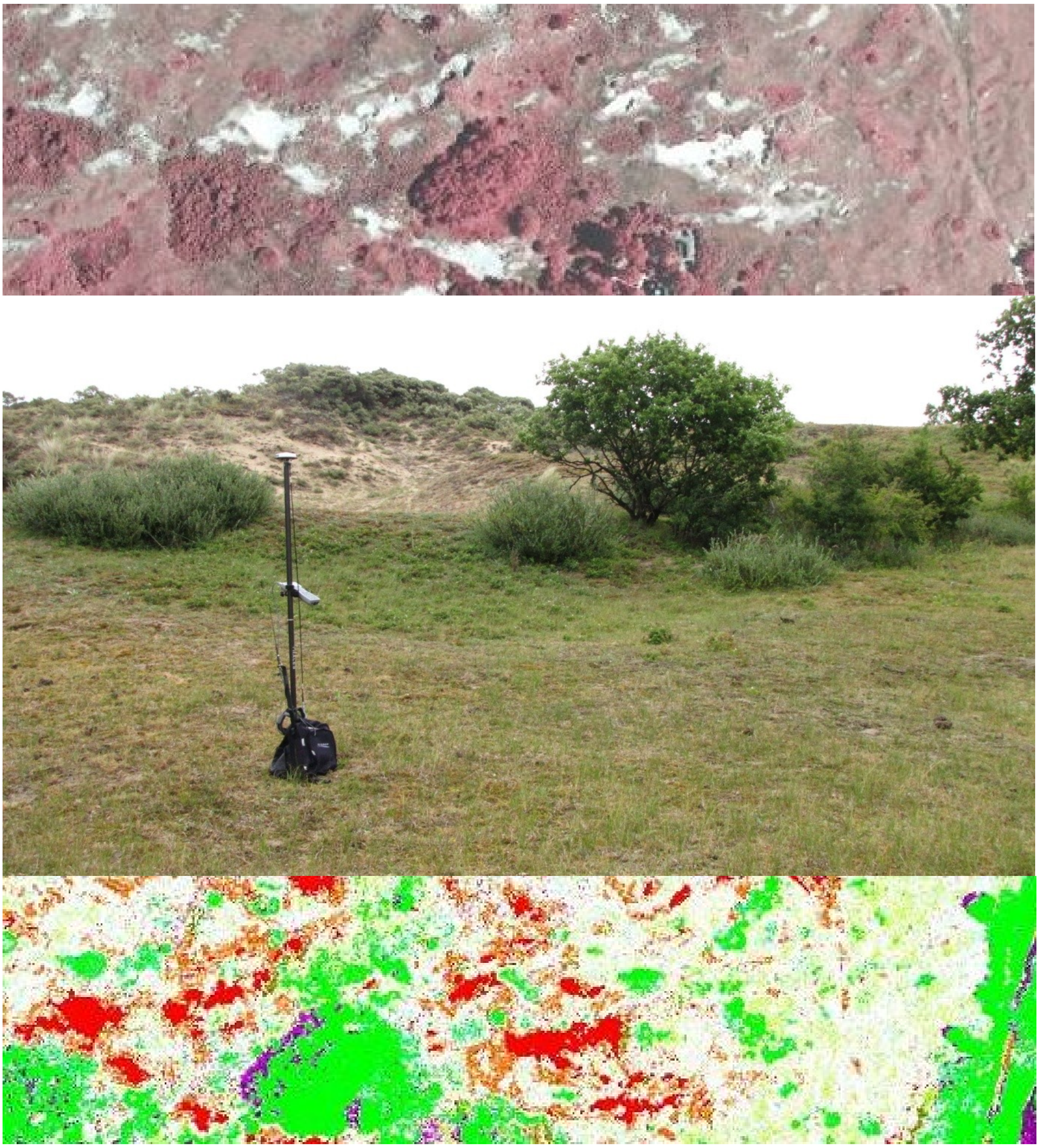
Classification of pattern and process in small-scale dynamic ecosystems; with cases in the Dutch coastal dunes

Assendorp, D.

Publication date
2010

Document Version
Final published version

Classification of pattern and process in small-scale dynamic ecosystems; With cases in the Dutch coastal dunes.



Dan Assendorp

CLASSIFICATION OF PATTERN AND PROCESS IN SMALL-SCALE DYNAMIC ECOSYSTEMS; WITH CASES IN THE DUTCH COASTAL DUNES

ACADEMISCH PROEFSCHRIFT

ter verkrijging van de graad van doctor
aan de Universiteit van Amsterdam
op gezag van de Rector Magnificus
prof. dr. D.C. van den Boom
ten overstaan van een door het college voor promoties ingestelde
commissie, in het openbaar te verdedigen in de Aula der Universiteit
op vrijdag 19 november 2010 te, 13:00 uur
door

DAN ASSENDORP

geboren te Velsen

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ACKNOWLEDGEMENTS

The research for this dissertation started in 1991, the actual writing in 2005. Therefore, it is not surprising that many people have to be thanked for helping and supporting me.

First of all I would like to thank Jan Sevink, my promotor, who immediately encouraged me in taking the opportunity to complete my years of research and projects in the dunes. Our discussions on the functioning of the landscape and his critical reading of my manuscript were inspiring and of great help.

After years of going different ways, it was once more pleasant and challenging to receive the thoughtful ecological critics of Annemieke Kooijman. In the final phase of writing this dissertation the enthusiastic support of Emiel van Loon was crucial in keeping up the spirit and helping me with the mathematics.

This dissertation could not have been written without Wim Schurink's the everlasting will to understand the problem and translating it to the DICRANUM application. The faith of Hans Lucas that the aerial photo projects eventually would succeed was inspiring and essential for the production of the vegetation structure maps.

The first developments in understanding the fuzzy character of landscape were not possible without Wim Droesen's cooperation and long pleasant discussions in Wageningen, Amsterdam and Vogelenzang. During the early stages of this project the initiatives and support of Frank van der Meulen were crucial. Constant factors in the support from the dune companies were Harrie van der Hagen and Mark van Til.

I would also like to thank the board of van Hall Larenstein for giving me the time and the opportunity to finish this apparently everlasting mission. The confidence and patience of Jos Wintermans gave me the calmness to stay focused on producing the chapters. Without the response and support of all my colleagues of Land and Watermanagement and Forestry and Nature Management, I would not have succeeded in finishing this dissertation. Special thanks for Mia Corbeek for understanding that my focus was not always on students. The endurance of Giel Bongers and Hedwig van Loon in hearing my stories on dunes and photos was of great help for me. Freek Vos and Jack Schoenmakers always had some time to give me tricks and tips on GIS.

The everlasting interest and confidence of Rob Assendorp was an important motivation for me to hold on to science.

Maarten Assendorp and Sanne Assendorp were of great help in giving me the time and the quietness to work in their living room and on their computer. Hidde, thank you for giving me big smiles and distracting me to less serious matters.

Without the loving support and stimulation of Jundy Menke the conclusion of this dissertation would have been written much later.

My sincerest thanks are for Henk Assendorp and Agi Geervliet who gave me my first map of the dunes and initiated my passion for dunes and landscape.

Dan Assendorp
Duiven, June 2010

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1
THE SERIAL LANDSCAPE MODEL, A CONTINUUM CONCEPT FOR SPATIO-TEMPORAL LANDSCAPE MODELLING

1.1 Introduction

Landscape ecology is the basis of this thesis, of which the primary subject is the classification of landscape pattern and process. Motive for this study is the necessity to better understand the structure and functioning of landscape, and the need for soundly based landscape management plans. In landscape ecology, the classification of pattern and process was mainly confined to static, crisp land units (e.g. Zonneveld, 1989). This thesis questions the more static approach and aims at the definition and application of new concepts, techniques and related management approaches. The question was induced by the development of techniques and materials that allow for surveying spatial and temporal dynamics of landscape with increasing detail. The developments are mainly in the field of remote sensing and digital image interpretation.

The general object of study of this thesis is the small-scale dynamic ecosystem (see Frame 1-1). Within the European context these systems have a high natural value. This is due to their high natural dynamics, resulting in a landscape with highly varied habitats and thus a high potential biodiversity. The small-scale dynamic ecosystems are primarily marginal landscapes and unsuited for reclamation and economic functions. These landscapes are more or less 'left over' and refuges for nature. Given the limited economic potential of these areas and the need for inventory and evaluation tools in support of their nature management, it is obligatory to develop and apply cheap and efficient techniques for monitoring. Remote sensing and digital image interpretation are such techniques (Van der Hagen and Van Til, 2001).

Remote sensing and digital image interpretation are wide spread methods to survey landscapes (Quattrochi and Pelletier, 1991; Griffith & Lee, 2000; Griffith & Mather, 2000; Groom et al., 2006). Survey or classification of landscape is carried out for a variety of purposes such as land evaluation (Zonneveld, 1989; Mulders & Jordens, 1993), land use planning (Stefanov et al., 2001; Randolph, 2004), (landscape) ecological research (Hall et al., 1991; Doing, 1995; Zonneveld, 1995) and nature management (Garbulsky & Paruelo, 2004; Carranza et al., 2008; Alexandrides et al., 2009). For a thorough discussion of remote sensing and digital image interpretation reference is made to several specialized textbooks (Campbell, 2006; Lillesand et al., 2008; National Research Council, 2008) and review papers (Groom et al., 2006) on this matter.

In the case of nature management high-resolution images like digital orthophotos obtained with airborne sensors are used (Van der Hagen & Van Til, 2001; Provoost et al., 2004; Provoost et al. 2005). These images, with resolutions ranging from 0.5m to several cm's and representing the Earth surface in the visible and near infrared spectrum, are especially useful in monitoring small-scale dynamic ecosystems. Great advantage of these images is that they can be easily compared with digital orthophotos produced on the basis of traditional analogue false colour infrared air photos. This makes it possible to perform multi-temporal analysis over longer ranges of time because traditional false colour infrared air photos are available over a longer span of time.

It is the purpose of this thesis to develop and test a methodology for the monitoring of small-scale dynamic ecosystems, based on high-resolution digital images. Important aspect of the thesis is the relation between landscape, data, techniques, and concepts. Basic concept is the Serial Landscape Model, introducing three dimensions with equal importance for the understanding of the functioning of landscape. These dimensions are time, space and attribute.

Before the Serial Landscape Model is introduced and elaborated in section 1.3, first some preliminary remarks are made on the classic approach of space, time and attribute in landscape ecology and vegetation science and its limitations (see section 1.2). Some first implications of classification with the Serial Landscape Model are given in section 1.4 after which the aim and objectives of the thesis are presented (section 1.6). Dry coastal dunes, being the particular object of study of this thesis, are shortly introduced in section 1.5. This chapter concludes with the structure of the thesis (section 1.7).

1.2 The classic approach in landscape and vegetation ecology and its limitations

Zonneveld (1995) extensively described the classic approach in landscape ecology. Its general objective is to understand the landscape as a whole, focusing on spatial patterns and relations. The method followed is to characterise discrete land units and describe the relation between parameters and attributes, such as geology, relief, soil, vegetation and land use, within the land unit (topologic relations) and the spatial relation between the land units (chorological relations). The temporal aspect in landscape ecology is recognised but mostly approached from a static landscape perspective. Observations on chorological relations between land units like lateral groundwater flow, seed dispersal or adjacent landforms (e.g. erosion – accumulation) are translated into processes and landscape dynamics.

In vegetation ecology, it is customary to construct succession series based on sequential relevée observations (see Table 2-1) and there is a good tradition in analysing temporal characteristics of vegetation. The traditional idea of the succession of vegetation through discrete states (Clements, 1916) is the leading concept though the observation that vegetation is spatially and temporally continuous has always been a topic in the scientific debate. For example Gleason (1939) states: "*The postulated uniformity of the community is therefore far from absolute*". The production of vegetation maps is common practice. However, as in landscape ecology, the temporal aspect is mostly spatially approached: observed plant communities are placed in series on the basis of their spatial position.

In landscape ecology as well as vegetation science, the classes used to describe spatial as well as temporal units are discrete. This approach originated from the traditional study of zonal and anthropogenic landscapes. In these landscapes as described by for instance Walter (1970; climatic zonal like tropical rainforest, savannah, etc.) or Forman and Godron (1986; urban and rural landscapes) the characteristics are unambiguous and give good clues in landscape management. However in small-scale dynamic natural ecosystems this is clearly not the case.

Summarizing, the classic approach of landscape dynamics in landscape ecology is primarily spatially oriented and the classic approach of dynamics in vegetation ecology is spatially or temporally oriented. In landscape ecology or vegetation ecology a fundamental spatio-temporal approach is lacking. Additionally, the descriptions of landscape and vegetation characteristics are discrete. Spatially heterogeneous and temporally dynamic landscapes that are highly valued for their biodiversity and natural heritage are, however, insufficiently understood with the classic perception of space, time and attribute. Aim of this thesis is to present and apply a new landscape approach for small-scale dynamic ecosystems (see Frame 1-1) that does justice to the specific spatial, temporal and thematic characteristics of these systems.

Basic conceptual element in the classic approach is general systems theory (Von Bertalanffy, 1969; Bakker et al., 1981; Klijn, 1995), mainly because the functioning of natural systems can be explained by the phenomenon of synergy. Synergy made it possible to perceive landscape as a whole by a limited set of parameters on a relative high level of organisation. The ‘correlative complex’ (Zonneveld, 2005) was used to limit the thematic complexity of landscape. However, in order to develop a landscape model which can be applied in modern techniques like GIS, Remote sensing and other numerical methods, spatial, temporal and thematic relations have to be clear and unambiguous.

In general, landscape dynamics are concentrated at boundary environments (Watt, 1947; Van Leeuwen, 1966; Wiens et al., 1985). This observation is in contradiction with a widely used technique in landscape ecology: the classification and recognition of uniform or stable elements (Zonneveld, 1989). Studying the heterogeneity (spatial) or dynamics (temporal) of landscape should include the recognition of heterogeneous or unstable elements. The deliberate classification of objects as crisp leads to the characterisation of unrealistic stable land units, whereas the study of landscape dynamics is concerned with the characterisation of changing land units and their boundaries or edges. In understanding small-scale dynamic ecosystems the focus should be on recognizing spatial and temporal continuity.

In the classic approach of landscape ecology and vegetation science, the thematic classification of the landscape plays a major role. However, the thematic information of the landscape was never recognised as a vital phenomenon in the functioning of landscape. In this thesis, the thematic information of the landscape is assigned equal importance as spatial and temporal information. The overall set of thematic characteristics of the landscape is defined as ‘semantics’ of the landscape (see Frame 1-2). For the description and study of complex landscapes, it is customary to use the adjective spatial and temporal for phenomena like pattern, dynamics, continuity and scale. Such adjective lacks for thematic characteristics of the landscape. However, with the introduction of ‘semantics of the landscape’, the adjective ‘semantic’ can be used.

Small-scale dynamic ecosystem

A small-scale dynamic ecosystem is a natural system that is characterised by a high spatial, temporal and thematic diversity resulting in a patchy ever-shifting mosaic of all possible stages of landscape development. The spatial pattern as well as the temporal diversity of small-scale dynamic ecosystems is clearly much more fragmented than other ecosystems in the climatic zone or ecozone under study.

‘Small-scale’ is not meant in a geometric sense unless otherwise stated. Small-scale means a heterogeneous pattern of relatively small patches and many continuous as well as crisp boundaries. A small-scale dynamic ecosystem is recognised by high spatial and temporal dynamics in comparison to surrounding ecosystems. The reason for this difference is comprehensively discussed in this thesis, but in general it is caused by high external control on these systems, such as geomorphic (wind erosion) or faunal (grazing) activity. The unique characteristics of small-scale dynamic ecosystems have been studied and described frequently. Examples for the temperate regions are dry coastal dunes (Dieren, 1934; Bakker et al., 1981; Droesen, 1999; Haperen, 2009), salt marshes (Janssen, 2001; Wolters, 2006), inland drift sands (Riksen, 2006) and flood plains (Looy, 2006).

Small-scale dynamic ecosystems are highly valued for their ecological richness. This ecological richness is expressed in: a high biodiversity (Hooper et al., 2005), a mosaic of small varying patches or ecosystems (Fuhlendorf & Engle, 2001) and a relative quick change (10 – 50 years) in cover according to a carrousel-like spatial model (Van der Maarel & Sykes, 1993). Small-scale dynamic ecosystems are very common in the European context of nature conservation

Frame 1-1 Definition of a small-scale dynamic ecosystem

1.3 The Serial Landscape Model

Notwithstanding the wide application of the discrete land unit concept, the spatially continuous nature of geology, relief, soil and vegetation was recognised since long and numerically characterised by a diversity of (geo)statistical methods (Davis, 2002; Fortin & Dale, 2005; Kent et al., 2006). With the introduction of digital techniques like remote sensing, digital image interpretation and raster-based GIS (Burrough & McDonnell, 1998; Lillesand et al., 2008), spatial continuity could be integrated in landscape ecology (Haines-Young et al., 1994).

The continuum concept for spatio-temporal landscape modelling that eventually resulted in the Serial Landscape Model has been developed for practical reasons; it emerged from the problem of combining specific material (colour Infrared air photos) with the need for management tools. Since 1975, colour Infrared air photos have been used to develop management tools for small-scale dynamic coastal dune ecosystems in The Netherlands, though landscape mapping of the coastal dunes with the use of Colour Infrared air photos was only initiated since 1985 (Van der Meulen et al., 1985; Doing, 1995). The possibility of considering the landscape as a continuous field emerged with the development of raster GIS, remote sensing and digital interpretation techniques. Such approach was first presented by Droesen (1999) and also applied to the salt marsh vegetation of the Waddensea area (Janssen, 2001). The classification model was made operational in particular for the dry coastal dunes of The Netherlands in 2004 (Assendorp & Schurink, 2005).

Though landscape ecology can be seen as an applied science, the development of scientific concepts is an important branch of landscape ecology. This thesis focuses on concept development as well as the application of the concept. This concept, the Serial Landscape Model, is presented in this section (see Figure 1-1). The indication 'Serial' is used because the landscape is thought to be a continuous series of states that can be perceived in spatial and temporal sequences. The description of these states is determined by the semantics of the landscape. The general application of the model in classifying ecosystems is elaborated in section 1.4.

Objectives of a landscape model can range from theoretical to applied (Baker, 1989). A (landscape) model can be constructed:

1. To present and elucidate a theoretical concept
2. To monitor spatial and temporal dynamics
3. To model future changes
4. To support nature management policy

In practice, nature management policy is the main objective for landscape modelling (Hill et al., 2005) and the first step, the concept, is neglected. This thesis aims at the above presented sequence and gives special attention to the basics: present and apply a sound theoretical concept and observation model. The observation model is made operational with the introduction of the semantics of the landscape (see Frame 1-2)

Droessen (1999) laid an important foundation for the above presented sequence. However, in constructing a (landscape) concept for a small-scale dynamic ecosystem he follows a strict spatial data structural sequence:

1. Development of a conceptual landscape ecological model
2. Development of a spatial model
3. Development of a data structure and strategy for data processing.

Droesen (1999) did not pay much attention to temporal and semantic aspects. This thesis must be seen as a sequel to the work of Droesen: the spatial concept is extended with a temporal and a semantic component and aims at modelling temporal and thematic aspects of the landscape and its ecology.

The dimensions of the Serial Landscape Model are space, time and attribute and they are revealed in the spatial, temporal and semantic domain. The Serial Landscape Model describes the character of the spatial, temporal and semantic domain with a nomenclature that is adopted from spatial vegetation description (Van Leeuwen, 1966). The nomenclature of Van Leeuwen (1966) is used because it primarily describes transitional or boundary environments. This is the place where the landscape changes and biodiversity and natural heritage values are high.

In theory, there are two extremes in pattern and boundaries as they can be observed in the spatial as well in the temporal domain:

1. a random spatial or temporal pattern
2. a homogeneous surface or constant time series

All patterns and time-series in between these extremes are any form of boundary.

According to Van Leeuwen (1966) a boundary can have the function of connection or separation: these two functionalities of a spatial or temporal boundary are the two opposing ends of a continuum. There are boundaries with a high level of concentration (Limes Convergens) and boundaries with a high level of separation (Limes Divergens). Within the scope of the example presented in Frame 1-4 the transition and boundary between a stable vegetation cover and wind erosion has a high level of concentration and can be defined as a converging landscape element. The transition from a stable vegetation cover to water erosion seems to be a random process and results in diverging landscape elements.

A maximum concentrated boundary in the spatial domain is a so-called crisp border. A maximum separated boundary in the spatial domain results in a random pattern. All the states in between these extremes are continuous. A maximum concentrated boundary in the temporal domain is a catastrophe. A maximum separated boundary in the temporal domain results in a random time series. All the succession types between these extremes are gradual or continuous changes.

Table 1-1 Domains and boundaries of The Serial Landscape Model

	Maximum concentration or convergence	Continuity	Maximum separation or divergence
I. Spatial domain	Discrete pattern (crisp)	Continuous patterns (fuzzy)	Random pattern
II. Semantic domain	Classes	Membership values	Random attribute values
III. Temporal domain	Catastrophe	Gradual changes	Random time series

To develop a meaningful and integrated landscape model, a connection has to be made between the spatial and temporal domain. This is achieved by the semantic domain. As in the spatial and temporal domain, there can be a high level of concentration and a high level of separation in the semantic domain. A maximum concentration in the semantic domain results in distinct classes: a spatial or temporal element differs fully and definite from adjacent or subsequent elements. A maximum separation in the semantic domain results in random attribute values: a spatial or temporal element differs unpredictably from adjacent or subsequent elements. Classification models in between are characterised by continuity and uses membership values as applied in fuzzy logic: spatial or temporal elements can be member of different sets or classes. The Serial Landscape Model is presented in Table 1-1 and further elucidated in Figure 1-1.

Boundary environments have their own unique characteristics. With The Serial Landscape Model, it is possible to describe all these unique boundary environments because the landscape is defined as a continuum between maximum concentration and maximum separation in the spatial, temporal and semantic domain. Boundary environments provide specific conditions for species with a certain ecological range. Maximum concentration provides conditions for specialised organisms, maximum separation provides conditions for species with a very wide ecological range. In boundary environments in the gradient between concentration and separation there are conditions for a wide range of species with varying ecological ranges. In small-scale dynamic ecosystems, this gradient is a common and natural phenomenon. This thesis focuses on the description of these boundary environments in the spatial and temporal domain by constructing a semantic domain with the total range from convergence to divergence.

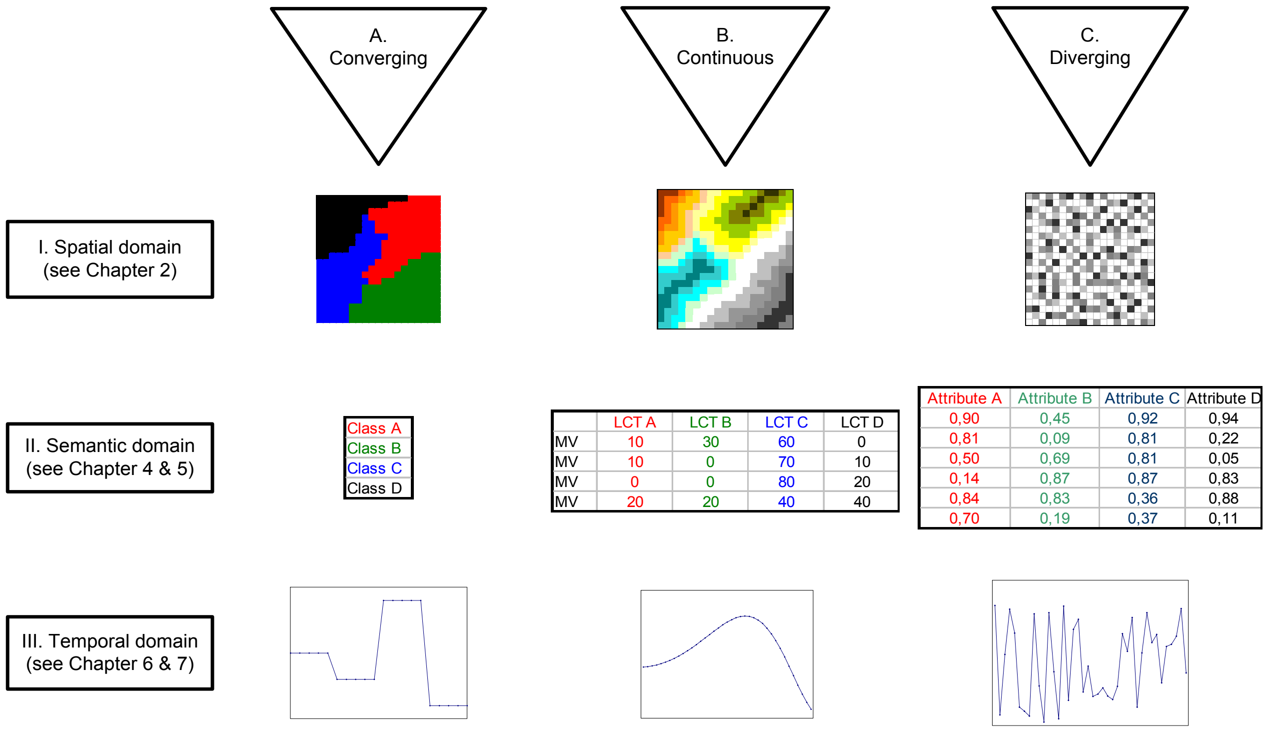


Figure 1-1 The expression of the spatial, temporal and semantic domain in a converging, continuous and diverging landscape: The Serial Landscape Model

Semantics of the landscape

Semantics is, in general, the study of 'meaning' and applied in a variety of disciplines. The adjective semantic can be explained as the abstract phenomenon 'meaningful'. Disciplines in which semantics play a major role are linguistics, logics, mathematics and computer science. Basically, it is the study or composition of formal rules in language or other forms of information transfer (Saeed, 2003).

The expression semantics or semantic has not been used in landscape ecology so far. It has been used in relation to digital modelling tools (Fall & Fall, 2001), data quality (Comber et al., 2005) and data heterogeneity (Ahlqvist & Shortridge, 2009). However, semantics can be used as the overall term to express the formal rules to describe the thematic characteristics of the landscape and its components. These formal rules can differ for diverse landscapes and survey methods and concerns the assignment of attributes to - and classification of - landscapes. The semantics of the landscape are only tangible when studied in a geographical context or during a certain time span. In other words: the semantics of landscape only exist in a geographical and temporal context. The opposite is also valid: geographic and temporal phenomena only exist when there is some form of semantic information. Therefore: a fundamental consideration of the semantics of the landscape is crucial in landscape ecological survey of the landscape.

Examples of the semantics of the landscape are given in Figure 2-2, Table 2-4, Figure 2-5, Table 4-4 and Figure 4-9 presenting the characteristics and integration of elements of dry coastal dunes as observed on images and in the field.

Frame 1-2 Semantics: the landscape ecological approach

1.4 Classification of small-scale dynamic ecosystems according to The Serial Landscape Model concept

The Serial Landscape Model (see Figure 1-1, Table 1-1) is developed as a framework for the classification of small-scale dynamic ecosystems (see Frame 1-1); dry dune ecosystems (see Frame 1-3) in particular.

Fundamental classification units in earth sciences, ecology and landscape ecology like pedon (Johnson, 1963), holon (Zonneveld, 1989), ecotope (Klijn & Udo de Haes, 1994), niche (Whittaker et al., 1973), biotope and habitat (Council of the European Communities, 1992) have in common that they have spatial, temporal and semantic crisp components in their definition. The Serial Landscape Model has no fundamental unit because continuity and heterogeneity are fundamental premises: units are fuzzy. The fundamental unit of The Serial Landscape Model only exists at a higher abstraction level of the semantic domain, the classification unit.

Examples of the classification of small-scale dynamic ecosystems for management purposes, dune ecosystems in particular, are numerous (Van der Meulen et al., 1985; Kruijsen et al., 1992; Ehrenburg, 1994). Notwithstanding the explanatory usefulness of these dune landscape maps, the use in management planning and evaluation is limited. Production is time-consuming and subjective and spatial complexity and temporal dynamics are reflected as highly concentrated or converging because the traditional land unit concept is applied. A fundamental consideration of the semantics of the landscape, leading to conclusions whether classification units are converging, continuous or diverging has led to a classification procedure that is better applicable in landscape management.

Attributes have to be chosen in order to define the semantic domain of a landscape model. Primary attribute in the case of monitoring dynamic coastal dune ecosystems with high-resolution false colour infrared images is the reflection of the Earth surface. This is classified or translated as the attribute vegetation structure.

Attributes must have a functional relation in order to become explanatory within the three domains of the Serial Landscape Model. When these relations are asymmetric, one can say there is a hierarchic relation. A relation is asymmetric when the mutual influencing of attributes is unequal. For instance: ground water level influences vegetation strongly, the effect of vegetation on the ground water level is much less. The classification procedure according to The Serial Landscape Model has a three level hierarchic structure. Central level is the vegetation structure as observed on remote sensing images, the lower organisation level comprises the attributes as observed in the field, and the higher organisation level concerns the, mostly aggregated, attributes used to stratify the classification. This functional hierarchic relation can be seen in Figure 1-1 where:

- classes on a high hierarchic level form spatially discrete units,
- membership values of classes on a central hierarchic level form spatially continuous units and
- attributes on a low hierarchic level form (nearly) random patterns.

Attributes on the level of divergence are studied in chapter 4, leading to a better understanding of the semantics of the basic classification units. A thorough discussion of supposed asymmetric (hierarchic) characteristics of small-scale dynamic ecosystems is given in chapter 5.

Organisms are well-defined objects in the temporal, spatial and semantic domain and therefore easy to classify in discrete units. In classifying organisms there is a maximum concentration. Vegetation structure types consist of groups of organisms and are therefore continuous in the spatial, temporal and semantic domains. This makes the Serial Landscape Model very well suited for studying vegetation structure in landscapes. Vegetation structure is continuous in the three domains though there are two convergent exceptions, one based on the image characteristics and one based on the landscape ecological characteristics of the vegetation structure in study.

1. The false colour infrared orthophotos used for the classification of small-scale dynamic natural ecosystem have a spatial resolution of 0.25m or less and a temporal resolution of five years. The individual organisms of shrubs and woods have a discrete spatial and temporal expression in the above-mentioned resolutions. Though a woody vegetation type consists of an assemblage of individuals and is therefore continuous in the semantic domain, shrubs and woods are considered as discrete classification units.
2. Land cover types without vegetation, like open water, drift sands or strictly anthropogenic land use types (roads, buildings etc.) are mostly characterised by unique radiometric values (Lillesand et al., 2008) and therefore well-defined in the semantic domain. For practical reasons these land cover and land use types can be classified in discrete units but also from a landscape ecological point of view they can be seen as discrete units in the spatial, temporal and semantic domain. Within the temporal resolution of five year, the land cover type characterising drift sands is catastrophic and therefore highly concentrated. This means that the land cover type emerges or disappears within five year. Because of the premise of connection between the three domains, drift sands are spatial, temporal and thematic discrete.

The classification, calibration, accuracy assessment and the subsequent monitoring of the object are conducted in a GIS environment. An ArcView© extension for image interpretation, named DICRANUM (Assendorp & Schurink, 2005), has been developed on the base of the Serial Landscape Model. In this thesis, results of the DICRANUM classification procedure lead to the further development of a landscape ecological concept.

1.5 Object of study of the thesis: dry coastal dunes

In this thesis, the particular object under study is a special case of the small-scale dynamic ecosystem viz. dry coastal dunes (see Frame 1-3). The object is studied by means of remote sense images and directly related data. As an example how the Serial Landscape Model can be applied, erosional processes and landforms are elucidated according to the three domains of the model (see Frame 1-4).

Dry coastal dune ecosystems

Dry coastal dune ecosystems are coastal dunes with a soil water regime determined by suspended water: there is no contact between phreatic groundwater and soil water in the rooting zone. This results in a vegetation adapted to temporary drought and high geomorphic activity.

Coastal dunes are primarily transitional landscapes that can be found at the sea-land interface of sandy coasts. There must be, or must have been, an apparent sediment source. Fluvial, tidal or wave processes, or a combination of these, induce coastal sand drift. Primarily inland winds form a variety of aeolian landforms (Pethick, 1995).

The substrate of coastal dunes is homogeneous: poorly sorted, rounded, fine sand. The mineralogy depends on the sediment source and has a strong influence on soil and vegetation. Especially the lime content of the substrate is important for species composition and soil profile development.

Geomorphology, in particular the morphometry, is highly heterogeneous. The interaction between natural succession of vegetation and extreme climatic conditions (high wind velocity in combination with high levels of salt-spray) result in heterogeneous patterns of stable and unstable landforms. The contrast between the stabilizing trend of vegetation (Dieren, 1934) and destabilising trend of aeolian processes (Rutin, 1983) result in a landscape with a high relief intensity.

Substrate and relief of coastal dunes in combination with net rainfall result in a fresh water reservoir and strong gradients between wet and dry ecosystems. However, gradients in dry coastal dune ecosystems caused by soil water regime are determined by differences in evapotranspiration and not by differences in freatic groundwater level. North exposed slopes are relative moist throughout the year with a moderate temperature regime, resulting in a vegetation of shrubs and lush grasslands with relative mature soils. South exposed slopes are much more extreme in soil water regime and temperature, temporary high temperatures and prolonged periods of drought result in a sparse vegetation of biennial herbs, grasses and mosses and a small-scale pattern of water and wind erosion (Rutin, 1983).

Frame 1-3 Dry coastal dune ecosystems

1.6 Conclusion: aim and objectives of the thesis

Summarizing, the aim of this thesis is twofold:

1. To elaborate the method to link digital data and techniques with the landscape ecology of small-scale dynamic ecosystems as presented in The Serial Landscape Model (see section 1.3). Equal attention has to be paid to spatial, temporal and semantic characteristics of the landscape.

The motive for this methodological aim is born by the need of the manager of small-scale dynamic ecosystems. This manager must have a monitoring tool that optimizes the potentials of digital data and techniques and maintains, or even renews, the existing landscape ecological concepts. It is important to realize that this principal goal is not only the development of a digital classification technique, but also the development of a theoretical and practical framework in which landscape development or succession can be studied.

Elements in connecting digital data and techniques with the actual characteristics and functioning of the landscape are:

- Basic information on the state of the landscape: examples are remote sensing material (digital data) and field observations.
- Techniques to establish the state of the landscape: this can range from digital classification techniques to general impressions of the landscape.
- Concepts on the state of the landscape: this can be a digital data model as well as a general ecological explanation for the functioning of the landscape.

2. To study the landscape development of small-scale dynamic ecosystems, dry coastal dunes in particular.

The motive for this practical, and even local, aim is also given by the terrain manager. Regulation at different levels of administration imposes surveys and monitoring schemes on the terrain manager. Studies of small-scale dynamic ecosystems must focus on semantic, spatial and temporal aspects. This puts special demands on the survey and monitoring scheme. The ecosystem characteristics for which the regulations are formulated must be surveyed on a relevant spatial and temporal scale.

Elements of local management information of small-scale dynamic ecosystems are:

- Presence and distribution of endangered species and habitats,
- Development of ecosystems containing endangered species and habitats,
- The effects of interventions on endangered species and habitats.

Following these aims and elements, with The Serial Landscape Model as premise, a sequence of research activities is executed. The objectives of these activities can be formulated as follows:

1. Develop a data and observation model for small-scale dynamic ecosystems.
2. Present relevant classification units for dry coastal dune ecosystems in particular.
3. Develop a digital classification technique for the relevant classification units, based on the data- and observation model.
4. Present classification results for dry coastal dune ecosystems and describe spatial variety in classification results.
5. Develop a technique to assess the accuracy of classification results of small-scale dynamic ecosystems.
6. Present a strategy for field survey in support of digital image interpretation of high-resolution images of small-scale dynamic ecosystems.
7. Develop a technique to link digital classification results with detailed landscape ecological field information.
8. Present classification units for dry coastal dune ecosystems with relevance for digital image interpretation, ecology as well as management goals.
9. Test the relevance of existing landscape ecological concepts when using the digital data model and classification technique.
10. Present and discuss a landscape ecological concept that closely relates to the digital data model and classification technique of small-scale dynamic ecosystems.
11. Develop transition matrices for sequential classification results of small-scale dynamic ecosystems.
12. Present succession schemes for dry coastal dune ecosystems.

The objectives result in the description of a methodology to link digital data and techniques with the ecology of small-scale dynamic ecosystems, given the fact that the primary characteristic of a small-scale dynamic ecosystem is extreme spatial, temporal and thematic heterogeneity. Another result is a description of the dynamics of dry coastal dune ecosystems.

Erosion in dry coastal dunes

Two major forms of erosion can be found in dry coastal dune systems: erosion by wind and erosion by water (Rutin, 1983; Jungerius and Meulen, 1988). Erosion in coastal dunes has well defined spatial, temporal and semantic characteristics.

Spatial characteristics of erosion in coastal dunes

An obvious feature that is the result of deflation by wind is the blowout (Jungerius et al., 1981), a bowl-shaped depression with crisp boundaries at the edge between stable vegetation and deflation, and fuzzy boundaries at the edge between accumulation and deflation.

Erosion resulting from overland flow is spatially much more entwined with the vegetation cover. Small linear landforms are integral components of a mosaic of several stages of vegetation development.

Temporal characteristics of erosion in coastal dunes

Erosion processes can be characterised by the net loss of substrate, though the change in extent of erosional landforms is an appropriate parameter. The transition from stable vegetation to deflation or accumulation of sediment by wind is catastrophic or crisp. The transition from deflation to accumulation and reverse has a much more continuous character.

Erosion by water emerges in thinly covered dry dune grassland as a slowly developing event. The transition from stable vegetation cover to erosion and vice versa is continuous. This is also observed at the transition from erosion to accumulation.

Semantic characteristics of erosion in coastal dunes

The parameters to characterise erosion are net loss of substrate, erosional landforms, soil degradation or initial soils and the lack of vegetation or the occurrence of degraded vegetation.

Synergy of space, time and attribute in erosion of coastal dunes

A description of erosion in dry coastal dunes is the integration of spatial, temporal and semantic characteristics. Every observation of some parameter has a spatial and a temporal component and every spatial or temporal characteristic has a semantic component.

Synergy is obvious from the fact that:

1. The observation of a parameter in a spatial context gives implicit information on temporal characteristics. The geometry and delineation (crisp or fuzzy) of a blowout gives information on the vigour of wind erosion processes. The intensity of water erosion can be concluded from the pattern and character of vegetation cover.
2. The observation of a parameter in a temporal context gives implicit information on spatial characteristics. The change in surface level, soil profile and vegetation cover characterizes the occurrence and intensity, and thus the expected pattern, of wind and water erosion.
3. The change of spatial patterns can be an indication for semantic characteristics. When a change from fuzzy to crisp boundaries is observed it is likely that erosion occurs with related landforms, soil profiles and (vegetation) cover.

The role of semantics in the description of synergy in the landscape has been described before by Doing (1995), who typifies it as the holistic characteristics of the landscape.

Frame 1-4 Erosion in dry coastal dunes within the scope of The Serial Landscape Model

1.7 Structure of the thesis

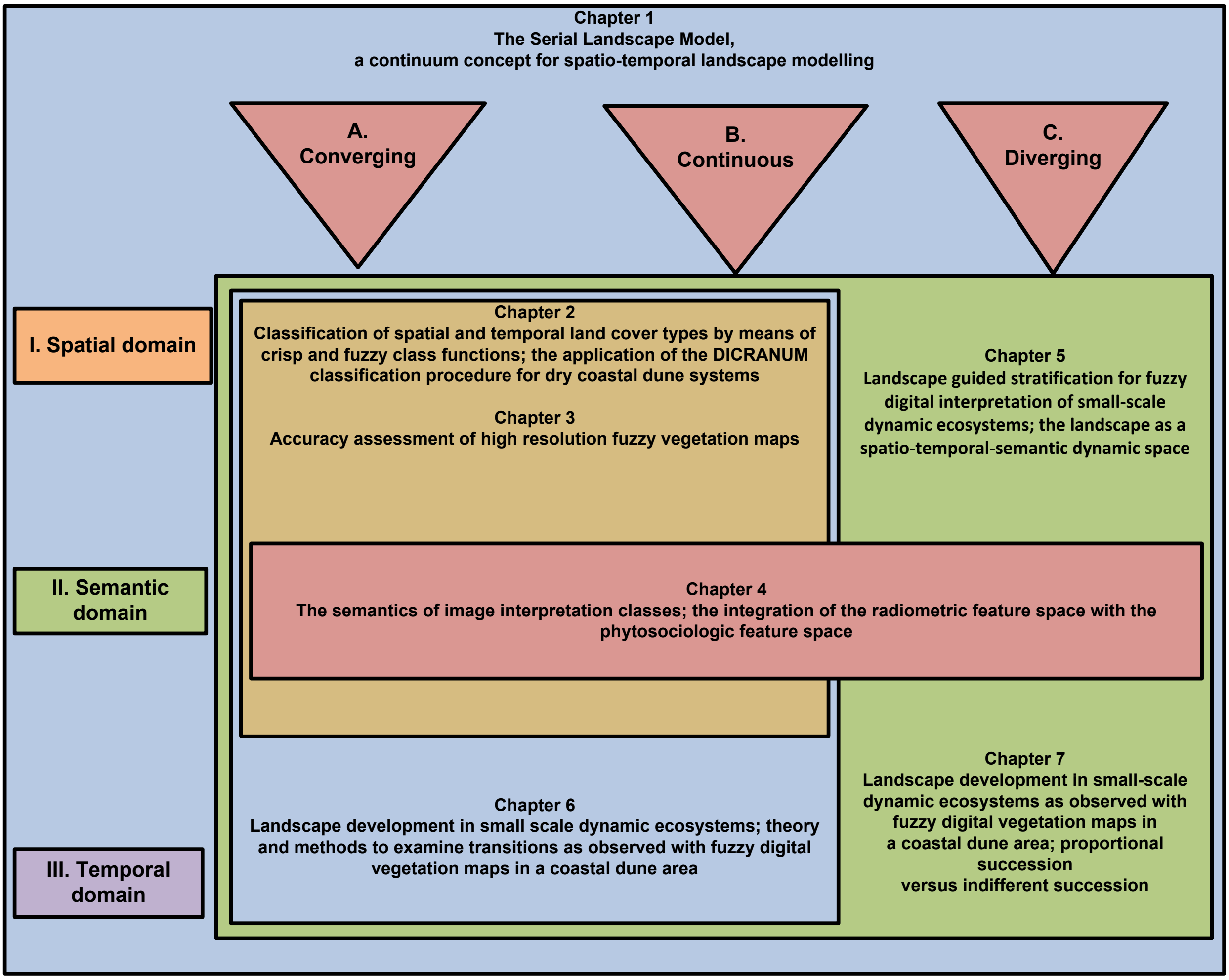


Figure 1-2 Structure of the thesis, presented in relation to the Serial Landscape Model

This thesis is organised according to the objectives formulated in the previous section. Notwithstanding the extensive use of numeric methods, the majority of the results are presented as a descriptive model. Objectives dealing with classification, accuracy assessment and studying the landscape ecology of classification units in depth (2 – 8, 11) are dealt with in a descriptive manner. The objectives resulting in new concepts for landscape ecology (1, 9 & 10) and new models for the temporal dynamics of small-scale dynamic ecosystems (12) are explanatory. All chapters of this thesis focus on some combination of elements of The Serial Landscape Model; this is elucidated in Figure 1-2.

The digital classification procedure is based on the Serial Landscape Model (Chapter 1) and made operational in an Arcview ® extension. The procedure and extension development is presented in Chapter 2. Classification results of dune areas along the mainland coast and the South Western Islands (see Figure 2-4) of The Netherlands are also presented and compared in Chapter 2.

No satisfactory technique to assess the accuracy of fuzzy classification results of high-resolution images of small-scale dynamic ecosystems existed. A technique, based on the accuracy assessment with a confusion or error matrix (Foody, 2002), was developed and is presented in Chapter 3. The calculated accuracies are considered as descriptive and result in a proposal for optimal digital data collection in the field. This is also described in Chapter 3.

A description of the method how to link digital classification results with detailed landscape ecological field information, with special attention to small-scale dynamic ecosystems, is presented in Chapter 4. The image interpretation classes for dry dune ecosystems are interpreted in the light of NATURA 2000 habitat-types (Council of the European Communities, 1992). Chapter 4 focuses purely on the semantics of the image interpretation classes in the total range from convergence to divergence.

Accuracies of stratified classification results are presented in Chapter 5. The stratification is carried out because it was thought that the classification results would improve. The hypothesis is based on hierarchy theory. However, the analysis and its results initiated the development of a new explanatory model; this model is presented in Chapter 5 and can be seen as an explanation of the complete range of convergence to divergence in the three domains of the Serial Landscape Model.

A method to describe the temporal dynamics of small-scale dynamic ecosystems with transition matrices and transition diagrams, based on the classification procedure as presented in Chapter 2, is presented in Chapter 6. Temporal dynamics of crisp (converging) and fuzzy (continuous) elements can be described with this method.

The transition matrices and diagrams of case study areas in the Meijendel dune area are presented in Chapter 7 and lead to some general statements on the temporal dynamics of small-scale dynamic ecosystems, dry coastal dunes in particular. The conclusions on the temporal dynamics of the dry dune area induced some recommendations for the management of dry dune areas.

In Chapter 8, the overall conclusions concerning dry coastal dunes, small-scale dynamic ecosystems and concept development in landscape ecology are presented and discussed.

All chapters of this thesis can be read independently of each other except Chapter 6 and Chapter 7. The theoretical framework of the transitions, as observed by the confrontation of the three domains of the Serial Landscape Model (section 6.4.1), is the basis for the transition diagrams and general model for landscape development presented in section 7.4 and 7.5. Furthermore, the Serial Landscape Model and the DICRANUM classification procedure are major elements of this thesis. The Serial Landscape Model is presented in this chapter (Chapter 1) and the DICRANUM classification procedure is presented in Chapter 2.

2 CLASSIFICATION OF SPATIAL AND TEMPORAL DYNAMIC LAND COVER TYPES BY MEANS OF CRISP AND FUZZY CLASS FUNCTIONS; THE APPLICATION OF THE DICRANUM CLASSIFICATION PROCEDURE TO DRY COASTAL DUNE SYSTEMS.

2.1 Introduction

Monitoring the dynamics of landscape components including (ground)water (Johnson, 2009), geomorphology (Kondolf & Piégay, 2003; Hubbard & Glasser, 2005), soil (Grunwald, 2006) and vegetation (Lindenmayor & Burgman, 2005), and the interaction between these components (Krönert et al., 2001) is widely used as instrument in the management and conservation of nature reserves (Van der Meulen & Jungerius, 1989; Goldsmith, 1991; Van der Meulen et al., 1996; Janssen, 2001; Janssen, 2004; Provoost et al., 2005). Monitoring pertains to both the spatial and temporal domain of the landscape. As to the first, the measured objects or phenomena have a geographical component; their geography generally being presented as a map. The survey of these elements can be field observations (with sensory perception or special equipment), remote sense images (air photos, satellite imagery) or a combination of both. As to the temporal domain a monitoring program can be “planned” or “unplanned”. In a planned monitoring program, images and field measurements or observations are obtained specifically for the program in a previously defined time schedule. In an unplanned monitoring program historic or existing data is used, often without time control. A combination of historic material and specifically obtained material is also an option. According to this grouping, a matrix of monitoring programs can be constructed. This matrix is presented in Table 2-1.

Based on an extensive review of the “Journal of Vegetation Science” and “Landscape Ecology” (2007 – 2009), presented in Table 2-1, it can be concluded that planned monitoring programs that combine field survey and images lack. Vegetation ecologists frequently exploit the advantages of sequential study of field plots, whereas the landscape ecologists use sequential (historic) images. Because historic images are often applied in monitoring programs, ground truth in the form of specifically surveyed field plots, is not available. Monitoring programmes set up according to the highest degree of planning are not known from literature.

Monitoring landscape dynamics is generally accepted as an invaluable aid in management and conservation of natural habitats (Legg & Nagy, 2006). Often, a monitoring program is started after the conservation or management problem has emerged. Therefore, the assessor is obliged to use historic material to describe the blank or baseline situation. In environmental impact assessment it is customary to describe the blank or baseline situation (Doomen et al., 2006).

Vegetation monitoring programmes based on repeated field survey are quite common though they are mainly limited to sequential point observations (Eertman et al., 2002; Kettner-Oostra et al., 2006; Aptroot et al., 2007) (see also Table 2-1). Repeated field mapping of extensive nature reserves is time consuming and therefore costly. The funds of nature reserve organisations are often limited because other terrain functions (agriculture, recreation) do not yield enough income. Monitoring programs for conservation and management of nature thus have to be cost-efficient.

This Chapter presents a cost-efficient methodology to describe the spatial domain of a small-scale dynamic ecosystem in the context of a set of monitoring programs in the coastal dunes of The Netherlands. The programs can be classified as being at the highest level of planning: images and field-data are acquired especially for the monitoring program. Coastal dunes are a very good example of small-scale dynamic ecosystems (see Chapter 1). High relief intensity and gradients in (micro) climatic conditions, groundwater and soil conditions result in a small-scale, patchy and relative quickly changing landscape. For monitoring and subsequent managing small-scale dynamic ecosystems a well planned and consistently executed monitoring program is obligatory, because the dynamics of the landscape (changes in the temporal, spatial and semantic domain) have to be recorded unambiguously. Otherwise, observed changes and conclusions based on these observations are unreliable (Legg & Nagy, 2006).

From the mid-70’s of the last century until today large scale photos or high-resolution false colour infrared images (scans) of three large coastal dune reserves in The Netherlands (Meijendel & Berkheide, 2849 ha; Amsterdam Water Supply Dunes, 3500 ha; North-Holland Dune Reserve ,5300 ha) are being recorded at a relative short interval of five to ten years. Though vegetation or dune-landscape maps have been produced at the end of the 80’s of the last century (Van der Meulen et al., 1985; Ehrenburg and Baeyens, 1992; Kruijsen et al., 1992; Ehrenburg, 1994; Doing, 1995) it was only at the beginning of the 90’s that a start was made with the development of a structural monitoring instrument based on supervised classification of sequential remote sensing images combined with field survey. This can be seen as vegetation or landscape monitoring at the highest level of planning. For this monitoring, a classification procedure with fuzzy as well as crisp classification procedures, combined with extensive ground truthing and landscape ecological field survey was developed (Assendorp & Van der Meulen, 1994; Droesen et al., 1995). After new images were acquired in 2001, a simultaneous field survey was carried out and the classification procedure was completed with a specific ArcView © script (Assendorp & Schurink, 2005).

In this chapter, the aims and requirements of an integral classification procedure for small-scale dynamic ecosystems are presented (Section 2.2). Crucial element in the classification procedure is the successive construction of continuous and discrete class functions. The underlying concept and methodology used are presented in Section 2.3. For a more comprehensive description of the concept: see Chapter 1. Section 2.4 focuses primarily on the information that can be extracted from the material used (field and image) and results in the presentation of the image interpretation classes. A more comprehensive landscape ecological interpretation of the image interpretation classes, based on field survey, is given in Chapter 4. The actual construction of the class functions, and thus the classification procedure, is presented in Section 2.5. Before general conclusions are drawn on the methodology for monitoring of small-scale dynamic ecosystems (Section 2.7), classification results for several Dutch coastal dune areas are presented and compared (Section 2.6). Preliminary conclusions are especially based on the accuracy assessment of crisp (discrete) class functions as determined with a classification error matrix. The discussion on crisp classification results leads to conclusions on the optimal extent and location of classification areas. Accuracy assessment of fuzzy image interpretation results is presented in Chapter 3 and thoroughly discussed in Chapter 5.

Table 2-1 Types of monitoring programs, arranged according to their level of planning (1 → 4, A → D); with examples as presented in the period 2007-2009 in "Journal of Vegetation Science" and "Landscape Ecology".

	1. Without field plots	**2. With historic field plots**	**3. With a combination of historic and specifically surveyed field plots**	**4. With specifically surveyed field plots**
A. Without images or maps		**Journal of Vegetation Science** Alpine [9] **Landscape Ecology** Forest [10]	**Journal of Vegetation Science** Alpine [11] Rural [12] Forest [13] **Landscape Ecology** Coastal [14]	**Journal of Vegetation Science** Flood plain [15] Arid [16] Alpine [17] Grassland [18] Bogs [19] Tidal marsh [20] Volcanic [21] Steppe [22] Rain Forest [23]
B. With historic images or maps	**Journal of Vegetation Science** Alpine [1] **Landscape Ecology** Rural [2] Forest [3] Grassland [4] Arid [5] Urban [6]			**Journal of Vegetation Science** Grassland [24] Mediterranean [25] Tropical forest [26] **Landscape Ecology** Rural [27] Forest [28]
C. With a combination of historic and specifically obtained images or maps	**Landscape Ecology** Rural [7]			
D. With specifically obtained images or maps	**Journal of Vegetation Science** Grasslands [8]			

-1- (Gehrig-Fasel et al., 2007; Stueve et al., 2009) **-2-** (Cousins et al., 2007; Falcucci et al. 2007; Ludwig et al., 2009; Ruiz & Domon, 2009) **-3-** (Wickham et al., 2007; Boucher et al., 2009) **-4-** (Coppedge et al., 2007) **-5-** (Pennington & Collins, 2007) **-6-** (Lepczyk et al., 2007; Xu et al., 2007) **-7-** (Hamre et al., 2007; Jansen et al., 2009) **-8-** (Felinks & Wiegand, 2008; Baasch et al., 2009) **-9-** (Jurasinski & Kreyling, 2007) **-10-** (Fritschle, 2009) **-11-** (Vittoz et al., 2008) **-12-** (Fried et al., 2009) **-13-** (Sánchez Meador et al., 2009) **-14-** (Talluto & Suding, 2008) **-15-** (Beltman et al., 2007) **-16-** (Osem et al., 2007) **-17-** (Anthelme et al. 2007; Erschbamer et al., 2008) **-18-** (Dzwonko & Loster, 2007; Ingerpuu & Kupper, 2007) **-19-** (Gunnarsson & Flodin, 2007) **-20-** (Wetzel & Kitchens, 2007) **-21-** (Del Moral, 2009; Tsuyuzaki, 2009) **-22-** (Matesanz et al., 2009) **-23-** (Laurance et al., 2009) **-24-** (Burnside et al., 2007) **-25-** (Duguy & Vallejo, 2008) **-26-** (Kassi N'Dja & Decocq, 2008) **-27-** (Domon & Bouchard, 2007; Sluiter & De Jong, 2007) **-28-** (Bergen & Dronova, 2007)

2.2 Aims and requirements of an integral classification procedure for dynamic natural ecosystems

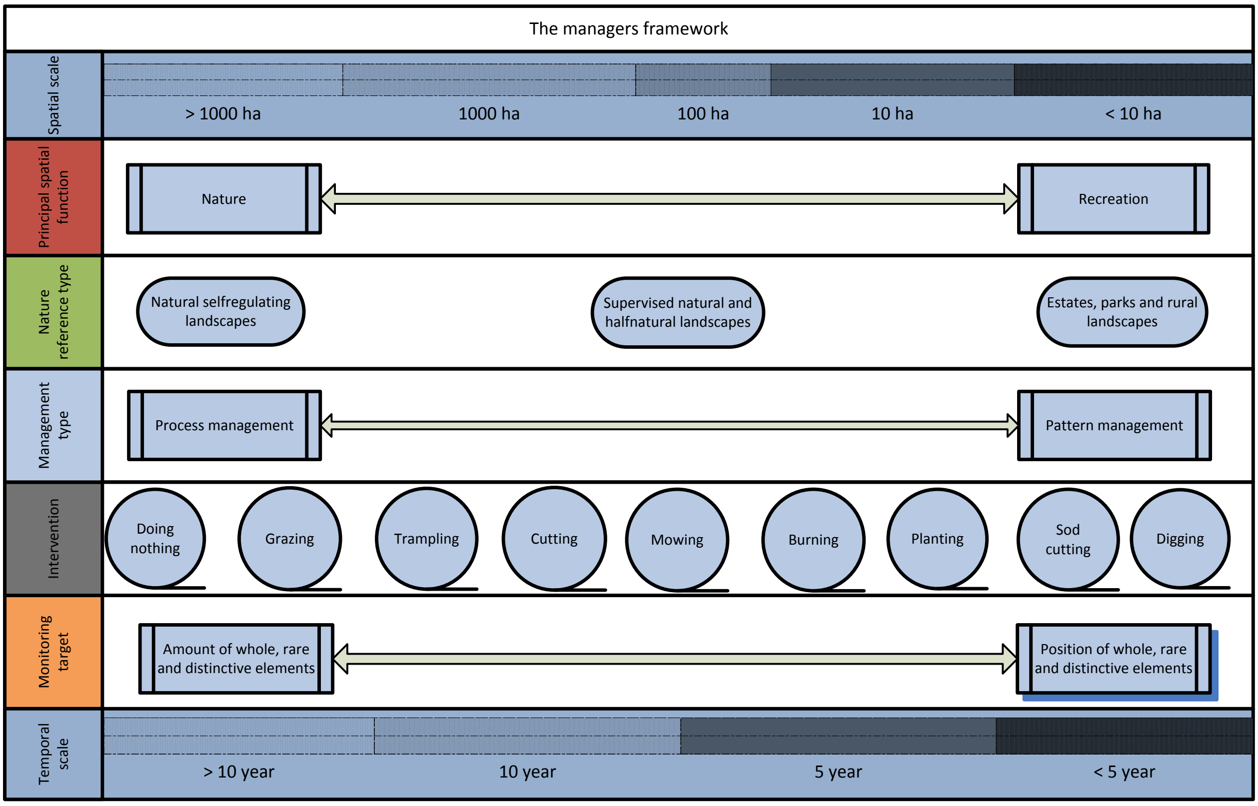


Figure 2-1 The manager's framework, see section 2.2.2 for a further discussion on the interventions.

