if compared to other kinds of data: they are multivariate and location specific. Although historically ecological modellers have focused on changes in time at single sites or small geographical areas, during the past two decades, they have started to incorporate spatial pattern in the models and apply them in large geographic areas (Hunsaker et al., 1993). Most GISs lack the predictive capabilities to examine complex problems, whereas numerically oriented models lack flexible spatial analytic components to respond to the spatial character of ecological problems (Parks, 1993).

The advantages resulting from the fully integrated approach are (Parks, 1993):

- Input variables are defined as continuous surfaces, thus areas different from the average can be recognised in the model;
- Spatially dependent operators such as effective distance can be included;
- Ability to deal with error propagation in the model.

GIS and ecological modelling have been employed in studies of terrestrial, freshwater, and marine ecosystems. Some examples include predicting forest compostition and structure (Ohman et al.2002) mapping benthic habitats (Urbanski and Szymelfenig 2003) and analysis of nutrient loads in rivers and streams (Pieterse et al. 2003)

Nature Conservation and GIS:

Some of the most common GIS applications in nature conservation include identifying and setting priorities either for further action and research (Kiester et al., 1996) or in the context of environmental impact assessment prior to development projects (Bojorquez-Tapia et al., 1995). Moreover, the integration of GIS together with other quantitative techniques for mapping/modelling vegetation communities (Brzeziecki et al., 1995), as well as habitat suitability (Guisan and Zimmermann, 2000) is a promising aspect of this relatively new field.

Habitat Modelling The term “habitat” has been used in many ways in ecological studies. According to Spellerberg (1992), habitat can be defined as “the locality or area used by a population of organisms and the place where they live”. The principles applied to habitat modelling are analogous to the ones for predictive vegetation mapping. Where census is difficult, inferring possible distributions can be an alternative solution in species-habitat studies. Habitat factors should be considered in these studies, since species ranges and richness are often correlated with these factors. Therefore, prediction is possible for areas where reliable maps do not exist. The habitat features assumed to influence species distribution patterns are mapped and subsequently analysed within a GIS.

Predictive models using the habitat-association approach have been employed in ecology to estimate species population sizes, geographical ranges as well as identifying potential impacts of habitat change (Fielding and Bell, 1997; Schwartz et al., 2001). Sperduto and Congalton (1996) used

GIS to locate potential habitat for a rare orchid, *Isotropia medeloides*. Two scenarios were employed: one based on a simple overlay model and another on a weighting scheme after using a chi-square test of the significance of each parameter taken into account. Potential habitat maps were produced and field evaluated to assess the accuracy of the predictive models. The chi-square model was found to be more accurate (78% accuracy) than the equal weight model (57% accuracy).

Predictive Vegetation Mapping:

Franklin (1995) defines predictive vegetation mapping as predicting the vegetation composition across the landscape from mapped environmental variables. The first attempt at predictive vegetation mapping was the work of Kessell in the late 1970s (quoted in Franklin, 1995). He called his approach “gradient modelling”, a term that was adopted by Austin (1987) and refers to the way species distributions respond to environmental gradients. Predictive vegetation studies start with the establishment of a model between the vegetation units and the mapped physical data, followed by the application of that model to a geographic database and over a wide range of spatial scales.

With the advent of GIS and remote sensing techniques as well as the availability of digital maps of environmental variables such as topography, geology and soils, the development and implementation of predictive models has found a wide range of applications in vegetation studies (see for example Millington et al., 2002). The procedure initially involves the determination of the vegetation units using a classification scheme and then mapping the spatial extent of these units over the study area. Vegetation patterns are determined by environmental factors that exhibit heterogeneity over space and time, such as climate, topography, soil, as well as human disturbance (Alexander and Millington 2000).

A number of modelling methods are available and can be classified into three main types (van Etten, 1998):

- Heuristic methods based on a combination of field data and expert knowledge are used to define the important environmental parameters for the vegetation;
- Decision trees attempt to define boundaries in environmental space for different vegetation communities, based on the middle value of a given predictor variable;
- Statistical models employ mainly regression to predict the value of the response variable if continuous, or the probability of class membership of a variable if categorical.

