# FUZZY CLASSIFICATION OF DIGITAL ORTHOPHOTOS FOR SPATIO-TEMPORAL LANDSCAPE MODELLING

Wim J. Droesen and A. Peter van Deventer
**Grontmij Geogroep bv**, Roosendaal, the Netherlands

Mark van Til
**Amsterdam Water Supply**, Amsterdam, the Netherlands

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The paper describes the process of conceptual and concrete digital landscape modelling based on digital photogrammetry. The methods are integrated in a high resolution monitoring system that is able to represent both discrete and continuous terrain features, i.e. objects and fields respectively. The objects are constructed through crisp image interpretation techniques, while continuous spatial variation is interpreted by fuzzy classification. The system is successfully applied for the mapping of vegetation dynamics in the Amsterdam Waterworks Dunes.

## 1 INTRODUCTION

In the last decade GI-systems have become a standard component of the instrumentation in landscape ecological research (e.g. Turner and Gardner, 1990; Haines-Young et al., 1993; Johnson, 1990). For a longer period remote sensing data have been recognised to be an indispensable source of information for the landscape modeller. Initially, analogue aerial photographs were used. Nowadays digitised aerial photographs with a resolution less than 1 metre and other digital remote sensing data such as satellite images are frequently used (Quattrochi and Pelletier, 1990).

The digital elaboration of aerial photographs yields products with a high geometric accuracy, like topographic maps and digital elevation models. When additionally to the geometric corrections some radiometric corrections are applied, digital orthophotos are produced ready for quantitative evaluation. These orthophotos can be treated like any remotely sensed image. Consequently, digital interpretation techniques can be applied to obtain all sorts of high resolution thematic information.

The availability of GI-systems for a structured processing of environmental data and digital high resolution image processing as a tool for spatial data acquisition opens new possibilities for the modelling of natural landscapes. However, the application of these techniques not only facilitates the construction process of a digital landscape model, but also brings about the need to reconsider the concepts underlying the modelling process (Haines-Young et al., 1993). While working with GI-systems and remote sensing, ecologists often adhere to concepts and working methods, whereby the digital environment is utilised but not fully exploited. The objective of this paper is to introduce some new concepts for landscape ecological modelling which enable the construction of digital landscape models that more closely represent reality compared to most conventional landscape models.

### 1.1 Landscape Monitoring System

The process of ecological conceptualisation of a landscape (i.e. structure, function and change) to a discrete representation can be subdivided into several levels of abstraction (fig 1). Kemp (1993) terms the models on the first level *geographic models*. Geographic models are conceptual models used by modellers 'as they evolve an understanding of the phenomenon being studied and extract its salient features from the background of infinite complexity in nature'. Because we focus on ecological features in this paper, it is more appropriate to term these type of conceptual models *landscape-ecological (LE) models*.

The second level of abstraction is represented by *spatial models*. Conceptual spatial models are formally defined sets of entities and relationships used to discretize the complexity of landscape-ecological reality (Goodchild, 1992). The entities in these models can be measured and the models completely specified. On the next level data structures describe details of specific implementations of spatial data models (Molenaar, 1994). Data structures and lower data layers are considered to be part of the instrumentation.

The spatial model has to follow from the specifications in the landscape-ecological model. However, in practise one works usually the other way around, starting from the spatial models readily implemented in commercial GI-systems. In general these spatial models do not provide sufficient functionality to represent complex landscape-ecological systems satisfactorily. Moreover the creativity of the modeller is confined. In an ideal situation landscape modellers in search of appropriate analytical tools and spatial modellers lacking an ecological background interact to produce a seamless coupling between the two modelling steps.