This section explores several topics that lead to a set of aims and requirements for a classification procedure for small-scale dynamic natural ecosystems. These topics are:

1. Balance in spatial, temporal and semantic scale
2. Physical and administrative requirements of the terrain manager
3. Economical constraints of the terrain management
4. Simplicity and transparency of the procedure.

2.2.1 Scale and classification

Whether a natural ecosystem is defined as "dynamic" depends mainly on the relation between the spatial and temporal scale at which the ecosystem is observed. The matter of scale is a major subject of study in landscape ecology (Forman & Godron, 1986; Allen & Hoekstra, 1992; Zonneveld 1995; Turner et al., 2001) and has led to general hierarchy theory (Klijn, 1995). It is accepted that landscape components characterising relative large areas change slowly and landscape components that characterise relative small areas change quickly (Turner et al., 1989). For instance, geology is characterised by large spatial units (formation) that build up over long time spans, while vegetation is characterised by small spatial units (association) that develop and change rapidly. The observed stability or dynamics of a system thus depends on the scale of observation (spatial, temporal and semantic). When geology is surveyed at the spatial scale and time span of vegetation there seems to be an extreme level of stability. On the other hand, when vegetation is surveyed at the spatial and temporal scale of geology there seems to be an extreme level of dynamics. Therefore, the complexity of an image interpretation system depends mainly on the spatial scale, the time span and the level of detail of the attributes in study.

Landscapes, where general assumptions of hierarchy theory do not hold in the sense that components have a more detailed pattern and change more quickly than could be expected from their hierarchic position, are characterised as small-scale dynamic. Examples include coastal dunes, drift-sands, salt marshes, flood plains and peat bogs. In these systems the components geomorphology, (ground) water, soil and vegetation exhibit a detailed pattern and change quickly.

The definition of the optimal scale or resolution of the monitoring program of small-scale dynamic ecosystems is important because spatial, temporal and semantic aspects are highly complex and diverse. The chance that typical characteristics of the system are falsely interpreted is high which is undesirable from a nature conservation point of view.

2.2.2 Physical and administrative requirements of the terrain manager

The need for an integral classification procedure for small-scale dynamic ecosystems is mainly the outcome of recent developments in nature reserves and their management. Processes like eutrophication (Kooijman et al., 1998; Ten Harkel, 1998), grass and shrub encroachment, and local extinction of species (Maes et al., 2006) pose an increasingly serious threat and urge terrain managers to develop detailed as well as large-scale monitoring and management programmes.

Before presenting a sound monitoring program for small-scale dynamic ecosystems, the relation of the terrain manager with nature conservation, management and spatial planning needs to be elucidated. This is done in the 'manager's framework' where the relation between the numerous topics a terrain manager has to deal with is presented (Figure 2-1). This figure does not pretend to be complete but gives an indication how often the terrain manager has to deal with scale dependent factors. The 'manager's framework' is based on the Dutch situation as described in several policy plans and directives (Turnhout, 2003). The spatial and temporal scales mentioned in this figure tend to be smaller in a small-scale dynamic ecosystem.

As illustrated in Figure 2-1, the manager of an estate, park or nature reserve has to deal with different aspects like spatial function (Willemen et al., 2008), nature reference type (Tekke & Salman, 1995), management type and intervention or measure at different scale levels. In nature conservation, a spatially diverse ecosystem that is characterised by natural processes with rare, whole and distinctive elements (species, plant communities, land-forms) is valued high. According to the spatial extent of the highly valued area to manage, the modelling and monitoring target differs.

In large, naturally self-regulating landscapes the manager is not interested in the exact location of the elements ('what is where') but only in their relative distribution ('how much of what'). However, in small-scale estates and parks the modelling and monitoring target is focused on the exact location and quality of the elements ('what is where').

In densely populated areas where spatial functions like industry, housing and infrastructure dominate, nature is forced back into small areas like estates, parks and rural enclaves. Here, the spatial function of nature is combined with the agricultural and recreational functions. Large nature reserves which primarily function as a nature conservation area are rare and isolated. This makes it even more important to monitor and model these ecosystems and a landscape descriptive model of a higher objective is needed: a controlling landscape ecological model to support nature management policy. The existence of relative large nature reserves in densely populated areas is often due to their small-scale dynamic characteristics. High relief intensity, low soil nutrient status, high salinity, extreme groundwater tables and extreme (micro) climatic conditions made these areas unfavourable for reclamation, leading to a set-aside policy. Coastal dunes, drift sands, salt marshes, peat bogs or moors, badlands and floodplains are examples of small-scale dynamic ecosystems that are locally preserved in relative large extents because they are unfit for anthropogenic functions.

In The Netherlands, the above-described need for a classification procedure of small-scale dynamic natural ecosystems came forth from an up-scaling in nature management in the beginning of the 90's of the last century. This policy was later adapted at a European scale (Jongman, 1995). Dutch nature policy and its elaboration in ecological networks initiated several forms of process management (Benett, 2004). Within certain margins nature was allowed to develop on its own and the nature manager developed from 'gardener', conserving individual species and communities, to an 'integral conditioner of ecosystems' initiating and facilitating natural processes. This development, combined with the implementation and evaluation of the European habitat directive, made it even more essential to develop a monitoring program for small-scale dynamic ecosystems.

2.2.3 Economical constraints

Next to this up-scaling of nature management, the actual process of monitoring and intervention commercialised. In the public and private sector, managing and the related monitoring and modelling of ecosystems had to become more efficient and more cost-aware. Because the economic value of nature is hard to exploit the terrain manager has to aim for a cost-effective monitoring program. The employment of manpower for survey, operating and expert judgement has to be kept as low as possible. Therefore, knowing that traditional vegetation and landscape ecological mapping is time consuming and thus very costly, computerization is essential. Nowadays, methods and resources for automated survey of natural ecosystems are numerous (Lillesand et al., 2008) (see also: Table 2-1).

2.2.4 Procedure

As comprehensively discussed in this thesis, a monitoring program based on the combination of field survey and remote sense images has to combine landscape ecological concepts and techniques with digital data concepts and techniques. To make this combination transparent for the operator as well as the user, it has to be as straightforward as possible and use commonly available software and data formats. In practice, this means that the procedure for field survey has to be unambiguous. It also means that the geographical data has to be stored and processed in a user friendly and standard GIS-environment.

2.2.5 Aims and requirements

Summarising, the following requirements for a classification procedure for small-scale dynamic ecosystems can be formulated.

- To characterize the dynamics of a small-scale ecosystem the spatial, temporal and semantic scale have to be in balance. This is done by choosing the right resolution or scale, time span and level of attribute detail.
- Multiple or composite attributes have to be examined in detail to describe the ecosystem. The pattern is more detailed and they change quicker than could be expected from general hierarchy theory.
- The classification procedure has to relate to processes that cause unfavourable states of the landscape.
- The classification procedure has to relate with the topics mentioned in the manager's framework (Figure 2-1).
- Because small-scale dynamic ecosystems cover relative large areas, the relative distribution ('how much of what') of elements has to be studied, instead of their absolute position ('what is where').
- The monitoring program has to be cost-effective.
- The field procedure has to be unambiguous and simple.
- The geographical data has to be stored and processed in a user friendly and general available GIS-environment.

Given the aim and the requirements, this resulted in The Serial Landscape Model (see Chapter 1) and the DICRANUM application (Assendorp & Schurink, 2005), a specific computer application for high-resolution digital images of dry coastal dunes. The classification procedure is an integral combination of an overall landscape model and a practical monitoring instrument for the highest degree of planning: supervised classification of sequential remote sensing images combined with field survey. Though the landscape model and computer application, as described in the following sections, were specially developed for the classification of high-resolution false colour images of dry coastal dune areas, the potential for their application in dynamic natural ecosystems in general was always kept in mind.

2.3 Concepts and methodology

The development of a procedure to classify small-scale dynamic landscapes, which meets the requirements as defined in section 2.2.5, is an integration of landscape concepts and classification techniques. From the concept of a continuous landscape between the states of convergence and divergence, data structures and algorithms to classify this continuity are developed. The availability of (spatial) continuous data and the abilities of information technology (high processing power and data storage), made it actually possible to consider a small-scale dynamic ecosystem as continuous.

Section 2.3.1 describes the continuous character of the small-scale dynamic ecosystem and the data used to perceive the small-scale dynamic ecosystem. This leads to the presentation of a methodology to embed a continuous classification technology in monitoring and management of small-scale dynamic ecosystems: the classification environment (section 2.3.2).

2.3.1 Concept: continuous landscape and data

An important connecting premise between the landscape model, the computer application and the data structure of a small-scale dynamic ecosystem is the notion that spatial and temporal transitions are continuous. Continuity is also perceived in the semantic domain: objects observed in a spatial and temporal context possess unique properties that can hardly be assigned to a unique class and a unique set of attributes. This, combined with the continuous character of the data, like grid based images and digital grid maps, offer high potentials for modelling continuity.

The foregoing statement is especially valid for spatial continuity because images and maps are a representation of spatial characteristics of the landscape. Temporal continuity remains a theoretical premise. In fact, remote sensing images are a snapshot and economical reasons make it impossible to produce images at such a high frequency that continuity is approximated. Fuzzy logic is a major resource to classify the continuous semantic character of the small-scale dynamic landscape (Droesen, 1999; Wilson & Burrough, 1999; Reynolds, 2001; Robinson 2003). Therefore, it can be concluded that continuity in the spatial, temporal and semantic domain is no theoretical premise but can be incorporated in the structure of the landscape model (the concept), the data processing (the computer application) and the data structure (high-resolution grid-based maps.

Numerous landscape ecological models or concepts can be found in literature whereby multiple hierarchic scale levels are in fact the spatial scale of observation (Bakker et al., 1981; O'Neill et al., 1989; Klijn & Udo de Haes, 1994). The power of these models is generally accepted in Landscape ecology. However, in small-scale dynamic ecosystems, multiple (semantic) components, like vegetation, soil and relief, act at similar spatial scales and result in multiple patterns and transitions (Hanan & Ross, 2010). As an example for small-scale dynamic ecosystems, the spatial, temporal and semantic characteristics, as observed with high-resolution remote sense images and field observations of dry coastal dunes, are presented in Table 2-2. The spatial characteristics are further elucidated in section 2.6, the semantic characteristics in Chapter 4 and the temporal characteristics in Chapter 7. From Table 2-2 it is clear that convergence, continuity and divergence can be observed in the three domains. Temporal convergence, continuity and divergence can be observed at comparable intervals. In the semantic domain convergence, continuity and divergence is perceived with different characteristics. The spatial domain reveals convergence, continuity and divergence at different resolutions. Therefore, the application of a hierarchic landscape concept in the classification of coastal dunes, as proposed by Bakker et al. (1981) and Van der Hagen et al. (2008) is not advisable. Chapter 5 describes the matter of hierarchy in more detail and leads to an alternative landscape model focusing on dynamics and complexity instead of scale levels.

Table 2-2 Characteristics of the spatial, temporal and semantic domain as observed with high-resolution remote sense images and field observations of dry coastal dunes ecosystems

	Converging: spatial, temporal and semantic characteristics are crisp	**Continuous: spatial, temporal and semantic characteristics are fuzzy**	**Diverging: spatial, temporal and semantic characteristics are random**
Spatial domain	Homogeneous landscape elements with a relative large spatial extent (> 5 m^2)	The membership value per fuzzy class per high-resolution grid cell. Resolution of 0.1 – 0.2 m.	Random pattern of species, life forms and soil parameters at selected sites at a 1m scale level.
Semantic domain	Nominal classes which exclude each other	Combination of membership values of more classes, classes can exclude each other or combine with other classes.	Presence or value of field-attributes referring to relief, geomorphic processes, soil and vegetation.
Temporal domain	Catastrophes within a 5 – 10 year time-span	Continuous transitions with a clear direction within a 5 – 10 year span	Random transitions within a 5 - 10 year span

Remote sensing images are a representation of the intensity of radiation reflected by the earth surface on a continuous scale. The digital structure of images and their interpretation is raster-based. When the objects on the earth surface are significant smaller than the resolution of the image the basic elements of the image ("pixel") represent a mixture of reflections ("mixel"). Spatially the mixel forms a continuous field. Therefore it can be concluded that remote sensing images, being a substantial source of information in the monitoring program, are continuous in the semantic and spatial domain. As stated before, continuity in the temporal domain is rather theoretical and is further discussed in Chapter 7. The data structure and data processing within the DICRANUM classification procedure focuses mainly on the combination of the spatial and semantic domain. Therefore, the classification procedure has to support the conceptual notion of continuity. Class description, class functions and the classification have to be continuous in any case.

However, in the classification procedure, convergence has to be supported because small-scale dynamic ecosystems contain objects with a spatial resolution or "grain" similar or larger than the image resolution (shrubs, trees, deflation areas): these are the converging elements of the small-scale dynamic ecosystem. This is possible by defining crisp class functions.

In small-scale dynamic ecosystems, divergence is a common state of the landscape: in the spatial domain it is characterised as a random field. As described by Van Leeuwen (1966), divergence is a transitional stage of the landscape. Van Leeuwen confines his theory especially to the spatial domain but The Serial Landscape Model has extended this to the semantic and temporal domain as well. In fact, divergence can be explained as a state of 'disorder' of the landscape where not one class dominates, spatially, semantic as well as temporarily. Information on the state of divergency in the landscape can be obtained by detailed field observations as presented in Chapter 4 as well as the spatial pattern, membership of fuzzy class functions and transition.

Because continuity is the leading premise in the construction of class functions, it is obvious that fuzzy logic is the appropriate technique (Droesen et al., 1995; Foody, 1996). The use of fuzzy logic in the construction of class functions has been put into practise since the development of raster GIS (Burrough, 1989; Robinson, 2003), digital image interpretation (Maselli et al., 1996) and digital landscape modelling (Irvin et al., 1997). In fuzzy logic, an object can be (partly) member of more than one class. This is expressed in the membership value or pseudo-probability (Robinson, 2003). Though calculation techniques in fuzzy logic resemble calculation of probabilities, there is one fundamental conceptual difference. In probability theory an object is part of a population or not but there is uncertainty whether the object is part of the population: the probability gives the chance whether the object is part of the population. In fuzzy logic it is assumed that an object is part of more than one population and the membership value or pseudo-probability is a measure how much the object belongs to a population (Zadeh, 1965). To prevent confusion the qualification membership value is used.

2.3.2 Methodology: the classification environment

Classification of the landscape plays a major role in monitoring and there are three levels of organisation within the process of classification:

1. The classification procedure, this is the processing of data to produce a map based on the data and resources of the classification and their relation.
2. The classification model, this includes the landscape concept, class definition and the resulting classification procedure.
3. The classification environment, this includes the aim, the actors and the application of the classification model.

The complex procedure followed in the development of a monitoring program and its implementation in management of dry coastal dunes is presented in Figure 2-3. In this classification environment, the class definition plays an important role. In monitoring programmes, classes can be defined only once because the execution of the monitoring program has to be consistent through time: changes in class definition, but also in field survey methodology and classification procedure, makes multi-temporal analysis difficult and lead to unreliable results. In practice, classes are often redefined because management targets and observation methods change over time (Van Dorp et al., 1985). In general, one can say that class redefinition typically occurs in monitoring programs with a low degree of planning. The monitoring programme of the dry coastal dunes of the Dutch main coast, presented in this thesis, was developed in the period 1991 – 1995 as a program with the highest degree of planning, implying that redefinition of classes is excluded. The class definition process, as highlighted in Figure 2-3, is performed once, at the start of the monitoring program. The actual classification is performed repeatedly with new data but the classification algorithms have to be followed consistently.

The class definition process is based on three resources: the digital image, the terrain manager and the small-scale dynamic ecosystem. By confronting the nature manager with results of a preliminary (supervised) classification in the actual reality of the small-scale dynamic ecosystem (the field) meaningful and useful classes can be defined. When the class definition is established, the classification is performed, based on field plots and the digital image. The classification procedure is presented in Figure 2-6 and further explained in Section 2.5. The results are a representation of the small-scale dynamic ecosystem in a set of image interpretation maps. When the classification process is repeated and compared, the result is also knowledge on the succession or development of the small-scale dynamic ecosystem. This information can lead to the decision to intervene in the landscape and the intervention can be evaluated in the following classification cycle.

From Figure 2-3 it is clear that the classification environment is a blend of resources, products and processes that are related to landscape, information technology- and management. So, a thorough exchange of information between the terrain manager, scientist and information technologist (computer operator) is crucial. In practice, a combination of tasks is preferable. For this reason, the classification procedure is developed in a user friendly and simple digital environment (see also Section 2.2.4).

2.4 The image interpretation classes

Based on the material used in monitoring dry coastal dunes in The Netherlands some observations concerning image characteristics (see section 2.4.1), field characteristics (see section 2.4.2) and manager demands (see section 2.4.3) are formulated. This leads to a set of conclusions concerning the definition of image interpretation classes for small-scale dynamic ecosystems in general. High-resolution, false colour infrared airborne images are highly preferred for the monitoring of small-scale dynamic ecosystems because they can provide crucial information on the leaf coverage (De Boer, 1993) and the nature of the vegetation (Totterdell & Blair Rains, 1973). Advantage of airborne image over satellite imagery is the resolution of 25cm or less and the fact that vegetation structure and species composition can be identified visually. As an alternative hyperspectral images can be used (De Lange et al., 2004). However, notwithstanding the promising results, hyperspectral images are rarely used in monitoring of small-scale dynamic ecosystems. De Lange et al. (2004) conclude that hyperspectral images are more appropriate for more stable landscapes with crisp spatial units.

2.4.1 Image characteristics

When defining image interpretation classes, convergent as well as continuous classes are recognised in the image. This is caused by the interaction between vegetation characteristics and image resolution. At a spatial resolution mostly used for digital orthophotos (25 cm or less), shrubs and trees are a multiple pixel object in the image. Add to this the fact that a shrub or tree is a three-dimensional object with a shadow side and a sun lit side, one tree or shrub or an assembly of trees and shrubs is not homogeneous in its reflection. This makes it impossible to construct fuzzy class functions based on reflectance characteristics. Ecological, this is supported by the fact that the boundaries of shrubs and trees with continuous vegetation types like grassland are convergent. Shrubs and trees have to be characterised by crisp classes. Herbaceous vegetation, partly or totally covering the surface, consists of individuals smaller than the image resolution or pixel size and is therefore continuous in space. Boundaries are therefore continuous and have to be characterised by fuzzy classes. Visual image characteristics relating to objects, continuous fields, boundaries and processes are presented and illustrated in Figure 2-2. These visual image characteristics give some important clues towards the definition of image interpretation classes (see section 2.4.4)

In digital image interpretation the construction of a feature space is common practice. The fact that green and red reflections, as revealed in digital false colour images, are highly correlated (Droesen, 1999) results in the fact that only the red and near infrared band of the original three band digital image are used in constructing the feature space. Droesen (1999) transformed the red and near infrared reflection into the perpendicular vegetation index (pvi) and soil line (Clevers, 1994) but this does not significantly improve the supervised classification of sand, shrubs and woods and herbaceous vegetation. The use of a 'simple' red – near infrared feature space gives acceptable classification results (see Table 2-5 - Table 2-11).

The construction or delineation of image interpretation classes in the feature space is achieved through statistical techniques. These techniques are generally focused on the definition of distinct objects in the feature space; however, fuzzy classes are also continuous in the feature space. The technical elaboration of defining crisp and fuzzy image interpretation classes in the red – near infrared feature space is presented in section 2.5. Prior to the construction of the image interpretation class functions, the image interpretation classes have to be defined in a way that they are meaningful for the terrain manager as well as applicable in the technical class function construction. It is accepted that there are areas in the feature space where fuzzy classes are unique. These are areas that are full member of a fuzzy class within the continuous character of the herbaceous or grassland vegetations. An iterative expert process of repeated image interpretation and field surveys made it possible to define these areas for dry coastal dune areas of The Netherlands (Assendorp & Van der Meulen, 1994). Five meaningful continuous or fuzzy vegetation structure classes emerged from the image characteristics. During this process, it was observed that also abiotic elements of the surface play an important role in the overall reflection characteristic. Dead ectorganic material or litter, which is characteristic for grass encroachment vegetation types, is clearly identifiable in false colour infrared images. This is also the case for blond sand in pioneer vegetations and grey sand with humic material in moss dominated vegetations.

2.4.2 Field characteristics

Based on the (continuous) semantics of vegetation structure in combination with the above-mentioned abiotic characteristics of soil and geomorphology, some powerful primary class description for dry coastal dunes in The Netherlands can be made. The power lies in the correlative complex of the attribute vegetation structure (Zonneveld, 2005). This means that vegetation structure is strongly correlated with attributes like phytosociology, soil and geomorphic process and is therefore a strong descriptor of the landscape at the scale level where the interaction between geomorphology, soil and vegetation takes place.

In the field, as well as in the image, crisp and continuous gradients or boundaries occur and form a heterogeneous pattern. Comparing images with the field situation, it is striking that land-cover types at the extremes of vegetation succession are convergent and the intermediate succession phases are continuous. According to generally accepted succession theory (Clements, 1916) bare sand can be characterised as the pioneer stage and shrubs and trees as the climax. These stages are convergent in the field as well as in the image. The spatial distribution of these 'converging' succession stages in small-scale dynamic ecosystems however is heterogeneous: a spatial gradient of primary succession is rarely observed.

2.4.3 Manager demands

Natural succession, resulting in a continuous landscape pattern, is valued high and is seen as an effect of natural self-regulating landscape development. Processes like the encroachment of grass and shrubs are forms of unnatural and accelerated aging of the landscape and result in extremely stable states. In modern nature management, catastrophic regression of vegetation is allowed and even initiated (Arens et al., 2004; Arens & Geelen, 2006). This type of regression is always the result of intervention of man or the active allowance of geomorphic processes. In dry coastal dunes, initiation and rejuvenation of blowouts is an often-used measure. Less catastrophic measures like grazing and mowing of grasslands (Olff & Ritchie, 1998;

Bissels et al., 2006; Aptroot et al., 2007) are also performed. Vegetation structure types related to processes of convergence and divergence are important in landscape monitoring because their dynamics are indices for landscape functioning and success of management policy. In larger natural areas or nature reserves (>500 ha) emphasize is on process management, the effect of this type of management is measured as the level of heterogeneity of the pattern. A set of thematic maps with the spatial pattern of different stages of succession can provide this information.

2.4.4 Image interpretation classes for dry dune ecosystems

Visual image characteristics of dry coastal dune areas, as can be observed on high-resolution digital false colour images, are summarized in Figure 2-2. Examples are taken from the material presented in Table 2-3, locations of the sample areas are presented in Figure 2-4. As an illustration, more extensive examples of the sample areas are given in Appendix A. From the examples in Figure 2-2, it is clear that homogeneous and heterogeneous well-delineated objects as well as continuous patterns can be recognised (1.). The continuous (fuzzy) pattern of the dune grasslands has five clearly distinguishable expressions, ranging from a bright reflection of sand and sparse pioneer vegetation to nearly black moss dominated vegetation (2.). The spatial domain of The Serial Landscape Model is very well represented by the high-resolution false colour infrared images because areas with boundaries suggesting convergence, continuity and divergence are present (3.) Also, the processes of major importance for the terrain manager of dry coastal dunes: wind activity, grass encroachment and shrub encroachment, can be seen on the images (4.).

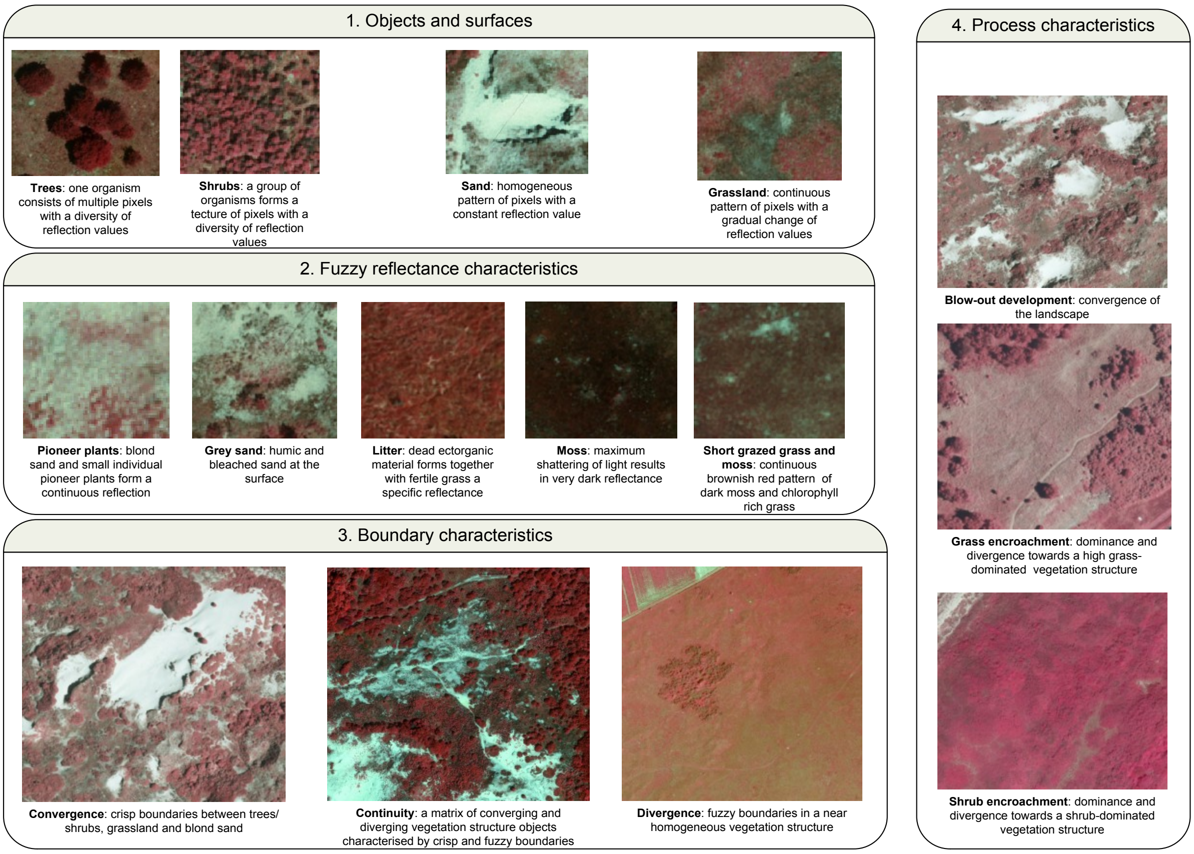


Figure 2-2 Visual image characteristics

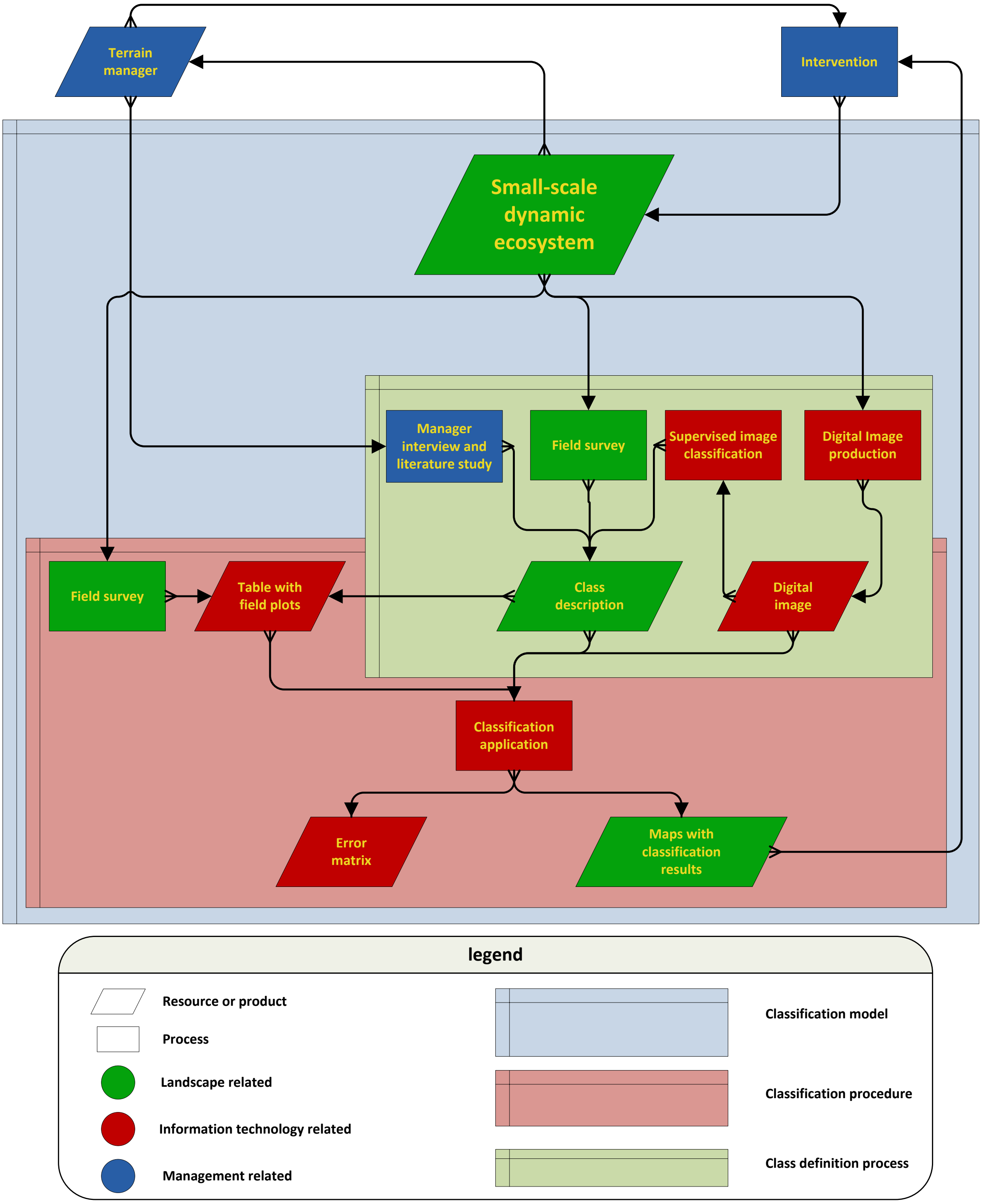


Figure 2-3 the classification environment, explanation is given in Section 2.3.2

Thus, the characteristics of objects and surfaces and the fuzzy reflectance characteristics are combined with the observed field characteristics and manager demands. This has led to a hierarchic class structure (see Figure 2-5). First, crisp classes are segmented and, secondly, the classes representing the continuous small-scale dynamic character of the coastal dune area are further segmented into fuzzy classes. Classes representing anthropogeneous activity and open water are also defined as crisp classes. The hierarchic class structure implies that dry dune grassland as a whole is a crisp class like bare sand and shrubs and woods. Of course, other crisp classes can be further segmented into fuzzy or crisp classes. A further segmentation of the crisp class shrubs and woods is advisable and fuzzy subclasses would be reasonable. However, because of the heterogeneous texture of shrubs and woods in the image, a fuzzy classification procedure would be highly complex and in contradiction with the demand of a user friendly and general available GIS-environment.

A general description of the image interpretation classes, representing for dry coastal dune systems, is given in Table 2-4. Chapter 4 gives a comprehensive ecological description of the image interpretation classes.

2.4.5 The definition of image interpretation classes for small-scale dynamic ecosystems

As a conclusion of this section some general observations on the definition of image interpretation classes for monitoring of small-scale dynamic ecosystems can be summarized. These observations are valid in case of using high-resolution false colour images and the integration of field survey.

1. Image characteristics
   a. The classes have to be significant in two radiometric bands: red and near infrared
   b. Resolution induces the recognition of plant-species at sub and super pixel level. Classes characterised by plant species at the super pixel level are crisp.
   c. Reflection is a mix of biotic and abiotic attributes, which must be expressed in the class description.
1. Field survey
   a. Vegetation structure is a direct effect of the interaction of processes in multiple landscape components. Field survey has to make clear which components and the class definition has to associate with these components.
   b. The spatial pattern of vegetation structure in small-scale dynamic ecosystems is continuous or convergent resulting in mainly fuzzy classes and some crisp classes.
2. Manager demands
   a. Management problems concern changes in multiple landscape components. Consultation of the terrain manager has to make clear which components and the class definition must associate with these components.
   b. Interventions deal with pattern development in vegetation structure acting on convergence as well as divergence: converging as well as diverging classes must be present

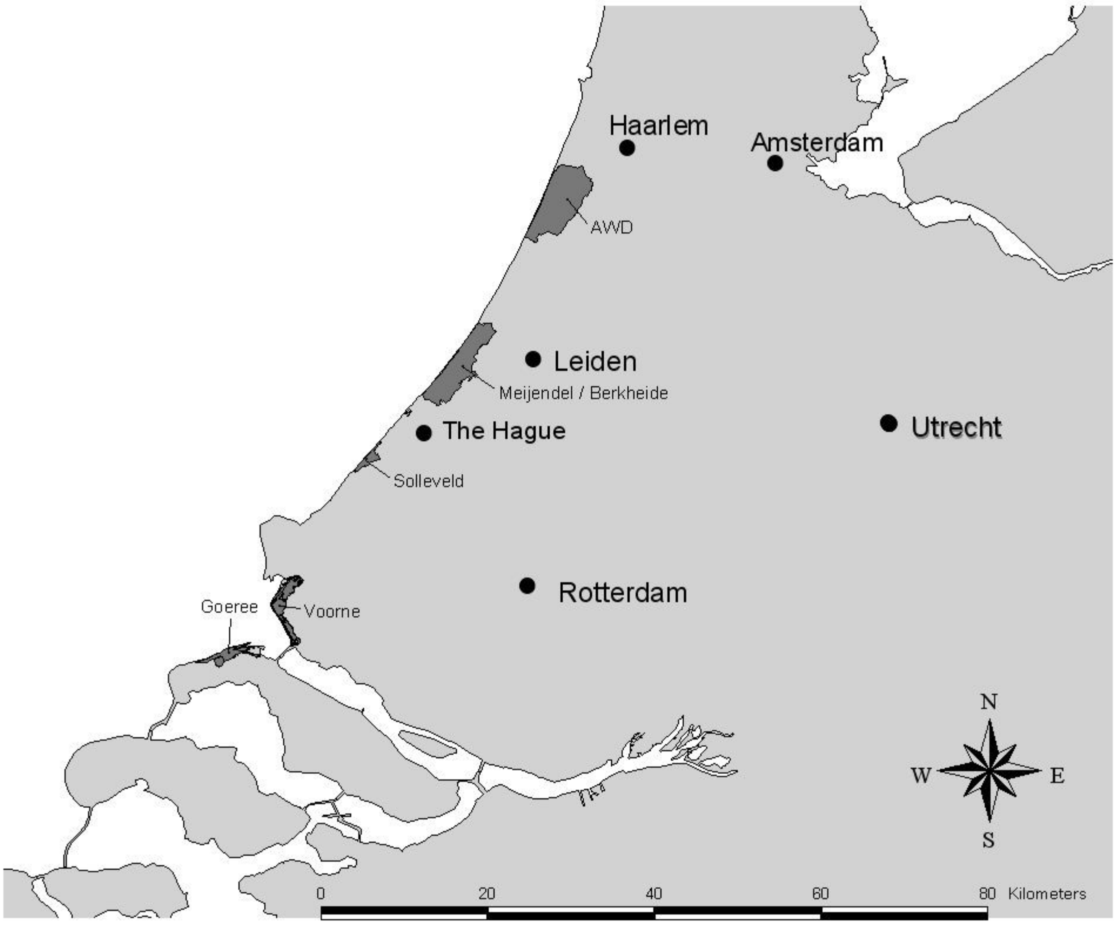


Figure 2-4 Location of the Sample areas

Table 2-3 Description of the material used in the image interpretation class definition and image classification of dry coastal dunes, for location see: Figure 2-4

• Amsterdam Water Supply Dunes (In appendices and figures referred to as AWD/2001), georeferenced and radiometric corrected scan of false colour infrared air photo, resolution: 0.25m, year of survey: 2001.
• Meijendel/Berkheide (In appendices and figures referred to as Meijendel/2001), georeferenced and radiometric corrected scan of false colour infrared air photo, resolution: 0.25m, year of survey: 2001.
• Solleveld (In appendices and figures referred to as Solleveld/2001), georeferenced and radiometric corrected scan of false colour infrared air photo, resolution: 0.25m, year of survey: 2001.
• Voorne (In appendices and figures referred to as Voorne/2005/Coastal ridge and Voorne/2005/Inner dunes), georeferenced images obtained with a digital photogrammetric camera, resolution: 0.20m, year of survey: 2005. During the process of classification poor classification results led to a stratification of the area in an area of natural inner dunes and an area of a superficial coastal ridge which was constructed in the 80's of the last century
• Goeree (In appendices and figures referred to as Goeree/2005/Younger dunes and Voorne/2005/Middle dunes), georeferenced images obtained with a digital photogrammetric camera, resolution: 0.20m, year of survey: 2005. During the process of classification poor classification results led to a stratification of the area in an area of natural younger dunes and an area of low relief grazed dune grasslands, the so-called "Middelduinen".

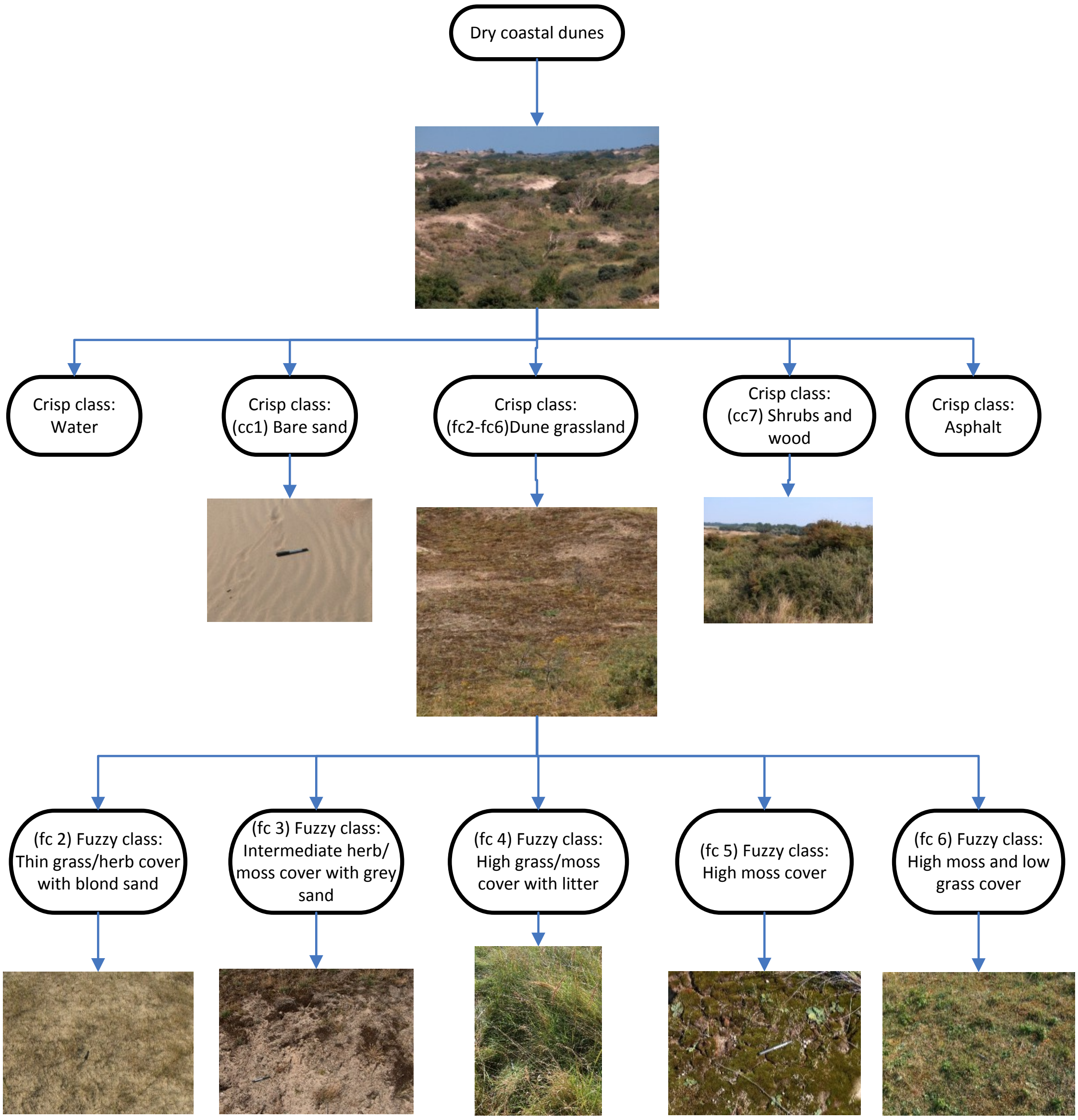


Figure 2-5 Hierarchic class structure for dry coastal dunes

2.5 Construction of the class functions and image interpretation map: the DICRANUM classification procedure

Key process in the classification procedure of small-scale dynamic ecosystems is the construction of the crisp and fuzzy class functions. The class functions are spatial objects in the so-called feature space that are consulted during image interpretation and map production. For dry coastal dunes, this process has been automated in an ArcView ® environment: the DICRANUM extension (Assendorp & Schurink, 2005). In theory, this process can be performed in any GIS or digital image interpretation environment, provided some specific image converging operations, raster-GIS operations, database operations and spatial interpolation procedures are available. Therefore, the classification process is further referred to as the "DICRANUM classification procedure". The DICRANUM classification procedure for small-scale dynamic ecosystems with fuzzy and crisp classes is presented in Figure 2-6.

Both crisp and fuzzy class functions are constructed on the base of expert observations. However, crisp class functions are based on on-screen training of the image and fuzzy class functions are based on the interpretation of field plots. The DICRANUM procedure must also give the opportunity to train random generated plots on-screen for fuzzy class function production. When historic false colour infrared images are used field survey is not possible. The use of this option is not preferred: this would reduce the overall degree of planning of the monitoring program. The field survey and the training of the image has to be performed by an experienced field ecologist who is experienced in digital image interpretation. This asks for an operator with an integrated knowledge of ecology, image interpretation and information technology.

Table 2-4 Description of the primary vegetation structure classes

Primary vegetation structure classes, discrete (crisp) and continuous (fuzzy). (adapted after Assendorp & Van der Meulen (1994) and Droesen (1999))	
Crisp (cc1): Bare Sand	The reflection characteristics and the spatial pattern of this spatial, temporal and semantic discrete class are defined by a 100 % coverage of blond aeolian dune sand. There is no vegetation cover and no grey humic sand at the surface.
Fuzzy (fc2): Thin grass/herb cover with blond sand	The reflection characteristic of this spatial, temporal and semantic continuous class is defined by a mixture of blond sand and pioneer plants. Blond sand, i.e. sand with a 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.
Fuzzy (fc3): Intermediate herb/moss cover with grey sand	The reflection characteristic of this spatial, temporal and semantic continuous class is defined by a mixture of grey humic sand and vegetation. Largest contribution to the overall coverage is by mosses who react more or less positive to or can sustain some geomorphic activity. Bare grey sand, i.e. sand with organic matter mainly in the form of humus coatings, has a substantial contribution to the overall coverage. Herbaceous 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.
Fuzzy (fc4): High grass/moss cover with litter	The reflection characteristic of this spatial, temporal and semantic continuous class is defined by a lush vegetation of grasses with a certain amount of 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.
Fuzzy (fc5): High moss cover	The reflection characteristic of this spatial, temporal and semantic continuous class is defined by mosses and lichens. The soil is totally covered with mosses and lichens, and very locally with some annual and biennial herbs. Grasses are nearly absent.
Fuzzy (fc6): High moss and low grass cover	The reflection characteristic of this spatial, temporal and semantic continuous class is defined by a mixture of mosses, herbs and grasses. 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 pixel level van occur.
Crisp (cc7): "Shrubs and woods"	The reflection characteristics and the spatial pattern of this spatial, temporal and semantic discrete class are defined by a 100 % coverage of woody plants with an individual organism size larger than the resolution of the image. Though presented as a homogeneous, discrete class internally there is a high level of heterogeneity in structure and species distribution.

The DICRANUM classification procedure has a two-dimensional feature space defined by the red and near infrared band of the image. At first, crisp classes are defined in the image feature space and classified in the image map space. Secondly, one or more crisp classes are further segmented: fuzzy class functions are constructed in the image feature space and classified in the image map space.

For crisp classes, the class functions are expert based irregular polygons and constructed in an iterative process of: class function construction, classification of the image, controlling the classification and subsequent adjusting the class function construction. This iterative process of crisp class function production aims at optimal classification results and is facilitated by digital techniques. The following steps of expert image interpretation are defined.

- Sampling of the radiometric characteristics of the crisp class (process nr. 3 in Figure 2-6). For homogeneous crisp classes (sand, water, asphalt) a limited amount of rather large samples is sufficient, for heterogeneous crisp classes (shrubs and wood) a considerable number of small samples have to be taken. The sampling strategy is to point out radiometric homogeneous samples and to sample the complete radiometric range of the crisp class.
- Examination of the radiometric characteristics of the crisp class by depicting the samples in the feature space (process nr. 4 in Figure 2-6). Mean and standard deviation of the red and near-infrared reflection of the samples result in ellipses in the feature space. These are a limited amount of large ellipses for homogeneous classes and a notable number of small ellipses for heterogeneous classes.
- Construction of the outline of the crisp class in the feature space (process nr. 5. in Figure 2-6). When the samples are taken correctly, the construction of a polygon that encloses the ellipses must yield a satisfactory result.
- Classifying the crisp classes on the base of the crisp class polygons in the feature space (process nr. 6 in Figure 2-6). The feature space with its polygons is considered as a look-up table. Pixels with a combination of red and near-infrared reflection values that lie within the crisp class polygon are assigned to that crisp class.

- Visual control of the classification results and consecutive adjustment of the crisp class polygons (process nr. 5 in Figure 2-6). Falsely assigned pixels are sampled by expert interpretation and the results leads to an adjustment of the crisp class polygons.
- Processes nr. 6 and 5 are repeated until the classification result is satisfactory according to the expert interpreter.

In the examples of Appendix A, the crisp class functions are drawn in full colours.

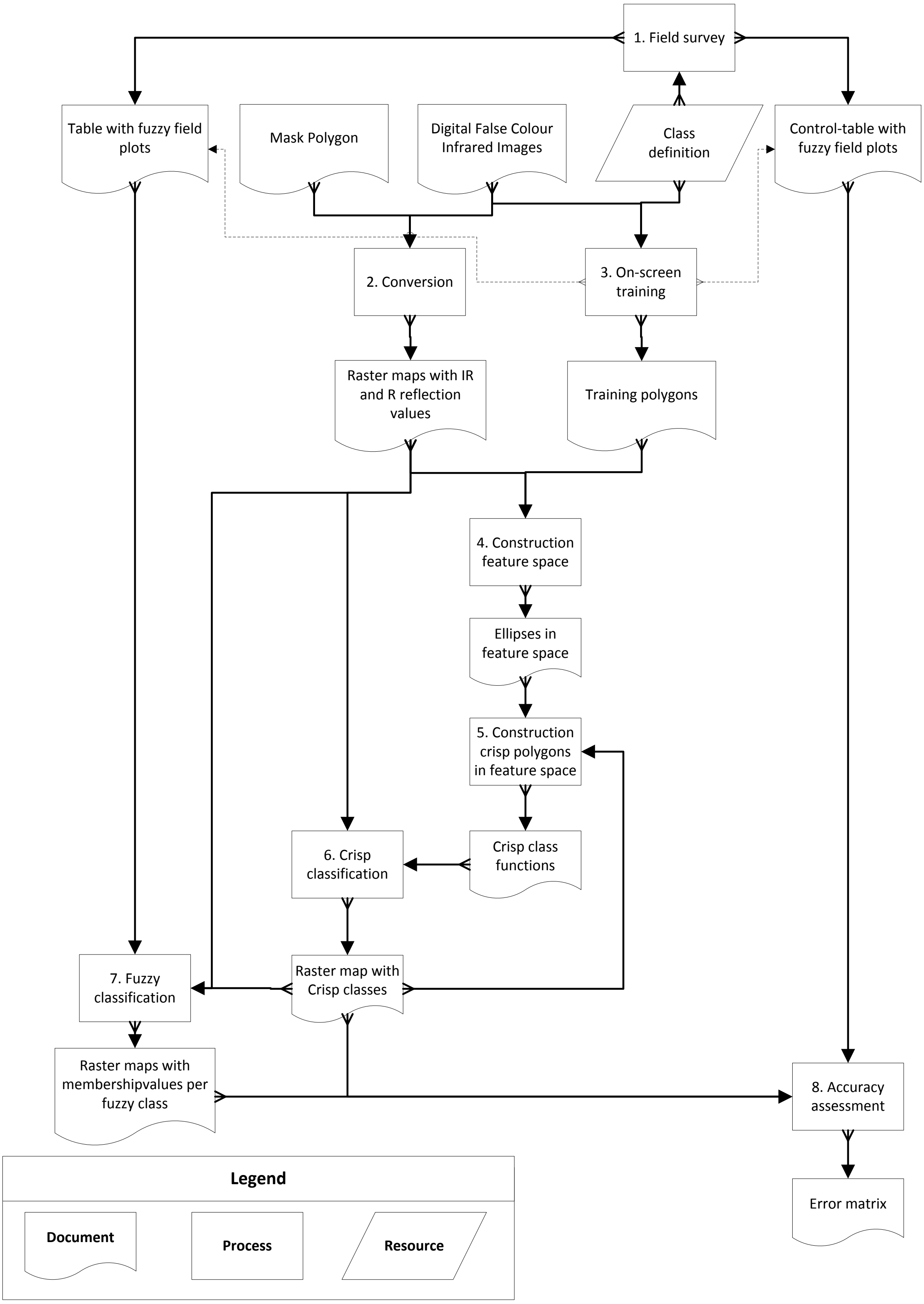


Figure 2-6 Flow diagram of the DICRANUM classification procedure

For fuzzy classes the class functions are expert based irregular graphs constructed by spatial interpolation of membership values of field sample points in the two dimensional near-infrared - red feature space. In the examples of Appendix A, the fuzzy class functions are drawn in fading colours. For every combination of red and near infrared reflection, the feature space with fuzzy class functions serves as a look-up table to determine the membership value for a specific fuzzy class. With the fuzzy class functions, a set of fuzzy image interpretation maps can be produced.

The fuzzy class functions are constructed by a spatial interpolation technique of membership values per fuzzy class in the feature space (for instance, a spline-interpolation). These membership values are recorded in the field in combination with an exact location (process nr. 1 in Figure 2-6). The location process has to be performed with the aid of differential GPS (Hofmann-Wellenhof et al., 2001) so that geometric field resolution and accuracy are in agreement with image resolution and accuracy. In the feature space, the recorded membership values and the corresponding reflection values, as can be found by the geographic position of the field plot in the image space, are combined. The membership values in the feature space are input for the construction of an irregular surface by spatial interpolation. The maximum extent of the surface is determined by the crisp class function wherefore the class is segmented into fuzzy classes. Important limiting condition in the construction of the interpolation surfaces per fuzzy class is the fact that for every point in the feature space the sum of surface values (which are in fact membership values) may not exceed the maximum membership value of the classification system (mostly 1 or 100%).

Theoretically, the surveyed location in the field should be the exact area of an image-element (pixel). Practically this is impossible so a round area with a diameter of ca. 1m^2 is surveyed and recorded. Therefore, one field recording mostly yields more reflection values that can be used for the interpolation in the feature space.

The accuracy of a fuzzy class function is presented by Droesen (1999) as the correlation between the image interpretation and reference measurements. The correlation coefficients are relatively high because of over-representation of low and high membership values. Therefore, this method is not adopted. The accuracy of the results of the DICRANUM classification procedure (process nr. 8 in Figure 2-6) are presented and discussed in Chapter 3. In this chapter also some results of the accuracy assessment procedure are presented. In the following Section (2.6) results of the DICRANUM classification procedure are presented.