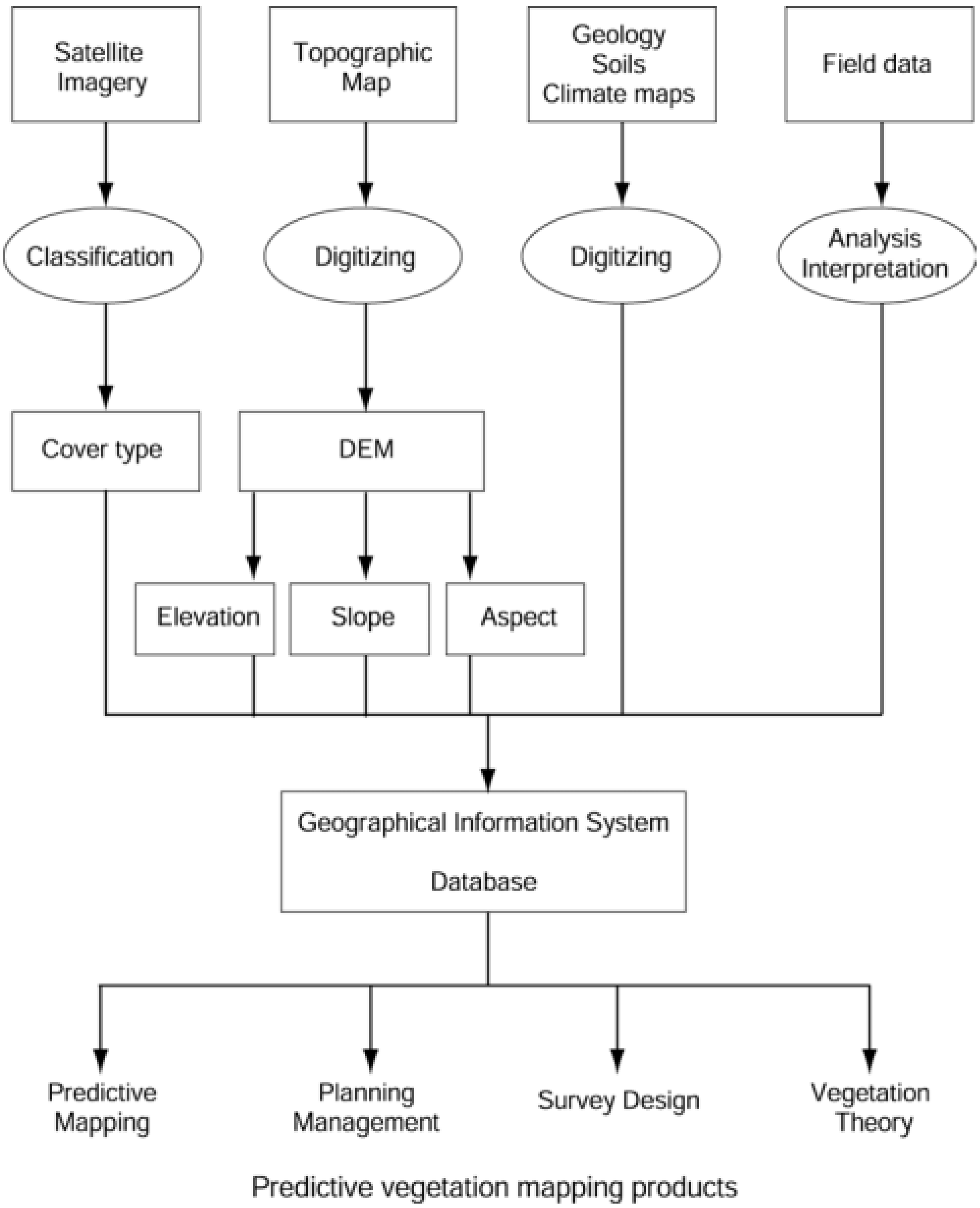

Fig. No.1 Introduction of Predictive vegetation mapping products

In particular regression analysis techniques have been traditionally employed in ecology for determining the relationships between species/communities and environments based on observations at given sites (Jongman et al., 1995). The advances in Generalised linear models (GLM) and generalised additive models (GAM) have led to their extensive application in ecological research as demonstrated by an increasing number of published papers (see review in Guisan et al. 2002).

The community approach has been criticised mainly due to the vague notion of the community concept and the fact that the classification needed in this approach is method-dependant (Wildi, 1998). Moreover, it has been argued that the approach is employed as an alternative in cases where sufficient data to model species distributions are lacking (Franklin, 1995). However, it is from the practical point of view that community modelling is preferable to species modelling. The main reason being that it is difficult to fully integrate the species ‘individualistic’ characteristics into static equilibrium models (Zimmermann and Kienast, 1999). The results of both species and community modelling approaches vary according to the variables used and the data available. For instance, rare species have been modelled with success where adequate information was available (Sperduto and Congalton, 1996). In other cases, however, species models gave accurate results for common but not for rare species under investigation, since the right variables were not chosen (Cherill et al., 1995).