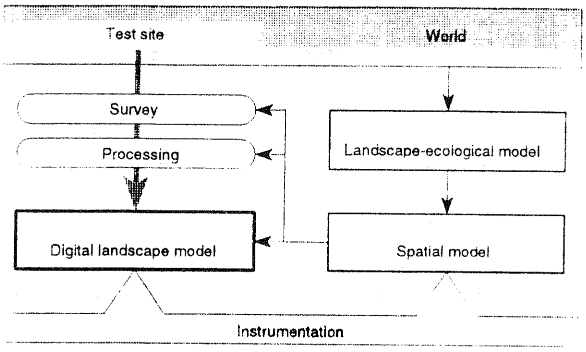

Fig. 1. Process of conceptual and concrete landscape modelling.

So far only conceptual models have been dealt with. The next step is the construction of a concrete or *digital landscape model* according to the specifications originating from the conceptual spatial model (fig 1). The specifications concern the implementation of the spatial model with some data structure, and the surveying and processing of the actual data, eg. digital photogrammetry.

## 2 HYBRID SPATIAL MODELLING: 'FIELDS IN OBJECTS'

Crucial in the development of a monitoring system is the specification of a spatial data model, which enables a proper representation of all features of interest. In spatial information processing two major approaches exist for the conceptual representation of spatial systems, the field and object respectively.

A (physical) *field* is a feature which is contiguously distributed over space and time. In a field the strength of the interacting forces is a function of the position within the field and the resulting pattern can also be expressed in terms of position dependent field values. Examples of terrain features with a field characteristic are relief and groundwater table and the gravity field. Also the electromagnetic radiation emitted or reflected by the earth surface and detected by human vision and remote sensing techniques is a field. For the representation of fields several data structures are available retaining a contiguous character, e.g. TIN, contour models and rasters.

As opposed to the field approach, the object-structured approach applies to discrete terrain features. The *object* approach assumes that the Earth's surface is populated with spatially interacting discrete units. Each unit or object has its own behaviour. The pattern resulting from these processes can be expressed by the spatial distribution and the state of the objects. Evident objects are individual plants or animals, but also less tangible spatial units like plant communities can be considered as objects.

Many landscape-ecological concepts use discrete spatial units to structure a landscape pattern. Kotliar and Wiens (1990) term their elementary units patch and define it as 'a nonlinear surface area differing in appearance from its surroundings'. Zonneveld (1989) introduces the term 'land unit' for 'an ecological homogeneous tract of land at the scale of issue'. All methods guiding the landscape ecologist in determining appropriate objects for the landscape under study have in common that the object has to be internally homogeneous in some respect and externally heterogeneous. Consequently, in the object approach spatial variation is modelled at the objects' boundary.

Two opposite approaches for the spatial modelling of natural landscapes have been introduced, the field and object respectively. Because natural landscapes often show both continuous and discrete variation in space and time, they are not properly represented in only one of the two alternatives. In order to be able to describe continuous and discrete variation simultaneously, a hybrid terrain description allowing the location of fields in an object is suggested. For example the distribution of solitary shrubs in a varying herbaceous vegetation can be modelled this way.

There is, however, no practical application yet of this hybrid approach known to the authors. This is surprising, because many landscape-ecologists recognise the existence of both discrete and gradual transitions in one landscape type. Moreover there is a strong analogy between the approach of fields in objects and the landscape-ecological concept of patches in a matrix (Forman and Godron, 1989). In this concept non-patch areas are called matrix when the following three criteria are met:

1. relative to the patchy area the non-patch area is more extensive,
2. the non-patch area is highly interconnected, and
3. controls many of the dynamics in the landscape.

Consider again the example vegetation, where shrubs form patches. Due to the criterium of more or less sharp boundaries around patches obviously not the whole landscape has to be patch covered. In the example the rest-area or non-patch covers the herbaceous vegetation. This non-patch typically meets the criteria for a matrix, because it covers most of the area and constitutes a single area. Moreover the omnipresence of the herbal vegetation determines the conditions for the germination and growth of shrubs and as such controls landscape development. Obviously, the patches are best represented by objects, while the continuous character of the matrix should be modelled as a field.