Information technology is an important and essential aid in the classification procedure but without the input of an experienced field ecologist and image interpreter the classification cannot be carried out. Crucial expert input steps in the classification procedure are:

1. On screen training of representative polygons of crisp classes,
2. Construction of crisp class polygons in the feature space
3. Field survey of fuzzy field plots

In the case of additional fuzzy plot production or when historic image material is used:

3. On screen training of fuzzy plots.

Above all, the expert link between image and field is essential. Additionally, when the procedure has to be automated for a specific platform, there has to be a strong functional link between the ecological expert and the expert on information and computer technology.

2.6 Results

The DICRANUM classification procedure has been applied to material presented in Table 2-3. This led to the production of a set of six basic maps per classified area: essential material for a monitoring program. For the areas managed by the drink water supply companies (Amsterdam Water Supply Dunes, Meijendel/Berkheide and Solleveld) this is part of the general cycle of nature management and evaluation (De Bonte et al., 1999; Van der Meulen et al., 2008), for the areas Voorne and Goeree it is base-line material for monitoring the effects of the construction of an extensive new harbour and industrial estate (Maasvlakte II) (Doomen et al., 2006). For every classification, one map is produced with the presentation of the crisp classes (cc1, fc2-fc6 combined and cc7; for class description see Table 2-4) and five separate maps with the membership value of the fuzzy classes (fc2, fc3, fc4, fc5 and fc6).

Though the maps are primarily produced for monitoring purposes, they can also be applied in the modelling of potential habitats of fauna. For instance, the modelling of the habitat of sand lizard (*Lacerta agilis* L.) is a combination of bare sand (cc1), low dune grassland (fc2, fc3 and fc6) and shrubs and woods (cc7) within a relative small area so the sand lizard has the opportunity to breed, sun, forage and hide.

A combination of the classification results is presented in Appendix A. In the feature space, crisp classes (cc1 and cc7) are presented, the fuzzy classes (fc2 – fc6) are represented when the membership value exceeds 50% and the membership value of the class is highest compared to other fuzzy classes. The same rules are applied to the representation of the image interpretation classes in the combined vegetation structure map. Interpretation of the vegetation structure maps can be focused on a range of aspects.

1. The overall structure of the terrain. The spatial distribution of crisp classes gives general information on the overall spatial and temporal dynamics of the terrain. A dominance of shrubs and woods, as can be seen at Voorne (Appendix A4, A5), is an indication of ongoing stabilisation of the terrain. This conclusion is supported by Van Dorp et al. (1985). A patchy structure of bare sand as well as of shrubs and woods in a matrix of dry dune grassland suggests a dynamic self-regulating landscape development. This pattern is observed in Meijendel (Appendix A2) and further elaborated in Chapter 7.
2. Grassland dominance and distribution in the terrain. Every (part of the) terrain seems to have a dominant grassland type or a specific distribution of grassland types: Solleveld (Appendix A3) and the Amsterdam Water Supply Dunes (Appendix A1) are dominated by short grazed dune grassland (fc6), the Younger dunes of Goeree (Appendix A6) have a clear gradient, ranging from grey dunes

(fc3) to a thick grass cover (fc4). The continuous character of the dune grassland cover is obvious.

3. Overall grassland distribution per image element. When more than one grassland type is (sub) dominant at the scale level of one pixel no colour is revealed. This can be observed in the Meijendel example (Appendix A2) and points at a high level of convergence: at the sub-pixel level there is a high spatial variability in grassland types.

The accuracy of the crisp classification is established by determining the user's, producer's and overall accuracy of the crisp classification with a confusion or error matrix (Foody, 2002). This type of assessment compares ground truth (obtained by the 'user') with classification results (determined by the 'producer'); the overall agreement between user and producer is reflected as the overall accuracy. Table 2-5 - Table 2-11 present the results of the accuracy assessments. The accuracies of the classifications of scanned analogue false colour images (the Amsterdam Water Supply Dunes, Meijendel/Berkheide and Solleveld) are within the range of 80% - 90%, generally accepted as good for a vegetation structure map. The accuracies of the classifications of images obtained by a digital photogrammetric camera (Goeree and Voorne) have a wider range: 73% - 96%. The reason is not the platform of digital data-acquisition. Most likely the wide range is caused by the variability in dominant vegetation structure, from shrubs and wood dominated vegetation (Voorne, Appendix A4 and A5) to open dune grassland (Middle dunes Goeree, Appendix A7). In this case, comparing accuracy matrices gives no direct information whether the data and data processing meet the requirements of a high-resolution monitoring program with the highest degree of planning.

Apart from the vegetation structure maps and accuracy matrices, the feature spaces can also be compared. Therefore, overlay images of feature spaces are composed: see Figure 2-7 - Figure 2-13. The differences between images obtained with different devices and at different moments are obvious (compare Figure 2-7, Figure 2-8 and Figure 2-9 with Figure 2-10, Figure 2-11, Figure 2-12 and Figure 2-13).

The 2001 crisp class feature spaces show that the polygons are more or less similar though small differences occur. The shrubs and woods polygon of Solleveld is less complex than those of AWD and Meijendel and the accuracy of the Solleveld shrubs and woods classification is significantly higher. The explanation seems rather simple: the extent of the Solleveld area is much smaller than that of the AWD and Meijendel area and therefore the inner complexity of the Solleveld area is smaller. However, a closer look at the Solleveld area contradicts such explanation. Solleveld is an area of different landscapes (Van der Meulen & Van der Maarel, 1993): dynamic fore-dunes, stable grasslands of the older dunes and woods of the inner dunes are all present. More likely, the cause must be found in radiometric diversity of the material. The 2001 digital image is a mosaic of a large set of photos: the larger the area, the greater the radiometric variety within the image to classify. This conclusion is strengthened by the relative high accuracy of the Solleveld classification. The radiometric complex images of Meijendel and AWD yield a less accurate classification result.

Comparison of the AWD and Meijendel shrubs and woods crisp class function yields the observation that both polygons have a broadleaved shrubs "bulge" but the AWD bulge is characterised by lower infrared reflection values than the Meijendel bulge. Differences in time of exposure can be the reason.

The crisp class functions defined for the classification of the coastal ridge of Voorne and the younger dunes of Goeree (Figure 2-10) are more or less similar. The difference in extent of the 'Bare sand' polygon can be explained from the origin of the exposed sand in this part of the dunes of Goeree. The sand is exposed at the surface as a result of rejuvenating some infiltration ponds. A relative high amount of slightly humic (grey) and moist sand reveals a wider range in reflection values.

The crisp class functions of the inner dunes of Voorne and the middle dunes of Goeree differ significantly (Figure 2-11), the much more diverse and complex character of the inner dunes of Voorne being the reason. For Goeree, the extent of the crisp class function of the younger dunes is much larger than those of the middle dunes (Figure 2-12). Here, the diversity and extent of the classified terrain is also the explanation. This conclusion is confirmed by the comparison of the complexity and extent of the crisp class function of the inner dunes of Voorne with the coastal ridge of Voorne (Figure 2-13). The coastal ridge of Voorne consists mainly of *Hippophae rhamnoides* shrub and *Ammophila arenaria* dominated grassland in contrast to the inner dunes, which are very diverse in shrubs and grassland types (Van Dorp et al., 1985; Van der Meulen & Van der Maarel, 1993; Van Haperen, 2009).

The conclusion for the crisp class function that the complexity of the terrain determines the complexity of the class functions can also be made for the fuzzy class functions. A more thorough sampling strategy seems to be needed (see Chapter 3) but this is not a guarantee for more coherent fuzzy class functions. If the field measurements in combination with image information yield incoherent functions with accuracies as presented it must be taken as reality.

It is striking that images of dry coastal dune areas, taken and processed in a nearly similar way (same platform, same date, geographically very close) yield significant differences in feature space composition. This conclusion is valid for crisp as well as fuzzy class functions. Small-scale local differences in landscape components like soil, relief and vegetation are of course a logical reason, but small differences in astronomic (position of the sun) and atmospheric condition (Richards & Jia, 2006) must be taken fully into account. Therefore, it is not desirable to classify high-resolution digital images of dynamic small-scale natural ecosystems on the base of purely physical measurements. This is partly supported by the findings of Van Til et al. (2004) who used hyperspectral imagery and field spectrometry to determine the spectral reflectance of coastal dune vegetation. It turned out that spectral characteristics change significantly during the growing season. Because the phase of the growing season can vary in a range of two to three weeks, spectral characteristics of vegetation are not a reliable source for image classification. An expert is highly competent to interpret vegetation structure types as presented in Table 2-4 in different phases of the growing season.

Table 2-5 Error matrix of the crisp class classification of GWA/2001

Error matrix: GWA/2001						
		Training set data				
		Shrubs and woods	Grassland	Bare sand	User's accuracy	**Overall accuracy**
Classification data	Shrubs and woods	99	13		88%	
	Grassland	27	76	3	72%	
	Bare sand			2	100%	
	Producer's accuracy	79%	85%	40%		
	Overall accuracy					**80%**

Table 2-6 Error matrix of the crisp class classification of Meijendel/2001

Error matrix: Meijendel/2001						
		Training set data				
		Shrubs and woods	Grassland	Bare sand	User's accuracy	**Overall accuracy**
Classification data	Shrubs and woods	92	8	1	91%	
	Grassland	27	81	2	74%	
	Bare sand			9	100%	
	Producer's accuracy	77%	91%	75%		
	Overall accuracy					**83%**

Table 2-7 Error matrix of the crisp class classification of Solleveld/2001

Error matrix: Solleveld/2001						
		Training set data				
		Shrubs and woods	Grassland	Bare sand	User's accuracy	**Overall accuracy**
Classification data	Shrubs and woods	39	16		71%	
	Grassland	2	112		98%	
	Bare sand			8	100%	
	Producer's accuracy	95%	88%	100%		
	Overall accuracy					**90%**

Table 2-8 Error matrix of the crisp class classification of Voorne/2005/coastal ridge

Error matrix: Voorne/2005/coastal ridge						
		Training set data				
		Shrubs and woods	Grassland	Bare sand	User's accuracy	**Overall accuracy**
Classification data	Shrubs and woods	119	2		98%	
	Grassland	10	42		81%	
	Bare sand		1	6	86%	
	Producer's accuracy	92%	93%	100%		
	Overall accuracy					**93%**

Table 2-9 Error matrix of the crisp class classification of Voorne/2005/inner dunes

Error matrix: Voorne/2005/inner dunes						
		Training set data				
		Shrubs and woods	Grassland	Bare sand	User's accuracy	**Overall accuracy**
Classification data	Shrubs and woods	190	3		98%	
	Grassland	63	15		19%	
	Bare sand		1	1	50%	
	Producer's accuracy	75%	79%	100%		
	Overall accuracy					**75%**

Table 2-10 Error matrix of the crisp class classification of Goeree/2005/middle dunes

Error matrix: Goeree/2005/middle dunes						
		Training set data				
		Shrubs and woods	Grassland	Bare sand	User's accuracy	**Overall accuracy**
Classification data	Shrubs and woods					
	Grassland	3	79		96%	
	Bare sand			5	100%	
	Producer's accuracy	0,00%	100%	100%		
	Overall accuracy					**97%**

Table 2-11 Error matrix of the crisp class classification of Goeree/2005/younger dunes

Error matrix: Goeree/2005/younger dunes						
		Training set data				
		Shrubs and woods	Grassland	Bare sand	User's accuracy	**Overall accuracy**
Classification data	Shrubs and woods	100	12		89%	
	Grassland	45	70	1	60%	
	Bare sand		9	17	65%	
	Producer's accuracy	69%	77%	94%		
	Overall accuracy					**74%**

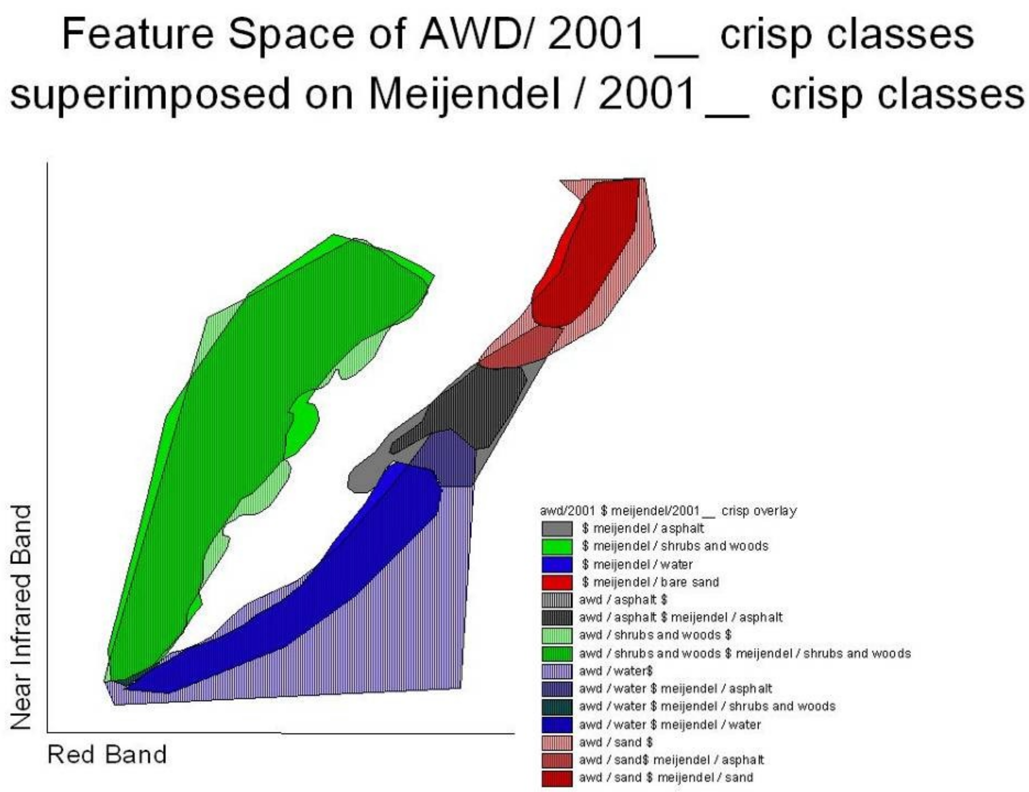


Figure 2-7 Comparison of crisp class functions of AWD/2001 with Meijendel/2001

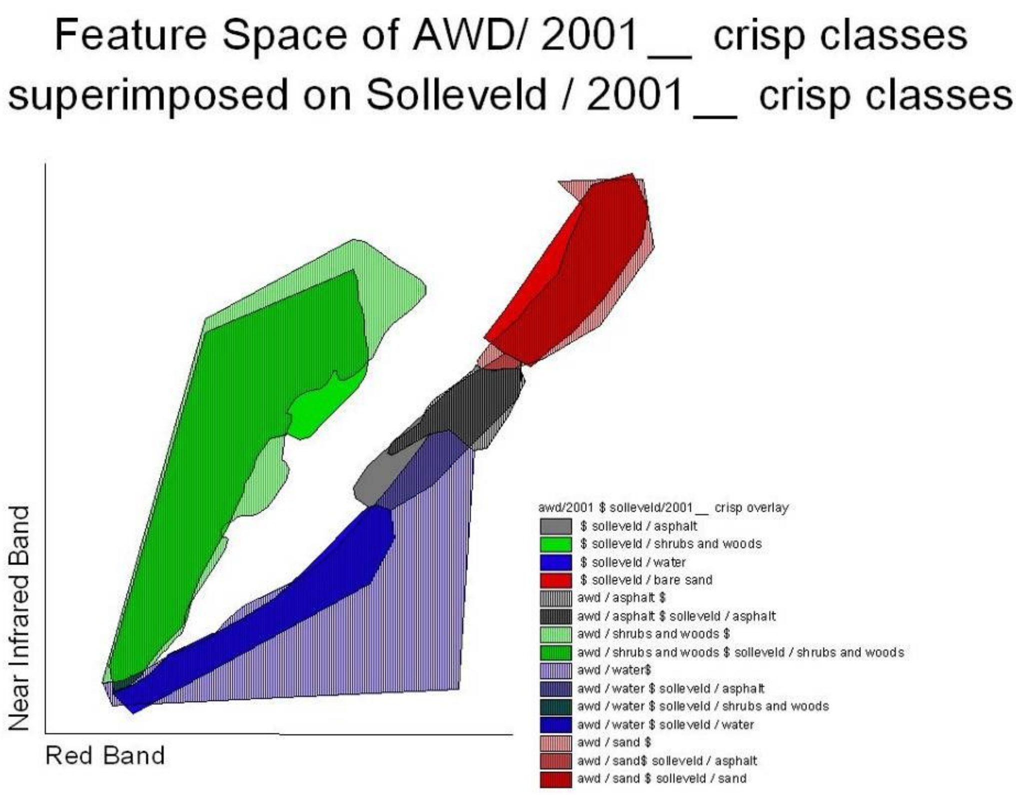


Figure 2-8 Comparison of crisp class functions of AWD/2001 with Soleveld/2001

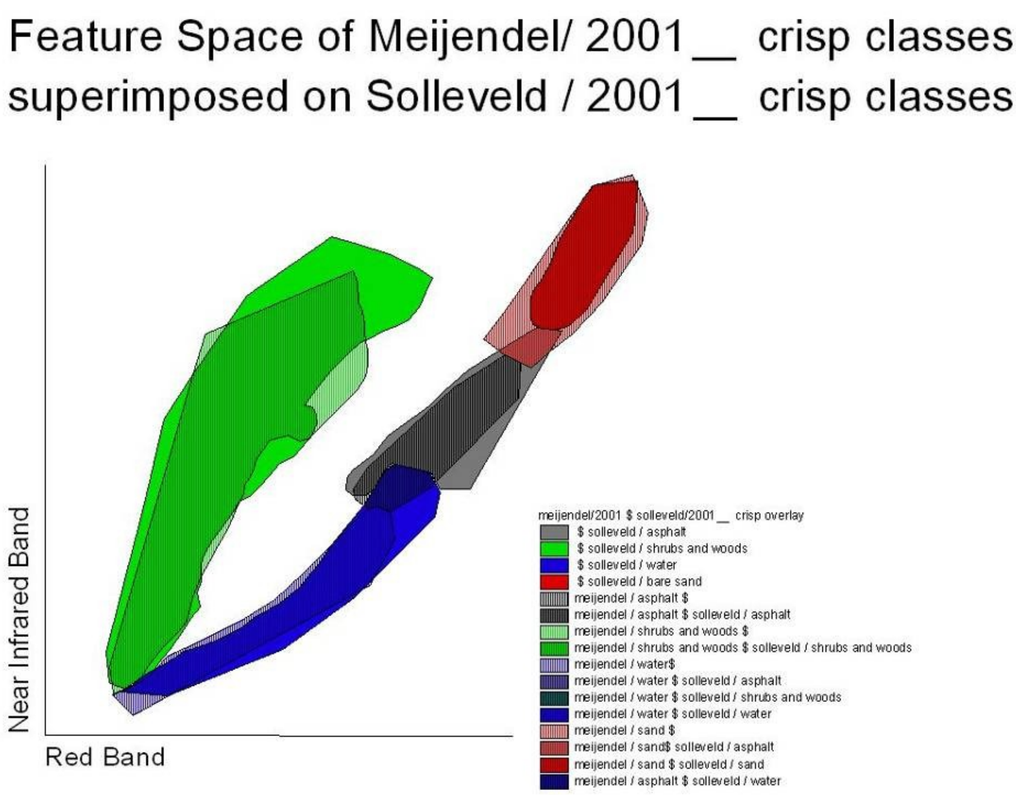


Figure 2-9 Comparison of crisp class functions of Meijendel/2001 with Solleveld/2001

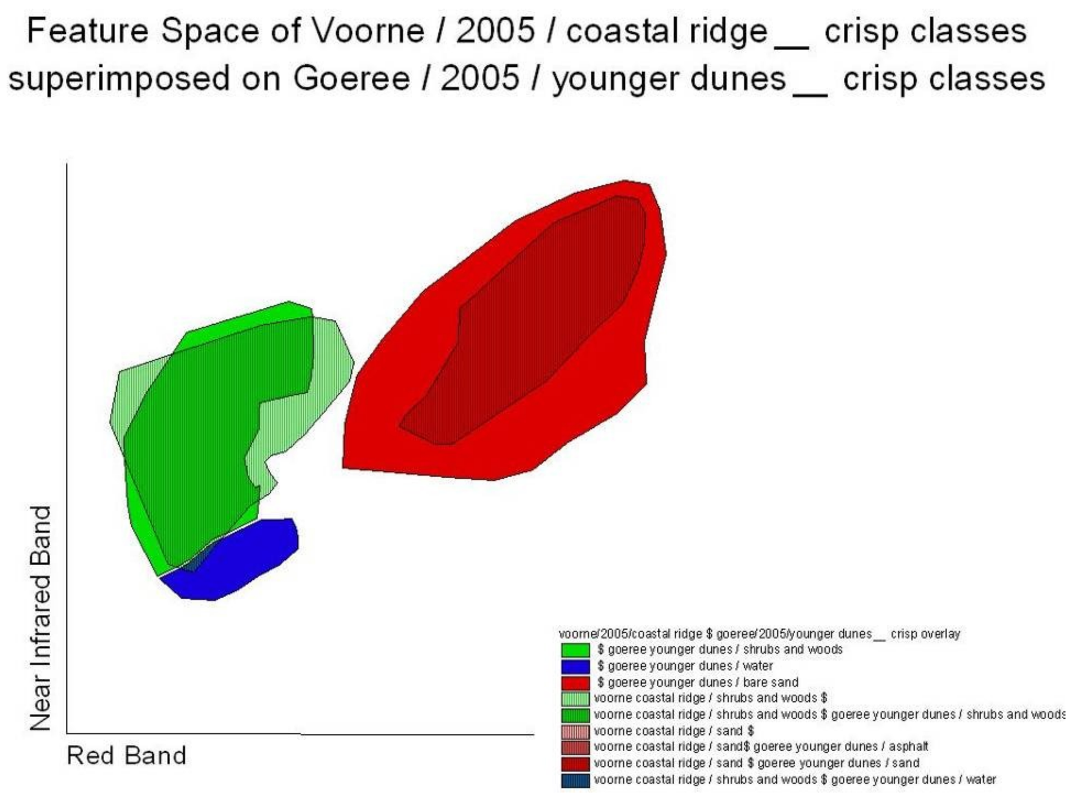


Figure 2-10 Comparison of crisp class functions of Voorne/2005/coastal ridge with Goeree/2005/younger dunes

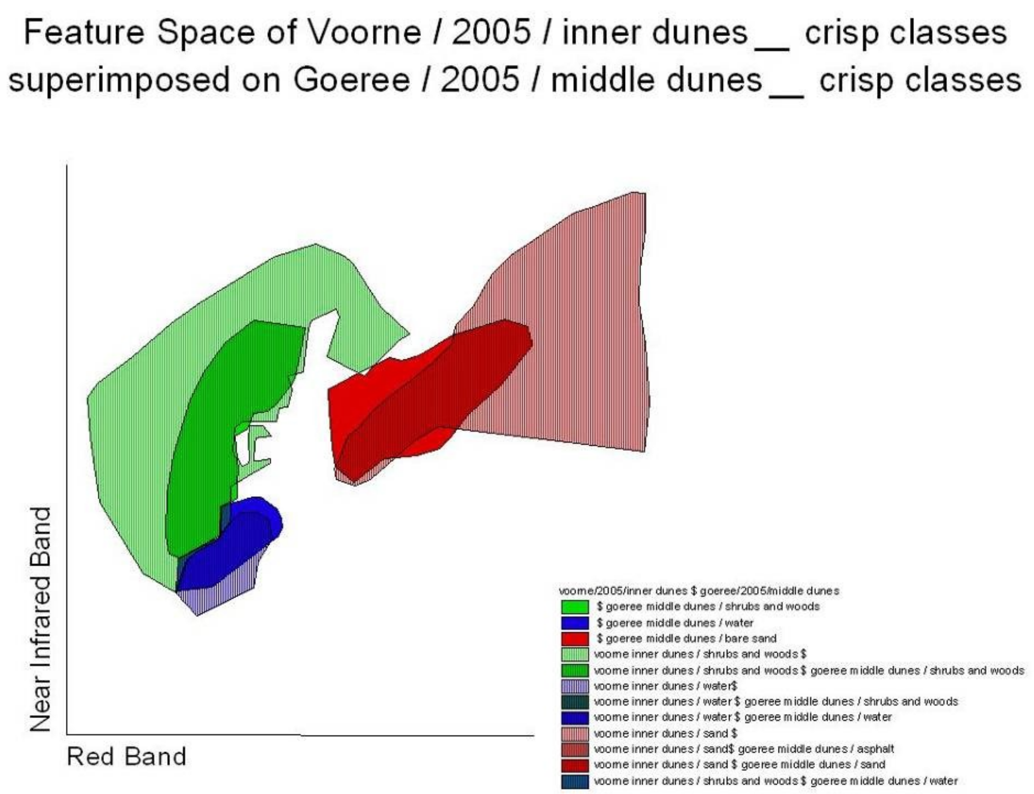


Figure 2-11 Comparison of crisp class functions of Voorne/2005/inner dunes with Goeree/2005/middle dunes

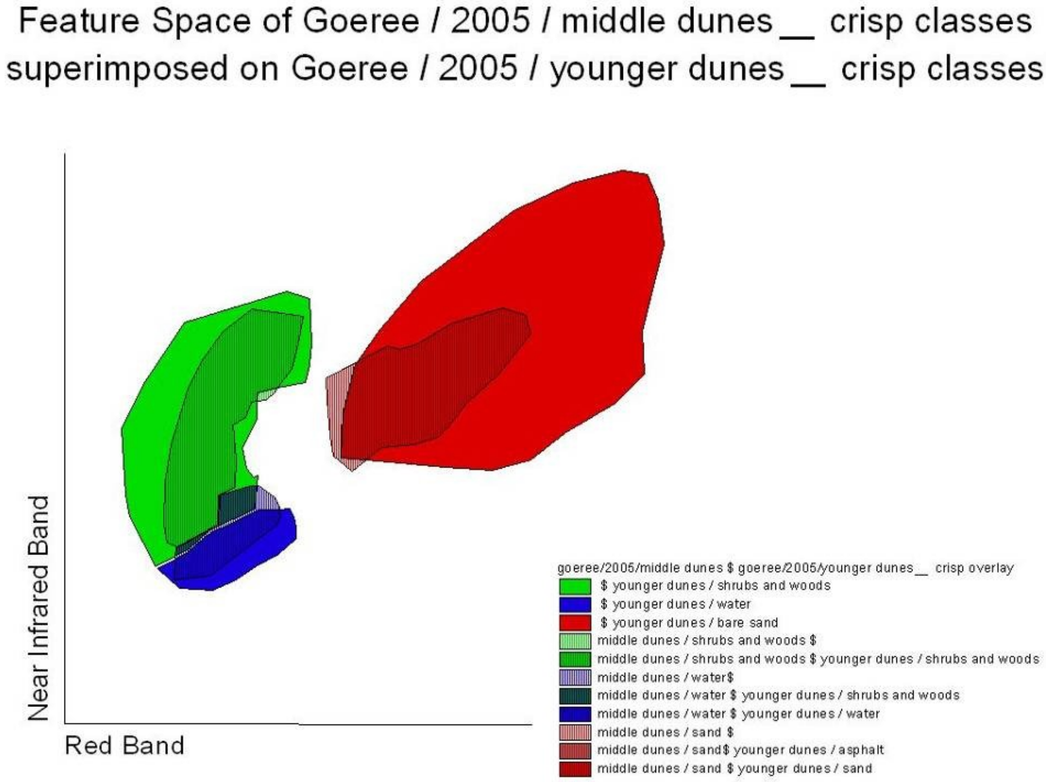


Figure 2-12 Comparison of crisp class functions of Goeree/2005/middle dunes with Goeree/2005/younger dunes

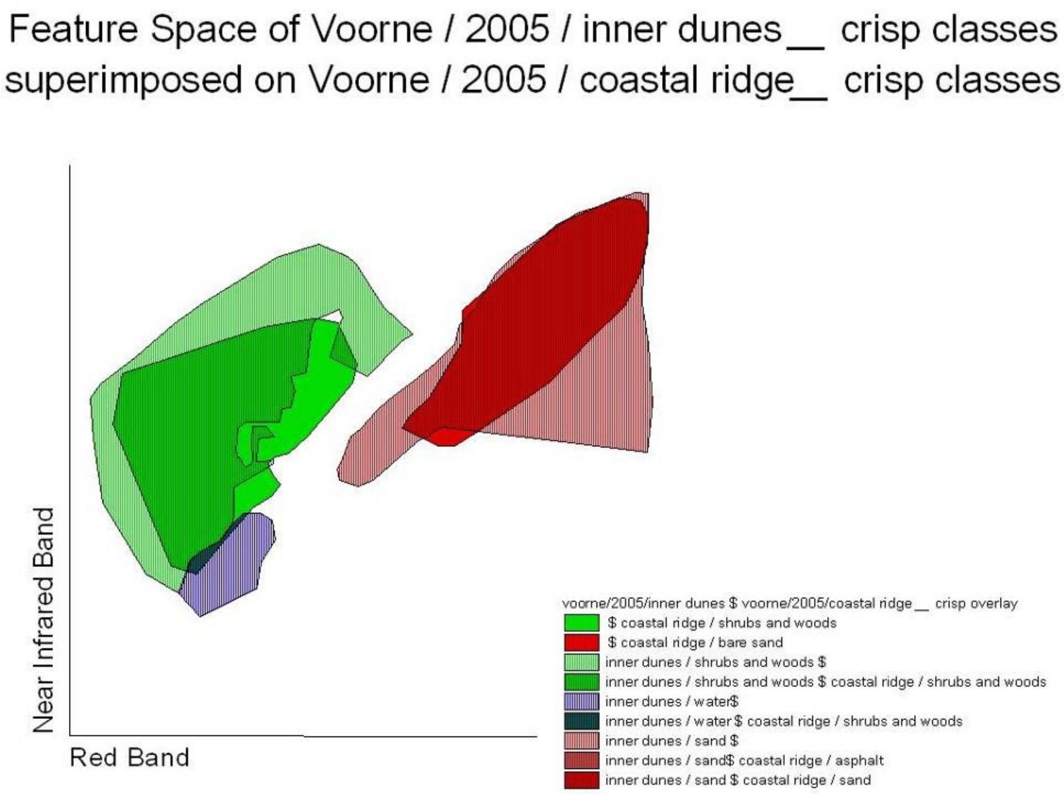


Figure 2-13 Comparison of crisp class functions of Voorne/2005/inner dunes with Voorne/2005/coastal ridge

2.7 Discussion and conclusions

Small-scale dynamic ecosystems are highly valued and the conservation of these systems is mainly focused on maintaining their dynamic character. This implies that also monitoring has to focus on this dynamic character. In this chapter it has been made clear that the dynamics can be monitored with high-resolution images, combined with specific and detailed field measurements. Application of fuzzy set theory to the digital image data as well as the field data is the most obvious method to describe and analyse convergence, continuity or divergence in the spatial, semantic and temporal domains. A variety of topics is combined to develop a monitoring program for small-scale dynamic ecosystems. Landscape ecology, terrain management and information technology result in a concept of continuous landscape and data.

From all examples on monitoring, found in literature (see, for instance, Table 2-1), not one reports institutional monitoring, that is a monitoring program initiated and supported by a nature management or conservation company. All examples report monitoring programs with a scientific goal. This is remarkable because monitoring should be an integrated part of the evaluation of management interventions, performed by a nature management company. Furthermore, from theory and material presented it is clear that a monitoring program of the highest degree of planning can only be achieved through a profound cooperation between nature manager, (landscape) ecologist and the data analyst/technologist.

A systematic monitoring program is important in the framework of the manager of a highly dynamic natural ecosystem, and digital imagery and digital image interpretation plays a significant role. Nevertheless, with the profound role of the field ecologist and the image interpreter, the classification environment must be clear and well-defined. The results presented strongly suggest that the roles of (1) the coordinator of the monitoring program (builder of concepts, organiser of action steps and tenders), (2) the field ecologist and (3) the image interpreter, has to be combined into one person. This leads to a highly integral approach whereby only one person bridges the gap between terrain manager and information technology expert.

The processes as reflected in Figure 2-1, Figure 2-3 and Figure 2-6 highlight the importance of an active interaction between landscape ecology and information technology. Personal experience of the author is that this project, which has been going on (with difficulties) for more than fifteen years, has led to the development of new landscape ecological concepts and new information technology concepts.

A concluding remark concerning the DICRANUM classification procedure concerns the fact that the rather quick, effective and standard production of landscape ecological maps is an economical and management advantage in this period, in which nature management organisations are confronted with European directives (Ostermann, 1998) and increasing commercial demands.

From the image interpretation results of high-resolution false colour infrared images it can be concluded that small-scale dynamic ecosystems are highly divers in spectral reflectance characteristics, revealed in the feature space. This means that classification, by, for instance, the DICRANUM classification procedure, has to be executed in relative small sub-areas (maximum of about 3000 ha) and in sub-landscapes with a similar basic structure.

Photo 1 Impression of a small-scale dynamic ecosystem: The Amsterdam Water Supply Dunes

3
ACCURACY ASSESSMENT OF HIGH-RESOLUTION FUZZY VEGETATION MAPS.

3.1 Introduction

For more than 20 years thematic landscape or vegetation maps of the Dutch coastal dunes have been produced on the basis of high-resolution false colour infrared images (Van der Meulen et al., 1985; Van Dorp et al., 1985; Doing, 1995; Droesen, 1999). The procedures for production of these maps are extensively described in the literature (Van Til & Mourik, 1999; Janssen, 2001). The traditional, analogue production of dune landscape and vegetation maps is well developed (Van Dorp et al., 1985) but with the emergence of high storage capacity and high processing speed in personal computers new classification procedures based on digital image interpretation were developed (Janssen, 2001; Provoost et al., 2005). These procedures are based on computational techniques as provided by digital image interpretation software (Lillesand et al., 2008). In practice, the standard classification procedures appeared to be not fully adequate for the classification of high-resolution false colour infrared images of the Dutch coastal dunes (Droesen et al., 1995). Causes are technical as well as conceptual: the classification procedures concerned are mainly focused on the segmentation of spatially as well as thematically crisp objects whereas natural ecosystems are characterised by spatial and temporal gradients (Van Leeuwen, 1966; Jungerius & Van der Meulen, 1988) (see also Chapter 1). Attributes that refer to landscape characteristics like vegetation, soil and geomorphology, are in essence an integration of more than one basic attribute and therefore spatially, temporally and semantically more or less fuzzy. For vegetation, this is rather obvious: a vegetation type relates to the co-existence of several plant species but the spatial distribution of individual plant species rarely coincides (Fortin & Dale, 2005). This is also valid for soil characteristics like texture and organic matter, and for geomorphic characteristics like relief and sediment type.

The ecologically rather obvious observation of fuzziness in dynamic natural ecosystems led to the development of a new landscape model (see Chapter 1) and classification procedure (see Chapter 2). This new procedure gives the opportunity to describe the temporal, spatial and semantic (thematic) gradients in small-scale dynamic ecosystems (see Frame 1-1). The technical elaboration was carried out by Droesen (1999) and later implemented in an ArcView extension: DICRANUM (Assendorp & Schurink, 2005). As explained in Chapter 2, the classification procedure can be performed in any GIS- or digital image interpretation environment, provided that some specific image converging operations, raster-GIS operations, database operations and spatial interpolation procedures are available. This new classification procedure results in a set of grid-maps: one map for the crisp classification results and a set of maps with membership values for every fuzzy class. A technique to assess the accuracy of these classification results was not yet available. In the literature, only examples of accuracy assessment of discrete thematic maps using fuzzy logic were found (Gopal and Woodcock, 1994; Woodcock & Gopal, 2000; Foody, 2002). This chapter describes the development and application of an accuracy assessment of fuzzy digital image interpretation maps.

Droesen (1999) was one of the first to propose a technique to assess the accuracy. He presents the correlation between field observations and pseudo-probabilities or membership values as determined according to the fuzzy class function. However, this is no accuracy assessment of the classification results, but an accuracy assessment of fuzzy class functions (see Figure 3-1). Moreover, the correlation coefficients as presented by Droesen are unrealistically high for two reasons:

1. The total set of field observations is used; this results in an overrepresentation of low membership values.
2. The field sampling strategy was focused on sampling points with high membership values for one fuzzy class; this results in an overrepresentation of high membership values.

So, membership values around 50% are underrepresented and it is these intermediate membership values that are major sources of inaccuracy. Therefore it is not surprising that the correlation coefficients are high.

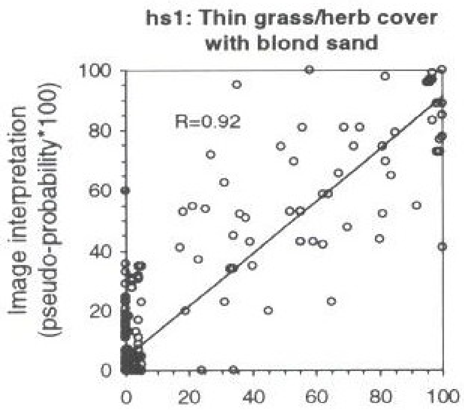


Figure 3-1 Example of the accuracy assessment of fuzzy class function as presented by Droesen (1999)

The essential difference between "Fuzzy class function accuracy assessment" and "Fuzzy vegetation structure map accuracy assessment" is illustrated in Figure 3-2. The combination of the digital image and ground truth leads to a fuzzy class function or more general: a feature space that can be applied in the digital image classification. With the fuzzy class functions a fuzzy vegetation structure map can be produced. When membership values of independent ground truth points are compared with the membership values as determined by individual fuzzy class functions, a fuzzy class function accuracy assessment is performed. When membership values of independent ground truth points are compared with membership values as presented in the fuzzy vegetation structure map a fuzzy vegetation structure map accuracy assessment is performed.

First, an introduction is given on the sources of inaccuracy in thematic maps, vegetation maps in particular (section 3.1.1). This is followed by an introduction on accuracy assessment in digital image interpretation techniques (section 3.1.2). Section 3.2 focuses on sources of inaccuracy of fuzzy, grid-based vegetation maps. This leads to the description of the technique to assess the accuracy as implemented in the DICRANUM classification procedure (section 3.2.2). Accuracies of classifications in Dutch coastal dune areas are presented in section 3.3. Finally, accuracies, used ground truth points and the strategy for ground truthing are evaluated (section 3.4), leading to some conclusions concerning the strategy for field survey (section 3.5).

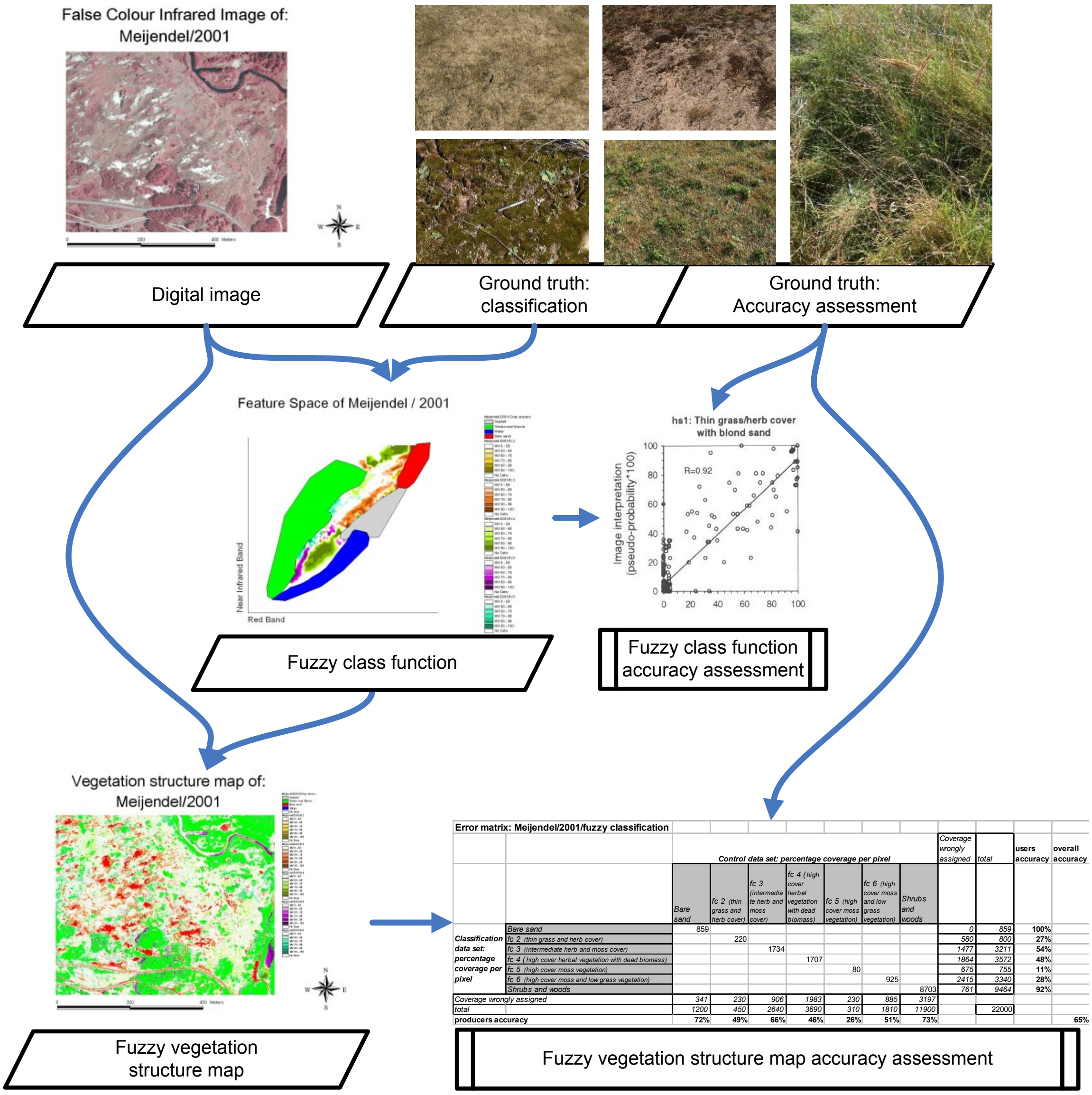


Figure 3-2 "Fuzzy class function accuracy assessment" and "Fuzzy vegetation structure map accuracy assessment" as part of the digital image processing procedure

3.1.1 The accuracy of thematic maps, vegetation structure maps in particular

In this section, the need for accurate thematic maps in landscape planning is briefly elucidated after which sources of error in analogue and digital vegetation structure map production are discussed.

The reliability of a valuation, of an impact- or hazard assessment or of a model for specific or general landscape development depends strongly on the accuracy of the underlying thematic maps (Kyriakides & Dungan, 2001; Wu & Hobbs, 2002; Gergel et al., 2007). The production of thematic maps in general comprises four successive process steps, each of which being relevant for the overall accuracy.

- acquisition,
- processing,
- storage,
- presentation.

Data acquisition, with the aim to produce a thematic map, can vary as a consequence of the procedures and survey methods used, ranging from exact field measurements with specialized devices (Goudie et al., 1990) to estimations of generalized or composite attributes (Zonneveld, 1989). Sources of inaccuracy in exact field measurements are primarily technical, the device generating errors or the operator being incompetent. Sources of inaccuracy in composite attributes like soil, vegetation type or ecotope are mainly caused by differences in interpretation or expert judgement, though incompetence of the field surveyor can be a source.

In traditional thematic map production, the accuracy of the map is mainly determined by the quality of the field measurement or observation and the data presentation. Subjectivity of the observer or the quality of the measuring device and the scale of the map are sources of inaccuracy. However, generalisation of data during data processing steps can be another major source of inaccuracy because imbalance between scale and attribute can lead to production of unrealistic maps. Particularly thematic maps of small-scale dynamic ecosystems can be inaccurate as a result of this imbalance. Where a scale of 1:10.000 is generally accepted, and even recommended, as accurate for vegetation or habitat mapping (Hill et al., 2005), the small-scale dynamic character of coastal dunes, salt marshes or flood plains cannot be surveyed accurately. A key for vegetation mapping at such a scale would be either too general to show relevant information for management purposes or a key with classes relevant for management would be too detailed to reveal correct spatial information at that scale.

Sequential vegetation structure maps are used to monitor changes in habitat types and habitats are used as a major reference in nature policy planning (Carranza et al., 2008). General procedures in analogue vegetation mapping and connected major sources of inaccuracy can be summarized as follows:

1. Data acquisition
    a. Image production: the quality and the applicability of high-resolution false colour infrared images depends on date, time and atmospheric condition during surveillance (Clevers, 1994).
    b. Sampling relevees: species can be falsely identified and their relative coverage incorrectly estimated. (Kent & Coker, 1992; Janssen, 2001).
    c. Land unit definition: interpretation of aerial photography or field work is a major source of inaccuracy, especially the subjectivity of the process (Kent & Coker, 1992; Janssen, 2001).
2. Data processing
    a. Classification: relevees are classified into abstract phytosociological units, highly valuable information on the gradient-rich character of the vegetation cover is simplified into crisp classes (Kent & Coker, 1992; Jongman et al., 1995).
    b. Land unit generalisation: Spatial units are generalised according to the class definition used; the assignment of vegetation classes to land units is a subjective process. If basic data is preserved, this process can be corrected. (Zonneveld, 1989; Janssen, 2001)
3. Data presentation
    a. Map scale: the extent of generalisation in vegetation maps strongly depends on their scale. Because land units represent the co-existence of species and individuals, every spatial scale has its own unique classification. The smaller the (metric) spatial scale the more generalised, and the larger the (metric) spatial scale the more detailed, up to the level of the individual species and object.
    b. Characteristic of vegetation revealed in the map: the more complex the distinguishing characteristics described in the map, the greater the chance for inaccuracy. For example, vegetation structure is much more explicit to interpret than phytosociologic units.

Since accuracy assessment is a process of comparison between model (map) and reality (the field), it is possible to assess the accuracy of an analogue map. However, it is nearly impossible to determine the source of inaccuracy because an analogue vegetation map remains a subjective estimation of reality with multiple correlated sources of inaccuracy. For instance, an image of poor quality influences the image interpretation results. When analogue maps are used for monitoring purposes, the accuracy of such temporal analysis is doubtful because sources of inaccuracy accumulate. Therefore, the results of Van Dorp et al. (1985) are disputable.

Nowadays, with the development of (semi)automated classification procedures on the basis of digital images, sources of error resulting from data processing and data storage are easier to detect and assess (Goodchild, 1993). Errors resulting from data storage are thought to be negligible because digitally stored data are unaltered, unless the operator defines an explicit operation. Examples are a change in storage device or conversion. Because of the high storage capacity of digital data systems it is more plausible that data are too extensive and detailed than too generalized. This can result in unrealistic map presentations where spatial- and semantic scale are not in balance.

3.1.2 Accuracy assessment in digital image processing

The production of a vegetation map with the help of explicit digital image interpretation procedures should make it possible to generate an accurate map. The only limiting condition is a correct set of ground truth data. However, in digital image processing expert judgement is commonly used, in particular with the production of vegetation maps. Moreover the attribute surveyed in the field or on-screen mostly has a composite character. Despite the opportunity to process the data digitally the acquisition of training data remains a source of subjectivity and therefore of inaccuracy in digital vegetation structure map production.

In digital image interpretation, accuracy assessment is generally a process of comparing classified data with independently acquired data. In case of a 100% reliable classification, classified data equals independently acquired data. In the case of an accuracy lower than 100% it is generally assumed that the difference is caused by classification errors. However, the observed inaccuracy can also originate from errors in the acquisition of control data. When control data are obtained with the same acquisition process as the classification data, sources of error resulting from acquisition are the same. Therefore, error assessment of thematic maps obtained by digital image interpretation by means of control points not only concerns the quality of the classification results but also the quality of the ground truth and control points.

Foody (2002) states that the confusion or error matrix is the most widely promoted method of accuracy assessment of thematic maps derived from digital imagery. With this matrix the producer’s accuracy and the observer’s accuracy can be obtained. This is, respectively, the accuracy of the classification in comparison with the control points and the accuracy of the control points in comparison with the classification result. The accuracy assessment is based on the prerequisite that the basic classification elements (grid cells) are exclusively member of one class.

In fuzzy classification procedures, one basic element can be member of more than one class. A technique to assess the accuracy of fuzzy thematic maps using the confusion or error matrix requires that this aspect is taken into account. In other words, the error assessment with a confusion or error matrix has to be adjusted to grid cells with membership values. Such method does not yet exist and is the topic of this chapter. Before this new method of accuracy assessment of fuzzy thematic maps is presented and its application to dry coastal dune ecosystems is discussed, sources of inaccuracy in a fuzzy classification procedure and sources of inaccuracy in the control data acquisition are presented.

3.2 Material and methods

High-resolution false colour infrared orthophotos and ground truth points were used to classify and map the vegetation structure of several dunes areas in the Netherlands (see Table 2-3). The dune areas were selected as examples of small-scale dynamic ecosystems that meet the requirements for the application of the Serial Landscape Model (see section 1.4). For a more detailed definition of small-scale dynamic ecosystems and dry coastal dune areas, reference is made to Frame 1-1 and Frame 1-3. Locations of the dune areas selected are given in Figure 2-4. The ground truth points used represent the membership value of five fuzzy classes, distinguished during classification. See Table 2-4 for a description of the crisp and fuzzy classes used.

For the classification and mapping the DICRANUM classification procedure (see Figure 2-6) was applied. The classification resulted in a set of digital maps: one representing the crisp classification units, and one for every fuzzy classification unit, based on membership values as established in the classification procedure.

This section describes two methodological aspects of the accuracy assessment of such high-resolution fuzzy vegetation maps. First, sources of inaccuracy in the DICRANUM classification procedure are defined and examined (Section 3.2.1). Second, a method is presented to construct an overall confusion or error matrix for a set of digital maps, representing the membership value per fuzzy class (Section 3.2.2).

3.2.1 Sources of inaccuracy of fuzzy, grid-based vegetation maps, DICRANUM maps in particular

This section gives a full inventory and discussion of possible sources of error in the fuzzy image interpretation procedure as carried out in the DICRANUM classification procedure (see Figure 2-6). It should be stressed that sources of inaccuracy in fuzzy classification procedures are similar to the sources described for thematic map production in general (see section 3.1.1).

An assessment of the relative contribution of individual sources to the overall inaccuracy is only possible when after every process step an accuracy assessment with control data is performed. However, in general, such data are compared with the end-result of the classification process and the relative contribution of a process step to the overall error is not assessed. In this section every process step and its respective source of error is discussed though the individual accuracy is not assessed.

The DICRANUM classification procedure (see Figure 2-6) is based on the principles of Remote Sensing and Digital Image Interpretation. According to basic theory on Remote Sensing and Digital Image Interpretation (Lillesand et al., 2008), four sources of inaccuracy can be discerned.

1. Image production
2. Ground truth
3. Data processing
4. Data presentation

Ad 1) Because remote sensing images are the representation of reflected energy from the earth surface, the medium of energy transmission is a major source of modification of this energy wave (Clevers, 1994; Schowengerdt, 2007). Images used for classification of small-scale dynamic ecosystems are mostly the representation of visible and near infrared reflection by the vegetation cover (Buiten & Clevers, 1994). Absorption and differential scattering are the main sources of inaccuracy. Especially when small spectral bands, as in hyperspectral scanning, are used, constant atmospheric conditions are necessary to guarantee unambiguous results (Van Til et al., 2004). When broad spectral bands are obtained, as is the case in analogue and digital false colour infrared photography, heterogeneity in spectral conditions is levelled out (Clevers, 1994).

In digital image production, raw images are geometrically and radiometrically corrected. This process can cause spatial and spectral shifting of the raw material (original analogue or digital images). Spatial shifting of data is undesirable in multi-temporal analysis. Radiometric shifting of data can cause problems in unambiguous interpretation of images. With the introduction of professional digital airborne camera's (Petrie & Walker, 2007) and automated data processing techniques (Schowengerdt, 2007) geometric and radiometric accuracy has improved (Toutin, 2004; Chen et al., 2005). However, it is the author's personal experience that in commercial digital image production the geometric accuracy is emphasized, whereas the radiometric accuracy is neglected. Lastly it should be realised that in landscape monitoring programs, employing remote sensing techniques, often older analogue material is used and that such material remains a major source of geometric and radiometric inaccuracy caused by differences in scale and observed wavelengths or bands(see Chapter 2).

Ad 2) In digital image interpretation, the availability of reliable ground truth is essential (See Figure 3-2). There are three major aspects in ground truth reliability: the quality of the geometric positioning, the quality of the field observations and the correspondence between image resolution and the extent of the ground truth point.

In the DICRANUM classification procedure ground truth is obtained by experts using DGPS (Droesen et al., 1995). DGPS localizes field plots with an accuracy of several cm's (Xu, 2007).

The quality of the expert judgement depends on the applicability of the land-cover classification system in the study region and the personal application and interpretation of the system by the expert. For highly complex attributes like landscape, soil and vegetation, expert field judgement is the quickest, cheapest and most transparent method (Geneletti, 2005), assuming that the expert records his opinion unambiguous. It is recommended that field experience of several experts is exchanged resulting in some level of standardisation of the expert judgement.

The extent of the ground truth point (ca. 1 m^2) always exceeds the image resolution (ca. 0.2 m) and is therefore a potential source of error.

Classification of complex natural ecosystems with digital image processing is mostly supervised (see literature in Table 2-1). This means that expert interpretation of the image or ground truth points is actively incorporated in the classification procedure. The quality of on-screen training of digital images depends largely on the acquaintance of the operator with the local situation. Arguments in the discussion on the quality of on-screen expert training are similar to the arguments used in ground truth expert judgement (see above).

Ad 3) Inaccuracy resulting from computational models used in data processing is another source of error. The interpolation of membership values in the object space is the only potential source of error resulting from the computational model. Other computational steps are straightforward combinations of data, based on predefined algorithms or look-up tables and not based on empirical or statistical models with inherent uncertainty.

Ad 4) Aspects of GIS based map representation are: post processing and the medium used for representation (digital or analogue). Sources of inaccuracy of fuzzy grid-based vegetation maps can be related to these two aspects. Because fuzzy vegetation map production is a digital process, post processing operations like reclassification, generalisation or combination are obvious actions but can always refer back to the basic material resulting from the step of data processing. This is also the case for inaccuracies resulting from the medium of representation, provided the digital source remains available. Therefore, the accuracy assessment method for fuzzy thematic maps is only based on the material as produced by the data processing steps.

Figure 2-6 gives an overview of the data processing steps in the DICRANUM classification procedure. An elaborate description of concept development, fuzzy class construction and classification procedure is given in Chapter 2. Figure 3-2 gives, as an example, a visual impression of source material, class functions in the object space and classification results of the Meijendel dune area.

The potential sources of error in the DICRANUM classification procedure are presented in Figure 3-3. From this figure, it is clear that expert judgement is the main source of inaccuracy in the DICRANUM classification procedure. It is applied in the field survey to produce ground truth for the production of the fuzzy class functions (1) and the combination of on screen training (3) with the on screen evaluation of crisp classification results (5) for the production of crisp class functions. The degree of representation of all states of the landscape (7) is a source of error that is entirely caused by expert judgement. It is reasonable that a ground truth data set with a balanced representation of membership values and fuzzy classes is the optimal data set for fuzzy class function production.