Modelling within a GIS has also been employed to investigate the potential effects of rapid anthropogenic climate change on both species and community distribution. Using climate response surfaces, Huntley et al. (1995) modelled the potential future ranges of eight higher plants in Europe. The study suggests that macroclimate parameters are correlated with the distribution of all eight species at European scale. Brzeziecki et al. (1995) examined the spatial distribution of forest communities in Switzerland under potential climate change. The approach used an empirical vegetation-site model to provide information about current communities’ distribution. A climate-sensitive model was subsequently employed to predict future distributions for two different climate scenarios.

Another tool frequently employed in vegetation studies, which has an important role to play, particularly in ecological sensitive areas such as the Amazon (e.g. Alves et al., 2003) is remote sensing. Based on the spectral reflectance of different vegetation types, the use of multispectral images provide a means for vegetation classification and mapping (Salvador and Pons, 1998; Lillesand and Kiefer, 2000). The basic features and suitability of satellite imagery as a source of data for vegetation mapping have been discussed in Scott et al. (2002) as well as Alexander and Millington (2000). In the past the main criticism to the use of satellite imagery and aerial photography was that neither of these had accomplished the level of detail often needed in vegetation studies (Kalliola and Syrjänen, 1991).

Therefore most of the vegetation studies based on remotely sensed data have performed analysis of the structure and physiognomy of vegetation rather than its floristic composition. However, the present generation of high resolution satellite systems (e.g. IKONOS) generates imagery with nominal resolutions between 1-5 m. This will substantially improve the capability for vegetation and habitat mapping (e.g. Reed 2003). The spatial detail available will be supplemented with the advantages of satellite imagery such as repeat viewing, large area coverage, digital format and good geometric properties (Griffiths et al., 1999).

The role of Digital Elevation Models in the study:

The influence of topography on vegetation patterns is well documented (Franklin, 1995) therefore the use of topographic attributes such as elevation and slope derived from a Digital Elevation Model are among the most common variables employed in vegetation modelling studies (e.g.

Tappeiner et al., 1998). In particular, DEM topography gives better results for community based approach rather than species based approach. As demonstrated by Zimmerman and Kienast (1999) for alpine grasslands in Switzerland, the main reason for that is that species-realised niches are too complex to be modelled using DEM derived topography.

A digital elevation model (DEM) is any digital representation of the continuous variation of relief across space (Burrough and McDonell, 1998). DEMs have many geomorphological, environmental and pedological applications (Moore et al., 1991; 1993). Today, increasing use is being made of digital elevation models (DEMs) within a GIS to obtain a range of terrain attributes. The terrain attributes derived from a DEM can be classified into primary and compound (Moore et al., 1991). The former refer to elevation, aspect and slope while the latter to potential solar radiation, soil properties as well as temperature.

The main data sources for most DEMs are: ground surveys, maps, satellite images and aerial photographs. Global Positioning Systems (GPS) have also been used recently to provide supplementary height data in order to improve model representation of breakline features (Stocks and Heywood, 1994).

Empirical Models for Vegetation Mapping study:

The efficient assessment of biodiversity requires a wide variety of biological, ecological and cultural information. Even in countries like the United States and the United Kingdom, where this information is readily available, it is generally not acquired as part of a co-ordinated environmental management system. As often pointed out, this information is scattered among different organisations in incompatible formats making their location and integration problematic (Griffiths et al., 1999).

The first refers to the design, compilation and use of an inventory of sites of major importance for nature conservation in the European Community (Council of Europe 1985). The second is the recent proposed network of protected sites within the European Union (Council of Europe, 1992).

Efficient decision-making in nature conservation is based on the availability of timely and accurate information. Traditionally the method for deriving this information has been field survey. However, both time and limited resources (i.e. human resources and money) limit the scope of surveys. For example, survey data are inevitably time and location specific. Another limitation on survey results can be imposed by the remoteness of the study area.

An approach with real potential to solve these problems is empirical modelling. The generic steps of empirical modelling is shown in following figure. The first step is a field survey of the entities in question and their environment. Then statistics is usually employed to establish a relationship between the entity (community, species) and some measurable (mappable) environmental variables. This results into a statistical model which is given spatial dimension within a GIS and applied to a wider area.