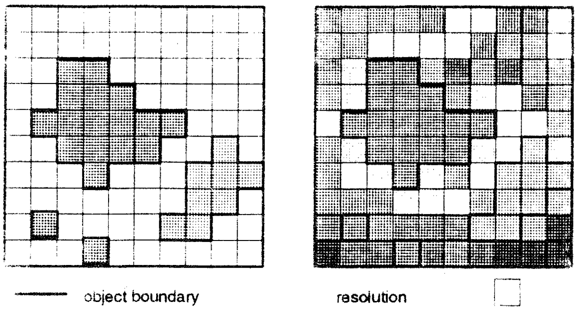

Fig. 2. The concept of fields in objects. One of the three different object types (left) retains its field character (right).

In the previous section it appeared that the modelling of fields in objects is a two step process. In the first phase the discrete terrain features are represented by objects (fig. 2left). In the second phase the objects covering continuous terrain features have to recover their field character. This can be achieved through the definition of a field within the object (fig. 2right). Obviously, internally homogeneous objects remain discrete. Because of the construction process, where a field is created within a heterogeneous object, the concept is called 'fields in objects'. Indeed this concept enables the modeller to represent the notion of objects located in a field, like the distribution of solitary shrubs over a continuously varying herbaceous vegetation.

In the next sections we will elucidate the construction of fields and objects with digital photogrammetry.

## 3 IMAGE PROCESSING AND INTERPRETATION

### 3.1 Production of digital orthophoto mosaics

A typical list of processing steps in the transformation of analogue photographs to digital orthophoto mosaics is scanning, radiometric correction, geometric correction and mosaicing. It is no problem to obtain pixel sizes and positional accuracies better than 1 metre. The radiometric correction is discussed in more detail.

Density variations in a photograph are not solely related to variations in terrain conditions. Factors influencing the density variation having nothing to do with the actual terrain characteristics are termed extraneous effects (Lillesand and Kiefer, 1987). Extraneous effects are of two general types: geometric and atmospheric. The magnitude of geometric factors varies structurally over the image while atmospheric effects are constant throughout the image. Obviously, these effects prevent false colour photographs from an accurate quantitative interpretation.

Clevers and Van Stokkom (1992) present a method to undo false colour photographs from all extraneous effects in order to derive reflectance factors. However, the method requires some information on camera and film characteristics and reference measurements in the field, which are usually not available. For classification purposes relative differences in density, which can be attributed to differences in the terrain, suffice. The latter is achieved by only removing geometric deviations in density. Lilesand and Kiefer (1987) enumerate some important geometric effects influencing film density:

- light fall-off caused by a geometrically based decrease in illumination at the film plane with increasing distance from the centre of the photograph.
- differential scattering by the atmosphere.
- non-lambertian reflection by natural objects.
- differential shading caused by relief in the vegetation cover, especially shrubs and trees.

Contrarily to the first two effects which are indifferent to terrain cover, the latter two factors are dependent on the terrain surface characteristics, e.g. the deviations are higher for woody vegetation than herbaceous vegetation. We applied a two dimensional second order polynomial function to correct for these deviations. The parameters are obtained by regressing the function through an extensively sample set obtained in herbaceous vegetation.

### 3.2 Crisp and fuzzy image classification

Radiometrically corrected orthophotos are ready for digital image interpretation. A straight way of interpreting digital images is the regression of spectral data with quantitative variables measured in the field like biomass and vegetation cover. Because the spectral patterns obtained from natural scenes are usually very complex, classification seems a more robust interpretation technique. Unfortunately remotely sensed data have tended to be crisply classified regardless of whether the vegetation exists as a well defined mosaic or as a series of continua (Wood and Foody, 1989). Consequently, many classification errors can be attributed to artificial boundaries in an image where in reality gradients exist. Crisp classification has to be treated with some caution in patterns of natural landscapes. Crisp classification is particularly suited to construct objects of different object classes.