In traditional, object based image interpretation, the accuracy can be assessed with traditional statistics. In the case of the DICRANUM classification procedure, pixels are assigned to one crisp class or a set of fuzzy classes. In the case of a crisp pixel, the pixel is full member of the class or not, in the case of a fuzzy pixel the pixel can be partial member of more than one class. Because this fuzzy logic procedure is part of the calculation, the traditional confusion or error matrix, as used in object oriented classification, cannot be applied. Droesen (1999) used the correlation coefficient between membership values as determined by fuzzy class functions and membership values as determined with ground truth points as a measure for the class accuracy in the map. This is essentially wrong because the data processing step from fuzzy class function to fuzzy map is integral part of the vegetation map construction and is not incorporated in this accuracy assessment. Errors resulting from this last step in data processing are not assessed with the method as carried out by Droesen (see also section 3.1 and Figure 3-2). The overall error assessment must be a comparison of the resulting vegetation map with ground truth data.

In the image conversion-process (2), digital numbers are converted into grid-cell values representing relative reflection values in red and near-infrared bands. This process is straightforward, not inducing errors. The primary production of the feature space (4) is a database procedure where image elements (pixels) are placed in a two-dimensional space that is constructed on the base of the reflection in red and near-infrared of the image elements. This process is without errors.

The provisional division of the object space in crisp classes by on-screen training (3) is a process of expert judgement and can therefore be a source of error. This is also the case with the iterative process of on-screen polygon construction in the feature space and subsequent check of the classification result (5). The crisp classification is a translation of reflection values into crisp classes on the base of the constructed object space (6) where no errors are added to the overall result.

The spatial interpolation, used in the production of the fuzzy membership functions (7a), is a data driven operation and therefore a source of error. The assumption that the total population of fuzzy field plots, which are acquired by expert judgement, is correct leads to the choice of using a spline interpolation: every fuzzy field plot value as represented in the feature space is part of the interpolation plane. For these points the error is totally dependent on the expert judgement in the field and the geometric accuracy of image and field measurement. Fuzzy classification of reflection values, which are not represented by fuzzy field expert judgement, have a source of error caused by the spline interpolation. The number of ground truth points that are used in the construction of the spline interpolation surface determines the accuracy of the fuzzy class function. Therefore, the degree of representation (or better: non representation) of a fuzzy class in the fuzzy field plots combined with the degree of representation of membership values per fuzzy class are also a source of error. In the discussion of the error assessment results this will be further dealt with.

The fuzzy classification is also a straightforward translation of reflection values on the base of fuzzy class functions in the object space and as such no source of error (7b). It can be concluded that the construction of fuzzy function classes is a source of error that is particularly caused by assuming continuity in the semantic domain. However, hanging on to crisp class functions would be in contradiction with the conceptual assumption of continuity in the spatial, temporal and semantic domain.

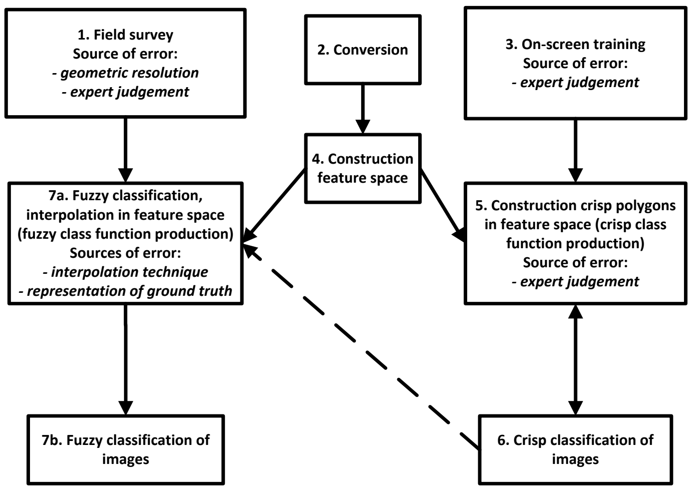


Figure 3-3 Potential sources of error in the DICRANUM classification procedure, numbers refer to process steps as presented in Figure 2-6

3.2.2 A confusion or error matrix for accuracy assessment of fuzzy thematic maps

The accuracy assessment of maps resulting from crisp class classifications with a confusion or error matrix (Foody, 2002) is essentially a binary process. A certain area is member of a class or not. For this reason, an error matrix of the comparison between the classified value (obtained by the producer) and the control value (obtained by the user) can be filled with p^2 elements (p being the number of classes). In the case of a fuzzy classified area, an error matrix can only be filled when the spatial distribution within the pixel is known. This is not in agreement with the classification technique that is developed in accordance with the concept of semantic continuity. The basic spatial element (a pixel) cannot be segmented into discrete spatial, temporal and semantic units. Therefore, an error matrix with p^2xq^2 elements should be used (q being the possible number of membership values); this error matrix is unrealistic and too large to interpret. Nevertheless, the construction of a confusion or error matrix is preferred and must comply with the constraint of a simple and clear classification procedure: the accuracy assessment should be simple and comprehensible for the user.

To overcome the problem of a large and incomprehensible error matrix two premises are defined.

1. The expression of the fuzziness of a certain area is the relative part this area belongs to a certain class. The membership value can be explained as the relative extent of a fuzzy class within an object. In the DICRANUM classification procedure this object is a pixel or grid cell. This premise seems in contradiction with the concept of spatial and semantic continuity as defined in The Serial Landscape Model. However, it must be seen at the right level of abstraction: this premise is a practical elaboration of continuity in the spatial and semantic domain on a lower level of abstraction.
2. It is assumed that the smallest membership value (and thus: extent according to the first premise) of a certain fuzzy class in either a classified spatial unit or a ground control point is correctly assigned to the basic object. The remaining membership value of that class is wrongly assigned and it cannot be assigned to any other fuzzy class. This remaining membership value, expressed as an extent according to the first premise, can be part of the classified spatial unit or the control point.

These two premises make it possible to fill the diagonal of the confusion or error matrix and determine the sum of the wrongly assigned extent. Now, the construction of the confusion or error matrix is relatively simple and presented, with an example, in Figure 3-4. The example is given for a classified grid cell and a control grid cell, both representing the same geographic location, with membership values for fuzzy classes A, B and C. In the classification result, the extent, according to premise 1, of class A is 20% of the total extent of the grid cell. In the control grid cell, the extent, according to premise 1, of class A is 10% of the total extent of the grid cell. So, according to premise 2, 10% of the total extent of the grid cell, classified and control, is accurate. This means that 50% of the extent of class A is accurately assigned to the class in the classification and 100% of the extent of class A is accurately assigned to the class in the control: the producer's accuracy for class A is 50% and the user's accuracy is 100%. This process can also be carried out for class B and C and results in the overall error or confusion matrix as presented in Figure 3-4. The overall accuracy is 80% because 80% of the classified grid cell and the control grid cell correspond with each other. In the case of a set of classification and control grid cells, the summation of accurately assigned extents are presented in the diagonal of the error or confusion matrix and the summation of falsely assigned extents are presented horizontal (falsely assigned in classification) and vertical (falsely assigned in control). Matrix elements that are not in the diagonal cannot be filled in because it is not known to which class the falsely assigned extent belongs to. This is due to the use of a fuzzy classification procedure. Here, the concept of spatial and semantic continuity is clearly respected.

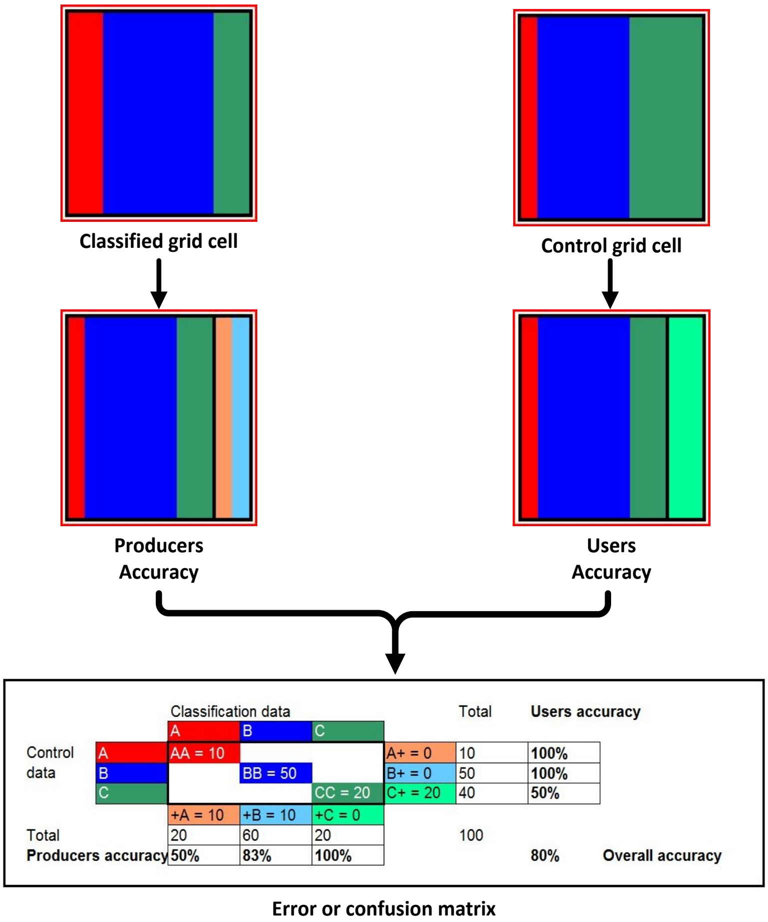


Figure 3-4 Production of the Error or Confusion Matrix in fuzzy thematic map production

With multiple grid cells and multiple fuzzy and crisp classes, the production of the error matrix is more complex. Basic information is obtained from a comparison of membership values of classified grid cells with the expert judgement of membership values for these grid cells. This information is extracted from field plots. Field plots, used for ground truth in the DICRANUM classification procedure, are larger than the grid cell size or resolution of the image: field plots are circles with a diameter of 1 m^2, while the image resolution is 0.25 m^2. The reason for this is that even though DGPS is extremely accurate (geometric resolution of several cm), it is practically unachievable to locate a pixel or grid cell of a digital image or map with a resolution of 25 cm or less in the field. So the ground truth point is thought to be the representation of more than one grid cell.
The sum of the membership values of fuzzy classes not always equals 100% when field control points are compared with the classification results. This is caused by the fact that crisp field control points or crisp image classification results are dealt with as being totally accurate or false assigned to the class. However, within the area of the field plot, grid cells with fuzzy as well as crisp classes can occur. Thus, all membership values of fuzzy classes have to be transformed so the sum per ground truth point equals 100%. For every ground truth point the minimal membership value per fuzzy class can be obtained with Formula 3-1.
Now, the falsely assigned extent per ground truth point per fuzzy class can be determined. This can be done by assuming that the ground truth points are correct (Formula 3-2) or the classification is correct (Formula 3-3). With these extents the producer's and the user's accuracy is calculated with Formula 3-4 and Formula 3-5, respectively. For these formula's, the signature of Foody (2002) is used. The overall accuracy is the percentage correctly assigned extent for all observed grid cells and calculated according to Formula 3-6.
The overall accuracy as calculated according to Formula 3-6 equals the Kappa coefficient as presented by Foody (2002).
The elements of the error or confusion matrix are presented in Table 3-1.

$$CMV_{M=N} = min\left[\frac{MV_M}{\sum_{i=1}^{M} MV_i} * 100\,, \frac{MV_N}{\sum_{i=1}^{N} MV_i} * 100\right]_{M=N}$$

$CMV_{M=N}$: *The smallest corresponding extent per ground truth point for class M = class N*

MV: *Membershipvalue*

M: *Control or ground truth point*

N: *Classified grid cell*

Formula 3-1 The smallest corresponding extent per ground truth point for similar classes recorded in the field and classified

$$EMV_M = \left|\left(\frac{MV_M}{\sum_{i=1}^{M} MV_i} * 100\right) - CMV_{M=N}\right|$$

EMV: *Falsely assigned extent per ground truth point*

Formula 3-2 Falsely assigned extent per ground truth point, assuming the ground truth point being correct

$$EMV_N = \left|\left(\frac{MV_N}{\sum_{i=1}^{N} MV_i} * 100\right) - CMV_{M=N}\right|$$

Formula 3-3 Falsely assigned extent per ground truth point, assuming the classification being correct

$$Producers\ accuracy = \frac{n_{ii}}{n_{+i}} * 100$$

$$n_{ii} = \sum_{i}^{M} CMV_{M=N,i}$$

$$n_{+i} = \sum_{i}^{M} CMV_{M=N,i} + \sum_{i}^{M} EMV_{N,i}$$

Formula 3-4 Producer's accuracy

$$Users\ accuracy = \frac{n_{ii}}{n_{i+}} * 100$$

$$n_{i+} = \sum_{i}^{N} CMV_{M=N,i} + \sum_{i}^{N} EMV_{M,i}$$

Formula 3-5 User's accuracy

$$Overall\ accuracy = \frac{\sum n_{ii}}{\sum n_{ii} + \sum n_{+i}} * 100\ or\ \frac{\sum n_{ii}}{\sum n_{ii} + \sum n_{i+}} * 100$$

Formula 3-6 Overall accuracy

Table 3-1 Error or confusion matrix for the accuracy assessment of fuzzy thematic maps, accuracy are presented according to the signature of Foody (2002)

		Training or control data (M)				
		Class A	*Class B*	*Class C*	Extent wrongly assigned	User's Accuracy
Classification data (N)	*Class A*	$\sum_{i}^{M,N} CMV_{A=A,i}$			$\sum_{i}^{N} EMV_{A+,i}$	$\frac{N_{AA}}{N_{A+}}$
	Class B		$\sum_{i}^{M,N} CMV_{B=B,i}$		$\sum_{i}^{N} EMV_{B+,i}$	$\frac{N_{BB}}{N_{B+}}$
	Class C			$\sum_{i}^{M,N} CMV_{C=C,i}$	$\sum_{i}^{N} EMV_{C+,i}$	$\frac{N_{CC}}{N_{C+}}$
	Extent wrongly assigned	$\sum_{i}^{M} EMV_{+A,i}$	$\sum_{i}^{M} EMV_{+B,i}$	$\sum_{i}^{M} EMV_{+C,i}$	Overall accuracy $\frac{\sum n_{ii}}{\sum n_{ii} + \sum n_{+i}} * 100$ $or\ \frac{\sum n_{ii}}{\sum n_{ii} + \sum n_{i+}} * 100$	
	Producer's accuracy	$\frac{N_{AA}}{N_{+A}}$	$\frac{N_{BB}}{N_{+B}}$	$\frac{N_{CC}}{N_{+C}}$		

Table 3-2 Error matrix of the Meijendel 2001 classification

Error matrix: Meijendel/2001/fuzzy classification

		Control data set: percentage coverage per pixel							*Extent falsely assigned*	*total*	**user's accuracy**	**overall accuracy**
		Bare sand	*fc 2 (thin grass and herb cover)*	*fc 3 (intermediate herb and moss cover)*	*fc 4 (high cover herbal vegetation with dead biomass)*	*fc 5 (high cover moss vegetation)*	*fc 6 (high cover moss and low grass vegetation)*	*Shrubs and woods*				
Classification data set: percentage coverage per pixel	*Bare sand*	859							*0*	*859*	**100%**	
	fc 2 (thin grass and herb cover)		220						*580*	*800*	**27%**	
	fc 3 (intermediate herb and moss cover)			1734					*1477*	*3211*	**54%**	
	fc 4 (high cover herbal vegetation with dead biomass)				1707				*1864*	*3572*	**48%**	
	fc 5 (high cover moss vegetation)					80			*675*	*755*	**11%**	
	fc 6 (high cover moss and low grass vegetation)						925		*2415*	*3340*	**28%**	
	Shrubs and woods							8703	*761*	*9464*	**92%**	
Extent falsely assigned		*341*	*230*	*906*	*1983*	*230*	*885*	*3197*				
total		*1200*	*450*	*2640*	*3690*	*310*	*1810*	*11900*		22000		
producer's accuracy		**72%**	**49%**	**66%**	**46%**	**26%**	**51%**	**73%**				**65%**

Table 3-3 Error matrix of the Solleveld 2001 classification

Error matrix: Solleveld/2001/fuzzy classification

		Control data set: percentage coverage per pixel							*Extent falsely assigned*	*total*	**user's accuracy**	**overall accuracy**
		Bare sand	*fc 2 (thin grass and herb cover)*	*fc 3 (intermediate herb and moss cover)*	*fc 4 (high cover herbal vegetation with dead biomass)*	*fc 5 (high cover moss vegetation)*	*fc 6 (high cover moss and low grass vegetation)*	*Shrubs and woods*				
Classification data set: percentage coverage per pixel	*Bare sand*	765							*0*	*765*	**100%**	
	fc 2 (thin grass and herb cover)		244						*343*	*586*	**42%**	
	fc 3 (intermediate herb and moss cover)			1891					*2099*	*3990*	**47%**	
	fc 4 (high cover herbal vegetation with dead biomass)				905				*456*	*1361*	**67%**	
	fc 5 (high cover moss vegetation)					68			*445*	*513*	**13%**	
	fc 6 (high cover moss and low grass vegetation)						2036		*3306*	*5342*	**38%**	
	Shrubs and woods							3733	*1410*	*5143*	**73%**	
Extent falsely assigned		*35*	*376*	*1239*	*4655*	*702*	*684*	*367*				
total		*800*	*620*	*3130*	*5560*	*770*	*2720*	*4100*		17700		
producer's accuracy		**96%**	**39%**	**60%**	**16%**	**9%**	**75%**	**91%**				**54%**

Table 3-4 Error matrix of the GWA 2001 classification

Error matrix: GWA/2001/fuzzy classification

		Control data set: percentage coverage per pixel							Extent falsely assigned	total	user's accuracy	overall accuracy
		Bare sand	fc 2 (thin grass and herb cover)	fc 3 (intermediate herb and moss cover)	fc 4 (high cover herbal vegetation with dead biomass)	fc 5 (high cover moss vegetation)	fc 6 (high cover moss and low grass vegetation)	Shrubs and woods				
Classification data set: percentage coverage per pixel	Bare sand	176							0	176	100%	
	fc 2 (thin grass and herb cover)		336						1236	1572	21%	
	fc 3 (intermediate herb and moss cover)			793					512	1305	61%	
	fc 4 (high cover herbal vegetation with dead biomass)				1818				1891	3709	49%	
	fc 5 (high cover moss vegetation)					212			984	1195	18%	
	fc 6 (high cover moss and low grass vegetation)						1068		2483	3552	30%	
	Shrubs and woods							9337	1154	10490	89%	
Extent falsely assigned		324	124	1037	2502	88	922	3263				
total		500	460	1830	4320	300	1990	12600		22000		
producer's accuracy		**35%**	**73%**	**43%**	**42%**	**71%**	**54%**	**74%**				**62%**

3.3 Results

Table 3-2, Table 3-3 and Table 3-4 present the error or confusion matrices for classifications that were carried out in three dune areas along the Dutch coast. The basic material for the production of fuzzy vegetation structure maps is similar for these three areas: a digital orthophoto based on analogue false colour infrared images taken in June 2001, scale 1:10,000, resolution 0.25m. The overall accuracies are rather low, though comparable to e.g. Schmidt et al. (2004) and Monserud & Leemans (1992). It is clear from the error matrices that these low accuracies are mainly caused by the low accuracies of the fuzzy classes; the crisp classes reveal high accuracies.

3.4 Discussion

Referring to Figure 3-3 it is clear that the main reason for the low accuracy, or the high level of error or confusion, is most likely to be caused by the quality of some form of expert interpretation. In all the process steps where an inaccuracy can be introduced expert interpretation plays a role. On-screen interpretation is highly subjective and hard to analyse as a source of error. However, because on-screen interpretation is only used in the crisp classification procedures of the DICRANUM classification process, the user's and producer's accuracies of the crisp classes give a good indication of the contribution of on-screen interpretation to the overall accuracy. The presented error matrices give relative high accuracies for the crisp classes so this contribution is relative low. This is not surprising because bare sand and shrubs and trees are easy to recognise on the images.

Ground truth points and interpolation are the major sources of inaccuracy in the fuzzy classification procedures of the DICRANUM classification process. Because the interpolation is based on ground truth points, the analysis of sources of inaccuracy in the fuzzy classification procedure should focus on the ground truth points. Literature on accuracy assessment of image interpretation does not give indications for assessing the quality of ground truth. In fact, it is general accepted that ground truth is correct. Obviously, this is not the case and the quality of ground truth consists of two aspects:

- The quality of observation by the field expert. This source of error should be assessed by repeated field observations by different experts. Such an analysis was not conducted in this study but is recommended in follow-up research.
- The balance in representation of the ground truth. This is the number of ground truth points and their relative distribution over the classes and membership values.

To analyse the representation of the separate fuzzy classes and membership values in the ground truth, Table 3-5 is constructed. In this table the following parameters are presented:

1. Number of ground truth points. This is the number of pixels with a membership value higher than 0 for this class.
2. Total of membership value. This is the summation of all the membership values for this class. Dealt with as a relative area in the error assessment, in reality the membership value is not a measure for the relative area this class can be found within the pixels. It is a measure representing how much the pixel belongs to this vegetation structure class. This parameter must always be seen in relation to the following two parameters.
3. Mean. This is the arithmetic mean of all the membership values of pixels who belong in any way to this vegetation structure class. This parameter can be seen as a measure of the fuzzyness of the ground truth points. The ground truth points of GWA areas have been taken with another sampling strategy than the Meijendel and Solleveld points. For the GWA area, the field expert has deliberately sought for more or less pure sample areas (100% membership value) whereas for the Meijendel and Solleveld areas the field expert has followed a more random sampling strategy. Therefore, this parameter is generally higher for the GWA ground truth points.
4. Standard deviation. The standard deviation of all the membership values of pixels that belong in any way to this vegetation structure class. This parameter can be seen as the variation of membership values round the mean. For the Meijendel and Solleveld ground truth points this parameter lies between 20 and 30 whereas for the GWA ground truth points this parameter has a larger range. It is reasonable to assume that this is also due to the ground truth sampling strategy. For example: Fuzzy class 2 (thin grass and herb cover) is a well-defined class that can be easily recognised in the field because the other fuzzy classes are broader in character. Fuzzy class 2 is more "crisp" than the

other classes and is therefore more represented with high membership values.

For the classifications with a random sampling strategy, there is a correlation between the total of the membership values and the producer's accuracy. Classes, which are poorly represented in the ground truth samples, give an unsatisfactory classification result. For the classification with a biased ground truth strategy this correlation is opposite. Classes that are very well represented give a low producer's accuracy. The explanation is the fuzzyness of the classes. Fuzzy class 3 (intermediate herb and moss cover) and fuzzy class 4 (high cover herbal vegetation with dead biomass) are very common in dry dune ecosystems and are characterised by vague and converging gradients. Classes with a natural tendency towards fuzzyness have a lower maximum possible accuracy than classes with a natural tendency towards crisp spatial characteristics: 'vague' classes are hard to observe and describe in comparison to crisp classes.

Table 3-5 Representation of fuzzy classes and membership values in the ground truth of three classifications

Meijendel/2001	***fc 2*** *(thin grass and herb cover)*	***fc 3*** *(intermediate herb and moss cover)*	***fc 4*** *(high cover herbal vegetation with dead biomass)*	***fc 5*** *(high cover moss vegetation)*	***fc 6*** *(high cover moss and low grass vegetation)*
number of ground truth points	47	105	68	25	72
total of membership value	3590	7780	4160	1790	5070
mean	76	74	61	72	70
standard deviation	25	27	32	22	23
Solleveld/2001					
number of ground truth points	7	43	23	7	38
total of membership value	370	2515	1235	260	2360
mean	53	58	54	37	62
standard deviation	28	28	30	20	26
GWA/2001					
number of ground truth points	67	70	210	62	154
total of membership value	6470	5990	10180	3660	9610
mean	97	86	48	59	62
standard deviation	6	22	34	32	27

3.5 Conclusions

Based on the constructed error matrices and the observed level of representation of the ground truth it can be concluded that all fuzzy classes should be well represented in the ground truth sample set with the addition that the total range of membership values per fuzzy class should be present. The ground truth strategy thus has to focus on:

- Good representation of poorly represented fuzzy classes,
- Good representation of low membership values of the more crisp classes,
- Good representation of high membership values of the more fuzzy classes.

The relative poor overall accuracies need to be seen in the light of the accuracy and accuracy assessment of vegetation maps in general. Vegetation mapping is very well documented and accuracy assessment of vegetation maps based on remote sensing and digital image interpretation is a generally accepted technique. It should be realised that these concern far less complex and dynamic landscapes, and even for these landscapes overall accuracies are often found to be low. Earlier studies on small-scale dynamic ecosystems, based on remote sensing and fuzzy classification techniques, already clearly demonstrated the problematic accuracy of fuzzy vegetation structure maps of such landscapes. However, these studies (Droesen, 1999; Janssen, 2001) did not result in the development of reliable methods for the assessment of their accuracy and thus do not allow for rigorous comparison of the accuracy of the various methods employed.

Comparing accuracies of crisp vegetation structure maps with fuzzy vegetation structure maps is problematic because a comparison is made between a univariate problem with a multivariate problem. Correlations between single variables (1 crisp class per pixel) are always superior to correlations between multiple variables (several fuzzy classes per pixel).

Referring to Figure 3-3 and the conclusions from the presented data, improvements of the classification results must be found in an adapted ground truth sampling strategy and a refinement of the data processing.

Photo 2 Aeolian processes in dry coastal dunes

4 THE SEMANTICS OF IMAGE INTERPRETATION CLASSES: THE INTEGRATION OF THE RADIOMETRIC FEATURE SPACE WITH THE PHYTOSOCIOLOGIC FEATURE SPACE.

4.1 Introduction

This chapter focuses on the analysis of the semantics of classes used in monitoring small-scale dynamic ecosystems. A method is presented to include the semantic domain in a monitoring program that uses high-resolution images and ground truth (see Chapter 2). Because monitoring programs of small-scale dynamic ecosystems are primarily carried out for management and conservation purposes, the semantics of the image interpretation classes have to relate to conservation targets. Therefore, some general aspects of nature conservation policy (section 4.1.1) and the conservation of small-scale dynamic ecosystems in particular (section 4.1.2) are discussed, also some general remarks are made on the recognition of spatial and temporal elements to be conserved. The analysis presented in this chapter is carried out for a dry dune area (see Figure 2-4 and Figure 4-1) and therefore examples used, refer to dry coastal dunes (see also Frame 1-3). Material and methods are described in section 4.3.

4.1.1 Nature conservation policy

In conservation literature there is a varying notion about what has to be conserved (Sutherland, 1998; Soulé & Orians, 2001; Redford et al., 2003): species (Raphael & Molina, 2007), habitats (Noss et al., 1997), communities, landscapes, ecosystems etc. (Hunter, 2002; Duffy, 2003). Nowadays, in addition to the ecological or biodiversity goals, also geodiversity (Gray, 2004) and cultural heritage (Lozny, 2008) are incorporated in nature conservation and management. Though important, in this analysis of the semantics of image interpretation classes, geodiversity and cultural heritage are not taken into account.

The European nature conservation policy as described in the NATURA 2000 directive (Council of the European Communities; 1992) only concerns some species and some habitats. Other conservation policies like those of the African Wildlife Foundation (AWF), Conservation International (CI) and the Wildlife Conservation Society (WCS) have a much wider scope and also incorporate processes (ecological and evolutionary) in their management targets. Notwithstanding its limited conservation targets, NATURA 2000 has a major impact on international and national conservation action plans and management, the allocation of funds and grants being based on the evaluation of management plans relative to NATURA 2000's targets. The dry dune area under discussion in this chapter (see Figure 4-1) is part of a NATURA 2000 area. Therefore, the image interpretation classes for this area, presented in Chapter 2, are related to habitat types as defined in the NATURA 2000 directive.

According to the EU directive, a habitat definition is primarily based on the semantics of the system: a habitat is a terrestrial or aquatic area distinguished by geographic, abiotic and biotic features, whether entirely natural or semi-natural. However, a habitat is not an ecosystem: interactions and system dynamics are not an integral part of the habitat definition. Even in an elaborate definition of the EU habitat types (Davies et al., 2004), system dynamics describing processes within the habitat and relations with other habitats are not involved. The main objective of the directive is the maintenance of biodiversity and a habitat is interpreted as the prime condition for the conservation of organisms. In other words, habitat conservation is considered as the main tool in biodiversity policy. The EU habitat directive thus does not provide for semantics that can be used to define image interpretation classes within the scope of the Serial Landscape Model. Therefore, the semantics of image interpretation classes had to be established independently and subsequently related to EU habitat types.

In applying the NATURA 2000 nature conservation policy, classification and monitoring of species and habitats is crucial. For this purpose "a landscape classification scheme that provides ecologically meaningful units for quantifying different aspects of landscape degradation" (Carranza et al., 2008) is needed. The NATURA 2000 habitat types, typical for the dry coastal ecosystems of The Netherlands, are ecosystems with a high degree of aeolian activity (H2110, H2120), dry dune grassland and heath (H2130, H2140, H2150) and ecosystems dominated by woody plants (H2160, H2170, H2180) (Council of the European Communities, 1992). Threats to these ecosystems are, next to advancing industrial, housing, recreational and infrastructural activities (Brown & Mclachlan, 2002), encroachment of shrubs and grasses (Kooijman & De Haan, 1995; Isermann et al., 2007) due to atmospheric deposition (Kooijman et al., 1998; Kooijman & Besse, 2002) and the decline of rabbit populations (Van der Hagen et al., 2008). Actually, these latter 'system' threats, in contrast to the 'physical threats', are mainly confined to the dry dune grasslands and heaths (Kooijman et al., 1998). These are the elements with truly small-scale dynamic character in the temporal, spatial and semantic domain. As explained in the Serial Landscape Model (see section 1.3), the actual state of the small-scale dynamic landscape is described by its spatial, temporal and semantic characteristics that can range from convergent (crisp, catastrophic) to divergent (random, chance) with continuity in the transition. Grassland and heaths are found in this continuous transitional phase. Therefore, the analysis of the semantics of image interpretation classes has to focus on the continuous semantic character of the classes.

4.1.2 Conservation and recognition of small-scale dynamic ecosystems

Following Redford et al. (2003), it is agreed that conservation targets should be focused on those elements, whose long-term persistence has to be ensured. In small-scale dynamic ecosystems these elements are revealed in an intricate spatial pattern of elements that changes quickly due to high levels of environmental and system dynamics. This results in specific features:

- Predominance of highly adapted plant species
- Active geomorphic processes
- Prominent spatial gradients

To preserve these features, the whole small-scale dynamic ecosystem, i.e. including spatial pattern and temporal dynamics, has to be monitored and managed. Evidently, the semantics of image interpretation classes has to contain information on the species composition and active processes, and allow for monitoring these features. In an optimal management situation, a small-scale dynamic ecosystem is self-supporting. If this is not realistic, re-activation of geomorphic processes and the construction of spatial gradients are options (Arens et al., 2004; Arens & Geelen, 2006).

Since long, it has been the objective of the terrain managers to survey and monitor the terrain according to standardised methods and descriptors (Goldsmith, 1991). A thorough field inventory is costly and time-consuming (see Chapter 2) and therefore more comprehensive methods to observe and classify habitat-types have been developed. For instance, Carranza et al. (2008) propose an ecosystem classification approach that integrates potential natural vegetation and dune EU habitats. However, the result would be a landscape map with only climax stages. This implies that succession stages and undesirable deviations from natural succession processes cannot be monitored whereas the biodiversity in small-scale dynamic ecosystems depends largely on the co-occurrence of more successional stages.

The use of remote sensing and digital image interpretation is generally accepted as an indispensible tool in the recognition of elements to be conserved (Acosta et al., 2005; Bock et al., 2005; Bekkby & Isaeus, 2008; Carranza et al., 2008; Alexandrides et al., 2009). However, for the monitoring and inventory of NATURA 2000 habitats, databases and information systems like TURBOVEG (Hennekens & Schaminée, 2001) and SynBioSys (Schaminée et al., 2007) are used. These systems are mainly based on relevées and phytosociology, and within these systems there is little or no possibility of incorporating remote sensing and digital image interpretation.

Crucial in the application of remote sensing images is the translation of image interpretation classes, as defined by spectral characteristics of the earth surface, into meaningful ecosystem or habitat characteristics. Because remote sensing products primarily reflect the physical state of the earth surface and the vegetation cover, it seems obvious to describe or classify functional characteristics of the vegetation like primary production and evapotranspiration (Garbulsky & Paruelo, 2004). However, these functional characteristics do not relate to species, habitats or successional processes and therefore cannot be linked to management or conservation targets.

For the translation of image interpretation classes into meaningful ecosystem characteristics, the use of expert knowledge is indispensible. Alexandridis et al. (2008) report a low performance in the correspondence between spectral classes and habitat types. They work out a reliable method but with the disadvantage that many separate products are used (vegetation survey, field visits, photomaps, satellite images, digital elevation model) and many steps in the proposed methodology are supervised so a high degree of subjectivity may occur. A simple procedure with a minimum of survey techniques, concerning image classification and field survey, is preferred above intricate classification techniques and meticulous field surveying. Nevertheless, a link between image interpretation techniques and field data interpretation is essential.

4.2 Aim

It is the aim of this Chapter to present and illustrate a method to analyse and describe the semantics of image interpretation classes of small-scale dynamic ecosystems with particular focus on the recognition of spatial and temporal elements for conservation, NATURA 2000 habitat types of dry dune grassland in particular. According to the introduction, the following requirements can be recognised.

- The characteristics of the image interpretation classes in the semantic domain are primarily continuous.
- The characteristics of the image interpretation classes in the semantic domain must refer to a system used in nature conservation policy.
- The semantics of image interpretation classes must include:
  - species
  - indicators of processes (biotic and abiotic)
- The semantics of the image interpretation classes must refer to field and image characteristics.
- The semantics of the image interpretation classes are the key in the link between field and image characteristics.

Therefore, basic elements in the study of the semantics of the image interpretation classes are the image as well as field observations. They are both a representation of the real world with their own techniques for abstraction. Image data are processed by digital image interpretation techniques, field data are processed by multivariate statistical techniques. The integration of the processed image and field data is performed according to concepts in landscape ecology (e.g. dynamics/stability) and vegetation science (e.g. successional stages).

4.3 Material and Methods

4.3.1 Research area

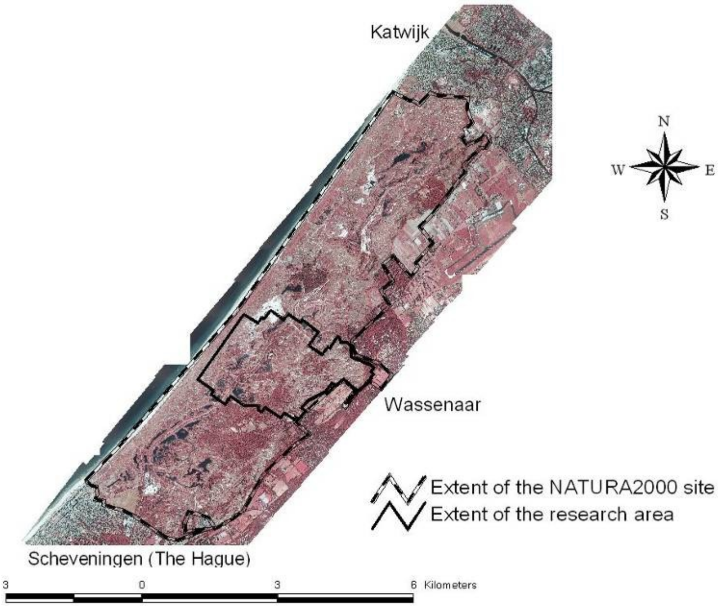


Figure 4-1 Extent and location of the NATURA2000 site and research area

The Netherlands has a high responsibility in the conservation and management of coastal dune ecosystems, thirteen dune areas with a total coverage of 266 km^2 having been assigned the status of NATURA 2000 site. The Meijendel/Berkheide study area is located North of The Hague and West of Wassenaar along the North Sea coast of The Netherlands and has the status of NATURA2000 site (see Figure 4-1, site code NL1000013). This area has been comprehensively described by numerous authors. Van der Meulen and Van der Maarel (1993) give a good review of the biotic and abiotic characteristics of the dry coastal dunes of the central and southwestern Netherland. Specific characteristics of the dune area are: a relative high lime content of the substrate (Eisma, 1968; Klijn, 1981), a profound gradient in geomorphology, soil development and vegetation structure from coast to hinterland (Jungerius & Van der Meulen, 1988), the presence and high-quality (in terms of biodiversity) of dune grassland (Ten Harkel & Van der Meulen, 1996), shrubs and forest (Van der Meulen & Wanders, 1985; Boerboom, 1960) and the high geomorphic activity (erosion and sedimentation by wind and water (Jungerius & Van der Meulen, 1988)). The area is managed by DUNEA, the drinking water company of western South-Holland. Management serves several goals: conservation and management of the dune ecosystem, drink water supply, water chain management and recreation. This study is carried out in the context of the nature conservation and management goal. Only part of the Meijendel/Berkheide area is used as research area (see Figure 4-1), this is the area where digital orthophotos of 1990, 1995 and 2001 have overlap. A major part (76 % of 4,69 km^2) of the research area is grazed by horses and cattle since 1992.

4.3.2 Material

Since 1975 large-scale false colour infrared aerial photos have been taken on a regular basis. The photos of 1990, 1995 and 2001 have been digitised and geometrically and radiometrically corrected so that high-resolution digital orthophotos are available. The digital images have a field resolution of 10cm (1990 and 1995) and 25 cm (2001) and give reflectance characteristics in green, red and near infrared.

Table 4-1 Short description of relevée grids

A	South exposed active blowout
B	Shrub-grassland margin without relief
C	Dune forest
D	South exposed slope with dry dune grassland
E	Slightly undulating dune grassland with patches of exposed grey humic sand
F	*Hippophae rhamnoides* shrub
G	Short grazed dune grassland without relief
H	North exposed slope with grassland and shrub
I	Stabilized blowout

The actual field situation is described in nine different areas (See Table 4-1) with relevées, laid out in a regular grid of seventeen relevées (5m x 5m each) per area (see Figure 4-2). Such regular grid is used to allow for geostatistical analysis of spatial dependence. The relevée-grids are selected in the centre of the research area with a maximum diversity in geomorphology and vegetation structure between the grids. Nearly bare sand (A), several types of dune grasslands (B, D, E, G, H, I) and shrubs (B, F, H) and woods (C) are represented. The geomorphology ranges from flat and slightly undulating areas (B, C, E, F, G) to steep north (H) and south (A) exposed slopes. Also the geomorphic activity varies strongly, high degrees of wind (A) and water erosion (E, I) are observed as well as stable surfaces. Different stages in soil profile development occur, though all soils can be characterised as immature. Differences observed pertain to decalcification of the profile, humification and (micro) podzol development. For all relevées the following parameters are recorded: plant species composition (higher plants and dominant mosses), landform (slope and exposition), geomorphic activity (wind and water) and soil (decalcification, humification and profile development), see also Table 4-2. The species cover is estimated in the field in percentage because this is the most appropriate score to use in numerical vegetation data analysis (Podani, 2006). Nomenclature for higher plants is according to Van der Meijden (2005), for mosses is according to Siebel & During (2006).

Vital material for the analysis is the occurrence and membership value of image interpretation classes of the relevées in the field since this provides the link between the semantic characteristics of the image and field.

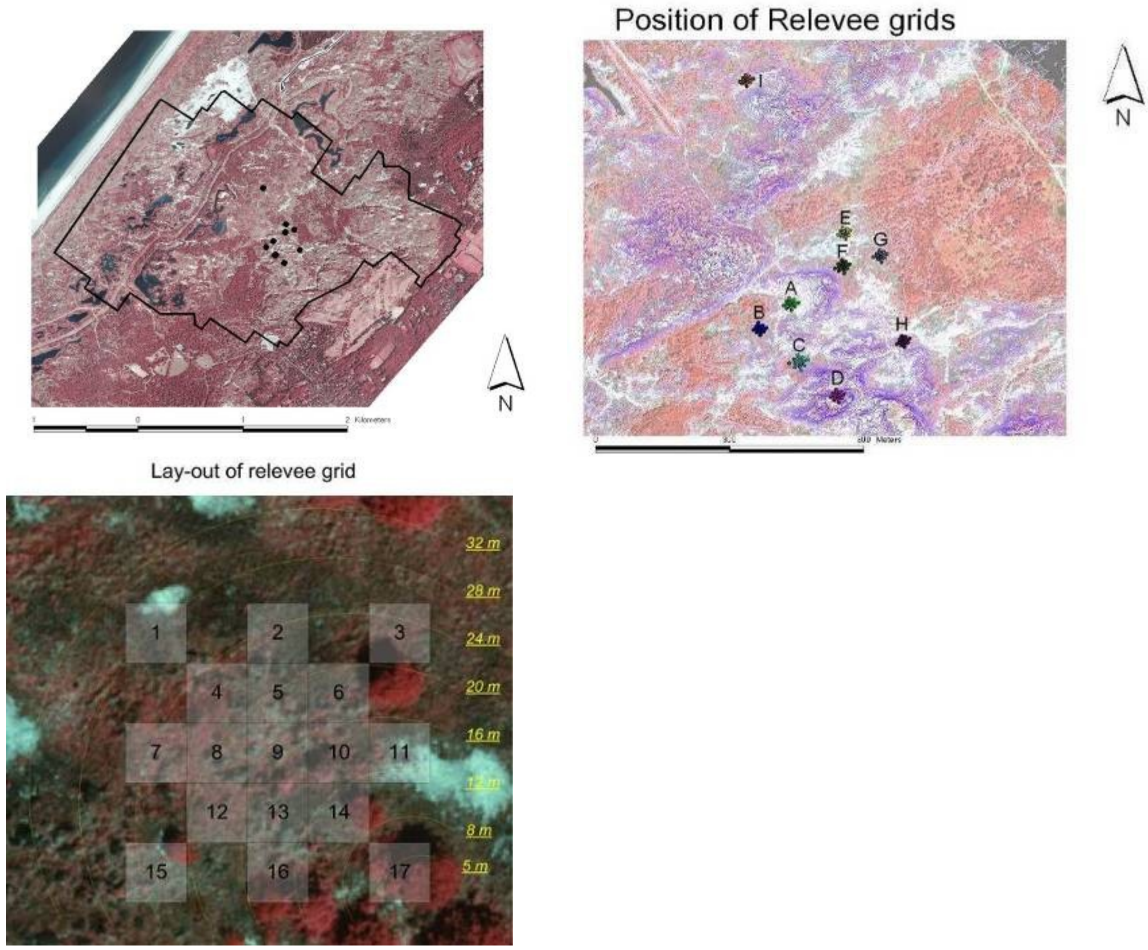


Figure 4-2 Position of relevé grids and lay-out of the grids

Table 4-2 Environmental variables used in the ordination

Environmental variables	
GEOWIND	Relative intensity of erosion and sedimentation by wind
GEOWATER	Relative intensity of erosion and sedimentation by water
SLOPE	Degrees from horizontal
ASPECT	Sin(aspect/2): south exposed slope equals 1, north exposed slope equals 0
DECALC	Depth of decalcification in cm
SOILORGA	Organic matter index: ordinal scale from 0 to 6 according to thickness and color A horizon
Vegetation structure	
MOSSES	Cover of Mosses in %
HERBS	Cover of herbaceous plants in %
WOOD.1M	Cover of woody plant smaller than 1m in %
WOOD1-2M	Cover of woody plants between 1m and 2m high in %
WOOD7-2M	Cover of woody plants between 2m and 7m high in %
WOOD.7M	Cover of woody plants higher than 7m in %
Image interpretation class (dealt with as independent variable in ordination	
CC1	Relative presence of image interpretation class CC1 in %
FC2	Relative presence of image interpretation class FC2 in %
FC3	Relative presence of image interpretation class FC3 in %
FC4	Relative presence of image interpretation class FC4 in %
FC5	Relative presence of image interpretation class FC5 in %
FC6	Relative presence of image interpretation class FC6 in %
CC7	Relative presence of image interpretation class CC7 in %

4.3.3 Methods

Different types of data processing and expert interpretation have to be performed in order to combine digital image information with field observations. The result must be meaningful ecosystem descriptions that can be related to NATURA2000 habitat types. This process is initiated by the definition of image interpretation classes as can be observed and classified with the digital image at hand. This preliminary step is illustrated in Figure 2-2 and presented in Chapter 2, section 2.4. From Figure 2-2 it is clear that objects, as well as continuous fields can be discerned, representing various combinations of ecosystem characteristics and processes. Continuous (fuzzy) and discrete (crisp) image interpretation classes are defined (see Table 2-4).

In digital image interpretation the feature space is a graph constructed with various reflectance bands where every unique combination of reflection values is assigned to an image interpretation class. The so-called image space is the geographic area represented by the digital image. Because the green and red reflection have a very high correlation (De Boer, 1993; Droesen, 1999), only the red and near infrared band of the digital images are used in constructing a feature space. In Figure 4-3 and Figure 4-4 it can be seen that crisp digital image interpretation classes are represented by objects and fuzzy classes are represented by continuous fields. This holds, in both cases, for the feature space (Figure 4-3) as well as in the image space (Figure 4-4). The image classification procedure is primarily based on radiometric information as provided by the image itself. The feature space, as constructed by the combination of red and near-infrared reflection, is defined as the 'radiometric feature space'.

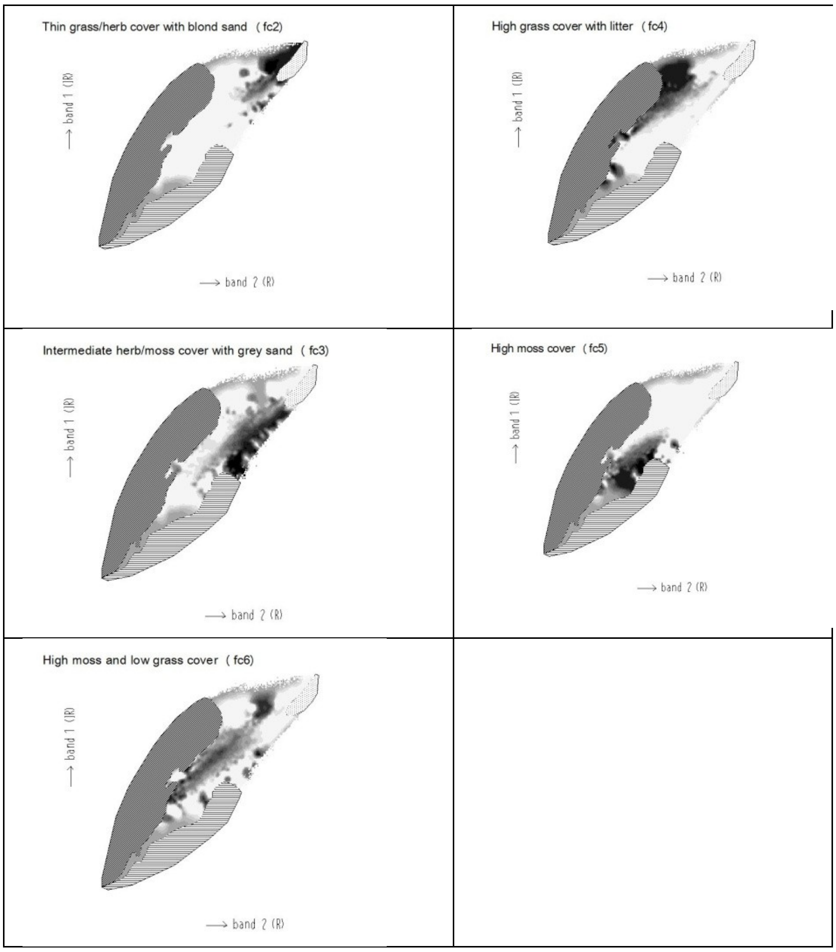
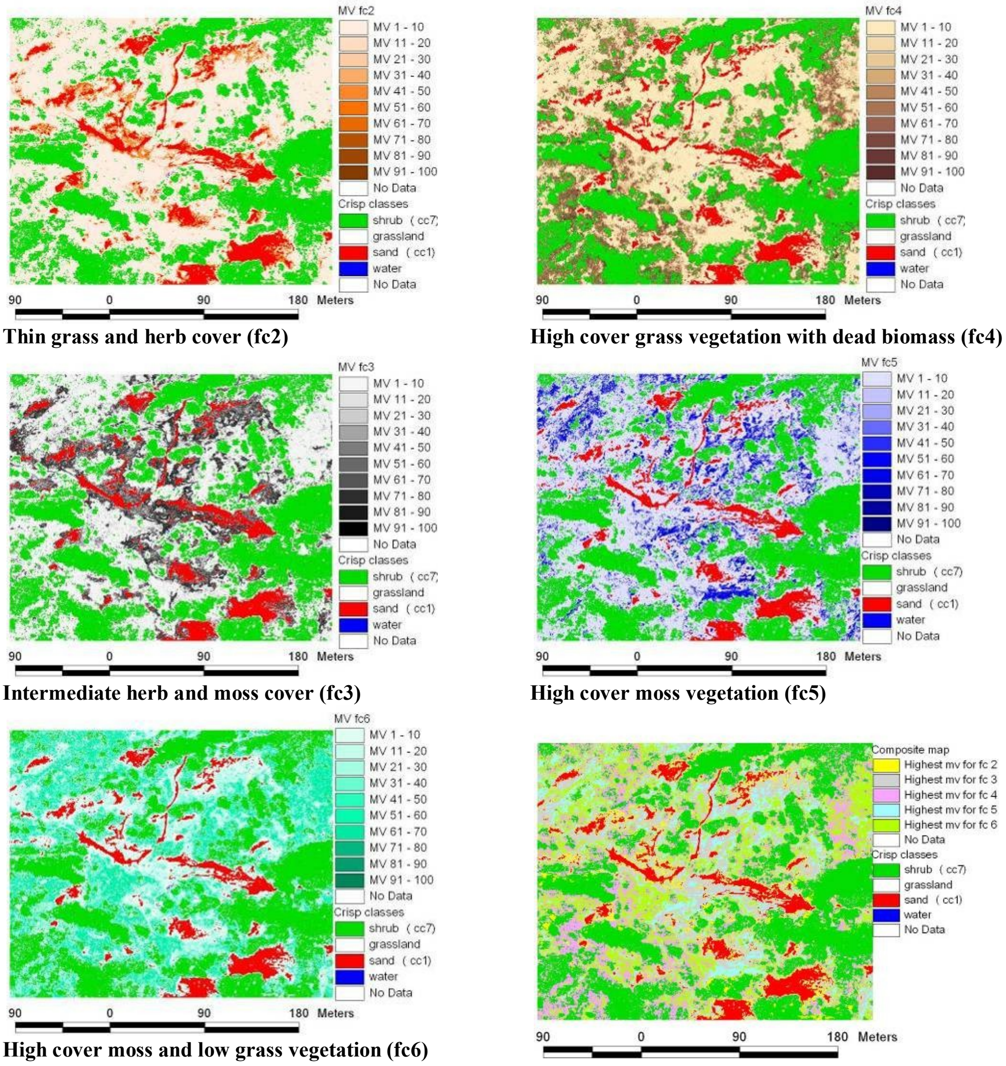


Figure 4-3 Radiometric feature space of the 2001 digital image; dotted: (cc1) blond sand, diagonal hatching: (cc7) shrubs and woods, horizontal hatching: open water, grey shade: membership value of fuzzy class (white=0%, black=100%)



Thin grass and herb cover (fc2)

High cover grass vegetation with dead biomass (fc4)

Intermediate herb and moss cover (fc3)

High cover moss vegetation (fc5)

High cover moss and low grass vegetation (fc6)

Composite map

Figure 4-4 Samples of the 2001 image interpretation map, crisp classes (shrub and woods and sand) are equal in every sample, separate samples give membership value for every possible fuzzy class. The composite map is a combination of crisp and fuzzy maps according to the rule that the fuzzy class with the highest membership value is presented.

Before the field observations can be related to image classes, the complex matrix of field data has to be processed. A generally accepted numerical method of processing complex field data, comprising varying data types and vegetation relevées is ordination (Jongman et al., 1995). The following characteristics of the field data lead to the choice of using a Detrended Canonical Correspondence analysis.

- The 152 relevées cover a wide ecological range, so the complete unimodal response curve of a species can be observed in the data and therefore Correspondence analysis is the most appropriate technique to construct a theoretical variable that explains the species data.
- Because of the wide ecological range the arch effect has to be eliminated by detrending the correspondence analysis.

It is the aim of this study to specify the semantics of image interpretation classes by describing them as ecosystems. Therefore, multiple parameters, including environmental variables, have to be incorporated in the analysis. It was concluded that a Detrended Canonical Correspondence Analysis (DCCA) is the most appropriate numerical method to summarize the field data.

A generally accepted illustration of ordination results is the ordination diagram: its gives the position of species, relevées and environmental variables in a multidimensional figure constructed with scores of these features on the ordination axes. Because the structure of the ordination diagram is primarily determined by the co-occurrence of plant species, the ordination diagram is defined as the 'phytosociologic feature space'. At the positions of the relevées in the phytosociologic feature space, the result of the image classification as obtained with the radiometric feature space, as well as the field estimation of image classes at the relevée locations, can be projected in the phytosociologic feature space. Information that concerns the image interpretation has to be dealt with as an independent variable in the ordination procedure. This is the key towards an ecological interpretation of the image interpretation classes.

According to Ewald (2003), phytosociology deals with plant species co-occurrences at the 'grain' of the plant community. In a small-scale dynamic ecosystem like dry coastal dunes this grain is spatially very small: within the range of several decimetres (Podani et al., 1993). Actually this is also the resolution of the digital orthophotos so it is acceptable to relate phytosociology with the spectral reflectance characteristics of the vegetation as presented in the radiometric feature space and made operational in the fuzzy and crisp image interpretation classes.

The interpretation of the phytosociologic feature space is carried out by defining species groups and the construction of response curves of the functional species groups: grasses, mosses, herbs and shrubs and trees on the ordination axes. The responses of the recorded environmental variables are also plotted on the ordination axes. Response curves are constructed by plotting the abundance of species and attribute values of environmental variables against their score on an ordination axis. The trend is revealed by modelling a polynomial curve. Based on their occurrence and abundance in corresponding relevées, species are assigned to a species group. This is achieved by comparing species scatter plots of the phytosociologic feature space and placing species in groups with corresponding scatter plots.

The ecological interpretation of the image interpretation classes is performed by the construction of a diagram that illustrates the relation between phytosociology, vegetation structure, environmental variables and image interpretation classes. This diagram is composed as an ecological cross section introducing deliberate continuous boundaries between states of the landscape. This confirms the concept, as presented in the Serial Landscape Model, of a landscape with continuous characteristics. The ecological cross section is in fact a spatial representation of the semantics of the landscape.