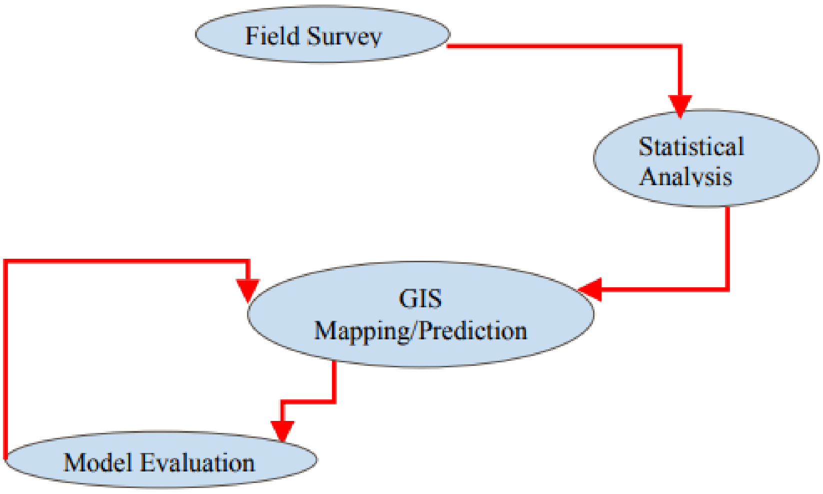

Fig. 2 Approaches of model evaluation

There are many successful applications of this approach to both habitat and vegetation modelling and mapping. For instance, Buckland and Elston (1993) demonstrated a case of empirical modelling in north-east Scotland. The models derived from literature, as well as site data for green woodpecker, redstart and red deer, were integrated with a GIS to measure habitat suitability, thus predicting the species' distribution.

Another study on the Mojave desert in California employed Generalised Linear Models and classification trees to predict the presence of four alliances (Miller and Franklin, 2002) based on topographic and climatic variables. Since empirical models are static, they perform better when used in a species-based approach. The main reason is that species assemblages are more transient than species in geological time, as palaeoecological evidence indicates (Franklin, 1995).

There are also a number of practical considerations that have to be taken into account when employing an empirical approach. First, how applicable is the modelling procedure in a different area or data set, i.e. extrapolation? In other words, how representative is the model for unsampled areas? It has been reported that when a model was applied to an area other for which it was developed its performance was reduced (e.g. Carmel et al., 2002).

Empirical models relating vegetation composition to measured site variables are based on ground samples. These samples of predetermined area, located subjectively in order to represent ideal vegetation types, inevitably comprise a small part of the mapped region (Davis and Goetz, 1990).

Another important consideration related to variable selection when extrapolating at a landscape level is the effect of the spatial scale of the study.

Generally, the number of important variables decreases as the scale of the study becomes coarser. This is due to the fact that some variables change more than others when the scale changes (Mentemeyer and Box, 1987).

When extrapolating species distribution in space, direct gradients (i.e. those that regulate physiological processes but not consumed by plants) or their surrogates should be used rather than indirect gradients (i.e these that have no direct influence on plant growth but are correlated with resources and regulators). The reason being that the latter, according to Austin and Smith (1989), are complex and location specific.

Although physical factors may explain species richness patterns better than history, as demonstrated by Birks (1996) for the flora of the Norwegian mountains, it has been suggested that the inclusion of disturbance history when mapping actual or potential vegetation, is necessary (Franklin, 1995). Where a long series of records have been available disturbance factors has been included in the modelling process (e.g. Carmel et al., 2001). However, it is generally admitted this type of information is rarely available for incorporation into a GIS (Norton and Nix, 1991).

Conclusion

The conceptual issues, methods and limitations of these models have been thoroughly reviewed by Franklin, (1995), Guisan et al. (2000) and Scott et al. (2002). During the last 30 years parallel developments in computer based cartography and modelling have improved our abilities to predict species and/or community distribution and therefore extend ecological research whether for nature conservation or planning applications. The main and indispensable tool for this purpose is a GIS due to its ability to merge data from different sources (i.e. field surveys, printed or digitised maps, remotely sensed imagery), construct spatial models or incorporate models build externally.

Moreover, other tools of spatial analysis are gradually being built into GIS environments providing new insights in ecological problems. For example, geostatistical methods for optimal interpolation have great potential for ecological applications. Although primarily used in soil science (Goovaerts, 1999; Webster and Oliver, 2001) geostatistics have been used to determine the spatial relationships between canopy openness and seedling performance in a secondary lowland forest in Borneo (Bebber et al. 2003), to examine the effects of migratory grazers on spatial heterogeneity of soil nitrogen properties in a grassland ecosystem (Augustine and Frank 2001) and to determine the patterns of diatom distributions at Lake Lama, Central Siberia (Kienel and Kumke, 2002).

The use of geo-statistics in combination with GIS has been advocated by Burrough (2001) and has been facilitated by the current availability of geostatistical routines/extensions within GIS software such as Idrisi and ArcGIS. In addition to geo-statistics most GIS packages have also inbuilt routines for fuzzy set theory (Zadeh, 1965). Fuzzy sets are inexactly defined classes that characterise an attribute or phenomenon that for various reasons does not have sharply defined boundaries

(Burrough and McDonnell, 1998). Fuzzy methodology has become an invaluable tool when dealing with spatial uncertainty in ecology (see review by Hunsaker et al., 2001).

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