In natural landscapes a continuous type of classification has to be applied to accommodate the quantification of ecological gradients. A proper representation of gradients is of ecological importance, because these situations often posses high natural values. The notion of continuous classes can be expressed with the mathematical concept of *fuzzy classification* (Wood and Foody, 1989; Blonda et al., 1991).

The process of image interpretation holds a number of hierarchically ordered classification steps following from a land-cover hierarchy. An example hierarchy is depicted in figure 3. On the first level vegetated and non-vegetated areas are distinguished. Because the cover types road and water can be easily derived from topographic maps, the only non-vegetated class to be isolated in the image is 'blond sand'. Hence, the isolation of blond sand is subject of the first interpretation step. The second step involves the subdivision of the vegetated area in woody and herbaceous vegetation. The third phase deals with the subclassification of wood into several species or species groups. Finally, the herbaceous vegetation is subdivided in structural types in the fourth phase.
Given the spectral and geometric resolution of the applied image and the appearance of the land cover types or classes in the terrain, one has to determine whether the class has a crisp or fuzzy character. Consider for example false colour images with a resolution of 0.5m, than the classes wood, herbaceous and sand are presumed to form discrete objects. Hence, the crisp classification of the image to the three classes deals with the estimation of a triple of membership values ($MV^{wood}$, $MV^{herbaceous}$, $MV^{sand}$) for each image pixel, where only the values 0 and 1 are allowed for no membership and full membership respectively. For instance the vector (0,0,1) means that the pixel is covered with sand. The subclassification of wood to species types is performed in a crisp classification applying texture features.

Subsequently, we want to quantify the continuous internal variation of the herbaceous cover class through fuzzy techniques. The variation in herbaceous vegetation structure is categorised in five classes $\mathbf{hs} \in \{hs_1, hs_2, ...hs_5\}$, which were qualitatively described as prototypes (table 1). In the terrain some sites will show a high resemblance with only one class, while others have properties belonging to two or more of these classes. Typically, these partial memberships can be quantified in a fuzzy classification, where the resemblance of a site with a class is indicated by a membership value $MV_{\mathbf{hs}} \in [0,1]$. Hence a site is characterised by a vector of five membership values ($MV_{hs1}$, $MV_{hs2}$, $MV_{hs3}$, $MV_{hs4}$, $MV_{hs5}$). For instance the vector (0, 0.6, 0.4, 0, 0) indicates that the site has nearly equal resemblance with $hs_2$ and $hs_3$ and no similarity with $hs_1$, $hs_4$ and $hs_5$. The problem of fuzzy image interpretation is now to estimate a vector of membership values for each image pixel covered with herbaceous vegetation. A detailed description of these estimation methods captured by a the supervised hierarchical classification system is reported by Droesen et al. (1995).

Tab. 1. Description of the herbaceous structural subclasses (hs) (after Assendorp and van der Meulen, 1994).

**hs1: Thin grass/herb cover with blond sand**
Blond sand, i.e. sand with negligible amount of organic matter, has, by far, the largest contribution in this coverage type. It is however accompanied by pioneer plant types. Herbs are annual as well as biennial. Grass types are mainly solitary and clonal which react more or less positive to wind activity. Tussock forming grass types can be present.

**hs2: Intermediate herb/moss cover with grey sand**
Largest contribution to the overall coverage is with mosses who react more or less positive to or can sustain some geomorphological activity. Bare grey sand, i.e. sand with organic matter content, has a substantial contribution to the overall coverage. Herbal plant types are annual and biennial with locally some perennials. Some woody plants at the sub-pixel level can occur, grasses are solitary and tussock forming.

**hs3: High moss cover**
A total coverage of the soil with mosses and lichens, very locally with annual and biennial herbs. Grasses are nearly absent.