4.4 Results

Based on previous classification results and the image characteristics as presented in Figure 2-2, seven image interpretation classes are defined (see Table 2-4). Two classes are crisp: a combination of red and near infrared reflection is fully member of the class or not. Five classes are fuzzy: a combination of red and near infrared can be member of more classes; this is expressed in the membership value. The radiometric feature space of the 2001 image is presented in Figure 4-3. Comparison of succeeding radiometric feature spaces is not possible because radiometric characteristics of sequential digital orthophotos differ too much. This is caused by differences in atmospheric conditions, date of exposure and vegetation development (De Boer, 1993) which results in unique radiometric characteristics of image interpretation classes in every successive radiometric feature space. Image classification results based on the radiometric feature space as presented in Figure 4-3 are presented in Figure 4-4. Up to this point in the classification process there is no relation with species and processes. Only the crisp classes are loosely related to species (shrubs and trees in cc7) and processes (wind erosion in cc1). To establish the semantics of the classification results the phytosociologic feature space has to be constructed and analysed.

The DCCA results in two ordination axes with eigenvalues of 0.6650 for axis 1 and 0.3257 for axis 2: the majority of all variance in the field data is described by these two axes. The ordination diagram constructed from axis 1 and 2 is defined as the phytosociologic feature space and presented in Figure 4-5 (relevées), Figure 4-6 (species) and Figure 4-7 (environmental variables, vegetation structure and image interpretation classes). The response curves of dominant species on ordination axis 1 are presented in Appendix B1 – B4, curves of subdominant species on ordination axis 1 in Appendix B5 – B7. The response curves of dominant species on ordination axis 2 are presented in Appendix B13 and B14, curves of subdominant species on ordination axis 2 in Appendix B15. The choice whether a species is dominant or subdominant is based on the calculated weight in the ordination process. The responses of environmental variables on ordination axis 1 and 2 are presented in Appendix B8 – B11 and Appendix B16 – B18 respectively. The response of the image interpretation classes is presented in Appendix B11 (axis 1) and B18 (axis 2).

As can be seen in Figure 4-5 and Figure 4-6, axis 1 explains the gradient from forest to grassland. This observation is confirmed by Figure 4-7 where high grades of soil profile development points towards the left of axis 1. Forest is seen as the climax in vegetation succession and usually has well developed soils. Also see Appendix B9 and B11 where responses of soil profile development and vegetation structure are plotted on ordination axis 1.

Axis 2 explains the variety in grassland types as observed in the dynamic dry dune ecosystem. A gradient of relevées and species from dynamic dune grassland with species like *Syntrichia ruralis* and *Erodium cicutarium* to stable dune grassland with species like *Luzula campestris* and *Campylopus introflexus* is observed in Figure 4-5 and Figure 4-6. Again, this observation is confirmed by Figure 4-7 and the responses of environmental variables that indicate geomorphic processes.

The ecological interpretation of the phytosociologic feature space is confirmed by a detailed examination of the plant species response curves on ordination axes 1 (Appendix B1 – B7) and 2 (Appendix B13 – B15). Stable dune shrub and forest is characterised by high scores of *Crataegus monogyna* and *Quercus robur*, more dynamic shrub types are dominated by *Salix repens* and *Ligustrum vulgare*. *Hippophae rhamnoides* is dominant in the most dynamic shrub types and accompanied by the most dominant grass species in dry coastal dune ecosystems on lime rich substrate: *Calamagrostis epigejos*. *Calamagrostis epigejos* has a more or less constant response curve on ordination axis 2. This implies that *Calamagrostis epigejos is present in every dune grassland type.* It is striking that *Ammophila arenaria* has its optimum on axis 2 on the left because *Ammophila arenaria* is thought to be a species of highly dynamic dune systems with initial soils (Van de Putten, 1989; Isermann, 2005), which can be found at the right of axis 2. However, according to literature (Kooijman et al., 1998; Provoost et al., 2004;), there seems to be a gradient along the coast of the North Sea from South to North in the susceptibility of *Ammophila arenaria* to stabilisation. In Flanders *Ammophila arenaria* decays approximately six years after dune stabilisation, on the Dutch Wadden isles *Ammophila arenaria* is highly dominant in grass encroachment and stabilisation.

A more thorough examination of response curves of grasses on axes 1 and 2 leads to the conclusion that the ecological significance of grassland types is not only confined to ordination axis 1. According to axis 1, *Festuca rubra and Festuca filliformis* can be interpreted as species of more developed succession stages; however, according to axis 2 *Festuca rubra* is a species of more dynamic grasslands and *Festuca filliformis* more stable grasslands. The role of *Carex arenaria* in grass encroachment (Veer & Kooijman, 1997; Remke et al., 2009) is confirmed by the results, *Carex* *arenaria* emerges in early succession stages (response curve axis 1) but has its optimum in stable grassland (response curve axis 2).

The mosses observed give similar results: *Hypnum cupressiforme* and *Dicranum scoparium* have their optimum at the left of ordination axis 2 and *Syntrichia ruralis* has its optimum to the right, this confirms the gradient from dynamic open grassland (right) to stable rabbit grazed dune grassland (left).

The overall conclusion that the phytosociologic feature space can be interpreted as a two-dimensional space of the ecological parameters succession and stability is also confirmed by the response curves on axis 1 and 2 of herbs and subdominant grasses. It can be discussed whether *Rubus caesius* is a herb or a shrub but it is striking this plant has its optimum, similar to *Hippophae rhamnoides* and *Calamagrostis epigejos*, at the centre of axis 1. The last two species are considered as 'problem' species by terrain managers for their tendency towards encroachment (Ehrenburg and Baeyens, 1992; Van Boxel et al., 1997; Veer & Kooijman, 1997). *Rubus caesius* decays after every growing season and is therefore not a real encroaching species. However, in Amsterdam Water Supply Dunes it can be highly dominant in stable, dry secondary dune valleys.

The above described observation confirms the opinion that more or less stabilised ecosystems with some form of soil development, positioned at the centre of ordination axis 1 and at the centre and the right of ordination axis 2, are vulnerable to grass- or shrub encroachment.

By projecting the occurrence and abundance of species in the phytosociologic feature space, groups of species with similar characteristics can be defined. These groups are presented in Table 4-3, in which different types of species groups are defined:

1. General dune species (7).
2. Groups with well-defined ecological characteristics: forest species (1), stable dune grassland species (5), dune grassland species on well-developed soils (6), and species of dynamic dune environments (10).
3. Groups with species with a wide ecological range in a well-defined dune environment: forests and shrubs (2), dune grassland (4), species that thrive on a high grazing intensity (9).
4. Groups with species that occur in varying environments: shrubs and North exposed slopes (3), shrubs and dune grasslands (8).

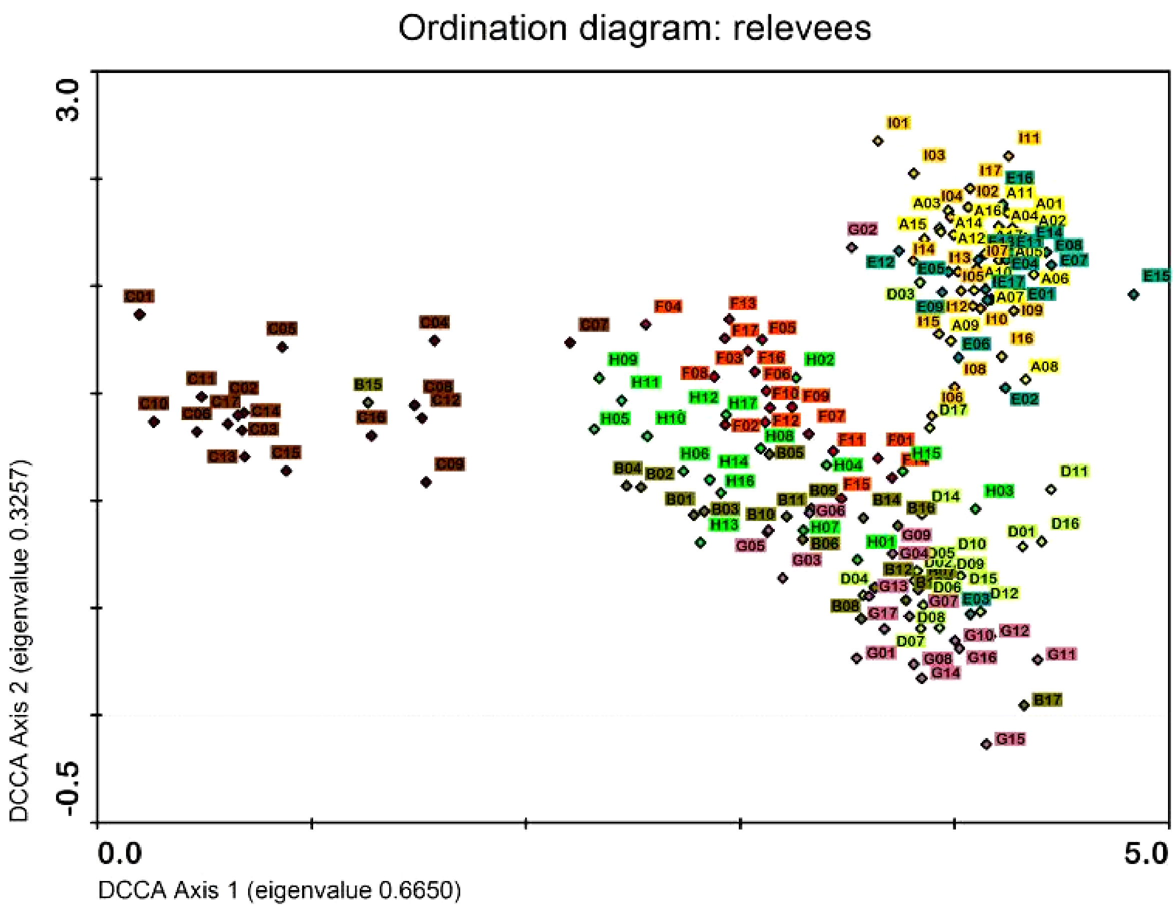


Figure 4-5 Ordination diagram or phytosociologic feature space of relevées, for characterization of the relevées: see Table 4-1

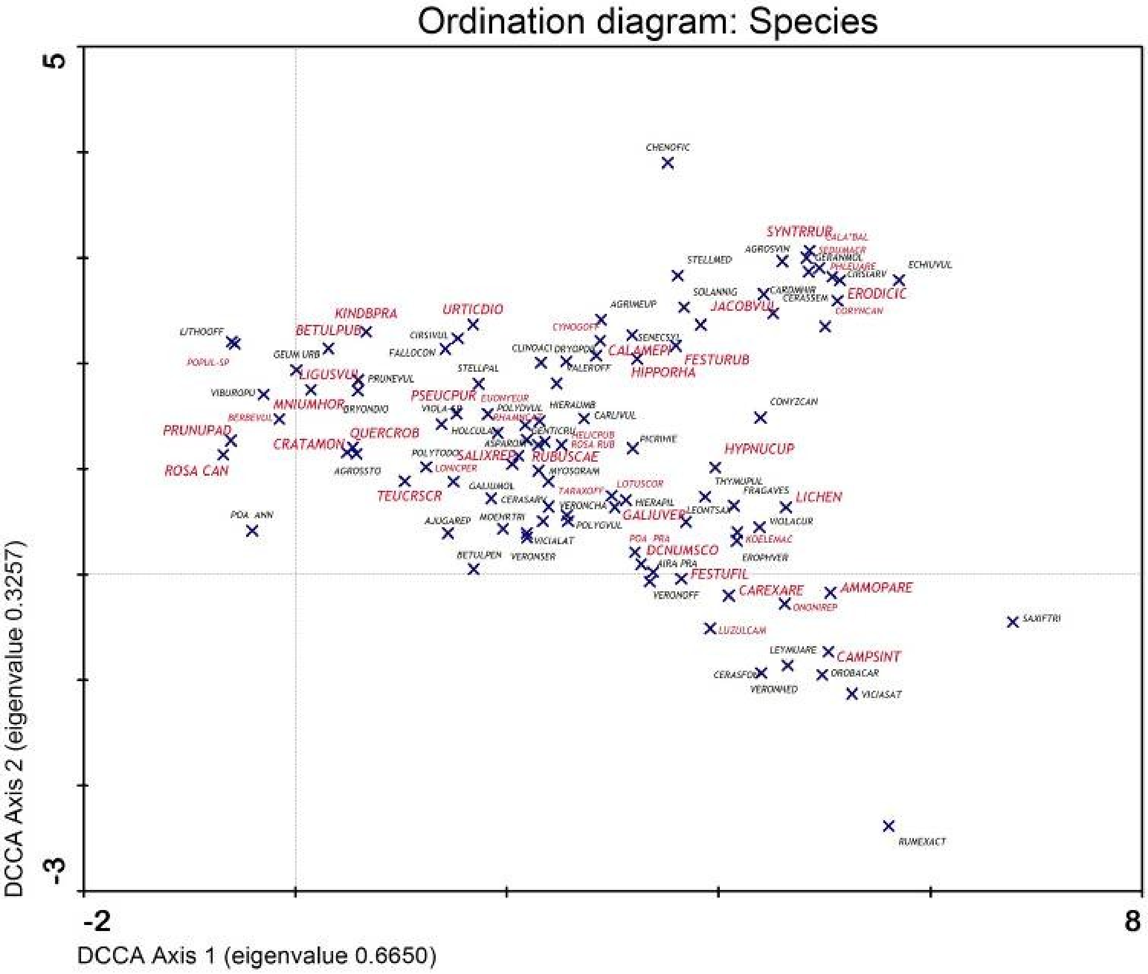


Figure 4-6 Ordination diagram or phytosociologic feature space of species; dominant species as presented in Appendix B1 – B4 and B13 – B14: red, large; subdominant species as presented in figure Appendix B5 – B7 and B15: red, small

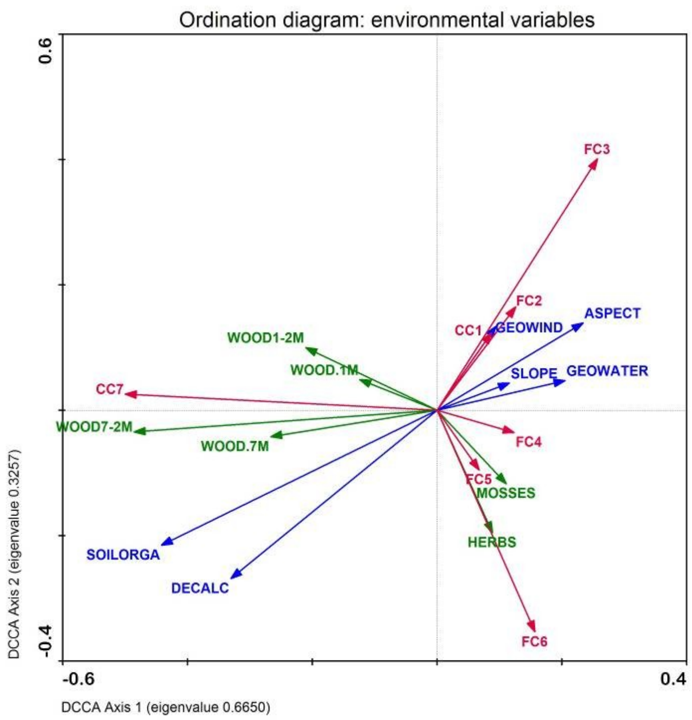
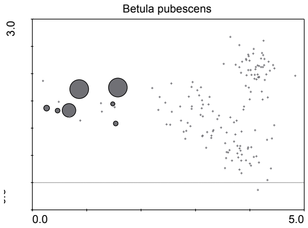
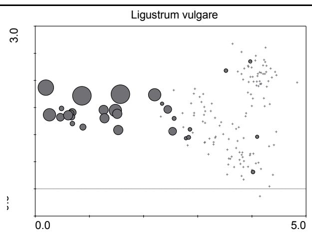
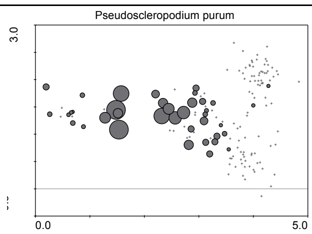
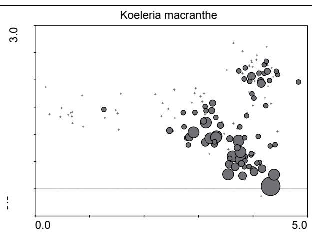
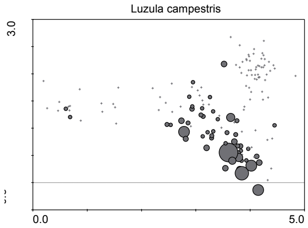
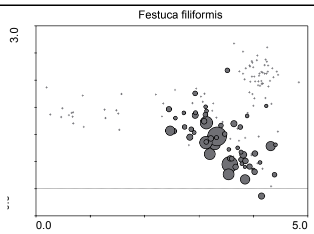
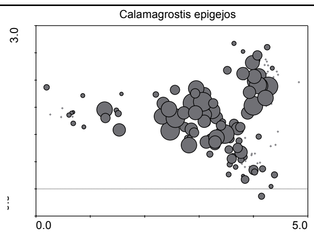
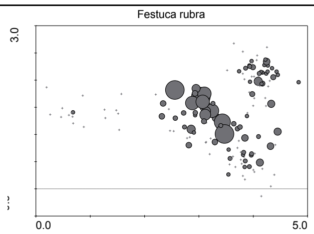


Figure 4-7 Ordination diagram or phytosociologic feature space of environmental variables (blue), vegetation structure as observed in the field (green) and image interpretation classes (red), see Table 4-2 for a description of the variables used

Table 4-3 Definition and description of species groups with a short ecological explanation; Species with a high weight in the DCCA are presented in bold

Species group	Phytosociologic feature space characteristics	Sample species ordination diagram	Species	Ecological characteristics
1	⇒ The presence of this group in the phytosociologic feature space is confined to the area that is characterised by high woody vegetation structure classes and high positive scores on soil organic matter and decalcification.		***Betula pubescens Ehrh.*** ***Populus* sp.** ***Prunus padus* L.** ***Rosa canina L.*** ***Teucrium scorodonia L.*** *Bryonia dioica* Jacq. *Lithospermum officinale* L. *Viburnum opulus* L.	Ecological this area in the phytosociologic feature space can be described as forest: the vegetation structure has reached its successional climax with a distinct soil development.
2	⇒ The area of this group in the phytosociologic feature space has an overlap with the area of group 1 but covers also an area that is characterised by lower shrubs and lower scores on environmental variables related to soil profile development.		***Berberis vulgaris L.*** ***Crataegus monogyna Jacq.*** ***Ligustrum vulgare L.*** ***Mnium hornum Hedw.*** ***Quercus robur L.*** *Agrostis stolonifera L.* *Ajuga reptans L.* *Geum urbanum L.* *Poa annua L.*	Species that are confined to this area in the phytosociologic feature space are common shrubs and trees in dune shrub: *Berberis vulgaris*, *Ligustrum vulgare*, *Quercus robur* and *Crataegus monogyna*. This is also valid for herbs and mosses of this species group.
3	⇒ An area that covers the central part of the phytosociologic feature space with outliers in areas as described for group 1 and 2.		***Euonymus europaeus L*** ***Pseudoscleropodum purum (Hedw.) Fleisch. Ex Broth*** ***Lonicera periclymenum L.*** ***Rhamnus cathartica L.*** *Asparagus officinalis L.* *Betula pendula Roth* *Cirsium vulgare (Savi) Ten.* *Polypodium vulgare L.* *Holcus lanatus L.* *Moehringia trinervia (L.) Clairv.* *Polygonatum odoratum (Mill.) Druce* *Fallopia convolvulus (L.) Å.Löve* *Prunella vulgaris L.* *Valeriana officinalis L.* *Veronica chamaedrys L.*	Species of level dune shrubs and North exposed slopes are part of this group. *Lonicera periclymenum* can be found as tree climber but also on the surface of North exposed slopes. *Rhamnus cathartica* and *Euonymus europaeus* are characteristic shrubs of lime-rich dune areas. *Pseudoscleropodum purum* is a common moss of woods, shrubs and moist grasslands.
4	⇒ The area of this ordination group is formed by the two outliers characterized by primary succession stages or stable dune grasslands.		***Ammophila arenaria (L.) Link*** ***Koeleria macrantha (Ledeb.) Schult.*** ***Lichen*** ***Jacobaea vulgaris P.Gaertn.*** *Agrimonia eupatoria L.*	This ordination group consists of species of geomorphic stable as well as unstable dune grasslands. *Koeleria macranthe* is typical for older and stable dune grasslands, *Ammophila arenaria* is an indicator of accumulation of fresh blown sand and decays with ongoing soil profile development. *Jacobaea vulgaris* is typically a species with a wide ecological range, its presence in the phytosociologic feature space points towards a higher presence in dune grasslands.

5	⇒ The area chracterized by herbal and moss vegetation with high scores for environmental variables related to soil profile development.		***Campylopus introflexus (Hedw.) Brid.*** ***Luzula campestris (L.) DC.*** ***Ononis repens L.*** *Carlina vulgaris L.* *Cerastium arvense L.* *Cerastium fontanum Baumg.* *Leymus arenarius (L.) Hochst.* *Orobanche caryophyllacea Sm.* *Rumex acetosella L.*	*Luzula campestris*, *Ononis repens* and *Campylopus introflexus* are typical species of grey dunes with a lack of geomorphic activity.
6	⇒ An area, that covers the central part of the phytosociologic feature space and the outlier towards high scores on Axis 1 and low scores on Axis 2. This is the area with high positive scores for the presence of mosses and herbs. There are also high scores for environmental variables related to soil profile development		***Helictotrichon pubescens (Huds.) Pilg.*** ***Festuca filiformis Pourr.*** ***Lotus corniculatus L.*** ***Rosa rubiginosa L.*** *Fragaria vesca L.* *Hieracium pilosella L.* *Picris hieracioides L.* *Polygala vulgaris L.* *Thymus pulegioides L.* *Veronica hederifolia L.* *Veronica officinalis L.* *Veronica serpyllifolia L.* *Vicia sativa L.* *Viola curtisii E.Forster*	This group consists of species typical for stabilized dune grasslands with a distinct soil development: *Helictotrichon pubescens*, *Festuca filiformis* and *Lotus corniculatus. Rosa rubiginosa*, a species of shrubs and North exposed slopes is also part of this group.
7	⇒ Species of this ordination group occur in a wide range of the entire area covered by the phytosociologic feature space. ⇒ Species that occur in the ordination areas that have high scores for environmental variables related to soil profile development as well as areas with high scores for geomorphic activity are also classified to this group.		***Calamagrostis epigejos (L.) Roth*** ***Cynoglossum officinale L.*** ***Eurhynchium praelongum (Hedw.) Schimp.*** ***Taraxacum officinale F.H.Wigg.*** ***Urtica dioica L.*** *Erophila verna (L.) Chevall.* *Galium mollugo L.* *Hieracium umbellatum L.* *Myosotis ramosissima Schult.* *Senecio sylvaticus L.* *Viola sp.*	Species with different life forms and ecological implications are member of this group. *Calamagrostis epigejos* is a grass that can be found in fringes of *Hippophae rhamnoides* shrubs, grey dune grasslands and grasslands with a high content of dead ectorganic material. The biannual *Cynoglossum officinale* is typical for grey dunes but as the phytosociologic feature space reveals, can be found in shrubs and woods as well. Other species of this group are *Urtica dioica*, *Taraxacum officinale* and *Kindbergia praelonga*.
8	⇒ This ordination group is similar to group 4 but species of this group also occur, with low scores, in the area that is characterized by higher geomorphic activity. Species of this ordination group can occur, with low scores, in the area characterized as woods with a distinct soil development.		***Festuca rubra L.*** ***Hippophae rhamnoides L.*** ***Poa pratensis L.*** ***Rubus caesius L.*** *Clinopodium acinos (L.) Kuntze* *Aira praecox L.* *Cardamine hirsuta L.* *Dryopteris dilatata (Hoffm.) A.Gray* *Salix repens L.* *Solanum nigrum L.* *Stellaria pallida (Dum.) Piré*	The ordination group consists of common grasses and shrubs with a wide ecological range: *Festuca rubra*, *Hippophae rhamnoides*, *Poa pratensis*, *Rubus caesius* en *Salix repens*. These species have a tendency towards dominance but, in successional sense, only in already more or less stabilized open dune grasslands. *Rubus caesius* is an exception, this species can also become dominant in areas with high geomorphic activity but this is not observed in the area covered by the relevee grids.

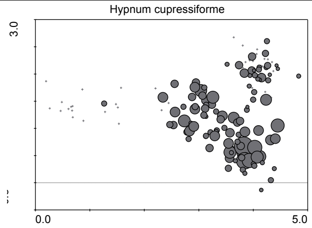
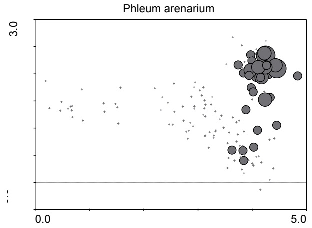
9	⇒ Species of this ordination group occur in a wide range of the entire area covered by the central and right part of the phytosociologic feature space ⇒ The presence of species of this group in the ordination area with high geomorphic activity is relatively small.		***Carex arenaria L.*** ***Dicranum scoparium Hedw.*** ***Galium verum L.*** ***Hypnum cupressiforme Hedw.*** *Conyza canadensis (L.) Cronq.* *Gentiana cruciata L.* *Leontodon saxatilis Lam.* *Vicia lathyroides L.*	Species of stable dune grasslands with a high influence of rabbit grazing can be found in this ordination group. Important fact is that these species are indicators of a relative high level of soil profile development. *Hypnum cuppressiforme*, *Dicranum scoparium* and *Galium verum* can be found on dune-micropodsols. *Carex arenaria* is found in stable dune grasslands as well as in areas with erosion and accumulation of sand by wind.
10	⇒ This ordination group is typically formed by the area characterised by high scores for environmental variables related to geomorphic activity.		***Cerastium semidecandrum L.*** ***Corynephorus canescens (L.) P.Beauv.*** ***Erodium cicutarium (L.) L'Hér.*** ***Phleum arenarium L.*** ***Tortula ruralis var. Ruraliformis (Besch.) Wild.*** ***xCalammophila baltica (Flüggé ex Schrad.) Brand*** *Agrostis vinealis Schreb.* *Chenopodium ficifolium Sm.* *Cirsium arvense (L.) Scop.* *Echium vulgare L.* *Geranium molle L.* *Saxifraga tridactylites L.* *Sedum acre L.* *Stellaria media L.*	Species with typical strategies to cope with extreme environmental conditions are member of this group: winter annuals like *Cerastium semidecandrum*, *Erodium cicutarium* and *Phleum arenarium*, tussock forming grass like *Corynephorus canescens* and the extreme drought resistant moss *Syntrichia ruralis*. *xCallamophila baltica* is a grass planted to stabilize blowing sand.

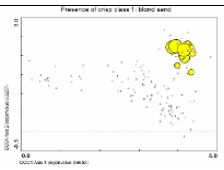
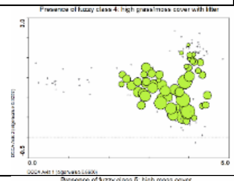
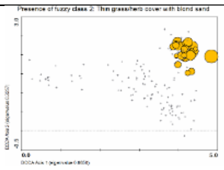
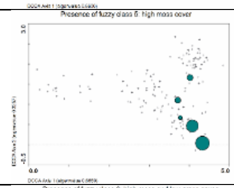
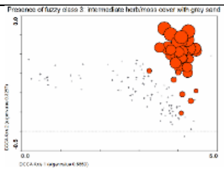
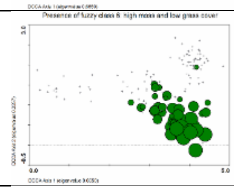
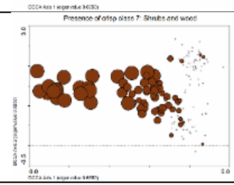
Image interpretation class	Overlap with species group	Image interpretation class	Overlap with species group
Crisp (cc1): "Bare Sand" 	**4, 7, 9,10**	**Fuzzy (fc4): High grass cover with litter** 	**2, 3, 4, 6, 7, 8, 9**
Fuzzy (fc2): Thin grass/herb cover with blond sand 	**4,7,9,10**	**Fuzzy (fc5): High moss cover** 	**4, 5, 7, 9**
Fuzzy (fc3): Intermediate herb/moss cover with grey sand 	**4, 7, 8, 9**	**Fuzzy (fc6): High moss and low grass cover** 	**4, 5, 6, 7, 8, 9, 10**
		Crisp (cc7): "Shrubs and woods" 	**1, 2, 6, 7, 8, 9**

Figure 4-8 Image interpretation classes plotted in the phytosociologic feature space

Now that the phytosociologic feature space and the position of species and ecological species groups within the feature space is clear, the ecological implication of image interpretation classes can be analysed. This is achieved by plotting the relative coverage of an image interpretation class, calculated with the help of the image interpretation map, in the phytosociologic feature space. This is presented in Figure 4-8.

From this figure, it is clear that the image interpretation classes “Bare sand” (cc1) and “Thin grass and herb cover with blond sand” (fc2) have a similar species composition and should be interpreted similar. The image interpretation class “Bare sand” should have no vegetation cover at all but the vegetation cover is extremely low and the individual plants are too small to have effect on the reflection characteristics. From this, it can be concluded that the classes cc1 and fc2 are phytosociologic similar, however geomorphic activity in class cc1 (deflation and/or accretion) is higher. The geomorphic activity in class fc2 is mainly accretion by wind-blown sand.

The image interpretation class, characterised as “Intermediate herb/moss cover with grey sand” (fc3) is ecological separated from the preceding two classes because of the lack of species of more extreme environmental conditions and the occurrence of more general dune species. “High grass cover with litter” (fc4) is located in the centre of the phytosociologic feature space. Therefore, species from several species groups can be found in this class but the fact that the class is characterised by a high amount of ectorganic material has to be taken into account. Fc4 is the class that can implicate grass encroachment. In a more natural situation this class is found as a fringe along shrubs. Image interpretation classes “High moss cover” (fc5) and “High moss and low grass cover” (fc6) are discriminated by species of stable dune grasslands with the division in species-poor (fc5) and species-rich (fc6). For image interpretation class “High moss and low grass cover” (fc6) the addition must be made that the vegetation structure is primarily maintained by rabbit grazing and therefore vulnerable in periods of high rabbit mortality. This mortality can be caused by myxomatosis (Ranwell, 1960b) and VHR (Van der Hagen et al., 2008). The most prominent class in the phytosociologic feature space is “Shrubs and woods” (cc7). It is clear that this class has a wide ecological range and should be further analysed and divided. Within the radiometric feature space this is not possible, alternative techniques like image texture analysis should be used.

The overall integration of the material presented above has led to the construction of an ecological cross section with a specific indication for the image interpretation classes. The cross section is presented in Figure 4-9.

Based on the species composition as determined in the field and their co-occurrence as analysed with the DCCA an indication of the vegetation type or plant community is given. Though the two ecological gradients, as observed in the phytosociologic feature space (DCCA axis 1 and 2), are presented in the ecological cross section, the gradient from forest to open dune grassland is most pronounced. Because this gradient is revealed on ordination axis 1, the ecological cross section is constructed according to this axis: forest on the left and open dune grassland on the right.

Because there is a fundamental conceptual difference between:

- the semantic domain of The Serial Landscape Model and its classes and
- classic phytosociology and its plant communities,

only an indication of corresponding plant communities (cf. Schaminee et al. (1998) and Stortelder et al. (1999)) is given in the ecological cross section. No attempt is made to correlate classes of the Serial Landscape Model with plant communities.

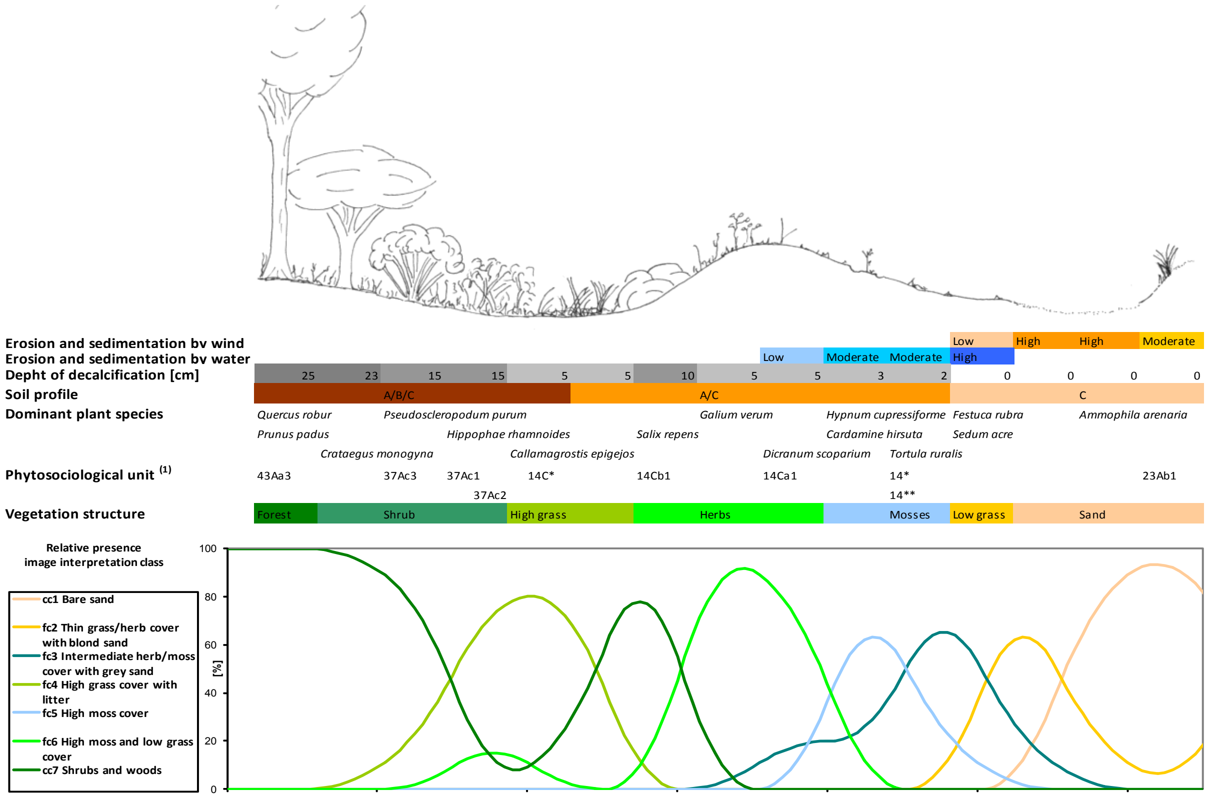
By indicating the expected membership value for the image interpretation classes as an integral part of the ecological cross section, the semantics of the image interpretation classes (Table 2-4) are revealed. These semantics are presented in Table 4-4.

It can be seen that the crisp classes are also presented as fuzzy classes. However, image characteristics as well as conceptual motives make it necessary to deal with these classes as crisp (see Chapter 2).

Final step in the procedure from image and field observation towards NATURA 2000 habitat types is the correlation of image interpretation classes and the relevant NATURA 2000 habitat types. Relevant habitat types for the Meijendel & Berheide NATURA 2000 site are (Council of the European Communities, 1992):

- H2120 Shifting dunes along the shoreline with *Ammophila arenaria* (‘white dunes’)
- H2130 Fixed coastal dunes with herbaceous vegetation (“grey dunes’)
- H2160 Dunes with *Hippophae rhamnoides*
- H2180 Wooded dunes of the Atlantic, Continental and Boreal region

The crisp class “Shrubs and woods” includes habitat type H2160 and H2180, all the fuzzy classes can be characterised as H2130. When encountered in the fore-dunes the crisp class “Bare sand” and the fuzzy class “Thin grass herb cover with blond sand” can be interpreted as H2120. Only a very small part of the research area can be defined as fore-dunes, see Figure 5-1. The implication of the overlap of image interpretation classes within the habitat class H2130 on the one hand and the overlap of habitat types within the image interpretation class “shrubs and woods” on the other hand is discussed in the following section.



(1)
43Aa3: ***Crataego-Betuletum pubescentis*** Boerboom 1960
37Ac3: ***Rhamno-Crataegetum*** Sloet van Oldruitenborgh ex Haveman, Schaminée et Weeda ass. Nov.
37Ac1: ***Hippophae-Sambucetum*** Boerboom 1960
37Ac2: ***Hippophae-Ligustretum*** Meltzer 1941 em. Haveman, Schaminée et Weeda
14C*: **RG *Calamagrostis epigejos-[Cladonio-Koeleretalia]***
14Cb1: ***Taraxaco-Galietum*** veri Boerboom 1957 em. Weeda, Doing et Schaminée
14Ca1: ***Phleo-tortuletum ruraliformis*** Braun-Blanquet et De Leeuw 1936 nom.inv. Géhu & De Foucault 1978
14*: **RG *Dicranum scoparium-[Koelerio-Corynephoretea]***
14**: **DG *Campylopus introflexus-[Koelerio-Corynephoretea]***
23Ab1: ***Elymo-Ammophiletum*** Braun-Blanquet et De Leeuw 1936

Figure 4-9 Ecological cross section

Table 4-4 Ecosystem description of image interpretation classes

Semantics of the image interpretation classes, discrete (crisp) and continuous (fuzzy).	
Crisp (cc1): Bare Sand	That part of a blowout complex with active aeolian processes and virtually no vegetation cover: erosion and accumulation of blond dune sand. (Jungerius et al., 1981; Rutin, 1983; Jungerius & Van der Meulen, 1989)
Fuzzy (fc2): Thin grass/herb cover with blond sand	Blond sand, i.e. sand with a negligible amount of organic matter, has, by far, the largest contribution in this coverage type. It is however accompanied by pioneer plant species. Herbs are annual as well as biennial. Grass types are mainly solitary and clonal and react more or less positive to wind activity. Tussock forming grass types can be present. Soil forming processes are negligible.
Fuzzy (fc3): Intermediate herb/moss cover with grey sand	Largest contribution to the overall coverage is by mosses that react more or less positive to or can sustain some geomorphic activity. The geomorphic activity is mainly erosion and accumulation of sand as a result of water repellency (Dekker et al., 2001). Bare grey sand, i.e. sand with organic matter mainly in the form of humus coatings, has a substantial contribution to the overall coverage. Herbaceous 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. Soil forming processes are unfavourable humification towards disperse humus, decalcification and eluviation (micro podzol forming). This ecosystem can be seen, in combination with image interpretation class “High moss and low grass cover” as the optimal development of “grey dunes”. (Ellenberg, 1988)
Fuzzy (fc4): High grass cover with litter	Grasses and perennial/clonal herbs cover the soil completely. Dead ectorganic matter is a substantial element of this type. Nutrient cycling and soil forming processes are complex and subject of research (Kooijman & De Haan, 1995; Kooijman et al., 1998) because grass encroachment leading to an ecosystem of this type is seen as unfavourable. It is caused by the absence of rabbit activity (grazing, digging) and atmospheric deposition of N. Along the fringes of shrubs (mainly *Hippophae rhamnoides),* this class is natural.
Fuzzy (fc5): High moss cover	The soil of this image interpretation type is totally covered with mosses and lichens and, very locally, with some annual and biennial herbs. Grasses are nearly absent. The dominant moss-type is *Campylopus introflexus* and was seen as a problem (Van Boxel et al., 1997; Kettner-Oostra & Sýkora, 2004). Nowadays, with the absence of rabbit grazing and the atmospheric deposition this image interpretation type becomes rare. Soil forming processes are similar to the class “intermediate herb/moss cover with grey sand”.
Fuzzy (fc6): High moss and low grass cover	The soil is totally covered with mosses combined with low herbaceous vegetation. Herbs and grasses are mainly small though larger woody plants at the sub pixel level can occur. This ecosystem is a stable dune grassland and represents, in combination with “intermediate herb/moss cover with grey sand” the optimal development of “grey dunes”. Soil forming processes are similar to the class “intermediate herb/moss cover with grey sand” with the addition that the soil profile is further developed.
Crisp (cc7): Shrubs and woods	This discrete class is defined by 100% coverage of woody plants with an individual organism size larger than the resolution of the image. Though presented as a homogeneous, discrete class, internally there is a high level of heterogeneity in structure and species distribution. This image interpretation class represents different types of ecosystems, ranging from dune forest to *Hippophae rhamnoides* shrub. Therefore, the soil forming processes are diverse.

4.5 Discussion

The ecological cross section (Figure 4-9) and ecosystem description of the image interpretation classes (Table 4-4) are considered as the landscape ecological basis for monitoring the dry dune ecosystems. It refers to the relation between biotic and abiotic parameters, species and processes. Furthermore, it is the integration of field and image characteristics and therefore highly applicable in ‘bridging the gap’ between information technology based observations and field ecology based information.

It is clear from the radiometric feature space (Figure 4-3), the phytosociologic feature space (Figure 4-5, Figure 4-6, Figure 4-7) and the results presented in the ecological cross section (Figure 4-9), that the image interpretation classes cannot be seen as individual spatial, temporal and semantic classes: together they make up the landscape as a whole. However, in general, the habitat approach is applied as a discrete paradigm (Bock et al., 2005; Provoost et al., 2005; Boyd et al., 2006). A geographic location is classified as one habitat and is therefore not another habitat. In reality a geographic location can have elements of more habitat types, this can be illustrated by the presented material. It goes without saying that in a geomorphic active dune-area the plant community *Elymo-ammophiletum* occurs also in parts of the dunes at further distance of the coastline. In the Meijendel/Berkheide area this can be more than three km where the dynamic dune grassland ecosystem is a mosaic of different habitat types with converging boundaries. According to the Dutch classification of habitat types this vegetation type is classified as 2120: “Shifting dunes along the shoreline with *Ammophila arenaria* (‘white dunes’)” with the restriction that it occurs in the fore-dunes. This definition is also used in the presented results.

This ambiguity can be solved by defining the managers monitoring goal clearly. When the terrain manager wants to know exactly which species is where a habitat map based on fuzzy interpretation classes is not applicable but when he only wants to know what is the relative coverage of a habitat in his terrain, a habitat map based on fuzzy interpretation classes is very well applicable (see also Chapter 2). An example based on the presented material can be seen in Figure 4-10, the absolute extent for crisp and fuzzy classes in 1990. 1995 and 2001. The extent of the fuzzy classes is calculated by multiplying the absolute cover of image elements (pixels) with the membership value assigned for the class. From this figure the terrain manager can conclude that ecosystems, characterised by elements typical for habitat type 2120 (species, processes and soil), declined slightly. From 1990 to 1995 habitat type 2130 declined considerable in favour of habitat type 2160 or 2180. From field observations it can be confirmed that it is mainly *Hippophaë rhamnoides* shrub that extended (habitat type 2160). General conclusion is that the dune area stabilises: according to the ecological cross section the dune area makes a shift to the left.

Because habitat type 2130 is a priority habitat type the terrain manager has a large (international) responsibility for this type. The fuzzy image classification discerns several ecosystems within the habitat type, which is a great advantage. From the ecosystem description of the image interpretation classes it is clear that image interpretation class “Intermediate herb/moss cover with grey sand” (fc3) and “High moss and low grass cover” (fc6) are the optimal manifestation of habitat type 2130 and “High grass cover with litter” (fc4) and “High moss cover” (fc5) are undesirable. Table 4-5 gives a clear result for the terrain manager: though the cover of dry dune grassland (Habitat type 2120 and 2130) has increased from 1995 to 2001, the enlargement of the area is mainly due to grass encroachment (fc4) and therefore the terrain manager has to act.

It can be concluded that in the definition of image interpretation classes, priority habitat types need extra attention and the effort must be on the definition of more image interpretation classes per priority habitat type.

As presented in the introduction, NATURA 2000 habitats can be monitored through digital image interpretation because this allows for a relatively cheap and quick survey, covering a total terrain. Disadvantage is the fact that only a selected set of parameters (reflection of the earth surface at some selected wave lengths) is the basic material for an integral ecosystem classification, so a comprehensive field survey and expert interpretation has to be carried out. When dealing with dynamic natural ecosystems with a typical small-scale mosaic this comprehensive survey and interpretation has to be carried out only occasionally, provided that all ecosystems are sampled and no dramatic changes resulting in the development of new ecosystem types take place. A major opportunity of the methodology presented is the fact that results can be applied in a versatile manner. The combination of image interpretation classes as defined in the radiometric feature space and ecosystem knowledge as obtained from the phytosociologic feature space can provide information at different levels of abstraction: individual species, plant communities and ecosystems. The results of the methodology can be applied in management policies varying from species conservation to general management evaluation. A major threat to the methodology is the constant development of new remote sensing platforms and digital interpretation techniques. This can result in a constant re-definition of image interpretation classes, so the monitoring program is inconsistent.

It is already discussed that within a NATURA 2000 habitat there can be a great variety of ecosystems so the semantic variety is large. This is also the case for spatial and temporal aspects of the NATURA 2000 habitats. Within an area occupied by a NATURA 2000 habitat the geographic position and the importance (as reflected in the membership value) of ecosystems changes constantly through time. A good perception of the semantic variety, spatial configuration and temporal dynamics within a NATURA 2000 habitat can give the terrain manager a good indication for interventions.

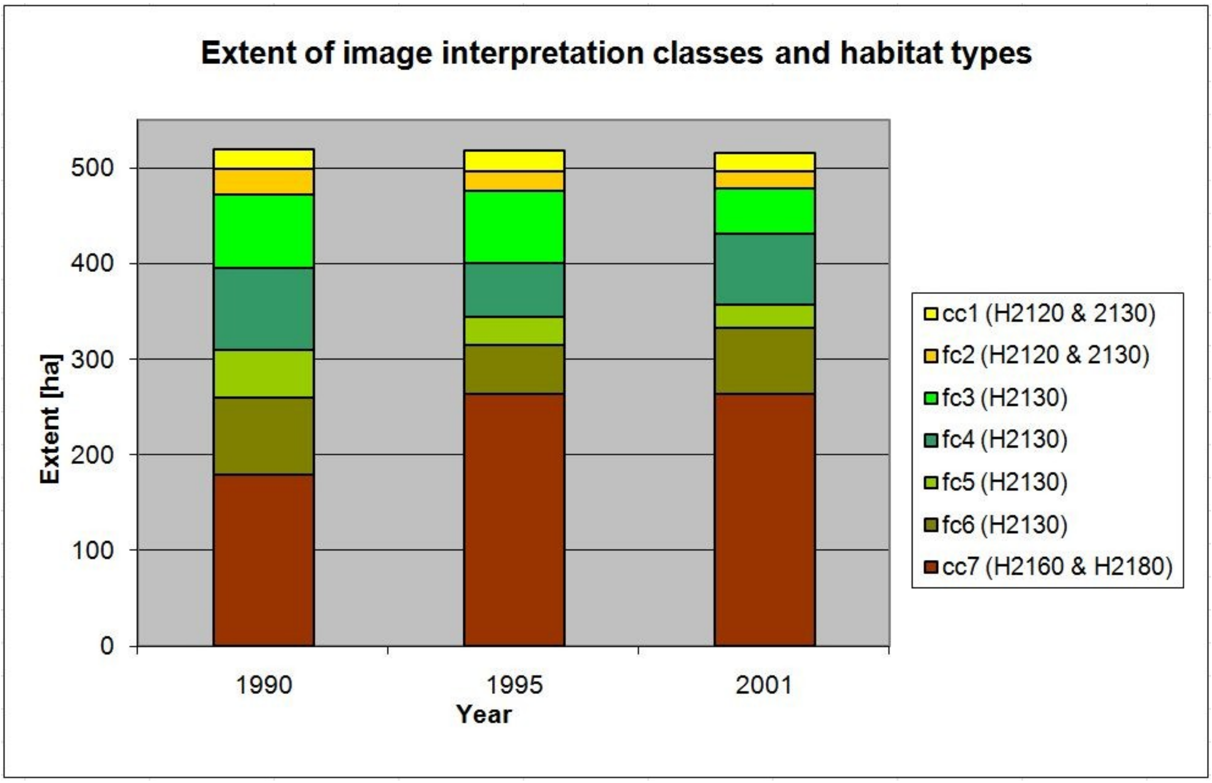


Figure 4-10 Extent [ha] of image interpretation classes and habitat types based on absolute cover and membership value

Table 4-5 Development of the extent of habitat types 2120 & 2130 and image interpretation class fc4 in the research area

	Total extent [ha] dry dune grassland (Habitat type 2120 & 2130)	Total extent [ha] dry dune grassland with characteristics of grass encroachment (fc4)
1990	323	86
1995	236	57
2001	248	74

4.6 Conclusion

It can be concluded that with an intricate combination of image interpretation techniques, field survey, multivariate statistics (ordination) and expert knowledge it is possible to define ecological meaningful classes for digital image interpretation that can be used in the evaluation of NATURA 2000 policy. The observation model consists of two elements: the radiometric feature space, which is leading in the class definition and image classification, and the phytosociologic feature space, which is leading in the ecological interpretation of the classes and the translation towards NATURA 2000 habitat types. Both elements are combined in the semantics of the image interpretation classes. The radiometric feature space as well as the phytosociologic feature space is continuous. This supports the notion of the continuous character of the landscape as expressed in The Serial Landscape Model. In combination, the feature spaces make it possible to present an integral model of a dynamic natural ecosystem with the use of remote sensing products.

Some limiting conditions in NATURA 2000 evaluation with remote sensing products can be defined.

- The digital images must have a spatial resolution equal to, or smaller than, the ‘grain’ of the landscape. In small-scale dynamic ecosystems this is very small and therefore only high-resolution airborne remote sensing products are adequate.
- Per priority-habitats multiple image interpretation classes have to be defined. This makes it possible to reveal the internal heterogeneity and dynamics (semantic, spatial and temporal), which can be used in establishing management interventions.
- In NATURA 2000 evaluation of small-scale dynamic ecosystems, not only ground truthing for supervising the digital image interpretation is needed but also a detailed field survey is obligatory because this provides essential ecosystem information.
- The field survey must have a deterministic landscape ecological focus, which means that several attributes of different landscape components have to be surveyed. A field survey with a holistic premise (one attribute explains all) will lead to circular reasoning: the interpretation towards an ecosystem is already part of the field survey.
- The approach of habitats being discrete spatial, temporal and semantic units must be avoided; if possible, combinations of habitat types and differentiation within habitat types must be possible in the observation model used.
- The terrain manager has to monitor and plan his management policy based on the relative coverage of habitat types and species, and not based on the exact location of habitat types and species. This means that the focus must be on landscape dynamics (spatial, temporal and semantic) and not on rigid configuration.

A workflow to produce NATURA 2000 habitat maps is presented in Figure 4-11. As can be seen from the figure: field observations, or in other words, the real world, are essential in

1. The definition of image interpretation classes,
2. The formation of the radiometric feature space through a field estimation of image interpretation classes,
3. And the formation of the phytosociologic feature space through the description of relevées.

By plotting the image interpretation classes in the phytosociologic feature space an ecosystem can be defined, which in turn can be interpreted as NATURA 2000 habitat types. Because image interpretation classes are semantically equal to the ecosystems described, the image interpretation map can be transposed to a NATURA 2000 habitat map. By analysing the configuration of this map and analysing change in sequential maps, NATURA 2000 based terrain management can be evaluated and re-defined.

When looking at Figure 4-11, it is striking that NATURA 2000 habitat description is only incorporated in the workflow at the concluding stage towards the production of the habitat map. From this, it is clear that the terrain manager must start from the principle that field information and the remote sensing product provide crucial information; NATURA 2000 is only a standardized reference for objective evaluation and impact assessment.

From the data presented it can be concluded that in the research area the priority habitat 2130 (“grey dunes”) has decreased and that within this habitat the undesirable state of high grass coverage with dead biomass, typical for grass encroachment, has increased, in spite of the management intervention of grazing by horses and cattle since 1991.

The decline of ecosystems related to geomorphic activity (cc1 & fc2) and the increase of shrubs and wood (fc7) has led to the conclusion that further research has to be focused on spatial, temporal and semantic dynamics of processes like blowout development, grass encroachment and shrub encroachment. Chapter 5 gives a further definition of the concept of temporal dynamics and spatial and semantic dynamics, which is further applied for the research area in Chapter 7.

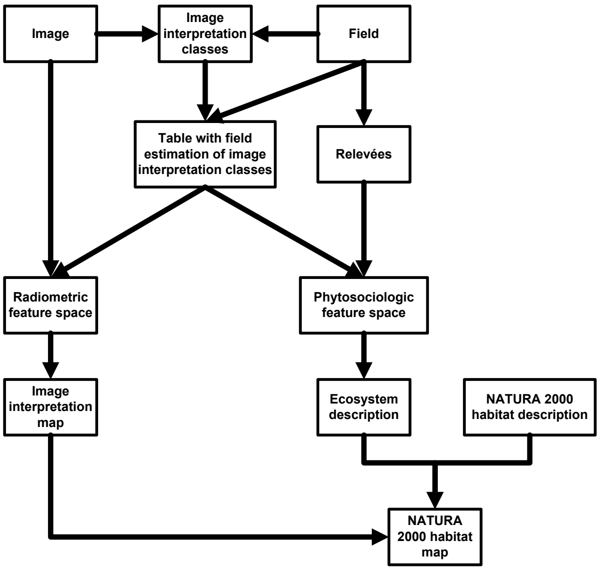


Figure 4-11 Workflow to produce NATURA 2000 habitat maps of small-scale dynamic ecosystems with remote sensing products and field survey

Photo 3 Impression of the Kabelpad case study area

5 LANDSCAPE GUIDED STRATIFICATION FOR FUZZY DIGITAL CLASSIFICATION OF SMALL-SCALE DYNAMIC ECOSYSTEMS; THE LANDSCAPE AS A SPATIO-TEMPORAL-SEMANTIC DYNAMIC SPACE.

5.1 Introduction

In landscape ecological research, focused on nature management, three elements have to be combined: the landscape concept (see Chapter 1), the observation model (see Chapter 2) and the management approach. The landscape concept must be seen as the abstraction of how the landscape is organised and functions. The approach can range from deterministic (Baker, 1989) to holistic (Doing, 1995; Naveh, 2000), hierarchic (Klijn & Udo de Haes, 1994) to chaotic (Farina, 2005) and topologic (Bakker et al., 1981) to chorologic (Forman & Godron, 1986). The landscape concept determines the rules how the landscape is observed and how the observations are combined and made operational. In other words: the observation model. The management approach is, on the one hand, prompted or even dictated by governmental policy. In the EU, for instance, management of landscape and nature reserves is governed by the habitat directive (Council of the European Communities, 1992) and NATURA 2000. On the other hand, the management approach is prompted by opinions of terrain managers and scientists. With the help of the observation model, the management and conservation of species and habitats is monitored, and the results are assessed and rewarded.

The three elements concerning concept, observation and management have to be in balance. This means that the material and procedures used in the observation must comply with the extent and characteristics of the managed area, and that the landscape concept is guiding in the processing and application of observation and analysis. Concept and observation model have to result in an optimal quality of management.

It is generally assumed that a hierarchic landscape concept produces optimal results in terms of balance between these three elements. However, this has not been tested for small-scale dynamic ecosystems. This is the topic of this chapter in which the observation procedure used is based on The Serial Landscape Model. This is further substantiated in section 5.1.1 and followed by a description of the aim of the analysis dealt with in this chapter (section 5.2). Subsequently, the match between hierarchic landscape concept and observation model is tested. This is achieved by comparing the classification accuracies of (hierarchic) stratified fuzzy vegetation structure maps of a dry coastal dune area with the accuracy of a fuzzy vegetation structure map of the total area (section 5.4). This results in the conclusion that a modification of the observation model based on hierarchy theory does not improve the quality of the observation. It provokes an extension of The Serial Landscape Model, introducing spatial complexity, temporal dynamics and semantic complexity (section 5.6).

The material collected and processed for this chapter concerns a dynamic dune area North of The Hague (Meijendel), studied as part of a larger research program dealing with a series of dynamic dune areas along the Dutch coast (see Figure 2-4). Location, material and methods are presented in section 5.3. Results, discussion and conclusions are based on material obtained for a small-scale dynamic ecosystem. For this reason, conclusions are only valid for such small-scale dynamic ecosystems (see Frame 1-1).

5.1.1 Observation model and landscape concept

In landscape ecological research based on remote sensing data and oriented towards monitoring impacts of land management and land use, the emphasis seems to be on new platforms, spatial resolution of images, data supply and classification procedures (Groom et al., 2006). However, a re-examination of classification and data concepts seems to be obligatory. This statement is supported by the above described argumentation: the landscape concept, the observation model and the management model must be in balance, and because the observation model has changed the landscape concept has to be re-examined. Particularly for small-scale dynamic ecosystems, advances have been made in observation and management decision (e.g. Droesen, 1999; Janssen, 2004; see also: Table 2-1). However, the material collected and processed has not yet been thoroughly evaluated for the balance between concept, observation and management.

During the 1990's an alternative digital image interpretation technique for false colour infrared digital orthophotos was developed (Assendorp & Van der Meulen, 1994; Droesen et al., 1995; Droesen, 1999), later incorporated in an ArcView© application (Assendorp & Schurink, 2005). Main premise in this classification technique is that the basic object (1 pixel) can be member of more than one class by using fuzzy logic technology. Although Droesen (1999) described high levels of accuracy for vegetation structure maps based on this technique, Chapter 3 shows that this is not the case and that overall accuracies are comparable to accuracies of traditional vegetation structure maps. The vegetation structure maps were produced for large areas (see Figure 2-4). These are generally characterised by a clearly defined gradient (coast – inland) that results in differences in geomorphology, soil and overall vegetation structure. Jungerius & Van der Meulen (1988) described this gradient very well and identified three compartments: a compartment with high geomorphic activity and primarily pioneer stages in vegetation development, a compartment where geomorphic activity and vegetation development are in balance and a compartment with low geomorphic activity and primarily climax stages in the vegetation development. Whereas Jungerius and Van der Meulen suggest that their model is scale independent, various nature managers hold the opinion that stratification of the images on the base of this gradient will improve the classification results. This is not surprising because nature managers require an optimal quality for their terrain inventory. Therefore, as basic material for this Chapter, separate classifications are performed for the respective spatial compartments.

The idea of stratifying an area to improve classification results emerges from the generally accepted landscape ecological concept of hierarchy. In landscape ecology, hierarchy theory has been used and applied since long (Bakker et al., 1981; Klijn & Udo de Haes, 1994; Klijn, 1995). Jongman et al. (2006) use hierarchy theory in an environmental stratification. The organisation of environmental variability is the primary cause of strata with a homogeneous distribution within, and a greater variety between the strata. This means that the strata are member of an organization at a higher hierarchic level compared to the level of organisation. Bastian et al. (2006) implicitly use hierarchy theory by characterising a "natural or biophysical unit" as an area of land with a uniform structure, but they emphasize that natural laws and the complex of abiotic and biotic components determine this uniformity. This means that strata have their internal organization with subsystems at a lower hierarchic level. Strata used in the segmentation of an image to improve the classification quality (see section 5.3.2) are discrete land units and comply to the before mentioned characteristics of the hierarchic landscape concept. By assuming that the organization level of stratification is member of a higher level of organization and comprises of the image interpretation classes at a lower level of organization, the hierarchic landscape concept is applied in the observation model.

5.2 Aim

The aim of classifying digital images of small-scale dynamic ecosystems is to describe the ecosystem as accurate as possible according to generally accepted standards, used in nature management policy (e.g. the European nature management policy: Council of the European Communities, 1992). Results should serve as basic material for the assessment of nature management measures. To accomplish this, an adjustment is made and implemented to the fuzzy classification procedure for high-resolution false colour infrared digital orthophotos of dry coastal dune ecosystems as developed by Droesen and Assendorp (Assendorp & Van der Meulen, 1994; Droesen et al. 1995; Droesen, 1999; Assendorp & Schurink 2005). This adjustment is based on hierarchy theory. Stratification of the area to be classified should result in a higher accuracy. This stratification is based on one or more landscape components that according to the hierarchic model are located at a higher level than the component classified.

Analysis and research methods are aimed at the confirmation of this assumed higher accuracy of an hierarchy based approach. Until now, this assumption is considered as valid and is rarely or not tested. In fact, for small-scale dynamic ecosystems no examples are found. If the assumption turns out to be false the use of a hierarchic landscape model and stratification in (fuzzy) digital image interpretation should be discussed. In this discussion the definition of the image interpretation classes (see Table 2-4) has to be taken into account. This definition has spatial, temporal and semantic elements and is further elaborated in the sections 5.4 (Results) and 5.5 (Discussion)

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5.3 Material and Methods

5.3.1 Study site

A set of digital image interpretations is carried out for an area in which digital orthophotos from 1990, 1995 and 2001 overlap (see Figure 4-1). This area is located along the mainland coast of The Netherlands, west of the village of Wassenaar and is approximately 3km (perpendicular to the coast line) by 2km (alongside the coast) in size. The area is characterised by fossil aeolian processes (Klijn, 1981; De Gans, 2007) as well as active aeolian processes (Jungerius & Van der Meulen, 1988) and is a dune area with high biodiversity, small-scale mosaic and temporal dynamics (Van der Meulen & Van der Maarel, 1993). The area can be characterised as a small-scale dynamic dry coastal dune system, with high relief intensity and a major gradient in environmental dynamics. This gradient is very well reflected in the vegetation structure: an open marram grass dominated vegetation in the fore dunes, a small-scale mosaic of dune grassland and shrub in the middle dunes and a well-developed dune forest in the hinterland (Doing, 1974; Van der Meulen et al., 1985).

5.3.2 Material

The digital orthophotos are produced from analogue false colour infrared air photos, scale 1:2,500 (1990 and 1995) and 1:10,000 (2001), have a resolution of 0.1m (1990 and 1995) or 0.25m (2001) and consist of three bands: green, red and near infrared. The photos were taken in June so that the biomass production is at its maximum and the near infrared reflection is optimal (De Boer, 1993).

The research area is stratified according to the dune landscape map of Meijendel (Van der Meulen et al., 1985) (see Figure 5-1). This map is produced according to the landscape-guided approach as described by Zonneveld (1995, 1989). In the legend, three hierarchic levels can be recognized, from low to high: vegetation, terrain form and main landscape. The level 'main landscape' can be seen as the resultant of the underlying levels. According to the hierarchic model of the coastal dunes of The Netherlands (Bakker et al., 1981), the attributes for this hierarchic level are substrate and groundwater. In correspondence with the stratigraphy of Jelgersma et al. (1970), the High-lying inner Dunes (Younger Dunes I), Parabolic Dunes and the Extensive dune valleys (Younger Dunes II) and the Fore Dunes (Younger Dunes III) can be interpreted as successive geological phases in the coastal dune formation of The Netherlands. Based on groundwater levels, a distinction can be made between the Parabolic Dunes and the Extensive dune valleys.

The image interpretation classes are defined by a process of expert judgement (see Table 2-4). For a further explanation, see Chapter 2. Because the image interpretation classes are described on the base of visual characteristics, in the field and on the image, they have a name referring to vegetation structure. However, as presented in Chapter 4, they have a much more complex semantic value. This means that the characteristics of the class are not only described by their formal name but are a unique combination of characteristics referring to more landscape components. For instance, the class "intermediate herb and moss cover" (fc3) is in fact what Ellenberg (1988) first described as "grey dunes" and is type 2130 according to the NATURA 2000 habitat types (Council of the European Communities, 1992) (see Chapter 4). This image interpretation class is characterised by aspects referring to geomorphology (erosion as a result of water repellency), soil (humic coatings), vegetation (annuals, biennials and grasses) and fauna (rabbit scrapes). The semantics of the image interpretation classes have been dealt with in Chapter 4 but have major implications for the discussion in this chapter.

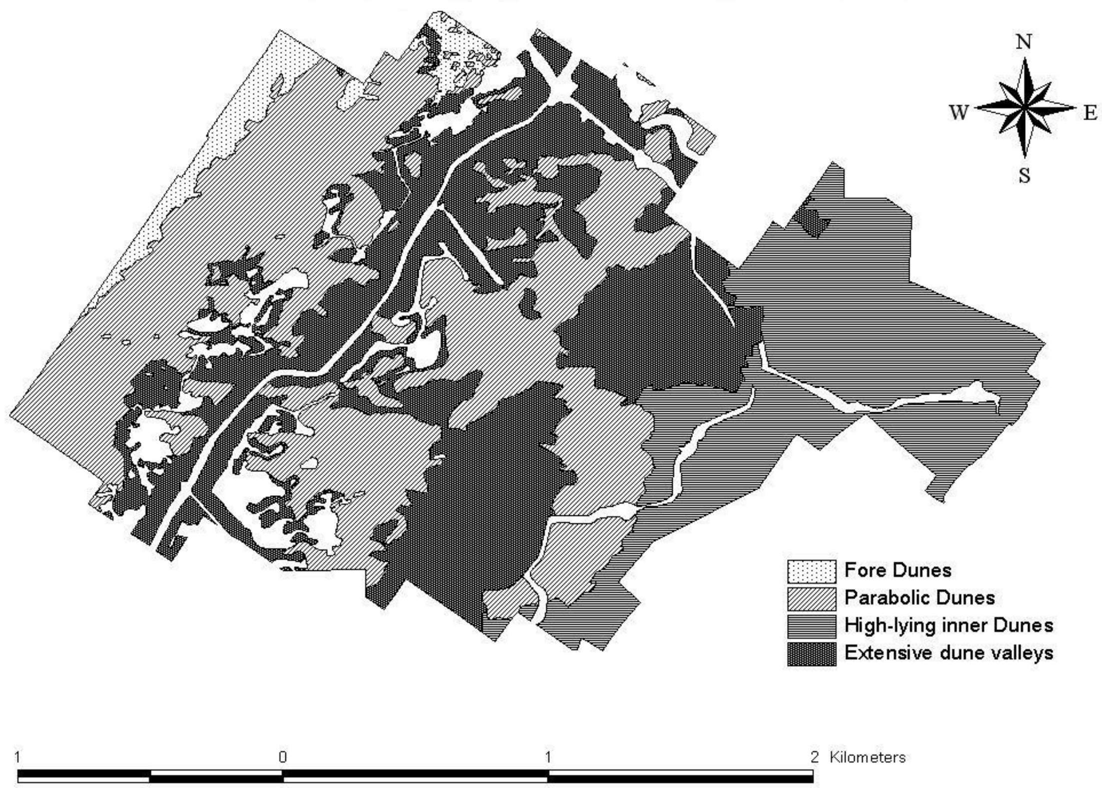


Figure 5-1 Main dune landscapes of the Meijendel research area as used in the stratification of the digital image interpretation

5.3.3 Methods

To test the assumption that hierarchic stratification improves the quality of classification results, the accuracy of non-stratified digital image classifications (the total area) is compared with the accuracy of stratified digital image classifications (subareas based on the dune landscape map). The stratification is carried out according to the hierarchic dune landscape map as presented in Figure 5-1.

Several digital image interpretations, according to the DICRANUM classification procedure (see Figure 2-6), are carried out based on three digital orthophotos dating from 1990, 1995 and 2001, respectively. For every digital orthophoto, one classification is performed for the total area and four separate classifications for the individual main dune landscapes. Classification, according to the DICRANUM classification procedure, comprises the image segmentation in 2 crisp classes and a resulting area that is classified by means of spatial interpolation of the object-space in five fuzzy classes.

The accuracies of the resulting image interpretation maps (stratified and non-stratified) were assessed by means of a newly developed method because a generally accepted method to assess the accuracy of fuzzy image interpretation results was not available. The theoretical backgrounds and statistical elaboration is presented in Chapter 3. The technique is an adaptation of the accuracy assessment with a confusion or error matrix (Foody, 2002). The accuracy assessment results in a matrix with the producer's accuracy and user's accuracy for every image interpretation class and an overall accuracy. To calculate the accuracy, 150 random points are sampled and trained by expert judgement. In the analysis, to test whether hierarchic stratification improves the quality of the classification result, the producer's accuracy and the overall accuracy are used. The training samples for the accuracy assessment of the non-stratified image classification are a compilation of the training samples used for the accuracy assessment of the stratified image classifications. This procedure and the question whether the accuracy assessment is valid is further discussed in section 5.5.3.

5.4 Results

The research area is classified according to the DICRANUM classification procedure, non-stratified for the total area and stratified for four sub areas. This procedure is carried out for images representing the dynamic ecosystem in 1990, 1995 and 2001. Figure 5-2 presents a sample of some classification results for a small sub area of approximately 200m by 200m. The crisp classes shrub (cc7) and sand (cc1) are presented in green and red, the membership value of the fuzzy class 'Intermediate herb and moss cover' (fc3) is presented in shades of grey. Visually it is nearly impossible to find differences between the stratified and non-stratified classification results. Differences between the years are clearer: blowout development recedes and shrub spreads but the boundaries become sharper. Figure 5-2 supports the statement that the coastal dune area is indeed a small-scale dynamic ecosystem with many small patches that change quickly.

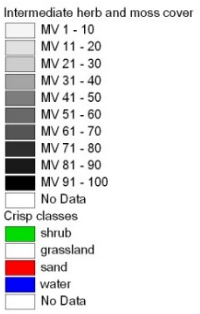
Differences in the quality of the classifications can be seen in Table 5-1, Table 5-2 and Table 5-3. Accuracies of stratified image classifications, higher than the accuracy of the non-stratified classification, are presented bold, underlined. According to the assumption formulated, there should be a notable majority of higher accuracies for stratified classifications. Out of 96 comparisons possible between stratified and non-stratified accuracies only 45 accuracies of the stratified classification are higher than the non-stratified classification. For the overall accuracies the result is even more disappointing. Out of twelve comparisons possible only five accuracies of the stratified classification are higher than the non-stratified classification.

It is striking that analysing Table 5-1, Table 5-2 and Table 5-3 sequentially there is no coherence. Differences in accuracy between stratified and non-stratified are not similar for the three successive years. This means that differences in the calculated accuracy are not the effect of differences in the quality of the orthophotos.

Changes in the configuration of the landscape leading to higher levels of convergence or divergence could also lead to difference in the calculated accuracy. A high level of convergence is positive for the quality of the classification: crisp classes show a relative high accuracy. A high level of divergence makes it difficult to uncover the spatial structure of the landscape resulting in relative low accuracies. A structural trend in accuracies through time could not be found, so difference in accuracy due to changes in the configuration of the landscape is not likely.

According to the tables presented it is more likely that differences are caused by the semantics of the classes. Crisp classes have a higher accuracy than fuzzy classes. This is not surprising because fuzzy classes are semantically more intricate and this phenomenon might also account for differences between fuzzy classes. This observation already gives an indication how the results should be interpreted: next to spatial and temporal aspects of the landscape, the semantic complexity deserves more attention.

From Table 5-1, Table 5-2 and Table 5-3 it is clear that hierarchic stratification does not improve results of the DICRANUM classification procedure. This result is further discussed and leads to the question whether digital image interpretation with classes based on a complex of different attributes fits in a hierarchic landscape model and, if not, what type of landscape model is appropriate for these classes.



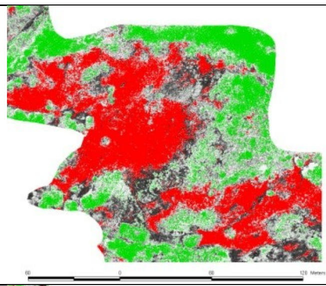
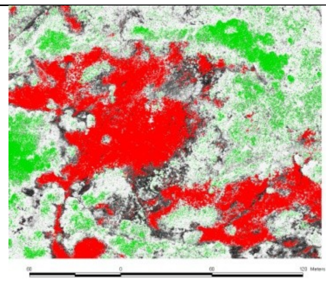
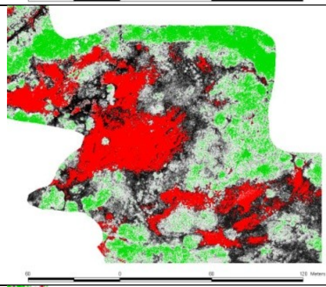
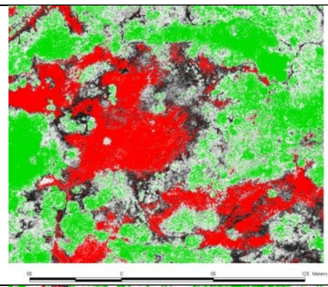
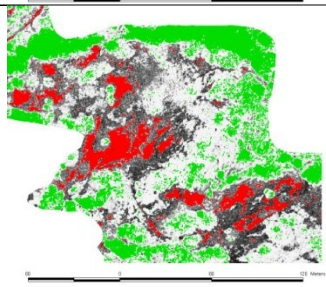
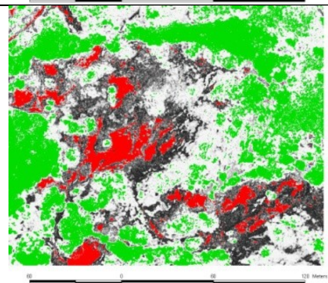
	Sample of image classification, stratified (parabolic dunes)	Sample of image classification, total research area
1990		
1995		
2001		

Figure 5-2 Classification results for a small subarea of the Meijendel research area (stratified and non-stratified for the years 1990, 1995 and 2001)

Table 5-1 Producer's accuracy of the 1990 image interpretation (stratified and non-stratified), accuracies of stratified classification higher than accuracies of non-stratified classification are *bold-underlined*

		1990				
		Non-stratified	Stratified			
		All	Fore Dunes	Parabolic Dunes	High-lying inner Dunes	Extensive Dune valleys
cc1	Bare sand	77 %	%	**_91_** %	**_99_** %	**_92_** %
fc2	Thin grass and herb cover	65 %	35 %	**_69_** %	55 %	57 %
fc3	Intermediate herb and moss cover	75 %	45 %	70 %	63 %	**_89_** %
fc4	High cover herbal vegetation with dead biomass	73 %	48 %	61 %	61 %	61 %
fc5	High cover moss vegetation	66 %	25 %	57 %	**_86_** %	**_78_** %
fc6	High cover moss and low grass vegetation	67 %	55 %	56 %	**_77_** %	57 %
cc7	Shrubs and woods	54 %	38 %	**_73_** %	**_85_** %	**_76_** %
	Overall	61 %	44 %	**_69_** %	**_78_** %	**_74_** %

Table 5-2 Producer's accuracy of the 1995 image interpretation (stratified and non-stratified), accuracies of stratified classification higher than accuracies of non-stratified classification are *bold-underlined*

		1995				
		Non-stratified	Stratified			
		All	Fore Dunes	Parabolic Dunes	High-lying inner Dunes	Extensive Dune valleys
cc1	Bare sand	97 %	***100*** %	71 %	93 %	%
fc2	Thin grass and herb cover	32 %	***38*** %	***38*** %	***36*** %	30 %
fc3	Intermediate herb and moss cover	83 %	59 %	***84*** %	64 %	77 %
fc4	High cover herbal vegetation with dead biomass	61 %	***73*** %	50 %	53 %	***63*** %
fc5	High cover moss vegetation	59 %	42 %	43 %	***68*** %	***89*** %
fc6	High cover moss and low grass vegetation	70 %	***79*** %	***79*** %	***85*** %	51 %
cc7	Shrubs and woods	94 %	40 %	81 %	***95*** %	93 %
	Overall	84 %	59 %	73 %	78 %	***85*** %

Table 5-3 Producer's accuracy of the 2001 image interpretation (stratified and non-stratified), accuracies of stratified classification higher than accuracies of non-stratified classification are *bold-underlined*

		2001				
		Non-stratified	Stratified			
		All	Fore Dunes	Parabolic Dunes	High-lying inner Dunes	Extensive Dune valleys
cc1	Bare sand	72 %	***97*** %	63 %	34 %	***100*** %
fc2	Thin grass and herb cover	27 %	***35*** %	***34*** %	***39*** %	***50*** %
fc3	Intermediate herb and moss cover	58 %	***73*** %	55 %	67 %	***67*** %
fc4	High cover herbal vegetation with dead biomass	65 %	56 %	56 %	52 %	56 %
fc5	High cover moss vegetation	39 %	***69*** %	***70*** %	***44*** %	***43*** %
fc6	High cover moss and low grass vegetation	67 %	65 %	52 %	49 %	***70*** %
cc7	Shrubs and woods	89 %	59 %	78 %	***91*** %	86 %
	Overall	76 %	69 %	65 %	69 %	***81*** %

5.5 Discussion

According to Groom et al. (2006), remote sensing data is free of human abstraction processes, because it only represents the reflectance of the Earth surface. However, to make this attribute operational in research and management of the landscape, at least one step of interpretation or classification has to be made. The interpretation or classification is based on an abstract model: the landscape concept. In Chapter 1, The Serial Landscape Model is described and used for the development of the observation model or classification procedure. To improve the observation model it was thought that an adjustment according to the hierarchic landscape concept had to be made. The results presented above very strongly indicate that this is not the case.

However, before it can be concluded that a hierarchic landscape model is not valid as a model for fuzzy digital image interpretation of small-scale dynamic ecosystems, the validity of the classification, stratification and accuracy assessment have to be discussed.

5.5.1 Validity of the classification

The overall classification accuracies range from 61% up to 84%. Comparison with other accuracies of high-resolution vegetation structure maps resulting from digital image classification is hard because few examples are found in literature (Acosta et al., 2005; Bock et al. 2005). Bock et al. (2005) find similar accuracies as presented in this paper. However their results concern spatially less complex landscapes. The Eider-Treene-Sorge lowland is cultivated and is a much more stable landscape. The Wye Downs National Nature Reserve has a fixed spatial structure with a very long history of constant management (hill grazing). Although Acosta et al. (2005) only uses manual interpretation of panchromatic aerial ortho-photographs, the accuracies are similar to the accuracies found in this analysis. For monitoring products, applied in management assessment for the implementation of NATURA 2000 policy, no accuracy requirements have been defined. In parallel to requirements used for other thematic landscape maps (geology, soil, vegetation), it is therefore assumed that an accuracy of 60% - 70% is acceptable.

5.5.2 Validity of the stratification

The land units, presented in the dune landscape map used for stratification, are based on a visual interpretation of false color infrared air photos and are therefore subjective. However, because the main landscapes are mainly fossil landforms, the land units are spatially, temporally and semantically stable within the time lag of the material used in the analysis (1990 – 2001). Looking at the resolution of the orthophotos (0.10m – 0.25m) in relation to the scale of the dune landscape map (1:5,000), there can be some inaccuracy in the boundary zone of the strata. This inaccuracy is caused by ambiguity whether a spatial unit on the orthophoto (a pixel) is member of the stratum or not. Assuming a zone of 25m (10 – 25 pixels on the digital orthophoto and 0.5cm on the dune landscape map) of boundary inaccuracy and observing that the pattern of boundaries is rather complex (see Figure 5-1); inaccuracy due to this boundary effect of the stratification can be of some importance. However, this type of inaccuracy would render a consequently higher inaccuracy in the stratified classification. The data presented in Table 5-1, Table 5-2 and Table 5-3 does not show an overall higher inaccuracy than expected in the stratified classification. It is therefore concluded that the rejection of the hierarchic landscape model in classifying small-scale dynamic ecosystems is not due to the process of stratification.

5.5.3 Validity of the accuracy assessment

A point of discussion in the comparison of the accuracy assessment of stratified and non-stratified classification results is the fact that accuracy assessments are based on one set of control points. The apparent random difference between the accuracy assessments (stratified and non-stratified) could be caused by a bad representation of accurate and inaccurate classification results in the control points used. Due to the relative large extent of shrubs and woods in the research area this vegetation structure type is overrepresented in the control points (see Table 5-4) and can be interpreted as well represented in comparison to the other vegetation structure classes. From the producer's accuracies of "Shrubs and woods" the same conclusion of random difference between the accuracy assessments can be drawn although the representation of control data is better. Therefore it is accepted that the accuracy assessment is valid.

Table 5-4 Representation of class "Shrubs and woods" in the control points for accuracy assessment of the classification results

	Representation of class "Shrubs and woods" in the control points for accuracy assessment of the classification results				
	Non-stratified	Stratified			
	All	Fore Dunes	Parabolic Dunes	High-lying inner Dunes	Extensive Dune valleys
1990	34 %	9 %	39 %	44 %	57 %
1995	57 %	9 %	37 %	44 %	70 %
2001	50 %	12 %	39 %	41 %	68 %

5.6 Conclusion: a new landscape concept

Now that it has been concluded that the classification, stratification and technique to assess the accuracy are valid, it can be concluded that a stratification of high-resolution false colour infrared air photos does not improve the classification results. Some conceptual conclusions can be made. Question is whether classes based on spatial, temporal and semantic continuity fit in the traditional hierarchic ecosystem concepts.

If the landscape was only a space-time construct (Haase, 1991) with constant or homogeneous classes, the organization of the thematic information should only be dictated by aspects of space and time. The dominant aspect of space and time, influencing thematic information, is scale. If scale was the dominant aspect in the organization of thematic information there should be a hierarchic dependency and classification results should improve by stratifying at the right level of resolution. This is not the case so the organization of the thematic information is influenced by other aspects.

According to the results the image interpretation classes cannot be assigned to a well-defined spatial scale level or resolution. This can be seen as a support of the idea that the classes do not fit in a hierarchic, topologic classification framework as described by Klijn & Udo de Haes (1994). It is more likely that the nature of the image interpretation classes is determined by the complexity of the topologic relations. Klijn & Udo de Haes (1994) define a set of topologic and chorologic relations (e.g. physical processes and movement of animals) but it is likely that relations at a higher level of abstraction and controlled by laws of systems theory (feedback mechanisms) (Wu & Hobbs, 2002) are responsible for the characteristics of the image interpretation classes.

In numerous landscape ecological textbooks and papers the emphasis is on the landscape as an entity based on temporal dynamics and spatial complexity (Forman & Godron, 1986). However, the characteristics of the thematic information have equal importance. The temporal dynamics and spatial complexity can only be perceived when there are thematic characteristics: differences in thematic characteristics determine the temporal and spatial dynamics. Therefore, it is concluded that the landscape, as perceived by discrete (crisp) and continuous (fuzzy) image interpretation classes, is a spatial-temporal-semantic construct. In Chapter 4 it is explained and concluded that the image interpretation classes have a complex thematic meaning. In other words, they are semantically complex. This phenomenon has before been explained as the "correlative complex": one attribute or observation is the indication of a set of characteristics (Zonneveld, 2005).

Semantic complexity refers to the topologic relations or interaction of factors. A system, described with one image interpretation class and with few, rather simple interactions between the factors has low semantic complexity. A system, described with one image interpretation class, but with many, complex interactions has high semantic complexity. For dry coastal dunes, two examples can be given. An active blowout is semantically not complex: geometry and sand transport are the basic factors that interact. When vegetation and soil formation become interacting factors it becomes a stabilising blowout. A forest is semantic complex: species composition, canopy stratification, soil, microclimate, nutrient cycling, etc. are all interacting factors.

From the results presented it is clear that the landscape studied and the image interpretation classes defined can be characterised by:

1. The complexity of the spatial pattern: spatial complexity.
2. The complexity of the thematic characteristics: semantic complexity
3. The rate and intensity of changes: temporal dynamics

5.6.1 Spatial complexity of the image interpretation classes

The choice whether a class is crisp or fuzzy is the consequence of its spatial characteristics and the elements that configure the class. Bare sand (cc1) is mostly present in a dynamic coastal dune ecosystem as a well-defined homogeneous form (a blowout) and therefore spatially discrete. Dune grassland (fc2-fc6) is an amalgamation of plant species, ectorganic material and small patches of humic sand in varying combinations at the sub-pixel level and therefore spatially continuous. Shrubs and woods (cc7) are an intricate amalgamation of plant species at the super pixel level and therefore defined as discrete. These spatial characteristics and the resulting spatial complexity follow from the visual image and field characteristics. Spatial dynamics is a time-related aspect and refers to the change in spatial pattern.

5.6.2 Semantic complexity of the image interpretation classes

The semantic complexity refers to the topologic relations within the class. Topologic relations in a blowout (cc1) are rather simple; it is the interaction between substrate, relief and climatic parameters (Jungerius et al., 1981; Jungerius & Van der Meulen, 1988). In a forest (cc7) topologic relations are more complex with interactions between numerous components and with intricate feedback mechanisms (Waring & Running, 1998). Undisturbed dune grassland types show increasing semantic complexity proportional to the level of primary succession. Pioneer stages (fc2) are semantic less complex than stable dune grassland (fc6). Herb and moss cover with grey sand (fc3) has an intermediate position in semantic complexity. Semantic dynamics is a time-related aspect and refers to the change in thematic characteristics.

5.6.3 Temporal dynamics of the image interpretation classes

Temporal dynamics are in fact a major reason for the digital image interpretation. Next from the fact that the terrain manager wants to know what the actual state of his terrain is (Redford et al., 2003), he wants to know whether it changes and how it changes (Van der Meulen & Jungerius, 1989; Vos et al., 2000). Pioneer stages of the vegetation succession (fc2) are characterised by high levels of instability and climax stages (fc6, cc7) are highly stable.

5.6.4 Spatial, semantic and temporal dynamics, a new landscape concept

In small-scale dynamic ecosystems there seems to be a balance between spatial complexity, semantic complexity and temporal dynamics. Every natural state of the landscape has a unique and balanced combination of spatial complexity, temporal dynamics and semantic complexity. A state that, according to nature management policy is undesirable, like grass encroachment (Veer & Kooijman, 1997) and shrub encroachment (Isermann et al., 2007) develops when this balance is disrupted. This observation is further dealt with in this section.

Image interpretation classes of small-scale dynamic ecosystems are non-hierarchic so a new landscape model or concept has to be postulated.

> *A landscape consists of elements that can be defined by a unique combination of temporal dynamics, spatial complexity and semantic complexity. The elements change through time (process description), have a geographical context (map, survey), have attributes (class description) and are projected in a 3-dimensional space constructed by the degree of temporal dynamics, spatial complexity and semantic complexity.*

In this definition the meaning of ‘dynamics’ is: force that produces change; the meaning of ‘complexity’ is: force that produces pattern and effects. Dynamics refers to time related aspects and complexity to spatial and semantic aspects. It must be realised that the term ‘element’ is not limited to the spatial dimension of landscape. It is an entity that is described by its spatial, temporal and semantic characteristics and can be placed in the ‘landscape dynamics space’. Furthermore, the term ‘element’ suggests a discrete unit in space, time or attribute but this is not the case. In correspondence with The Serial Landscape Model, the element has a continuous character in its temporal dynamics, spatial complexity and semantic complexity. The element is transitional between convergence and divergence, and is in agreement with the fuzzy classification model.

When classifying an image into segments, “real landscape objects” (Groom et al., 2006) or crisp objects, it is assumed that the landscape consists of elements without semantic complexity. However, crisp objects have to be defined in the case of maximum semantic complexity because a maximal mutual influencing of landscape forming factors infers such complex spatial and temporal patterns that classification is nearly impossible. This is the case for the image interpretation class “shrubs and woods” (cc7).

Figure 5-3 is the elaboration of the model for dry coastal dunes as described with the image interpretation classes presented in Table 2-4. The two crisp classes form the endpoints of a diagonal through the 3-dimensional space constructed by the degree of temporal dynamics, spatial complexity and semantic complexity. Bare sand (cc1) is characterised by minimal spatial and semantic complexity, complexity of form and attributes describing the element of bare sand is low. On the other hand, temporal dynamics are high because bare sand or blowouts change rather quickly. This is very well illustrated in Figure 4-10 and Figure 5-2: it can be seen that within a time span of eleven years the area bare sand declines dramatically. Natural forest and shrubs are located on the opposing end of the diagonal and characterised by a maximum complexity in form and interrelating components. However, the element shrubs and woods (cc7) is very stable in time. The natural succession series of pioneer vegetation (fc2) through grey dunes (fc3) to dune meadow (fc6) is characterised by an increasing stability, spatial complexity and semantic complexity and therefore placed on the diagonal.

5.6.5 Implications of the concept for terrain management

It is striking to realize that image interpretation classes deviating from the diagonal are landscape elements that are considered as undesirable by the terrain manager. The element, which results from the process of grass encroachment (fc4), is temporal very stable and complex in topologic relations, like shrubs and woods, but has a very low spatial complexity (Kooijman et al., 1998; Kooijman &

Besse, 2002). It is not surprising that the terrain manager uses grazing by large mammals as an intervention (Kooijman & De Haan, 1995; Kooijman & Van der Meulen, 1996). This increases the spatial complexity and brings it back to the diagonal. Bringing back temporal dynamics by the initiation or rejuvenation of blowouts (Van Bohemen, 2004) is also an option but this brings the system back to the starting point of the diagonal and seems to be not desirable when stable dune grassland is the management target. This is further dealt with in Chapter 7. Very stable moss dominated vegetation (fc5), an entity with practically no dynamics and complexity (spatial, semantic and temporal), can be brought back to the diagonal by rejuvenation of blowouts (Van Boxel et al., 1997) and thus maximise the temporal dynamics.

Digital image interpretation, identifying classes that cannot be placed in a hierarchic landscape model, should definitely not be seen as a poor method. On the contrary, defining the image interpretation classes as elements in a 3-dimensional landscape dynamics space, the basic factors driving landscape dynamics and landscape complexity are much better understood. The model can be of help for the terrain manager in identifying management interventions. Being developed for and applied to dry coastal dune ecosystem, future research has to confirm its more general applicability to other small-scale dynamic ecosystems with high levels of environmental dynamics.

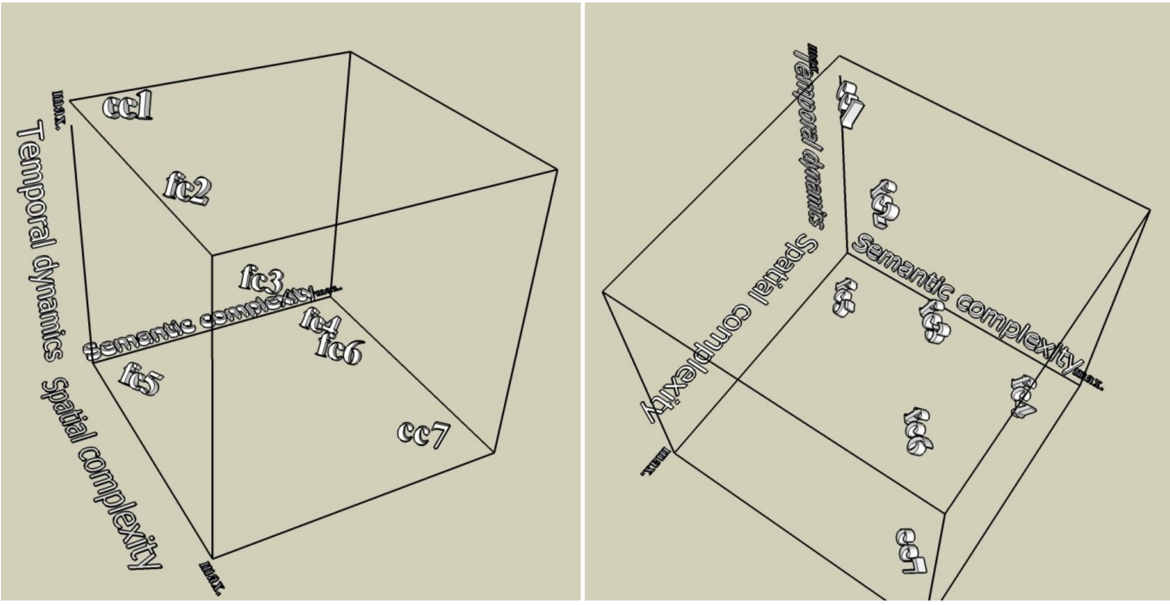


Figure 5-3 The image interpretation classes, organised according to their temporal dynamics, spatial complexity and semantic complexity: a new landscape model

Photo 4 Impression of the Bierlap case study area

6
LANDSCAPE DEVELOPMENT IN SMALL-SCALE DYNAMIC ECOSYSTEMS; THEORY AND METHODS TO EXAMINE TRANSITIONS AS OBSERVED WITH FUZZY DIGITAL VEGETATION MAPS IN A COASTAL DUNE AREA.

6.1 Introduction

Remote sensing images are widely applied in temporal research of ecosystems (Van Dorp et al., 1985; Goldsmith, 1991; Janssen, 2001; De Lange et al., 2004; Hill et al., 2005; Chuvieco, 2008) (see also Table 2-1). Three topics are crucial in the technical elaboration of such temporal analysis.

1. The method of multi-temporal analysis.
2. Time lag and scale of the material.
3. Relation between the temporal analysis and the ecological concept.

Before presenting the aim of this chapter in detail (section 6.2) these three topics are further elaborated in the following sections.

6.1.1 Methods of multi-temporal analysis

Vegetation maps, representing the state of the vegetation development at one moment, are often used in the identification of successional stages of the vegetation. This procedure, however, applies an implicit model of vegetation succession. Only sequential, multi-temporal analysis can result in an explicit model for vegetation succession. When the model is quantitative, it is possible to test it.

A first prerequisite for multi-temporal analysis is that class definitions and boundary characteristics at the subsequent moments of observation and classification are identical. When maps and field observations are obtained with varying methods of survey and data processing, only a qualitative interpretation of data is possible. When there is coherence between the successive observations of the landscape, a quantitative sequential analysis is possible. When remote sensing images are classified for the study of temporal changes, the factor time can be incorporated at different levels of integration.

- Low: Separate images are classified, independent of the classification result per image. The classified images are combined afterwards, resulting in transition diagrams.
- Medium: Separate images are classified. However, some information of the former classification results is incorporated in the classification procedure. Afterwards, the classified images are combined, resulting in transition diagrams.
- High: Sequential images are used for a multi-temporal classification. This procedure results in one classification result that represents the change in state of the landscape. Classification units are defined on the basis of their temporal dynamics.

Examples of temporal research at a low level of integration are manifold (see Table 2-1). The incorporation of the temporal domain in the classification procedure at a medium level of integration has been carried out by Janssen (2001, 2004). He used the 'Previous Boundary Method' as a temporal extension of a traditional visual interpretation of air photographs. Multi-temporal classification of sequential images is a general applied method in digital image interpretation (Bruzzone & Bovolo, 2008). Mostly, a Principal Components Analysis is performed (Byrne et al., 1980; Deng et al., 2008) resulting in a multi-temporal image interpretation map. This means no transition matrix is produced where the results of multi-temporal analysis at a low and medium level of integration can result in a transition diagram (Baker, 1989). The transition diagram is in fact a commonly used statistical aid in multi-temporal analysis. Bruzzone & Serpico (1997) propose an algorithm, based on the "compound classification rule", to perform a multi-temporal classification that results in a transition matrix. However, examples of multi-temporal classification in landscape ecology resulting in a transition matrix are not known to the author.

A conceptually attractive application of multi-temporal classification is presented by Mota et al. (2007). They incorporate three knowledge modalities in the classification procedure: spectral, spatial and temporal. Transitions are not presented and the class adjudication is partly based on a former state. This method can be considered as a medium level of integration of sequential data processing. Limiting condition in the classification technique of Mota et al. (2007) is the use of crisp classes. The method is very well applicable in a crisp land use / land cover classification but does not conform to a system with continuous vegetation structure classes as defined according to the Serial Landscape Model for small-scale dynamic ecosystems.

In this study, landscape change is studied by observing the transitions that occurred between fixed moments. Therefore, a low level of temporal integration is achieved. However, nearly all methods in landscape ecology and terrain management are not based on continuous monitoring, but on observations over discrete time intervals. A monitoring program for small-scale dynamic ecosystem has to be unambiguous and simple; referring to generally accepted and understood procedures and data storage for the terrain manager. This is discussed in much more detail in section 2.2, including its implications for monitoring

6.1.2 Time lag and scale

The relation between spatial and temporal scale in (natural) ecosystems has frequently been studied (Forman, 1995; Zonneveld, 1995; Turner et al., 2001; Wiens & Moss, 2005). It is generally accepted, and already elaborated in Chapter 1, that the temporal scale and spatial scale have to be in balance. Characteristic for small-scale dynamic ecosystems is the fact that phenomena and attributes change more quickly and have a more detailed pattern than is generally expected. Therefore, material with a high spatial resolution and with a relative short temporal interval has to be used.

In practice, an inconsistency can occur with respect to this requirement. Digital satellite imagery is available with a relative short time interval but the resolution (> 1m) is not adequate for the identification of intricate spatial patterns. Digital airborne orthophotos have an adequate spatial resolution to survey the spatial pattern of a small-scale dynamic ecosystem (< 0.25m) but the interval between digital orthophoto series is generally too long. Because conclusions on the dynamic character of ecosystems or landscapes are primarily based on sequential (ortho)photo analysis (Van Dorp et al., 1985; Jungerius & Van der Meulen, 1989; Aavikso, 1995; Shanmugam & Barnsley, 2002), a well-founded statement on the optimal time lag for multi-temporal analysis of small-scale dynamic ecosystems is hard to make: the snake bites its own tail.

6.1.3 Ecological concept

The most appropriate method to model landscape changes in time is with Markov models (Aavikso, 1995, Balzter, 2000) which give the transition probability from any state to any other state. Using crisp classes, a Markov model can be constructed and tested rather easily (Van Hulst 1979). However, applying The Serial Landscape Model as a basic concept, fuzzy classes are used which is a major complicating factor. A transition matrix of landscape change is primarily constructed with features with a geographic component; these components can be raster cells or land units. However, it gives the transition of one discrete state to another in absolute or relative cover, regardless of geographic location or the surroundings of that location. The membership value or pseudo-probability, as used in fuzzy logic, is the measure that an object belongs to a certain class (Zadeh, 1965; Droesen, 1999) and is therefore no discrete feature. Following the Serial Landscape Model, fuzzy set theory is applied in the semantic domain as a tool in describing continuous states of the landscape (see Chapter 2) and should likewise be used in the construction of a transition matrix. The application of fuzzy set theory in Markov models or Markov chains is confined to fuzzy transition probabilities between discrete states (Sullivan & Woodall, 1994; Yoon & De Korvin, 2001; Figueroa Garcia et al., 2008) or in fuzzy decision processes (Bhattacharyya, 1998). Surprisingly, no example is found of the application of Markov chains or any other numerical method to describe the transition between fuzzy states of the landscape.

When applying The Serial Landscape Model in the temporal domain, the transition should be modelled in a continuous Markov chain. However, as described in section 6.1.2, the material used in studying temporal dynamics of small-scale dynamic ecosystems are sequential high-resolution digital images with a discrete time lag. Therefore a standard transition matrix might be used when the continuous states are transformed to discrete states, albeit in conflict with The Serial Landscape Model. The most important conceptual conflict concerns the fact that a set of membership values of fuzzy classes for a spatial element at a certain moment describes a specific state of the landscape at that geographic location and is not a set of independent spatial sub-elements or probabilities of the element as a whole. The conceptual conflict has to be kept as minor as possible by finding a compromise between the conceptual advantage of applying The Serial Landscape Model and applying simple and generally understood procedures.

According to Van Hulst (1979) the major question in using multi-temporal material is how much knowledge is required for predicting landscape or vegetation development. Van Hulst (1979) states that processes can only be considered when enough information is included in the state description of the system. When the change observed is Markovian, the present landscape or vegetation composition is a perfect reflection of its history.

Limiting conditions for the application of first order Markov models are the fact that the change described in the Markov chain are stationary (Orey, 1991). For transitions in vegetation cover this was translated to the following conditions (Van Dorp et al., 1985):

1. There must be a finite number of states,
2. The transition probability may not change through time,
3. Transition probabilities must be independent of the spatial position of the objects in study.

When the transition can be described according to a first order Markov model they can be used in numeric modelling.

6.2 Aim

The aim of this chapter is to describe the construction, presentation and application of transition matrices as constructed with fuzzy thematic maps.

Studying transition matrices has two clearly diverging lines of approach:

1. The statistical approach with the emphasis on describing and applying Markovian properties,
2. The semantic approach with the emphasis on the observation and explanation of the meaning of the transitions.

This chapter follows the statistical approach; in chapter 7 the semantic approach is followed. The semantic approach can only be followed after transition matrices are constructed. Therefore the statistical approach always precedes the semantic approach. Both the statistical and the semantic approach are crucial in evaluation and planning of terrain management because the terrain manager is interested in presence and (relative) extents of the transitions but the terrain manager is also interested in semantic explanation of the transitions.

The procedure for temporal analysis of high-resolution, short time-lagged sequential fuzzy classification results is presented in three steps of results. At first, the formal mathematic description is presented (section 6.3.1). Secondly, the formal description is explained with some examples (section 6.3.2). Lastly, the ecological implications of resulting diagrams and figures are given (section 6.4.1) and some preliminary results on the temporal dynamics of the research area are presented (section 6.4.2). Transition tables and diagrams are also presented and explained in section 6.4.2. The further semantic elaboration of the general line of vegetation succession and some specific types of vegetation development in dry coastal dunes are discussed in Chapter 7. The presence of Markovian properties of the analysed material are further treated in the discussion (section 6.5) and conclusion (section 6.6) of this chapter. Recommendations for further research and method development are also given.

6.3 Material and methods

The basic data sets used in the examples (section 6.3.2) and diagrams (section 6.4.2) are three sets of crisp and fuzzy vegetation structure maps of a small case study area in the Meijendel dune area (see Figure 7-1: Meijendel case study area). These maps are grid-based with a resolution of 0.01m and represent the membership value for seven vegetation structure types, two crisp and five fuzzy (see Table 2-4 and Table 4-4). The Meijendel case study area is located in a dynamic dry dune area ca. two km from the coastline. The case study area is more or less similar to the area analysed by Van Dorp et al. (1985) with the limitation that the Meijendel case study area is confined to dynamic dry coastal dune vegetation.

In contrast to Van Dorp et al. (1985), who refer to point observations, this study refers to areal units. This makes it possible to calculate actual extents of observed transitions.

6.3.1 Formal description of temporal transition as observed with fuzzy thematic maps

Examples of the calculations described in this section are given in section 6.3.2 and Table 6-1.

A fuzzy thematic map has spatial objects or elements that can be member of more than one fuzzy set. The membership of a spatial element is presented in Formula 6-1. When the spatial element is member of multiple fuzzy sets this can be expressed by a vector (see Formula 6-2). In fact, the state of the landscape at a certain moment is the union of all fuzzy sets. This is expressed in Formula 6-3. The transition of the state of the landscape is the Cartesian product of the fuzzy sets representing the state of the landscape at two moments (see Formula 6-4). The transition of a spatial element can also be expressed by vector (see Formula 6-5). However, the number of dimensions of the vector makes it nearly impossible to visualize the semantics of the change described by the vector. Moreover, the terrain manager is not primarily interested in the change of one spatial element: the emphasis lies on the overall change and the development of the characteristic and rare elements of the small-scale dynamic ecosystem. Therefore, a further quantitative analysis of the fuzzy set, representing the state of the landscape at two moments, has to be performed.

In the quantitative analysis of sequential thematic maps, two types of aims can be discerned:

1. The analysis of the actual transition process

The transition process, as observed with fuzzy thematic maps, is revealed in the transition of membership values between classes. The dependency of a membership value for a class at time t+1 on the membership value of a class at time t can be perceived in the fuzzy set $\{V_{1..c,t\rightarrow t+1}\}$. In section 6.4 this is further dealt with.

2. The analysis of change in geographical extent.

In order to analyse the change in presence of classes every extent of subsets belonging to $\{V_{1..c,t\rightarrow t+1}\}$ has to be determined. Because the spatial elements of a grid based map are uniform the count of every $p_{(x,y)}$ that is characterised by a unique transition can be the base for a numerical analysis of landscape transition. As explained in section 6.1.3, there is a conceptual conflict: the set of membership values characterising one spatial element describe the integrated, continuous state of the landscape and in fact is inseparable. A compromise is found by assuming that the membership value is the actual extent of a fuzzy class within the spatial element. Now, the extent of a transition can be calculated by multiplying the count of every $p_{(x,y)}$ with the membership value observed. However, the number of every unique transition can be very large: the product of the squared number of fuzzy classes and the squared number of membership values. Therefore the number of membership values have to be kept as low as possible by determining the count of every $p_{(x,y)}$ for predefined membership value intervals of fuzzy classes at *t* and *t+1*. Now, spatial objects can be selected and counted according to Formula 6-6.

The extent of a specific transition can thus be calculated by multiplying the number of spatial objects that belong to a fuzzy set as specified in Formula 6-6 (transition $t \longrightarrow t+1$ for two specified membership value intervals and two specified classes) with the median of one of the two membership value intervals and the basic spatial object-area. A deliberate choice has to be made whether the membership value interval of the class at t or t+1 is used, this is caused by the assumption that the membership value is the actual extent of the class within the spatial element. Therefore, two possible solutions for the extent of subsets belonging to $\{V_{1..c,t\rightarrow t+1}\}$ exist, this is presented in Formula 6-7.

With the results of Formula 6-7, the extent of every transition between fuzzy classes can be determined. However, two possible results exist: see Formula 6-8. The overall transition $A_{t,1\rightarrow 2}$ must be interpreted as the extent of a fuzzy class that changes into another class and $A_{t+1,1\rightarrow 2}$ must be interpreted as the extent of a fuzzy class that originates from another class.

The ratio of the extents of the overall transition between two fuzzy classes as determined according to the membership value interval at *t* and according to the membership value interval at *t+1* (see Formula 6-9) can be used as an indication for the fuzzy transition type.

When $a_{(t,t+1),1\rightarrow 2} > 1$ more transitions from high membership values to low membership values occur, this means that the importance of this class for the overall landscape decreases. When $a_{(t,t+1),1\rightarrow 2} < 1$ more transitions from low membership values to high membership values occur, this means that the importance of this fuzzy class for the overall landscape increases.

$$\left\{ p_{(x,y)} \in V_c \,\middle|\, 0 \leq m(p_{(x,y)}) \geq m(max) \wedge \sum_{c=1}^{n} m(p_{(x,y)}) = m(max) \right\}$$

$p_{(x,y)}$ is a spatial object
V_c is the fuzzy set of spatial elements belonging to class c
$m(p_{(x,y)})$ is the grade of membership or the membership value of the spatial object
$m(max)$ is the maximum membership value that can be assigned to a spatial object

Formula 6-1 A fuzzy set of spatial objects

$$\overrightarrow{p_{(x,y)}} = \begin{pmatrix} m(p_1) \\ \cdot \\ \cdot \\ m(p_c) \end{pmatrix}$$

Formula 6-2 A vector of a spatial object, constructed with the membership values of c classes

$$\{V_{1..c,t}\} = \{V_{1,t} \cup V_{c,t}\}$$

Formula 6-3 State of the landscape reflected in the union of all fuzzy sets at time t

$$\{V_{1..c,t \to t+1}\} = \{\{V_{1..c,t}\} \times \{V_{1..c,t+1}\}\}$$

Formula 6-4 Transition of the state of the landscape

$$\overrightarrow{p_{(x,y),t \to t+1}} = \begin{pmatrix} m(p_{1 \to 1}) \\ \cdot \\ \cdot \\ m(p_{c \to c}) \end{pmatrix}$$

Formula 6-5 Transition of spatial elements as displayed in a vector

$$Np_{t \to t+1,1(r..s) \to 2(t..u)} = \left| \left\{ \{\{p_t \in V_1\} | m_r < m(p) > m_s\} \wedge \{\{p_{t+1} \in V_2\} | m_t < m(p) > m_u\} \right\} \right|$$

Formula 6-6 Number of spatial objects of the transition between fuzzy class 1 (membership value interval r-s) and fuzzy class 2 (membership value interval t-u)

$$A_{t,1(r..s) \to 2(t..u)} = Np_{t \to t+1,1(r..s) \to 2(t..u)} \cdot \widetilde{m_{r..s}}$$
$$A_{t+1,1(r..s) \to 2(t..u)} = Np_{t \to t+1,1(r..s) \to 2(t..u)} \cdot \widetilde{m_{t..u}}$$

$\widetilde{m_{t..u}}$ is the median of membership value interval t..u

Formula 6-7 Extent of the transition of fuzzy class 1 (membership value interval r..s) to fuzzy class 2 (membership value interval t..s)

$$A_{t,1 \to 2} = \sum_{i=(0..m(max))}^{n} A_{t,1(r..s) \to 2(t..u)}$$
$$A_{t+1,1 \to 2} = \sum_{i=(0..m(max))}^{n} A_{t+1,1(r..s) \to 2(t..u)}$$

Formula 6-8 Total extent of transition of fuzzy class 1 to fuzzy class 2

$$a_{(t,t+1),1\to 2} = \frac{A_{t,1\to 2}}{A_{t+1,1\to 2}}$$

Formula 6-9 Fuzzy transition index

6.3.2 Quantifying temporal transition as observed with fuzzy thematic maps, the vegetation structure of a small-scale dynamic ecosystem in particular.

The vegetation structure, as classified according to the DICRANUM classification procedure (see Chapter 2), is characterised by a set of grid-based maps. Grid-cells are dealt with as spatial objects and represent the membership value for one fuzzy class. In the case of the data set, representing the Meijendel case study area, crisp classes can occur. However, crisp classes can be seen as a special case of fuzzy classes. Grid-cells assigned to crisp classes are complete member of the crisp class and the maximum membership value possible is assigned to the grid-cell. In the example, this value is 100.

With consistent class definition over time, one transition results in c^2 combination grids, c being the total amount of classes. In monitoring programs, it is crucial to be consistent in the class description from period to period. Only in the case when real new land cover types emerge new classes may be introduced. Dividing existing class definitions into new classes or ascribing (parts of) existing class definitions to new classes makes the results of the monitoring program inconsistent.

As shown in the preceding section, an analysis of the transition (process and change in extent) asks for a grid-cell count of membership values of all fuzzy class combinations. In the Meijendel case study data set, membership values range from 0%-100%. In order to compress data, membership values are grouped in intervals of 10. The choice of 10 is made because this decreases the amount of grid-cell counts with a factor 100 but still makes it possible to make reasonable statements about the transition process.

Steps in the procedure of analysing landscape transition with fuzzy, grid-based maps are: numerical combination of grid-cell based digital maps, membership value interval grouping, grid-cell count and the calculation of transition extents. These are relative simple (grid-based) GIS and spreadsheet procedures. The overall procedure and an elucidation with examples are presented in Table 6-1.