**hs4: High moss and low grass cover**
The soil is totally covered with mosses combined with a low herbaceous vegetation. Herbs and grasses are mainly small though larger woody plants at the sub-resolution level can occur.

**hs5: High grass/herb cover with litter**
Mainly grasses and perennial or clonal herbs cover the soil completely. The herbs are partly woody plants at the sub pixel level. Dead ectorganic matter determines partly the nature of this type.

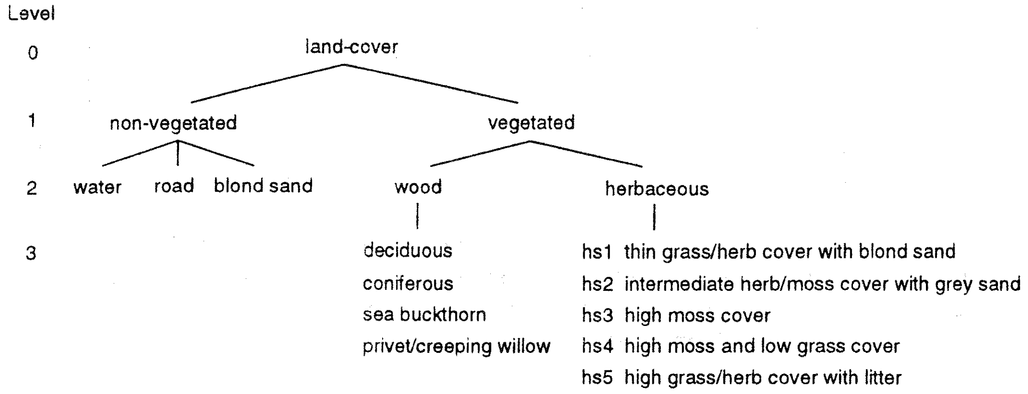

Fig 3. Example land cover hierarchy.

### 3.3 Aggregation of fuzzy data

The image interpretation in the previous section yields a 7-fold vector of membership values ($MV_{sand}, MV_{hs1}, MV_{hs2}, MV_{hs3}, MV_{hs4}, MV_{hs5}, MV_{wood}$) for each image pixel. Although it is possible to detect temporal changes in membership values on the pixel level, it is usually better to aggregate the membership values to larger cell sizes in order to minimize the effects of classification errors on the temporal analysis.

The aggregation of fuzzy data is dealt with by Klir and Folger (1988). First step is the calculation of a *pseudo-frequency* N(**c**) for each state of the aggregate **c** $\in$ {sand, hs1, ..hs5, wood}. Since values of N(**c**) need not be whole numbers, it is better not to use the therm frequency. In order to accomplish that each cell contributes equally to the pseudo-frequencies the membership values of a single cell have to sum to one. If not so, the membership values have to be normalized in this sense. The pseudo-frequency for each state or class is calculated as the sum taken over all cells within the segment defining the spatial extent of the aggregate.

The pseudo-frequencies are now used to estimate the value of a fuzzy measure, i.e. possibility or probability, indicating the strength of the relationship between the aggregate and a class. The (pseudo-)probability distribution is calculated by dividing a pseudo-frequency by the sum of all pseudo-frequencies:

$$p(\mathbf{c}) = N(\mathbf{c}) / \sum_{\mathbf{z} \in HS} N(\mathbf{z})$$

The aggregation did not change the vector of attribute names, unlike their measure for quantification, which changed from membership values to pseudo-probability values ($p_{sand}, p_{hs1}, p_{hs2}, p_{hs3}, p_{hs4}, p_{hs5}, p_{wood}$). Note that the link between the concept of fuzzy sets and fuzzy measures is effectuated by the pseudo-frequency distribution. See table 2 for an example.