The procedure results in a set of tables with detailed information on the transition process within and between the fuzzy classes. Particularly tables resulting from procedure step II provide detailed information on the characteristics of the transitions. At this point of the procedure the major advantage of fuzzy classification is exploited. With fuzzy classification of grid-based images one can look (partly) inside the image pixels and therefore inside the composition of the vegetation structure. With information on the composing elements of the landscape before and after transition, the transition process itself is better revealed.

In the example of the Meijendel case study area 36 tables are produced at procedure step II: one table for every transition between fuzzy classes (5x5) and one table for every transition of a fuzzy class to crisp classes and the other way round (2x5). There is also one table representing the pure crisp transitions. These 36 basic transition tables are linked up in two overall transition tables presenting the summation of all fuzzy transitions. This is procedure step III. One table with extents as calculated from the premise of “change into” and one table with the premise of “originating from”. The transition indices (procedure step IV) can also be presented in a table.

To enhance the clarity of the results and link up with vegetation ecology, the transition tables are presented as bar charts and transition diagrams (see Figure 6-1 - Figure 6-13). The transitions between fuzzy classes observed in the basic transition tables are called continuous semantic transitions because the prevailing information is concerned with the meaning of the transition. The extent of the transition is only obtained after post-processing the data, resulting in two different solutions. Exact quantification of transitions from fuzzy class to fuzzy class is not possible; the calculated transition extents are a semi-quantitative rather than a precise quantitative indication. When using these extents in quantified management evaluation this restriction has to be made.

Table 6-1 Procedure for the calculation of transition extents with fuzzy thematic maps, elucidated with examples from the Meijendel case study area (for class description: see Table 2-4)

Basic Material			
Grid maps 1990		**Grid maps 1995**	
cc1 & cc7 (value 1 & 3)		**cc1 & cc7** (value 1 & 3)	
fc2 (value is membership value)		**fc2** (value is membership value)	
fc3 (value is membership value)		**fc3** (value is membership value)	
fc4 (value is membership value)		**fc4** (value is membership value)	
fc5 (value is membership value)		**fc5** (value is membership value)	
fc6 (value is membership value)		**fc6** (value is membership value)	
Procedure		**Example**	
I: maps are combined into a set of combination maps according to the following algorithms:			
Combination crisp - crisp	**(map_t ·10)+map_t+1**	1	The value 13 in the combination map t(cc1 & cc7)→t+1(cc1 & cc7) represents a cell with the transition "Sand" in year 1 into "Shrubs and trees" in year 2
Combination fuzzy - crisp	**(INT(map_t/10) ·10) +map_t+1**	2	The value 53 in the combination map t(fc4)→t+1(cc1 & cc7) represents a cell with the transition 50< membership value of "High grass cover with litter"<60 in year 1 into "Shrubs and trees" in year 2.
Combination crisp - fuzzy	**(map_t ·10) +(INT(map_t+1/10)**	3	The value 19 in the combination map t(cc1 & cc7)→t+1(fc2) represents a cell with the transition "Sand" in year 1 into 90 < membership value of "Thin grass/herb cover with blond sand" < 100 in year 2.
Combination fuzzy - fuzzy	**(INT(map_t/10) ·10) +(INT(map_t+1/10)**	4	The value 37 in the combination map t(fc3)→t+1(fc6) represents a cell with the transition 30 < membership value of "Intermediate herb/moss cover with grey sand" < 40 in year 1 into 70 < membership value of "High moss and low grass cover" < 80 in year 2.
II: In every map, for every unique number, a cell count is performed. Every cell count is used to estimate the area for that transition according to the following algorithm: Crisp classes: (cell count) ·cell area Fuzzy classes: (cell count) ·(median of the membership value interval/100) ·cell area When a fuzzy class is part of the transition (from or to), two results exist: one based on the membership value interval at t and one based on the membership value interval at t+1. The membership value of a crisp class is 100% by definition.		1	A cell count of 25378 for this transition is observed, this means 253,78 m^2 has changed from "Sand" into "Shrubs and trees"
		2	A cell count of 194020 is observed for this transition. This means that, based on the membership value interval at t, 1067.11 m^2 of "High grass cover with litter" has changed into "Shrubs and trees" and, based on the crisp class at t+1, 1940.20 m^2 of "Shrubs and trees" originate from "High grass cover with litter" with a range in membership value of 50 - 60
		3	A cell count of 9167 is observed for this transition. This means that, based on the crisp class at t, 91.67 m^2 of "Sand" has changed into "Thin grass/herb cover with blond sand" and, based on the membership value interval at t+1, 87.09 m^2 of "Thin grass/herb cover with blond sand" with a range in membership value of 90 - 100 originate from "Sand".
		4	A cell count of 170 is observed for this transition. This means that, based on the membership value interval at t, 0.60 m^2 of "Intermediate herb/moss cover with grey sand" with a range in membership value of 30 - 40 has changed into "High moss and low grass cover" with a range in membership value of 70 – 80. Based on the membership value interval at t+1, 1.28 m^2 of "High moss and low grass cover" with a range in membership value of 70 - 80 originate from "Intermediate herb/moss cover with grey sand" with a range in membership value of 70 - 80.
III: The total area per transition is now calculated by summing all areas per range in membership value		1	The transition from "Sand" into "Shrubs and trees" is 253.78 m^2
		2	4670.01 m^2 "High grass cover with litter" changes into "Shrubs and trees", 10108.33 m^2 of "Shrubs and trees" originate from "High grass cover with litter".
		3	10717.50 m^2 "Sand" changes into "Thin grass/herb cover with blond sand" and 4020.82 m^2 of "Thin grass/herb cover with blond sand" originates from "Sand".
		4	7689.01 m^2 of "Intermediate herb/moss cover with grey sand" changes into "High moss and low grass cover" and 6594.56 m^2 of "High moss and low grass cover" originates from "Intermediate herb/moss cover with grey sand".
IV: The fuzzy transition index is the ratio between the extent that "changes into" and the extent that "originates from"		1	The fuzzy transition index for two crisp classes is always 1
		2	The fuzzy transition index for the transition of "High grass cover with litter" into "Shrubs and trees" is 0.46: this means in general there are transitions from low membership values to high membership values.
		3	The fuzzy transition index for the transition of "Sand" into "Thin grass/herb cover with blond sand" is 2.67: this means in general there are transitions from high membership values to low membership values.
		4	The fuzzy transition index for the transition of "Intermediate herb/moss cover with grey sand" into "High moss and low grass cover" is 1.17: this means in general there are transitions from high membership values to low membership values.

6.4 Results

6.4.1 A theoretical framework for the interpretation of fuzzy semantic transitions in small-scale dynamic ecosystem

The study of vegetation succession primarily deals with the temporal domain of the landscape. In the analysis of vegetation succession as observed with sequential maps it is generally accepted that the observed transitions are discrete or crisp. According to The Serial Landscape Model this confines the temporal domain to convergence. However, in succession theory it is accepted that transitions are gradual (Clements, 1916; Gleason, 1939; Connell & Slatyer, 1977; Van Hulst, 1980). Therefore, general succession theory fits very well in the concept of the Serial Landscape Model: succession or changes in the temporal domain can be converging, continuous and diverging. When discussing the temporal domain in relation to the spatial and semantic domain within the scope of the Serial Landscape Model, two forms of continuous transitions can be recognised. On the one hand, spatial continuous transitions are, in rising level of abstraction, migration of plant species (Watt, 1947), spatial shifts of plant communities (Smith & Huston, 1989) and displacements of ecotopes (Geerling et al., 2006). On the other hand, semantic continuous transition is traditional succession, adopted as central concept and studied since the very beginning of vegetation science and landscape ecology. Several types of succession are described, including the mechanisms that cause the continuous change (Connell & Slatyer, 1977; Pickett et al., 1987; Del Moral & Bliss, 1993). According to the material presented, being changes between fuzzy classes, the focus is on semantic transitions. For small-scale dynamic ecosystems the most obvious types of semantic continuous transition are: primary succession from pioneer to climax and regression of complex vegetation structures towards more open vegetation. Abrupt semantic changes or catastrophes do also occur in small-scale dynamic ecosystems; they initiate (continuous) secondary succession. In combination, these transitions result in a carrousel-like model of vegetation change as described for individual species by Van der Maarel & Sykes (1993).

It is clear that semantic continuous transition can be analysed by the procedure described in section 6.3: the transition is characterised by the combination of the membership value at *t* and *t+1*. Theoretically, three types of semantic transitions between two fuzzy classes can occur:

1. The relation between the membership value at *t* and the membership value at *t+1* is positive,
2. The relation between the membership value at *t* and the membership value at *t+1* is negative,
3. There is no relation between the membership value at *t* and *t+1*.

Because the membership value is obtained through a statistic procedure (see Chapter 2) it can be interpreted as a (pseudo)probability (Droesen, 1999). Therefore, the three types of semantic transition can also be described as follows:

1. Proportional transition: given a high membership value of class ‘a’ at *t*, the probability of a high membership value of class ‘b’ at *t+1* is high and given a low membership value of class ‘a’ at *t*, the probability of a low membership value of class ‘b’ at *t+1* is high.
2. Inverse proportional transition: given a high membership value of class ‘a’ at *t*, the probability of a low membership value of class ‘b’ at *t+1* is high and given a low membership value of class ‘a’ at *t*, the probability of a high membership value of class ‘b’ at *t+1* is high.
3. Indifferent transition: the membership value of class ‘b’ at *t+1* is independent of the membership value of class ‘a’ at *t*.

These cases of semantic transitions have their own ecological implication. Proportional transition is a clear path of natural transition or succession that can be explained by normal vegetation succession theory and presented in a succession/replacement diagram: ‘a’ is followed by ‘b‘ etc.. Inverse proportional transition is supplementary to proportional transition: when high membership values of a certain vegetation type precede high membership values of a specified other type, the membership values of remaining preceding vegetation types must be low. In the case of indifferent transition the presence or absence of the vegetation type is caused by other factors than the system itself. This last case fits well in the non-Markovian transition as described by van Van Hulst (1979): historical interactions between classes do not play a role in the change observed.

Small-scale dynamic ecosystems are characterised by a blend of several types of transition. All types of transition occur and these three theoretical types of semantic transitions can be explained in terms of the presence or absence of feed-back mechanisms. Proportional and inverse proportional semantic transitions occur in succession series dominated by positive as well as negative feedback mechanisms. In initial vegetation succession, the vegetation types with a relative high level of organisation originate from pioneer types with a relative low level of organisation as a result of proportional transitions (positive feedback). Development towards climax stages, characterised by more negative feedback mechanisms, is also involved with proportional transitions. From this theoretical approach there has to be a turn-over point or threshold where transition between classes change from proportional to inverse proportional and from inverse proportional to proportional. Indifferent semantic transitions occur in systems or part of systems with low levels of self-organisation. The occurrence of high or low membership values is not dependent on its predecessor but is caused by external factors.

In a small-scale dynamic ecosystem, all directions in general succession and all types of transition occur in an intricate web of succession – replacement relations. With the material of the Meijendel case study area (see section 6.3) and the transition tables produced, the above described transition types can be recognised. This is presented in the following section.

6.4.2 Transition tables and diagrams of temporal transitions as observed with fuzzy thematic maps

The transition of one fuzzy class to another can be presented in a simple table representing the extents of all possible combinations of membership value-intervals between two possible fuzzy classes, calculated according to Formula 6-7 (See Table 6-2).

Because the count of pixels or objects with low membership values is always disproportional high in comparison to objects with high membership values (there are more pixels where the class does not occur in comparison to pixels where the class does occur), the extents are also disproportional high, even after multiplying with the relative low median of the membership value interval. Therefore the transition table cannot be presented in a diagram representing absolute extents. It is presented in a graph representing the relative transition of a membership value interval at time *t* towards a membership value interval at time *t+1*. In Figure 6-1 the information of this table is presented graphically, a table with the absolute extents is added so relative importance of membership value intervals can be estimated. In this graph, it can be seen that the occurrence of a high membership value of class fc3 (Intermediate herb/moss cover with grey sand) in 1995 is strongly dependent on the occurrence of a high membership value of class fc3 in 1990. This is a clear example of proportional (auto-) transition. The supplementary inverse proportional transition is observed in the transition of fuzzy class 3 towards fuzzy classes 4 (High grass cover with litter), 5 (High moss cover) and 6 (High moss and low grass cover). This can be observed in Figure 6-2, Figure 6-3 and Figure 6-4 where relative high membership values of fuzzy class 3 are preceded by relative low membership values of fuzzy classes 4, 5 and 6.

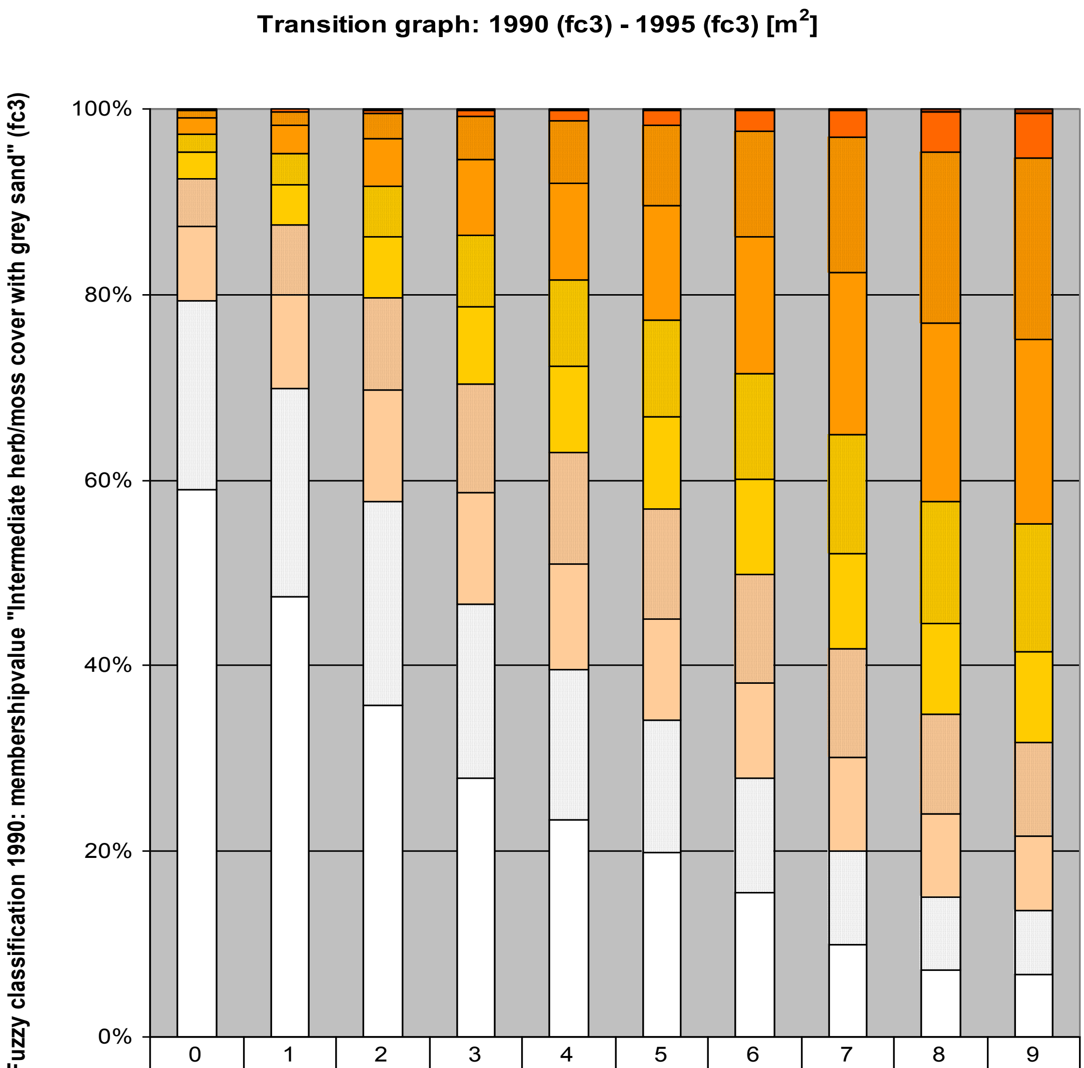
The transition of fuzzy class 3 towards fuzzy class 2 (Thin grass/herb cover with blond sand) can be interpreted as indifferent transition (Figure 6-5). There seems to be no dependence between the occurrence of fuzzy class 3 in 1990 and fuzzy class 2 in 1995. External (aeolian) processes are responsible for the development of fuzzy class 2.

The described procedure is characterised as the semantic typology of the fuzzy transitions.

The presented figures (representing fuzzy transitions from fuzzy class 3 to other classes) are typical graphs of transitions originating in a class with a high presence in the area under study: approximately 20% of the total extent of the case study area consists of fuzzy class 3 in 1990. When the extents of a class are much lower, the graphs are different. Low membership values dominate the graph. This is illustrated in Figure 6-6: the high membership values can only be observed in the upper part of the graph. However, also from this figure a conclusion on the transition type can be drawn. In the case of Figure 6-6 it is clear that this is a proportional transition: the probability that fuzzy class 2 changes into fuzzy class 3 is high. Because the overall occurrence of fuzzy class 2 is low, the occurrence of fuzzy class 3 preceded by fuzzy class 2 is also low.

Table 6-2 Table of the (auto)transition of image class fc3 in 1990 to image class fc3 in 1995

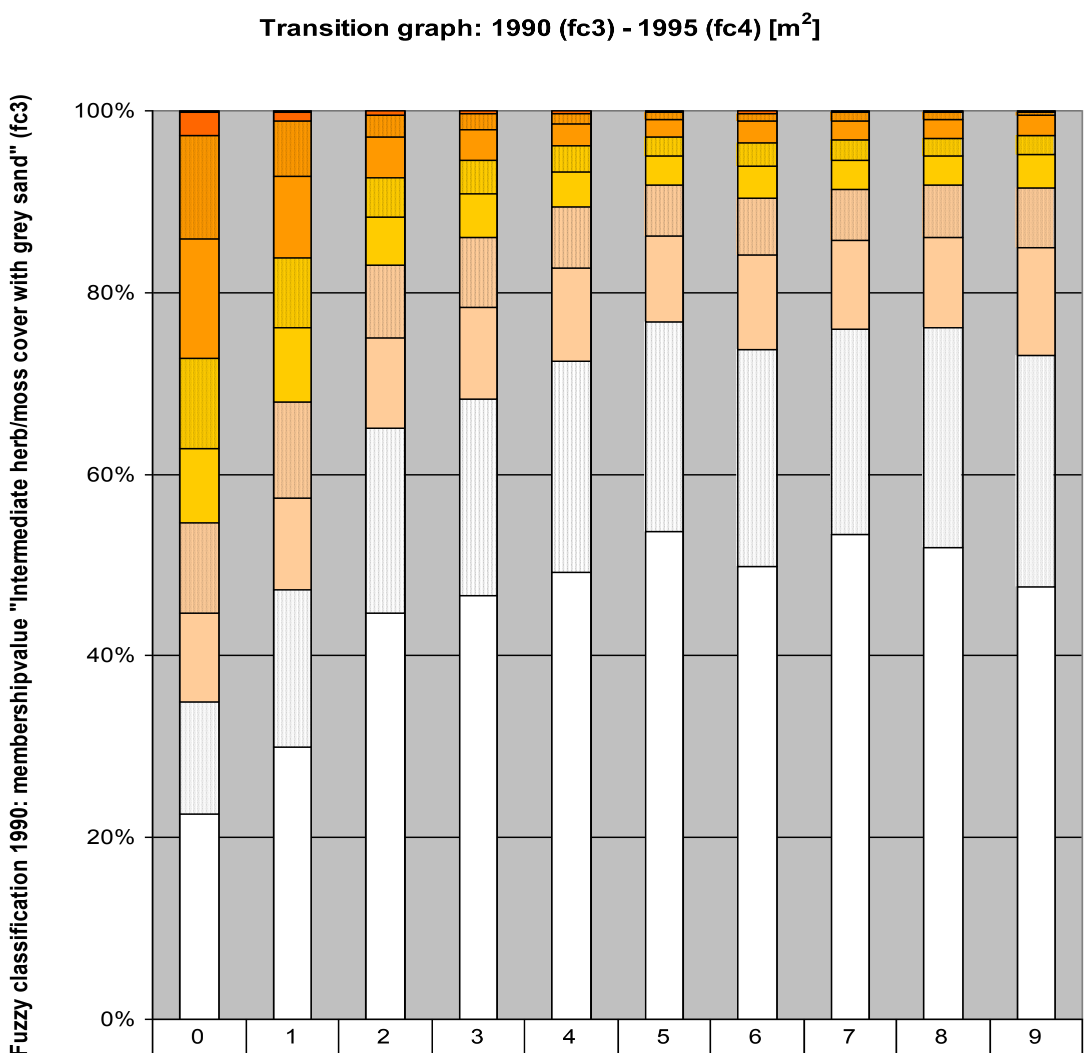
		1995 image, fc3 "Intermediate herb/moss cover with grey sand"									
	Membership value interval	**0 - 10**	**10 - 20**	**20 - 30**	**30 - 40**	**40 - 50**	**50 - 60**	**60 - 70**	**70 - 80**	**80 - 90**	**90 - 100**
1990 Image, fc 3 "Intermediate herb/moss cover with grey sand"	**0 - 10**	24712	16265	7662	4113	2656	2230	1873	1018	1375	111
	10 - 20	8560	7665	4689	2754	1840	1599	1472	1026	1510	115
	20 - 30	3343	3430	2587	1773	1290	1207	1230	1036	1725	131
	30 - 40	2172	2578	2140	1712	1361	1342	1418	1195	2046	167
	40 - 50	1208	1532	1397	1247	1063	1111	1229	1053	1870	162
	50 - 60	794	1130	1150	1134	1046	1155	1375	1305	2524	227
	60 - 70	747	1035	1119	1189	1183	1387	1765	1780	3686	328
	70 - 80	346	511	571	684	762	976	1372	1483	3541	323
	80 - 90	58	82	92	109	133	174	261	297	815	80
	90 - 100	10	18	20	14	14	16	21	22	67	8



	0	1	2	3	4	5	6	7	8	9
9	10	18	20	14	14	16	21	22	67	8
8	58	82	92	109	133	174	261	297	815	80
7	346	511	571	684	762	976	1372	1483	3541	323
6	747	1035	1119	1189	1183	1387	1765	1780	3686	328
5	794	1130	1150	1134	1046	1155	1375	1305	2524	227
4	1208	1532	1397	1247	1063	1111	1229	1053	1870	162
3	2172	2578	2140	1712	1361	1342	1418	1195	2046	167
2	3343	3430	2587	1773	1290	1207	1230	1036	1725	131
1	8560	7665	4689	2754	1840	1599	1472	1026	1510	115
0	24712	16265	7662	4113	2656	2230	1873	1018	1375	111

Fuzzy classification 1995: membershipvalue "Intermediate herb/moss cover with grey sand" (fc3)

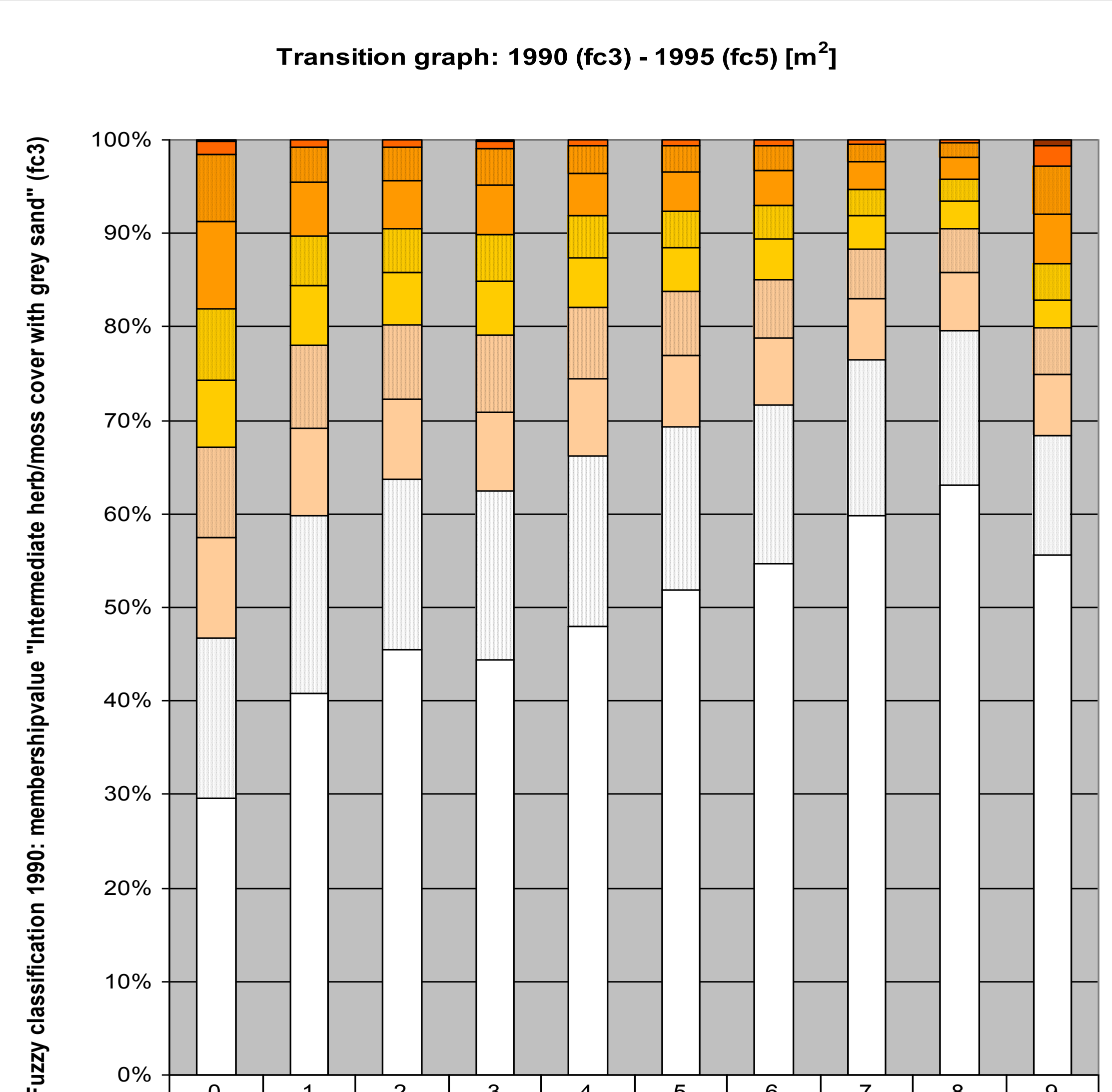
Figure 6-1 Relative (Auto)transition of image class fc3 in 1990 to image class fc3 in 1995



	0	1	2	3	4	5	6	7	8	9
9	128	43	17	9	5	3	2	1	2	0
8	1351	531	133	46	16	9	5	5	5	1
7	6255	3010	799	284	95	49	23	23	24	6
6	7268	4385	1419	595	213	116	67	57	69	29
5	5453	3793	1395	620	235	124	66	56	69	28
4	4487	4024	1704	807	326	187	98	84	106	48
3	5527	5208	2602	1289	566	342	168	150	190	88
2	5369	5031	3176	1724	857	564	281	256	336	158
1	6761	8511	6577	3651	1953	1385	643	598	811	339
0	12490	14775	14371	7904	4132	3225	1344	1404	1739	633

Fuzzy classification 1995: membershipvalue "High grass cover with litter" (fc4)

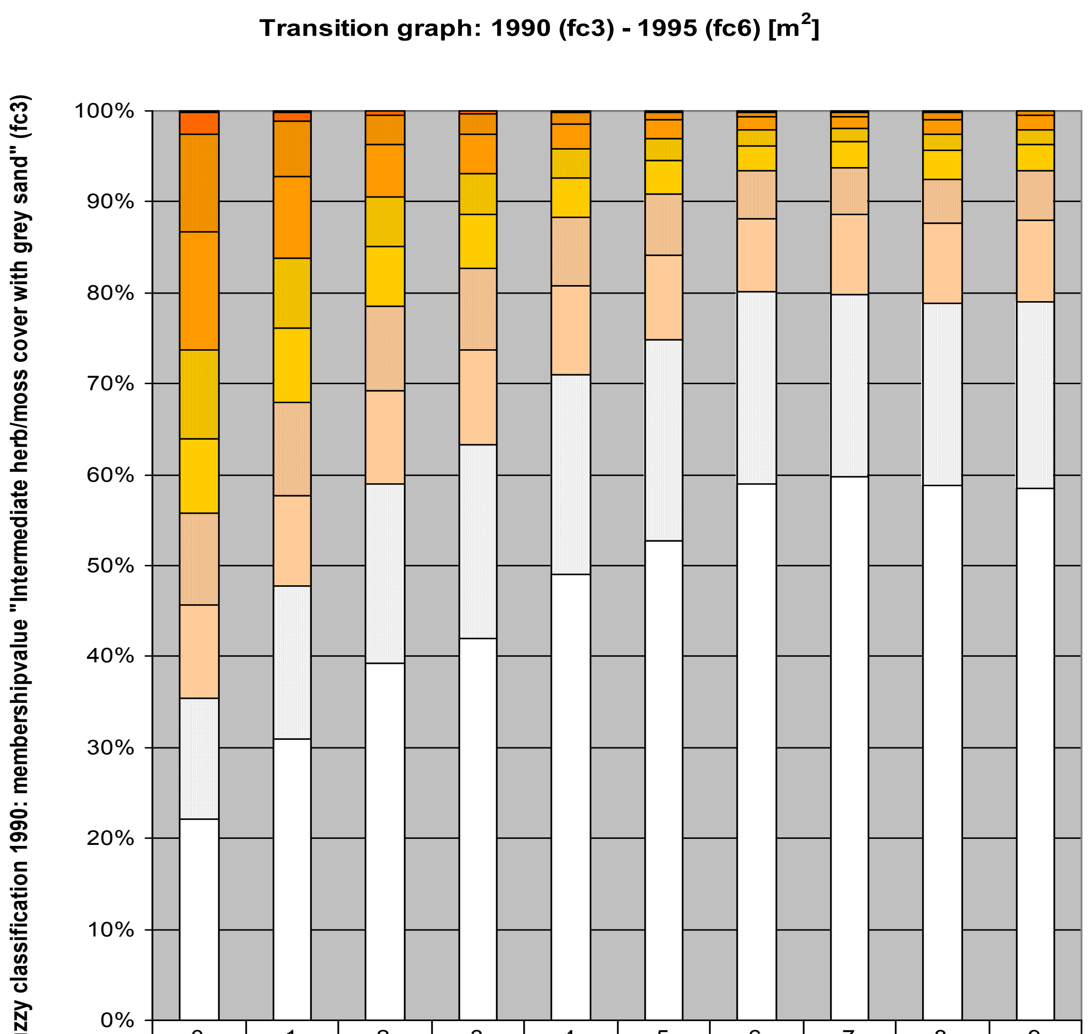
Figure 6-2 Relative transition of fuzzy class 3 in 1990 to fuzzy class 4 in 1995



	0	1	2	3	4	5	6	7	8	9
9	179	15	5	4	2	1	1	2	1	0
8	1759	174	52	40	22	11	14	16	13	0
7	8716	997	258	201	122	59	69	79	66	1
6	11464	1509	371	280	182	86	100	120	106	1
5	9277	1397	341	258	177	80	95	114	100	0
4	8814	1655	405	297	213	97	114	144	131	0
3	11756	2339	573	420	311	140	165	219	206	1
2	13040	2448	612	434	330	154	189	271	274	1
1	21094	4932	1321	934	735	357	449	679	724	2
0	36086	10696	3285	2290	1929	1063	1443	2444	2771	7

Fuzzy classification 1995: membershipvalue "High moss cover" (fc5)

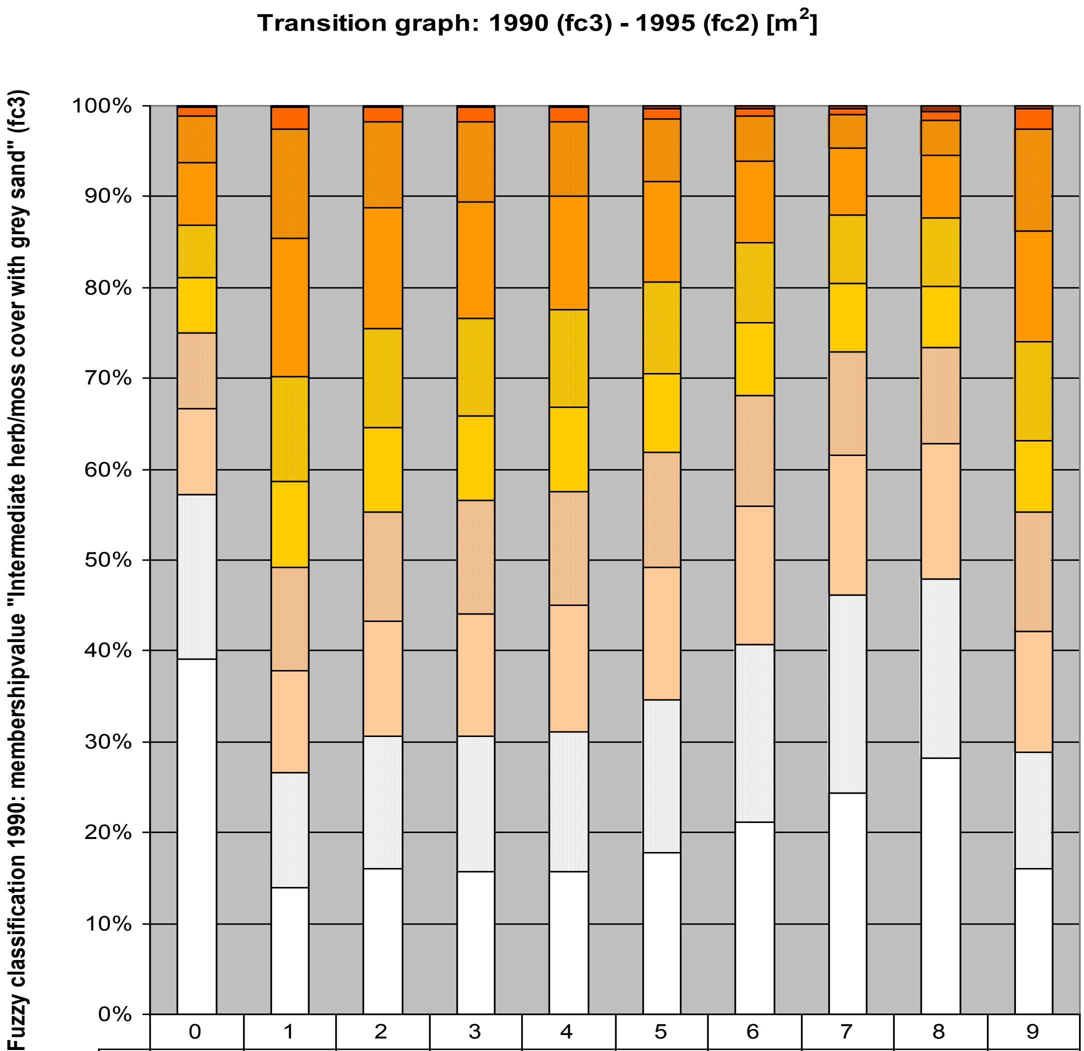
Figure 6-3 Relative transition of fuzzy class 3 in 1990 to fuzzy class 5 in 1995



	0	1	2	3	4	5	6	7	8	9
9	166	20	9	7	5	4	1	0	0	0
8	1671	225	81	61	33	26	4	0	0	0
7	7803	1298	545	443	258	196	24	1	1	0
6	9379	1913	970	875	568	452	57	2	2	1
5	7091	1655	948	905	640	529	68	2	2	1
4	5963	1741	1127	1180	921	822	107	5	4	1
3	7305	2175	1592	1809	1553	1475	205	8	6	2
2	7376	2137	1739	2112	2007	2034	318	14	11	3
1	9687	3596	3375	4268	4526	4881	832	32	25	7
0	16037	6589	6724	8440	10106	11612	2319	95	74	19

Fuzzy classification 1995: membershipvalue "High moss and low grass cover" (fc6)

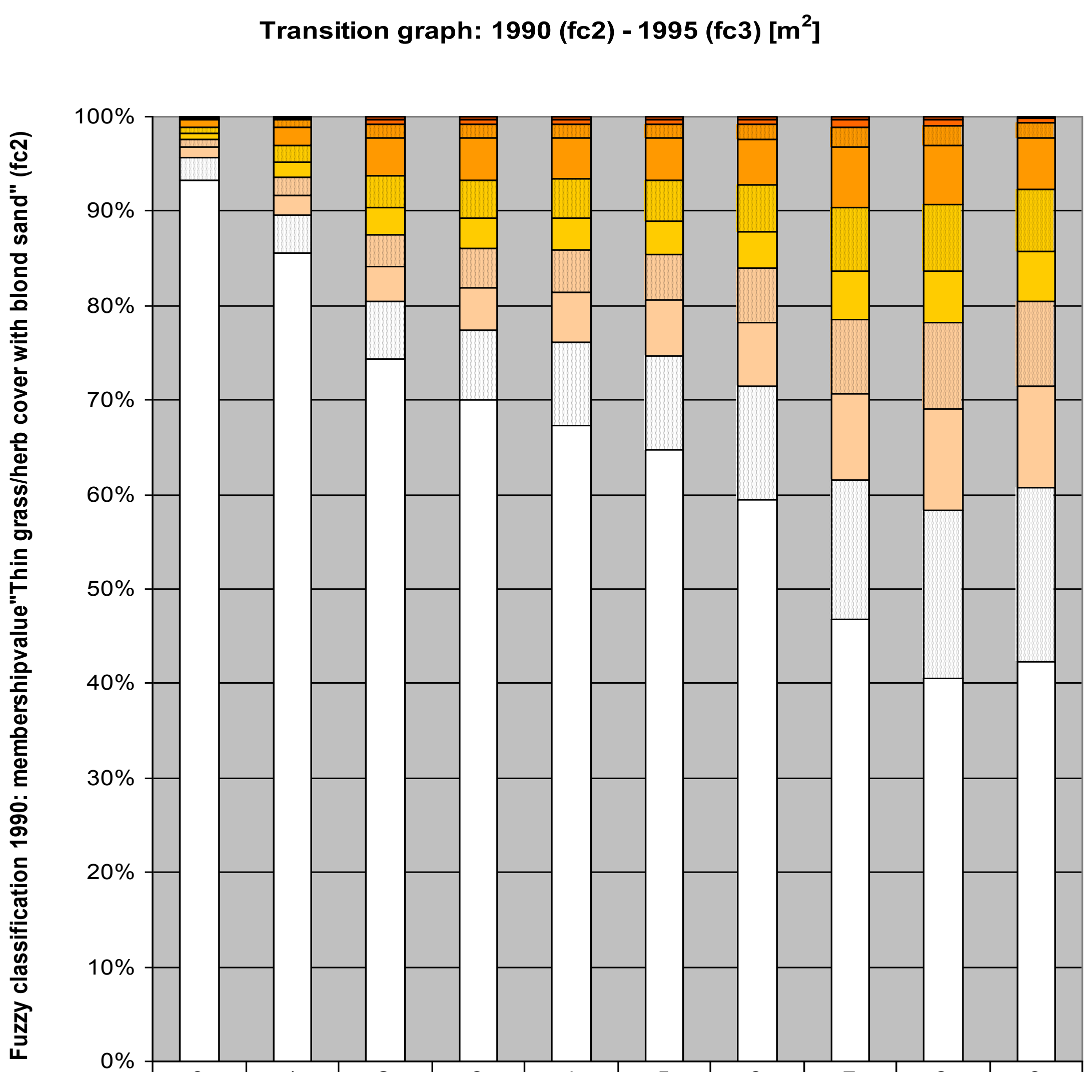
Figure 6-4 Relative transition of fuzzy class 3 in 1990 to fuzzy class 6 in 1995



	0	1	2	3	4	5	6	7	8	9
9	138	27	12	8	5	6	10	4	0	0
8	1521	315	106	55	35	31	30	9	1	1
7	7461	1619	598	310	195	169	164	47	2	4
6	9888	2050	856	457	295	273	298	93	4	4
5	8311	1555	701	382	253	247	288	96	5	4
4	8873	1268	597	330	217	216	268	95	4	3
3	12201	1544	778	441	297	311	401	145	6	4
2	13549	1517	807	476	328	361	505	195	9	4
1	26346	1695	941	530	359	416	648	277	12	4
0	56714	1879	1025	554	371	438	703	309	17	5

Fuzzy classification 1995: membershipvalue "Thin grass/herb cover with blond sand" (fc2)

Figure 6-5 Relative transition of fuzzy class 3 in 1990 to fuzzy class 2 in 1995



	0	1	2	3	4	5	6	7	8	9
9	20	54	70	47	32	31	35	40	63	4
8	31	80	107	71	51	51	58	69	116	8
7	99	245	311	222	164	163	188	217	390	26
6	311	678	843	650	499	501	587	661	1220	89
5	287	594	732	585	470	491	589	683	1345	108
4	279	538	613	483	385	391	467	520	1056	89
3	341	646	727	601	514	550	686	806	1741	148
2	429	748	797	666	595	648	819	925	2059	178
1	1026	1329	1282	1090	996	1122	1445	1516	3392	304
0	39125	29330	15946	10314	7641	7246	7143	4778	7776	700

Fuzzy classification 1995: membershipvalue "Intermediate herb/moss cover with grey sand" (fc3)

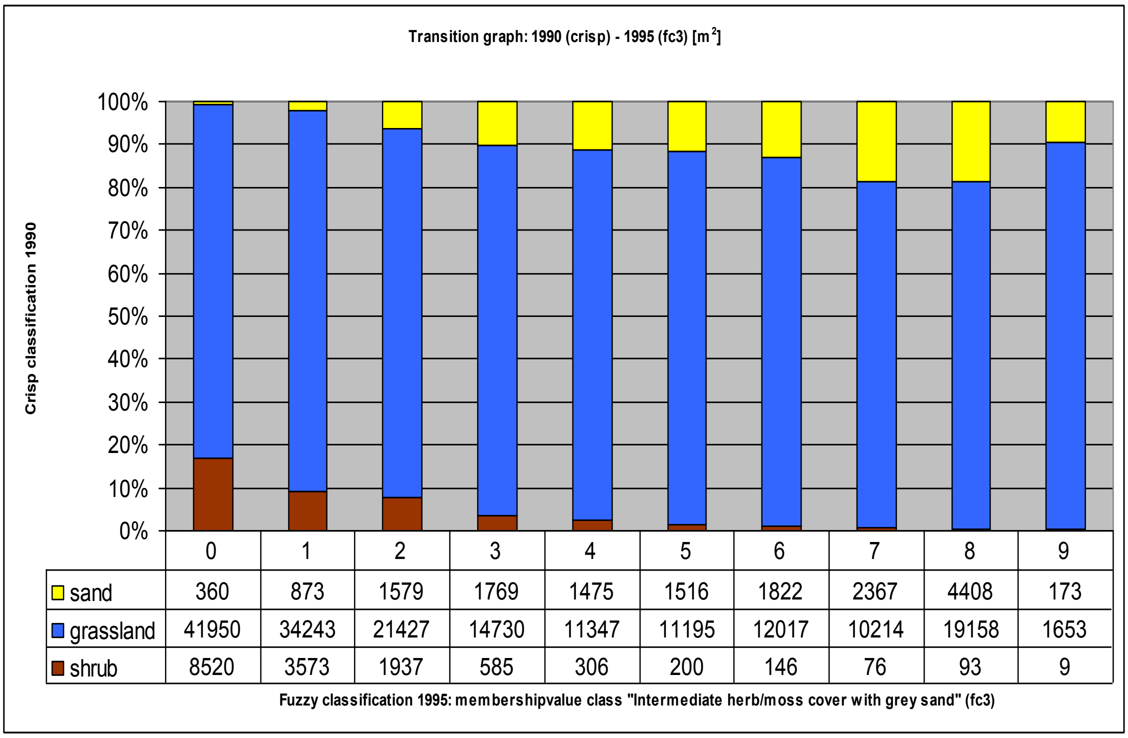
Figure 6-6 Relative transition of fuzzy class 2 in 1990 to fuzzy class 3 in 1995

Transitions of crisp classes to fuzzy classes are also presented in separate graphs per fuzzy class. Figure 6-7 gives an example of a transition graph of crisp classes in 1990 to fuzzy class 3 in 1995.

From Figure 6-7 it is clear that only elements with low membership values for fuzzy class 3 are preceded by shrub, it can be concluded that this is inverse proportional transition. Shrubs and woods rarely precede high membership values for fuzzy class 3. It can be seen that the transition of sand to fuzzy class 3 is complementary to the transition from shrub. It is proportional transition: when preceded by sand, it is more likely that fuzzy class 3 occurs as a high membership value.

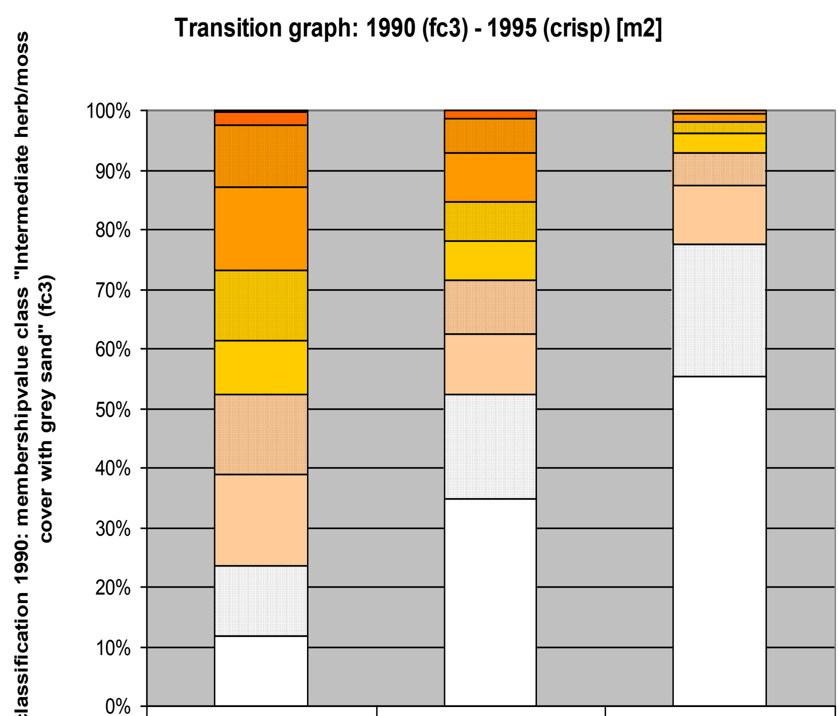
Figure 6-8 illustrates the transition of a fuzzy class to a crisp class: the transition graph of fuzzy class 3 in 1990 to crisp classes in 1995. By definition, the transition observed in Figure 6-8 is inverse proportional because the membership value of the resulting (crisp) class is always higher: 100%. In spite of this observation, it is clear from Figure 8 that the crisp class sand more likely precedes high membership values of fuzzy class 3. Therefore, despite inverse proportionality by definition, this transition is classified as proportional. Likewise, the transition of fuzzy class 3 to shrubs can be classified as inverse proportional transition: the presence of crisp class 7 (shrubs and woods) is most likely preceded by a low membership value of fuzzy class 3.

The graph of the transition between crisp classes is rather simple because pixels or spatial objects are 100% member of the class so the question whether the transition is proportional, inverse proportional or indifferent cannot be answered. The variable of fuzzyness (membership value) is excluded so transitions of more time intervals can be rendered, including the information on the origin. In fact, it is a traditional transition diagram as presented by numerous authors (Londo, 1974; Van der Maarel et al., 1985; Van Dorp et al.,1985; Roozen & Westhoff, 1985). Figure 6-9 gives an example of a crisp transition graph. Because all fuzzy classes are grouped in the crisp class 'grassland' this graph has the function of a framework wherein the fuzzy transitions, as presented in the preceding graphs, take place. All transitions of fuzzy classes to fuzzy classes are grouped in the transition grassland – grassland, crisp to fuzzy transitions can be observed in the transitions sand – grassland and shrub – grassland and fuzzy to crisp transitions in the transitions grassland – sand and grassland – shrub. Crisp classes presented in the starting point of transition analysis (1990) cannot be presented in transition groups. Therefore, they are presented as autotransitions.



	0	1	2	3	4	5	6	7	8	9
sand	360	873	1579	1769	1475	1516	1822	2367	4408	173
grassland	41950	34243	21427	14730	11347	11195	12017	10214	19158	1653
shrub	8520	3573	1937	585	306	200	146	76	93	9

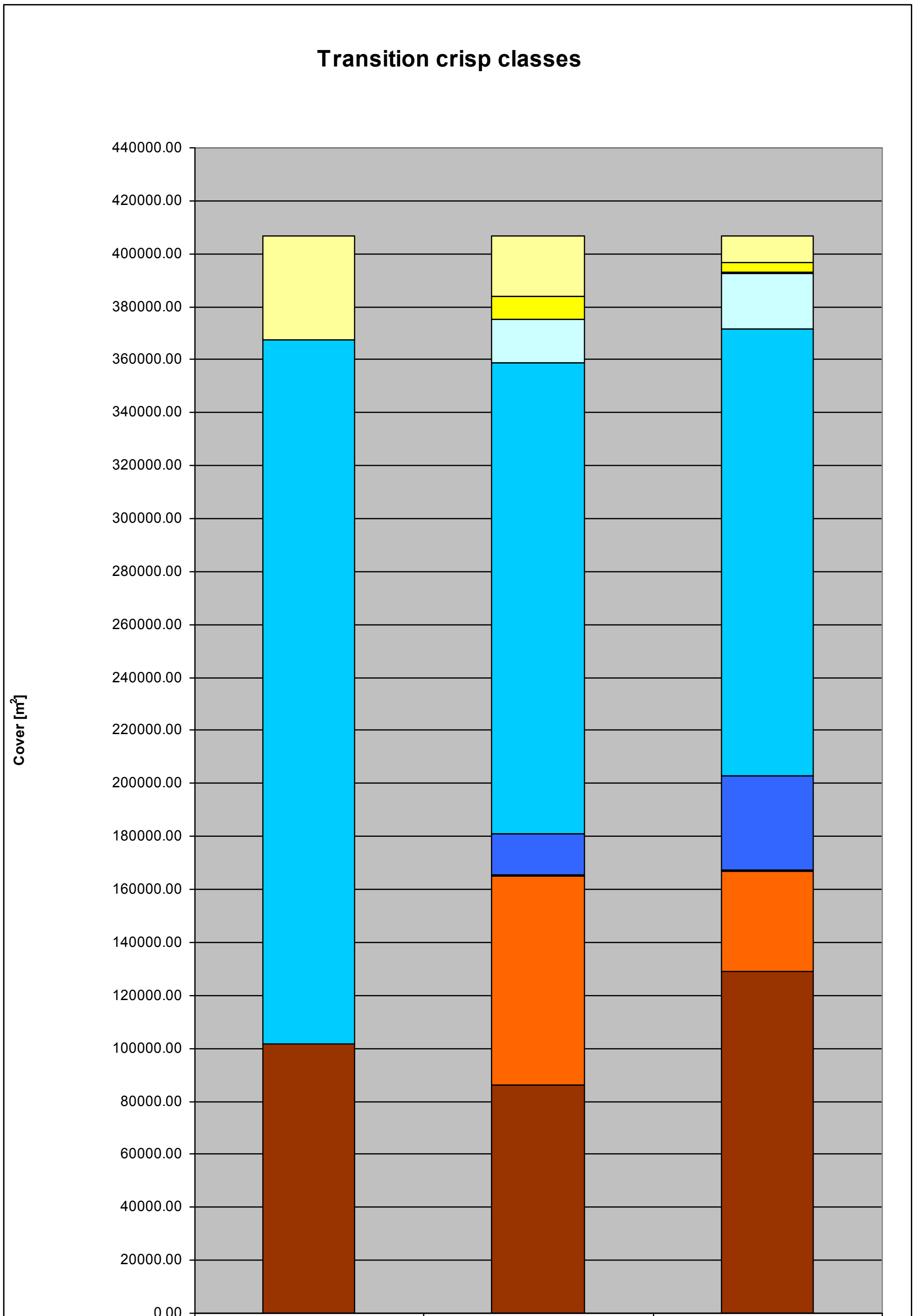
Figure 6-7 Relative transition of crisp classes sand (cc1), grassland and Shrub (cc7) in 1995 to fuzzy class 3 in 1995



	sand	grassland	shrub
9	32	211	13
8	188	2102	40
7	917	10568	342
6	1253	14218	1189
5	1045	11841	1405
4	796	11871	2564
3	1193	16130	4415
2	1358	17752	7816
1	1064	31228	17579
0	1035	62015	43732

Crisp classification 1995

Figure 6-8 Relative transition of fuzzy class 3 in 1990 to crisp classes sand, grassland and shrub in 1995



	- 1990	1990 - 1995	1995 - 2001
sand - sand	39446.80	22842.18	10357.44
grassland - sand		8871.53	3416.55
shrub - sand		90.47	583.18
sand - grassland		16325.75	21043.61
grassland - grassland	265842.17	177877.98	168614.70
shrub - grassland		15445.05	35673.20
sand - shrub		278.87	403.13
grassland - shrub		79092.66	37617.53
shrub - shrub	101554.12	86018.60	129133.75

Transition from - to

Figure 6-9 Transition graph of crisp classes

Because the fuzzy transition graphs presented so far illustrate relative transition, no conclusions can be drawn on the absolute extent of a transition. The algorithm to do so is presented in Formula 6-8. The assumption is made that the membership value is a measure for the relative extent within the object or pixel so two results exist. One extent based on a calculation with the membership value at *t* and one extent based on a calculation with the membership value at *t+1*. Because of the algorithm used, high membership values result in relative large extents and low membership values in small extents. This explains differences in calculated extents for one transition. When the general trend in the transition is from high membership values towards low membership values the calculated extent based on *t* is the largest. When the general trend in the transition is from low membership values towards high membership values the calculated extent based in *t+1* is the largest. The fuzzy transition index (Formula 6-9) is a measure for the trend in change of membership value.

There is no direct relation between the fuzzy transition index and the transition type as observed from the relative transition graphs. The fuzzy transition index gives information on the character of the fuzzy transition overall, the semantic typology of fuzzy transition gives more detailed information on the fuzzy transition process. Major difference is the fact that the fuzzy transition index is absolute and undisputable and the semantic typology is a more or less subjective interpretation of a graph.

The overall transition in a study area is presented in a set of two transition tables (Table 6-3 and Table 6-4), completed with a fuzzy transition index table (Table 6-5). Figure 6-10, Figure 6-11 and Figure 6-12 present these data in a graph. From the fuzzy transition index graph (Figure 6-12), it is clear that crisp – fuzzy transitions produce high indices and fuzzy – crisp transitions low indices. This is merely caused by the fact that a crisp value of an object or a pixel is always superior in membership value to a fuzzy value of an object or pixel.