Tab. 2. Illustration of probability (p) distribution estimates derived from a pseudo-frequency distribution N calculated over 5 cells.

| **c\cell** | 1 | 2 | 3 | 4 | 5 | N(**c**) | p(**c**) |
|---|---|---|---|---|---|---|---|
| sand | 0 | 0 | 0 | 0 | 1 | 1.0 | 0.20 |
| herb1 | 0.2 | 0.3 | 0.5 | 0 | 0 | 1.0 | 0.20 |
| herb2 | 0.8 | 0.7 | 0.1 | 0 | 0 | 1.6 | 0.32 |
| herb3 | 0 | 0 | 0.4 | 0 | 0 | 0.4 | 0.08 |
| herb4 | 0 | 0 | 0 | 0 | 0 | 0.0 | 0.00 |
| herb5 | 0 | 0 | 0 | 0 | 0 | 0.0 | 0.00 |
| wood | 0 | 0 | 0 | 1 | 0 | 1.0 | 0.20 |

## 4 QUANTIFICATION OF ECOLOGICAL PROCESSES

By the proposed aggregation procedure the objects and fields are converted in a field. In this field the presence of each vegetation type is expressed by a probability, resulting in a vector of 7 probability values ($p_{sand}, p_{hs1}, p_{hs2}, p_{hs3}, p_{hs4}, p_{hs5}, p_{wood}$). Obviously, this vector specifies a point in a 7-dimensional vegetation space, where each vegetation type defines an axis of this space.

Changes in the vegetation composition on a specific site (x,y) from date t to t+Δt result in a move through this space from point $(p_{sand}, p_{hs1}, p_{hs2}, p_{hs3}, p_{hs4}, p_{hs5}, p_{wood})^{t}_{xy}$ to point $(p_{sand}, p_{hs1}, p_{hs2}, p_{hs3}, p_{hs4}, p_{hs5}, p_{wood})^{t+\Delta t}_{xy}$ respectively. Each cell shows a specific change in the vegetation space and from all these movements general processes of vegetation change can be calculated. Because a single vegetation composition on different sites might develop into different directions, each vegetation composition on time t relates to many possible vegetation compositions on time t+Δt. This set of possible future compositions forms a cluster in the vegetation space. The cluster of possible vegetation compositions can be conveniently described by its point of gravity and standard deviation.

## 5 CONCLUDING REMARKS

The paper presents some concepts for the construction of a high resolution landscape monitoring system based on:

- a tailored spatial model called 'fields in objects',
- radiometrically corrected orthophotos, and
- a supervised hierarchical classification system applying crisp and fuzzy mathematics.

These concepts enable the representation of both discrete and continuous terrain features in space and time. Because many natural landscapes show a mosaic of gradual and discontinuous spatial and temporal changes, digital landscape models constructed according to the proposed methods are a more adequate representation of reality compared to conventional methods based on the concept of land units and patches.

The proposed methods are successfully applied for the modelling of the vegetation structure of the catchment area of the Amsterdam Water Supply, i.e. the Amsterdam Waterworks Dunes (Droesen et al., 1995). This dune area counts as one of the most complex natural landscapes in the Netherlands considering its geomorphology and vegetation. Two false colour photographs on a scale 1:5000 and a 10 year interval were transformed into digital orthophotos with a resolution of 0.5 metre. In a step wise supervised classification the crisp and fuzzy classes are interpreted conform the example land cover hierarchy in figure 3. Due to the hierarchical set up of the interpretation process, all land cover classes could be accurately classified. The classification accuracy for all classes varied between 90 and 95 percent. During the presentation the results of the case will be shown and discussed.

The monitoring system yields a wealth of high resolution land cover information providing the Amsterdam Water Supply a sound starting point for a wide range of activities like landscape ecological research, fauna habitat analysis and policy making with respect to hydrological management, nature management and recreation.

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The authors can be contacted at **Grontmij Geogroep bv**,
PObox 1747, 4700 BS Roosendaal, the Netherlands.
E-mail: wdroesen@geogroep.mhs.compuserve.com
Phone: +31-165-575859
Fax: +31-165-568013