Table 6-3 Overall transition table, extents based on t_1 membership value

Extent in m^2 based on 1990 membership value	1995_cc1	1995_fc2	1995_fc3	1995_fc4	1995_fc5	1995_fc6	1995_cc7	**Total**
1990_cc1	22842	11232	15981	3266	549	1528	279	**55678**
1990_fc2	3485	8260	17144	8313	2098	5480	1370	**46149**
1990_fc3	3541	12156	41111	25782	10515	19813	7593	**120511**
1990_fc4	777	5827	26973	32954	11072	28517	21113	**127233**
1990_fc5	81	932	14548	15263	13326	14797	10800	**69748**
1990_fc6	242	2997	24827	30528	13969	28285	19440	**120287**
1990_cc7	90	1333	6925	13347	4706	9979	86019	**122399**
Total	**31059**	**42737**	**147510**	**129453**	**56234**	**108399**	**146613**	***662005***

Table 6-4 Overall transition table, extents based on t+1 membership value

Extent in m^2 based on 1995 membership value	1995_cc1	1995_fc2	1995_fc3	1995_fc4	1995_fc5	1995_fc6	1995_cc7	
1990_cc1	22842	4177	9512	805	151	412	279	**38180**
1990_fc2	7347	6497	25318	5843	1769	4673	5025	**56473**
1990_fc3	7845	8624	48766	20076	9187	20506	30948	**145953**
1990_fc4	2441	5341	29175	27831	11137	29988	47469	**153382**
1990_fc5	253	693	13120	8740	9365	11064	20396	**63631**
1990_fc6	939	3000	27709	25704	13285	29813	49309	**149760**
1990_cc7	90	475	1712	6163	2003	3901	86019	**100364**
	41757	**28809**	**155314**	**95163**	**46897**	**100357**	**239445**	***707742***

Table 6-5 Fuzzy transition index

Fuzzy transition index: extent(1990)/extent(1995)	1995_cc1	1995_fc2	1995_fc3	1995_fc4	1995_fc5	1995_fc6	1995_cc7
1990_cc1	1,00	2,69	1,68	4,06	3,63	3,71	1,00
1990_fc2	0,47	1,27	0,68	1,42	1,19	1,17	0,27
1990_fc3	0,45	1,41	0,84	1,28	1,14	0,97	0,25
1990_fc4	0,32	1,09	0,92	1,18	0,99	0,95	0,44
1990_fc5	0,32	1,34	1,11	1,75	1,42	1,34	0,53
1990_fc6	0,26	1,00	0,90	1,19	1,05	0,95	0,39
1990_cc7	1,00	2,80	4,04	2,17	2,35	2,56	1,00

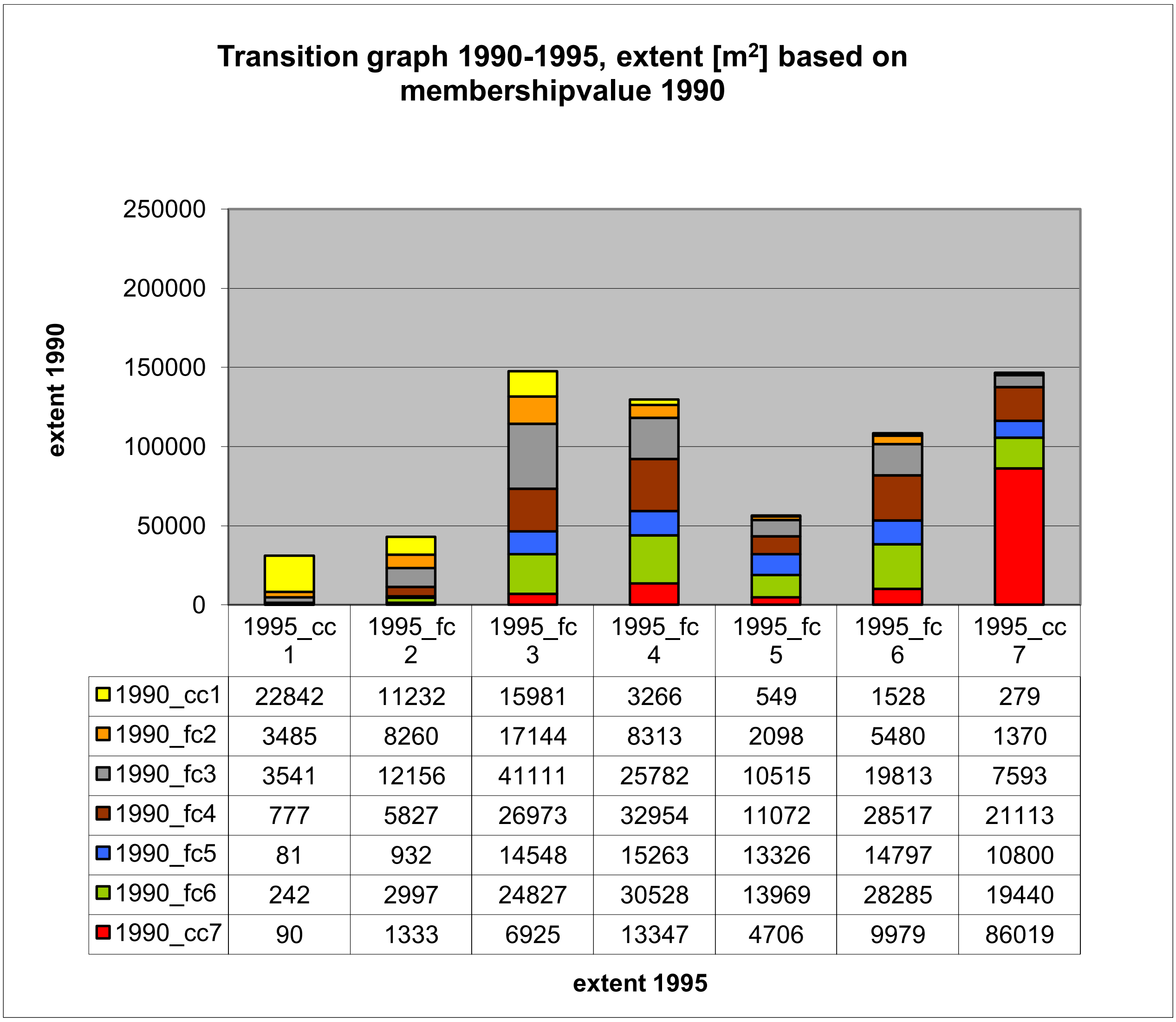
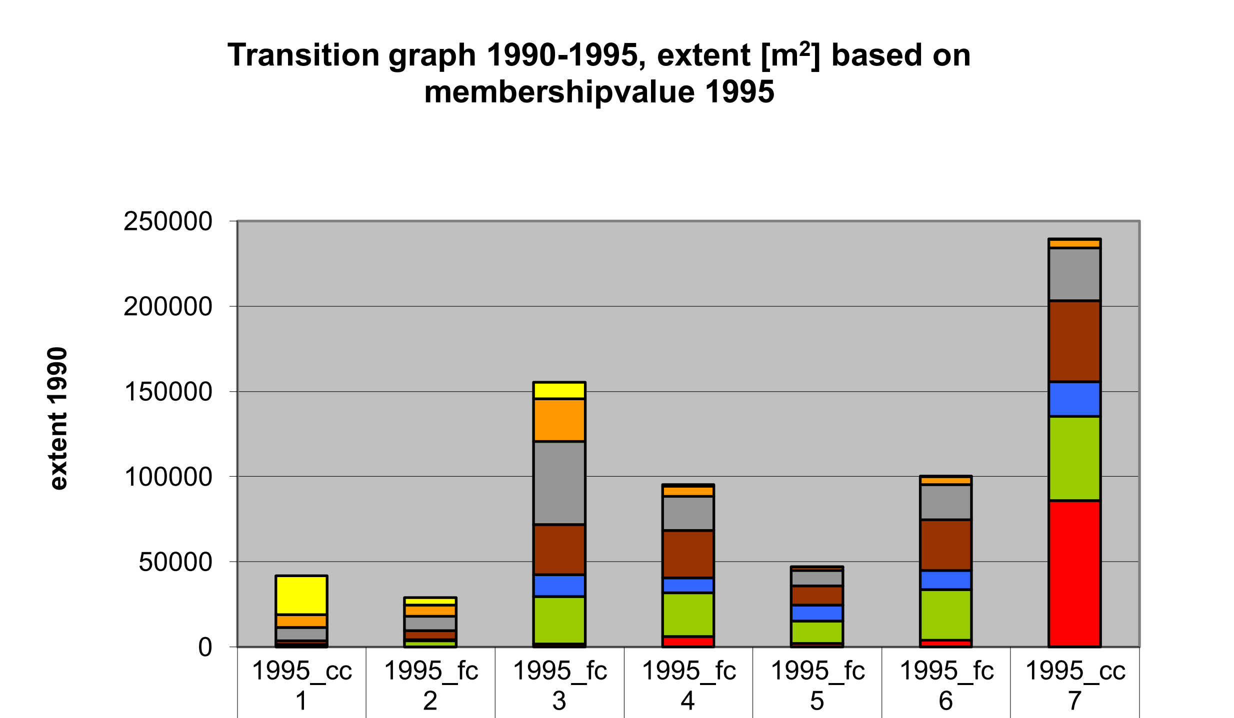


Figure 6-10 Overall transition graph, based on t_1 membership value



	1995_cc 1	1995_fc 2	1995_fc 3	1995_fc 4	1995_fc 5	1995_fc 6	1995_cc 7
1990_cc1	22842	4177	9512	805	151	412	279
1990_fc2	7347	6497	25318	5843	1769	4673	5025
1990_fc3	7845	8624	48766	20076	9187	20506	30948
1990_fc4	2441	5341	29175	27831	11137	29988	47469
1990_fc5	253	693	13120	8740	9365	11064	20396
1990_fc6	939	3000	27709	25704	13285	29813	49309
1990_cc7	90	475	1712	6163	2003	3901	86019

Figure 6-11 Overall transition graph, based on t_2 membership value

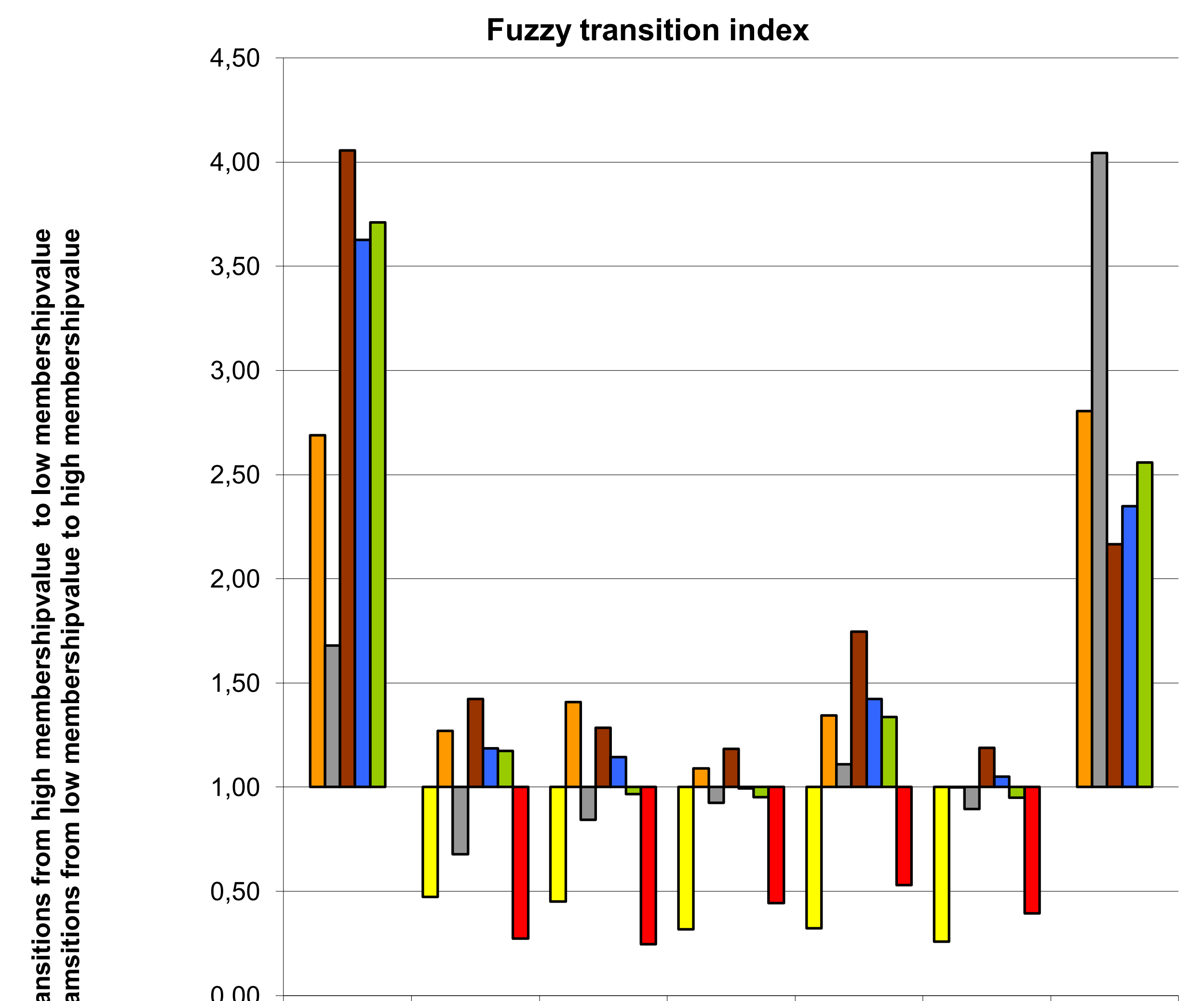
These tables and graphs give a good synopsis of the large amount of data produced in sequential fuzzy image interpretation, the analysis of change in extent of vegetation structure classes in particular. The analysis of the actual fuzzy transition process as observed with the relative transition graphs (semantic transition typology) is not incorporated in the synoptic tables and graphs. To do so, a synoptic fuzzy transition graph and a synoptic fuzzy transition table are designed. Relative extents and semantic transition typology are combined in the graph and the table.

Data available for the synoptic transition graph and synoptic transition table are:

- (relative) extent of the vegetation structure classes at *t* and *t+1*
- (relative) extent of the transition between *t* and t+1
- Indication of the transition process

The indication of the semantic transition typology (proportional, inverse proportional and indifferent) is crucial because this is the extra value added to the analysis by using fuzzy sets.

The synoptic fuzzy transition table (Table 6-6) presents transitions of more than one time-lag so changes in fuzzy transition process are revealed. In addition, the synoptic fuzzy transition table is sorted by class at *t* and sorted by class at *t+1*. The synoptic fuzzy transition diagram, as presented in Figure 6-13, is more in accordance with general accepted vegetation transition schemes. The weight of the circles and lines are an indication of the calculated extent of class occurrences and transitions. The diagram reveals that in this small-scale dynamic ecosystem, transitions from nearly every class to every class occur in an intricate web. It could even be interpreted as chaos though at first sight there seems to be a tendency towards proportional transition in the development of climax vegetation types. Development towards vegetation types deviating from the general line of succession seems to be caused by inverse proportional and indifferent transition. Synoptic fuzzy transition graphs of the Meijendel case study area are further analyzed and discussed in Chapter 7.



	1990_cc1	1990_fc2	1990_fc3	1990_fc4	1990_fc5	1990_fc6	1990_cc7
1995_cc1	1,00	0,47	0,45	0,32	0,32	0,26	1,00
1995_fc2	2,69	1,27	1,41	1,09	1,34	1,00	2,80
1995_fc3	1,68	0,68	0,84	0,92	1,11	0,90	4,04
1995_fc4	4,06	1,42	1,28	1,18	1,75	1,19	2,17
1995_fc5	3,63	1,19	1,14	0,99	1,42	1,05	2,35
1995_fc6	3,71	1,17	0,97	0,95	1,34	0,95	2,56
1995_cc7	1,00	0,27	0,25	0,44	0,53	0,39	1,00

Figure 6-12 Fuzzy transition index

Table 6-6 Synoptic fuzzy transition table of the Meijendel case study area (black: crisp transition, green: proportional transition, orange: indifferent transition, red: inverse proportional transition)

		overall			
t	t+1	90-95		95-01	
		∑(90)	∑(95)	∑(95)	∑(01)
cc1	cc1	3,5%	3,2%	1,5%	1,5%
fc2	cc1	0,5%	1,0%	0,1%	0,4%
fc3	cc1	0,5%	1,1%	0,3%	0,5%
fc4	cc1	0,1%	0,3%		0,1%
fc5	cc1				
fc6	cc1		0,1%		
cc7	cc1			0,1%	0,1%
cc1	fc2	1,7%	0,6%	2,3%	0,8%
fc2	fc2	1,2%	0,9%	0,8%	0,7%
fc3	fc2	1,8%	1,2%	2,4%	1,2%
fc4	fc2	0,9%	0,8%	0,3%	0,4%
fc5	fc2	0,1%	0,1%	0,1%	0,1%
fc6	fc2	0,5%	0,4%	0,2%	0,2%
cc7	fc2	0,2%	0,1%	0,5%	0,2%
cc1	fc3	2,4%	1,3%	2,9%	1,6%
fc2	fc3	2,6%	3,6%	1,5%	2,2%
fc3	fc3	6,2%	6,9%	6,6%	5,0%
fc4	fc3	4,1%	4,1%	1,6%	2,1%
fc5	fc3	2,2%	1,9%	0,7%	0,7%
fc6	fc3	3,8%	3,9%	1,5%	1,4%
cc7	fc3	1,0%	0,2%	1,4%	0,4%
cc1	fc4	0,5%	0,1%	0,6%	0,2%
fc2	fc4	1,3%	0,8%	0,9%	1,0%
fc3	fc4	3,9%	2,8%	4,1%	4,4%
fc4	fc4	5,0%	3,9%	3,4%	5,2%
fc5	fc4	2,3%	1,2%	1,4%	1,8%
fc6	fc4	4,6%	3,6%	4,0%	4,6%
cc7	fc4	2,0%	0,9%	4,7%	2,6%
cc1	fc5	0,1%		0,2%	0,1%
fc2	fc5	0,3%	0,2%	0,3%	0,4%
fc3	fc5	1,6%	1,3%	3,0%	2,1%
fc4	fc5	1,7%	1,6%	1,0%	1,5%
fc5	fc5	2,0%	1,3%	1,1%	1,1%
fc6	fc5	2,1%	1,9%	1,3%	1,3%
cc7	fc5	0,7%	0,3%	1,0%	0,3%
cc1	fc6	0,2%	0,1%	0,8%	0,2%
fc2	fc6	0,8%	0,7%	1,2%	1,3%
fc3	fc6	3,0%	2,9%	7,1%	6,3%
fc4	fc6	4,3%	4,2%	3,9%	5,8%
fc5	fc6	2,2%	1,6%	2,1%	2,8%
fc6	fc6	4,3%	4,2%	4,8%	5,3%
cc7	fc6	1,5%	0,6%	4,4%	1,5%
cc1	cc7			0,1%	0,1%
fc2	cc7	0,2%	0,7%	0,2%	0,4%
fc3	cc7	1,1%	4,4%	0,7%	2,3%
fc4	cc7	3,2%	6,7%	1,8%	3,9%
fc5	cc7	1,6%	2,9%	0,8%	1,9%
fc6	cc7	2,9%	7,0%	1,1%	2,9%
cc7	cc7	13,0%	12,2%	19,1%	19,2%

		overall			
t	t+1	90-95		95-01	
		∑(90)	∑(95)	∑(95)	∑(01)
cc1	cc1	3,5%	3,2%	1,5%	1,5%
cc1	fc2	1,7%	0,6%	2,3%	0,8%
cc1	fc3	2,4%	1,3%	2,9%	1,6%
cc1	fc4	0,5%	0,1%	0,6%	0,2%
cc1	fc5	0,1%		0,2%	0,1%
cc1	fc6	0,2%	0,1%	0,8%	0,2%
cc1	cc7			0,1%	0,1%
fc2	cc1	0,5%	1,0%	0,1%	0,4%
fc2	fc2	1,2%	0,9%	0,8%	0,7%
fc2	fc3	2,6%	3,6%	1,5%	2,2%
fc2	fc4	1,3%	0,8%	0,9%	1,0%
fc2	fc5	0,3%	0,2%	0,3%	0,4%
fc2	fc6	0,8%	0,7%	1,2%	1,3%
fc2	cc7	0,2%	0,7%	0,2%	0,4%
fc3	cc1	0,5%	1,1%	0,3%	0,5%
fc3	fc2	1,8%	1,2%	2,4%	1,2%
fc3	fc3	6,2%	6,9%	6,6%	5,0%
fc3	fc4	3,9%	2,8%	4,1%	4,4%
fc3	fc5	1,6%	1,3%	3,0%	2,1%
fc3	fc6	3,0%	2,9%	7,1%	6,3%
fc3	cc7	1,1%	4,4%	0,7%	2,3%
fc4	cc1	0,1%	0,3%		0,1%
fc4	fc2	0,9%	0,8%	0,3%	0,4%
fc4	fc3	4,1%	4,1%	1,6%	2,1%
fc4	fc4	5,0%	3,9%	3,4%	5,2%
fc4	fc5	1,7%	1,6%	1,0%	1,5%
fc4	fc6	4,3%	4,2%	3,9%	5,8%
fc4	cc7	3,2%	6,7%	1,8%	3,9%
fc5	cc1				
fc5	fc2	0,1%	0,1%	0,1%	0,1%
fc5	fc3	2,2%	1,9%	0,7%	0,7%
fc5	fc4	2,3%	1,2%	1,4%	1,8%
fc5	fc5	2,0%	1,3%	1,1%	1,1%
fc5	fc6	2,2%	1,6%	2,1%	2,8%
fc5	cc7	1,6%	2,9%	0,8%	1,9%
fc6	cc1		0,1%		
fc6	fc2	0,5%	0,4%	0,2%	0,2%
fc6	fc3	3,8%	3,9%	1,5%	1,4%
fc6	fc4	4,6%	3,6%	4,0%	4,6%
fc6	fc5	2,1%	1,9%	1,3%	1,3%
fc6	fc6	4,3%	4,2%	4,8%	5,3%
fc6	cc7	2,9%	7,0%	1,1%	2,9%
cc7	cc1			0,1%	0,1%
cc7	fc2	0,2%	0,1%	0,5%	0,2%
cc7	fc3	1,0%	0,2%	1,4%	0,4%
cc7	fc4	2,0%	0,9%	4,7%	2,6%
cc7	fc5	0,7%	0,3%	1,0%	0,3%
cc7	fc6	1,5%	0,6%	4,4%	1,5%
cc7	cc7	13,0%	12,2%	19,1%	19,2%

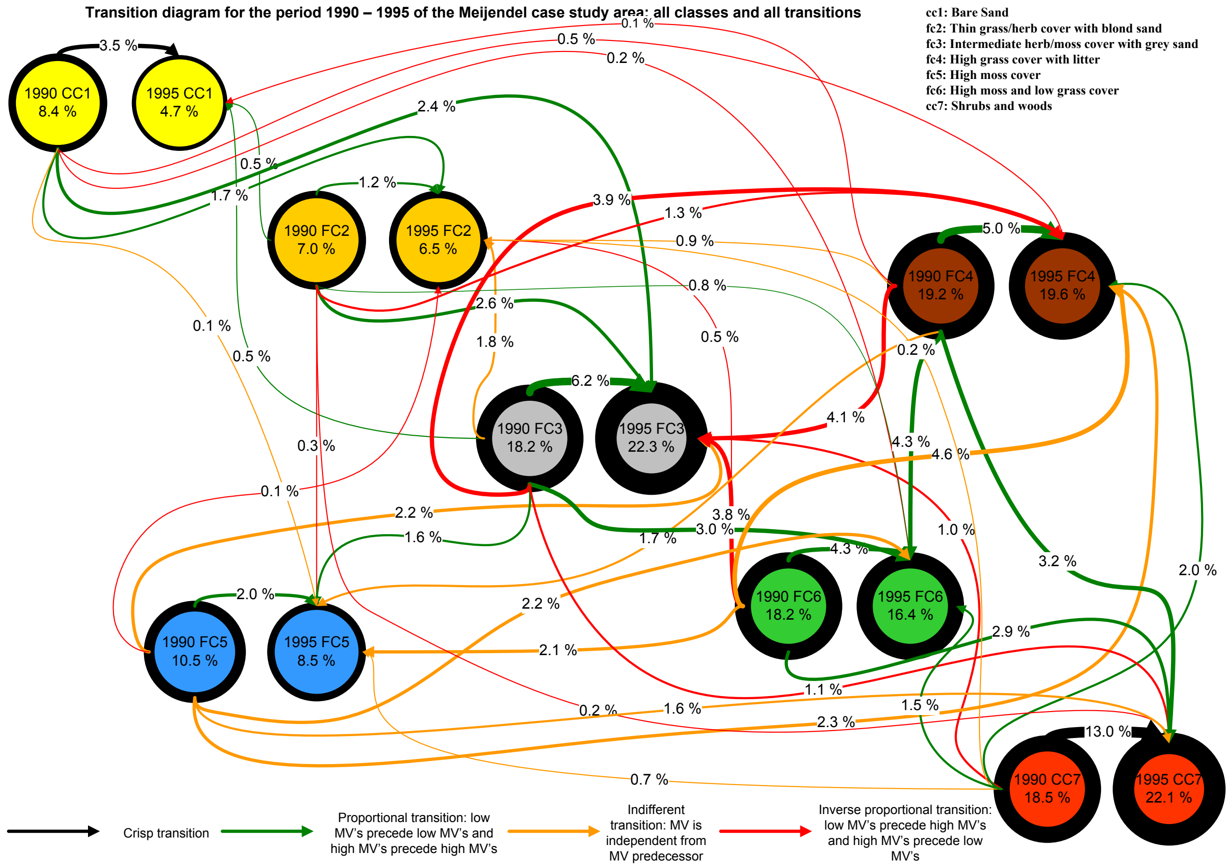


Figure 6-13 Synoptic fuzzy transition diagram for one time lap, based on t_1 membership value

6.5 Discussion

Data generated with fuzzy sequential thematic maps, vegetation structure maps in particular, are:

- Transition tables and graphs presenting the transition between combinations of fuzzy classes, fuzzy and crisp classes, and crisp classes. The transitions are visually classified in three semantic transition types.
- Overall transition tables and graphs presenting the extents of transitions calculated according to two algorithms.
- Fuzzy transition index table and graph presenting an indication whether the transition is from low membership value to high or vice versa.
- Synoptic fuzzy transition table and graph presenting (indications of) transition extent and semantic transition type.

With this data, the theoretical framework presented in section 6.4.1, is qualitative confirmed. A quantitative confirmation or direct numerical test is not possible. Elements in the test should be: level of organisation, succession stage, feedback type and transition type. These elements are highly abstract features that form the vocabulary or study environment of the landscape ecologist. Important is to notice the fact that the transitions as presented in the graphs and extent-tables cannot yet be regarded as succession types, let alone landscape development. The translation of the intricate transition web into a model of vegetation succession and landscape development of small-scale dynamic ecosystems is presented in chapter 7.

Important question is whether the synoptic fuzzy transition graph or the synoptic fuzzy transition table is most appropriate for the succession analysis. In general, using crisp sequential classification, a transition graph is used (Van der Maarel et al., 1985) where an a priori interpretation of the data is made. As can be seen in Figure 6-13 a hypothesised (primary) succession series is presented as a central pathway of succession. Vegetation structure types, regarded as undesirable by the terrain manager (see also Chapter 5), are presented as stages diverging from the central pathway. Whether this actually is the case must be matter of discussion and only after thorough analysis of the transition pattern between vegetation structure types these types may be interpreted and presented as undesirable.

The most appropriate method in studying and modelling temporal transitions in vegetation is the use of Markov models (Van Hulst, 1979). The results of the analysis of temporal change demonstrate that the results cannot be applied in Markov models. The three limiting conditions (see section 6.1) are discussed hereafter.

In fact, the choice of using fuzzy logic is in contradiction with the condition that there must be a finite number of states. When combining fuzzy and crisp thematic maps, the number of states is, according to Formula 6-10, near to infinity. In the case of the Meijendel case study area, this would give 1005^2 states, or, when using the membership value intervals as presented in the transition graphs, 105^2. The overall transition, as presented in Table 6-3 and Table 6-4 has only seven states, (the number of fuzzy and crisp classes) and could be used in Markov models. Because the calculated overall transition is the result of a set of successive algorithms, aimed at the summary of multiple states, it can be questioned whether this is advisable.

The condition that the transition probability may not change through time is in contradiction with the aim of numerous research projects: the description and explanation of vegetation or landscape development deviating from the natural course of development. Markov models can only be applied to systems with temporally and spatially invariant succession series.

Spatial independency is a condition that is never the case in the development of small-scale dynamic ecosystems. Biotic as well as abiotic factors influence the surroundings of the objects in study. In primary succession, a trend in spatial dependency can be observed. In pioneer stages abiotic processes like deflation and accumulation (Rutin, 1983; Pluis & De Winder, 1989; Arens & Geelen, 2006) or, for instance, tidal processes (Roozen & Westhoff, 1985) are dominant. Developing towards climax stages the vegetation structure influences its surroundings, for instance by shading or seed dispersal.

$$S_n = m(max)^{(f)} * (c)$$

S_n is the number of states

$m(max)$ is the maximum number of membership values

f is the number of fuzzy classes

c is the number of crisp classes

Formula 6-10 Number of states of the landscape when using fuzzy and crisp classes

6.6 Conclusion

Transition data, generated from fuzzy sequential thematic maps, and eventually presented in synoptic fuzzy transition tables and synoptic fuzzy transition graphs cannot be tested for first order stationarity. Moreover, the complexity of the data processing makes it problematic to use the results in quantitative modelling. However, the tables, graphs and diagrams can give important qualitative information on vegetation succession and landscape development.

Another conclusion that can be drawn from the methods presented is the fact that fuzzy sequential maps can provide crucial information on the transition process within semantic fuzzy objects where the use of semantic crisp objects would result in an unrealistic brisk transition. Conclusions on the development of the pattern, as reflected in changes in extent, are less clear to be made because extents for the transition between classes are ambiguous. This is caused by the algorithm used. However, the difference between calculated extents of similar transition extents, as revealed in the fuzzy transition index, can be regarded as a measure for the character of fuzzy transition.

The methods presented and discussed in this chapter are crucial for the comprehension of the vegetation succession or landscape development of small-scale dynamic ecosystems.

Photo 5 Impression of the Parabole dune case study area

7 LANDSCAPE DEVELOPMENT IN SMALL-SCALE DYNAMIC ECOSYSTEMS AS OBSERVED WITH FUZZY DIGITAL VEGETATION MAPS IN A COASTAL DUNE AREA; A MULTI-TRAJECTORY MODEL

7.1 Introduction

The temporal dynamics of small-scale dynamic ecosystems are a major field of study (Grootjans et al., 1997; Kiehl et al., 1997; Ten Harkel, 1998; Veer, 1998; Droesen, 1999; Janssen, 2004; Geerling et al., 2006; Koster, 2009). There are two reasons:

1. processes of landscape change can be studied in relative small areas over small time spans and
2. these ecosystems contain rare and characteristic species, habitats and processes so they are subject to conservation activities.

Landscape development is studied at two levels: 1) the observation of landscape changes, resulting in the description of transitions, and 2) the interpretation of the transitions resulting in the description of succession or landscape development. The production of transition matrices and transition diagrams as well as the statistic interpretation of the matrices, focusing on the Markovian properties of the matrices, is described in Chapter 6. The semantic interpretation of the transition matrices and transition diagrams, with emphasis on observing and explaining the transitions, and the development of models for vegetation succession and landscape development, are presented in this chapter.

Both the statistical and the semantic approach are crucial in evaluation and planning of terrain management. The statistical approach can be applied in the quantitative evaluation and modelling of terrain development and management. The semantic approach is more appropriate for a qualitative evaluation of landscape development and the identification of series for vegetation development.

The study of landscape development with transition matrices and diagrams is the integration of the temporal and semantic domain. According to the Serial Landscape Model (see Chapter 2) there can also be a spatial approach in the temporal analysis of landscape. Major assumption in such spatial approach is that the development of landscape elements is spatially dependent in their development. This dependency is described on several scale levels of the landscape. Individual plants can influence each other by mutual competition in light, water or nutrients (Connell & Slatyer, 1977; Smith & Huston, 1989; Tilman, 1990; Olff et al., 1993). Ecosystems can be spatially influenced by processes like seed dispersal (Nathan & Muller-Landau, 2000), lateral (ground-) water movement (Zhao et al., 2005; Jansson et al., 2007) and sediment influx (Ketner-Oostra & Sýkora, 2000; Arens & Geelen 2006). The notion of spatial dependency in vegetation development was first introduced by Watt (1947).

Although the spatial domain is very important for understanding succession and landscape development, this chapter focuses mainly on the relation between the temporal and semantic domain. Spatial processes are incorporated in the explanation of transitions and the development of explanatory models for landscape development. Because the material used for the sequential analysis (see section 7.3.1) are high-resolution fuzzy digital vegetation maps it is possible to analyse the transitions in detail. As presented in Chapter 6, it is possible to characterise the transitions according to the presence of classes and the occurrence as presented by membership values. More generally formulated: with the use of fuzzy digital vegetation maps it is possible to look “inside” the pixel and fuzzy transition graphs (see Figure 6-1 - Figure 6-8) make it possible to characterise individual transitions between (fuzzy) classes as proportional, inverse proportional and indifferent. In fact, these three semantic transition types are described on the base of descriptive statistics (fuzzy transition graphs) providing a new understanding of vegetation succession and landscape development. For a good apprehension of the transition diagrams presented in this chapter it is crucial to understand the explanation of semantic transition types as presented in section 6.4.1.

In this chapter, the concepts of convergence and divergence are used as an integral element of the Serial Landscape Model. An elaboration of their meaning is given in section 1.3. In the Serial Landscape Model convergence is defined as crisp and divergence as random: spatially, temporally and semantically. The range between convergence and divergence is continuity and perceived as fuzzyness. According to Van Leeuwen (1966) convergence can be characterised as concentration and divergence as separation.

In studying semantic aspects of landscape dynamics in small-scale ecosystems, dry coastal dune areas are taken as an example. Coastal dune areas are characterised by a frail balance between stability and instability (Jungerius & Van der Meulen, 1988; Van der Meulen & Van der Maarel, 1993). Vegetation development in dry dunes with high relief intensity seems to tend towards a dynamic pattern with a stable relative distribution of vegetation structure types. Such has been described as a small-scale diverse pattern of vegetation types of the xerosere, ranging from pioneer to climax stages (Van Leeuwen & Van der Maarel, 1971). The vegetation pattern is strongly related to landform: south exposed slopes tend towards open dune grassland, north exposed slopes towards shrub (Van der Meulen & Van der Maarel, 1993). However, numerous external factors, like grazing and aeolian activity influence vegetation development strongly (Jungerius & Van der Meulen, 1989; Provoost et al., 2004). Lately there seems to be a trend towards increasing stability in dry coastal dune areas with processes like stabilization of blowouts, grass encroachment and shrub encroachment (Veer & Kooijman, 1997; Shanmugam & Barnsley, 2002; Arens & Geelen, 2006).

The coastal dunes of The Netherlands are highly valued for the presence of these dry dune habitats. According to European legislation there is an international responsibility in the management and protection of these habitats (Heslenfeld et al., 2004). The dynamics of the small-scale dry coastal dune areas are a blend of natural primary succession and numerous externally initiated changes. Changes in vegetation structure towards more stable states are thought to be a threat. Therefore, it is important to understand the stabilising processes but also, as a key towards potential management, the mobilising processes. In section 7.2 the major processes of succession and landscape development in dry coastal dunes are presented. There is special attention for aeolian processes (section 7.2.1), grass encroachment (section 7.2.2) and shrub encroachment (section 7.2.3).

After the aim (section 7.3) and material and methods (section7.3.1) are described, transition diagrams and tables of landscape development in a dry coastal dune area in general and focused on aeolian dynamics, grass encroachment and shrub encroachment are presented (section 7.4). After the discussion of the results (section 7.5), recommendations for the management of dry coastal dune grasslands are given (section 7.6).

7.2 Succession in small-scale dynamic ecosystems, dry coastal dune areas in particular

Landscape development and vegetation succession of coastal dune areas have been a major topic of study since the very beginning of vegetation science. During his visit to the Netherlands, Linnaeus already studied species of the coastal dunes near Haarlem (Lam & Van Loo, 1957). Only after the introduction of the “French-Swiss school” of vegetation science, comprehensive studies of the landscape development and vegetation succession in the coastal dunes were carried out (Van Dieren, 1934; Westhoff, 1947; Westhoff, 1949). In the majority of these studies, the emphasis is on primary vegetation succession. For dry coastal dunes this is the xerosere. An area with predominant primary succession is characterised by the fact that stages in the succession are replaced by types with a higher order of organisation. This process continues until the climax stage is reached. However, in small-scale dynamic ecosystems many stages co-occur in an intricate pattern as a result of local secondary succession and regression, initiated by external factors. This process has been described (Ranwell, 1960a; Bornkamm, 1981; Cowling & Pierce, 1988) but has never been recognised as a unique form of landscape and vegetation development particularly encountered in small-scale dynamic ecosystems.

Van Dorp et al. (1985) describe the rapid transition of vegetation in a coastal dune area: within 46 years the vegetation classes are completely replaced by other classes though auto-transitions are observed in relative high frequency at shorter time-lags. From their results it can be concluded that there is a clear path of primary succession from pioneer towards climax stages for the overall dune area at a time scale of several decennia. However, at a time scale of several years there seems to be another type of temporal dynamics characteristic for a small-scale dynamic ecosystem. The most appropriate model to describe these short-term temporal dynamics is a multi-trajectory model where numerous stages in vegetation development occupy the landscape in an intricate continuous pattern that changes relative quickly in several directions. Every vegetation type changes in every vegetation type. This can be observed in the synoptic fuzzy transition diagram presented in Figure 6-13. The ‘multi-trajectory model’ acts at a higher spatial scale level than the ‘carousel model’ presented by Van der Maarel & Sykes (1993) who describe similar temporal dynamics for individual plants. The difference between the ‘carousel model’ and the ‘multi-trajectory model’ is the fact that the fundamental unit in the carousel model is a crisp object (an individual plant) and the fundamental unit in the multi-trajectory model is a fuzzy object. The multi-trajectory character of small-scale dynamic ecosystems in general and dry coastal dunes in particular can also be observed in transition diagrams presented by several authors (Londo, 1974; Roozen & Westhoff, 1985; Van Dorp et al., 1985; Van der Maarel et al., 1985): the diagrams are intricate and there seem to be transitions between any state of the landscape.

With the theoretical framework, used for the interpretation of fuzzy semantic transitions as observed with the transition graphs presented in Chapter 6, this ‘multi-trajectory model’ for small-scale dynamic ecosystems can be described as well as explained. With the fuzzy transition graphs (see Figure 6-1 - Figure 6-8), transitions between any state can be characterised as being either proportional, inverse proportional or indifferent. The multi-trajectory character is caused by the occurrence of all transition types in the landscape. Succession towards states with higher grades of internal organisation with a typical shift from positive feedback to negative feedback as well as the inverse (regression) occurs. Theoretically this can be observed in the presence of proportional and inverse proportional transitions. Changes caused by external factors lead to indifferent transitions. As shown in Figure 6-13, all types of transition occur in small-scale dynamic ecosystems. How these transitions relate to each other, resulting in a dynamic landscape is the topic of study of this chapter.

The proposed ‘multi-trajectory model’ is in agreement with the general dune landscape model presented by Van Haperen (2009). He described the dynamics of coastal dunes as an alteration between “Alternative stable states”: only severe intervention, whether natural or antropogenic, can initiate the transition towards a new stable state. Spatial and temporal scale of these states are large (long time-span, large area). Within a stable state cf. Van Haperen (2009), the multi-trajectory model, as observed and described with sequential fuzzy vegetation maps and fuzzy transition graphs, explains the temporal dynamics.

For the stability of a small-scale dynamic ecosystem as a whole, with its characteristic spatial pattern and temporal dynamics, rejuvenation is an important requirement. Otherwise the landscape should ‘age’ and eventually change in a stable climax situation. Rejuvenation in dry coastal dune areas is primarily caused by aeolian activity (Arens et al., 2004; Arens & Geelen, 2006; Wiedemann & Pickart, 2008): it initiates the development of higher grades of relief intensity and provides influx of fresh mineral material. In natural situations aging of the landscape is the development towards a varied forest, shrub or stable grassland. Aging of the landscape is also observed as grass- and shrub encroachment. For a better understanding of processes that maintain or transform the stable states of the dune landscape, a detailed study of rejuvenation and aging of the landscape is necessary. In the following sections a short introduction into aeolian dynamics, grass encroachment and shrub encroachment in dry coastal dunes is given.

7.2.1 Aeolian dynamics

Principle factors in the initiation and continuation of aeolian processes are: (micro)-climate (Arens, 1996b), sediment availability (Hugenholtz et al., 2009), erodibility (Jungerius & Van der Meulen, 1988) and vegetation cover (Lancaster & Baas, 1998). Aeolian dynamics in coastal dunes can be primary or secondary. Primary aeolian dynamics result in the formation of fore dunes through a successive process where stabilisation by vegetation cover plays a major role (Van Dieren, 1934). Important process in the maintenance of this primary process is the transportation of sand from the beach to the fore-dunes (Arens, 1996a). Secondary aeolian dynamics in coastal dunes are caused by the degradation of the vegetation cover and exposure of fresh (blond) sand to wind (Jungerius & Van der Meulen, 1988). As described by Ellenberg (1988) and defined as priority habitat according to NATURA 2000 (Council of the European communities, 1992) the dynamic character of grey dunes is predominantly caused by these secondary aeolian dynamics. Stabilisation of secondary aeolian features (blowouts) in grey dunes is initiated by algal crusts (Pluis & De Winder, 1989) in deflation areas and predominant colonisation with *Ammophila arenaria* and *Hippophae rhamnoides* in accretion areas (Jungerius & Van der Meulen, 1997).

The extent of secondary aeolian processes can range from relative small in lime-rich dunes (Jungerius et al., 1981) to very large in lime-poor dunes (Van Dieren, 1934). The turnover point from erosion to stabilisation in blowout development in the grey lime-rich dunes is triggered by geometry resulting in the stabilisation of blowouts larger than ca. 30m. Only in special occasions a blowout can develop into a deflation plane: when the down-wind slope is approximately 6°. Secondary aeolian processes are a major factor in the small-scale dynamic character of dune landscapes where the sub-processes erosion, transport and sedimentation (Pye & Tsoar, 2009) occur at relative small distance from each other. Aeolian dynamics result in a spatial and temporal diverse landscape with clearly distinguishable spatial elements with discrete as well as continuous margins (spatial) and transitions (temporal) between differing levels of deflation and accretion. Different levels of active accretion result in a continuous spatial pattern of plant communities adapted to the specific level of accretion (Jungerius & Van der Meulen, 1997; Maun, 1997). It was concluded by Ketner-Oostra & Sýkora (2000) that the maintenance of typical vegetation of dry coastal dunes (lichens in *Violo-Corynephoretum*) is optimal when fresh sand is blown in. The process of stabilisation and colonisation of deflation as well as accretion areas result in a more homogeneous landscape.

7.2.2 Grass encroachment

The process of grass encroachment was first encountered and ascribed to atmospheric deposition in species-poor heathland communities (Heil & Diemont, 1983). Also dry dune grasslands seemed to be vulnerable to this process (Veer & Kooijman, 1997) and grazing with cattle and ponies was (re)introduced in coastal dunes (Kooijman & De Haan, 1995). Main expression of grass-encroachment is the dominance of one grass-species (*Calamagrostis epigejos, Carex arenaria* or *Ammophila arenaria*) with a subsequent surplus in dead ectorganic material. The unfavourable position in light competition for annuals and biennials results in a decrease in biodiversity (Ten Harkel & Van der Meulen, 1996). The lush grass vegetation makes it impossible for rabbits to maintain species rich dune grassland by selective grazing.

From detailed process studies focusing on the relation between soil chemistry, plant nutrient status and grass encroachment (Kooijman et al., 1998; Kooijman & Besse, 2002, Kooijman et al., 2009) it is concluded that the process of grass encroachment is slow in lime rich dunes compared to lime poor dunes. In iron rich areas organic matter is a decisive factor in the speed of grass encroachment.

It is surprising that spatial studies on grass encroachment based on sequential maps lack because grass encroachment has a spatial as well as temporal diverging effect on the dry dune landscape. Because grass encroachment is particularly encountered in spatially homogeneous landscapes (extensive dune valleys, eroded slightly undulating dunes), the diverging effect is strengthened. At the fringes and in open spaces in shrublands, grassland types with characteristics of grass encroachment can be encountered. However, at these positions, with a heterogeneous, converging spatial pattern, this grassland type is natural and therefore not unfavourable.

7.2.3 Shrub encroachment

Shrub encroachment is spatially and temporally comparable to grass encroachment. It has a diverging effect on the dry dune landscape. Isermann et al. (2007) concluded that the expansion of *Hippophae rhamnoides* is a major threat to the plant species richness of open coastal dunes. However, as mentioned in literature (Van Boxel et al., 1997; Grootjans et al., 2002) shrub encroachment has not been studied as fundamentally as grass encroachment in small-scale dynamic ecosystems. Shrub encroachment is described as a problem in large-scale stable ecosystems (steppe and semi-arid grasslands) due to anthropogenic activity (Jeltsch et al., 1997; Knapp et al., 2008). This could be an indication for the fact that especially stable states of the landscape are vulnerable to diverging processes like grass and shrub encroachment.

7.3 Aim

It is the aim of this chapter to describe and explain the multi-trajectory character of a small-scale dynamic ecosystem, the dry coastal dune ecosystem in particular. The focus is on the natural internal dynamics of vegetation development as well as on natural external factors. The most obvious natural external factor is aeolian activity, a primarily converging process. The effect is a landscape with a high level of concentration observed as discrete spatial units, quick (catastrophical) changes and crisp classes. Stabilization of deflation and accretion areas is primarily a diverging process: the effect is a landscape with a high level of separation, observed as spatial units hard to limit, high stability and high similarity in the semantics. Diverging processes, triggered by unnatural external factors like atmospheric deposition and decline of natural grazing intensity, are also studied. The question whether these diverging processes are positive or negative for the multi-trajectory character of small-scale dynamic ecosystems is examined.

With a dry coastal dune ecosystem as case study area, vegetation development is confined to stages encountered in the xerosere or psammosere of coastal dunes. However, in this study the xerosere of coastal dunes is not used as the ultimate succession model for dry coastal dunes, but as a framework that describes plant communities present in dry coastal dunes. It is the premise of this study that vegetation development of small-scale dynamic ecosystems cannot be modelled with one or two trajectory series, and the aim to show that the dynamics can be modelled through a multi-trajectory model.

The results presented are confined to the description of changes in pattern leading to spatial explanations. Of course, topologic relations like the dynamics of nutrients (N, P) and soil forming processes are important to understand the basic mechanisms that cause these spatial developments. However, the integration of pattern and processes requests a multidisciplinary approach. This is beyond the aim and possibilities of this study.

It is also the aim of this chapter to give indications for the management of dry coastal dune ecosystem. Processes that are characteristic for divergence (grass and shrub encroachment) of the landscape and processes that could lead to convergence (aeolian dynamics) are dealt with in separate analyses. The concluding statements are based on the semantics (description and explanation) of the landscape development of a small case study area (see section 7.3.1). Therefore conclusions are confined to this small area though an attempt is made to extrapolate the results to dry coastal dunes of The Netherlands in general.

7.3.1 Material and methods

Four case study areas are selected representing: the overall development of a dry dune area, an area with aeolian activity, an area with grass encroachment and an area with shrub encroachment. The areas are presented in Table 7-1 and Figure 7-1. All four case study areas are grazed by cattle and horses since 1990 as a measure against grass encroachment. Therefore, the results must be interpreted as landscape development with the effect of grazing. Transition tables and diagrams, based on a set of sequential fuzzy digital vegetation maps of a dry coastal dune area, are constructed according to the methods described in Chapter 6.

The resolution of the digital vegetation maps is 0.1m. The maps represent the vegetation cover in 1990, 1995 and 2001. Therefore two successive sets of fuzzy transitions could be calculated: the 1990-1995 transition and the 1995-2001 transition. The fuzzy vegetation maps are produced according to the DICRANUM classification procedure (see Chapter 2) with the image interpretation classes presented in Table 2-4.

The semantics of the classes, i.e. the integrated description of relief, soil and vegetation, are described in Chapter 4 and presented in Table 4-4.

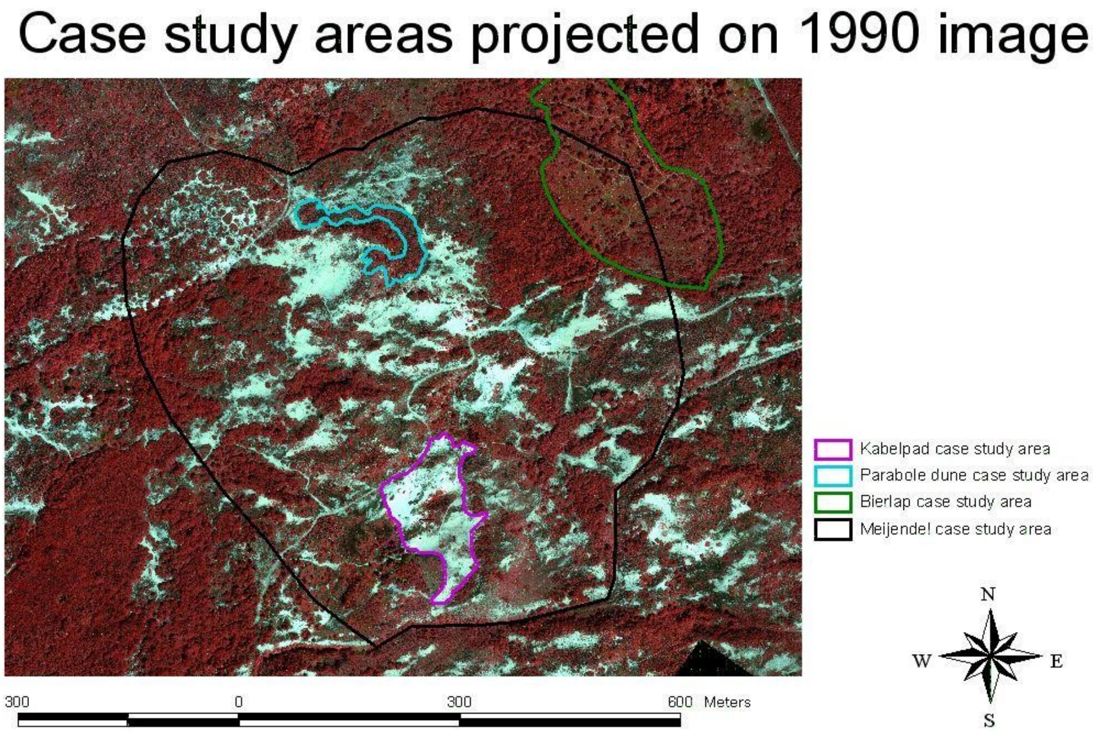
All the fuzzy transitions are presented in transition graphs (see for some examples: Figure 6-2 - Figure 6-6) and interpreted according to the three transition types presented and substantiated in section 6.4.1. The relative transition and the transition type are presented in synoptic fuzzy transition tables (Table 7-2 - Table 7-5). These tables give the transition of both time intervals (1990-1995 and 1995-2001) so the change in relative cover as well as the change in transition type can be examined.

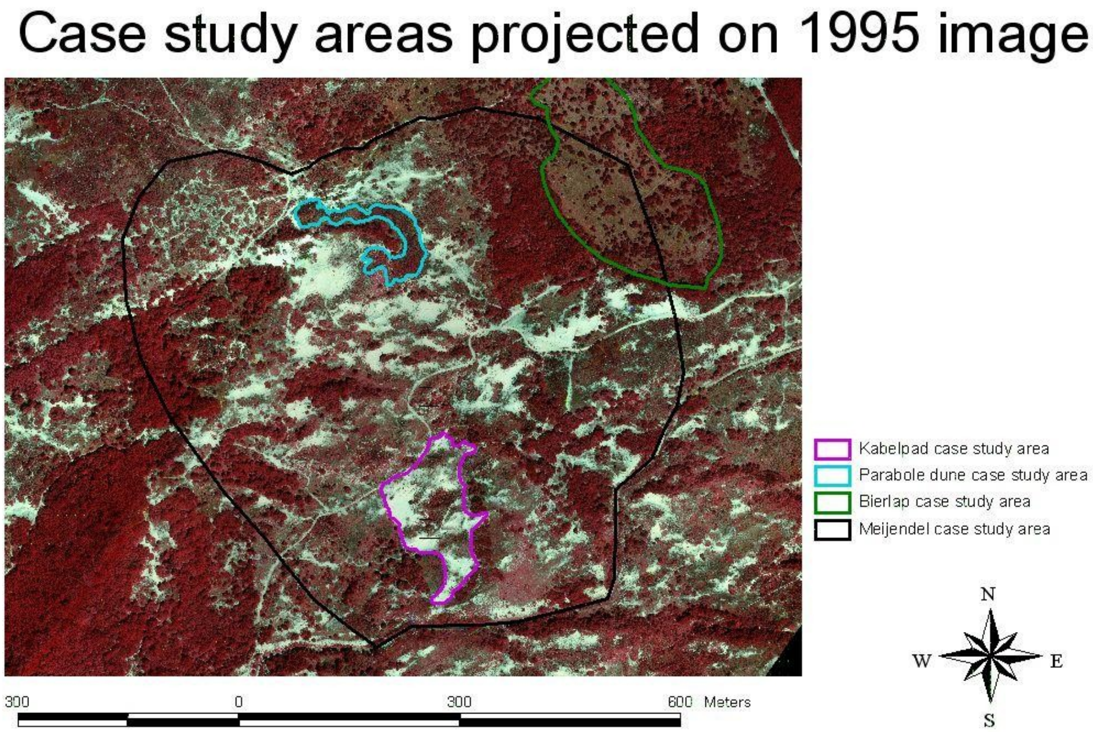
The fuzzy transitions are also presented in a set of synoptic fuzzy transition diagrams (Figure 7-2 - Figure 7-9), arranged according to the observed semantic transition types. Image interpretation classes with a mutual proportional transition are grouped in a vertical line, classes with a mutual inverse proportional transition are placed in opposing positions and classes with indifferent transitions are placed in a separate position above the classes with proportional and inverse proportional transitions. The weight of the lines and circles represent the relative occurrence of the transition and class respectively.

The most obvious results from the synoptic transition tables and diagrams are described and discussed for all four case study areas in section 7.4. Overall multi-trajectory models for the landscape development in dry coastal dune areas in general (Figure 7-10) and in the case of aeolian activity (Figure 7-11), grass encroachment (Figure 7-12) and shrub encroachment (Figure 7-13) are discussed and presented in section 7.5. Arrows in Figure 7-10 - Figure 7-13 represent two directions of transition: from class A to class B and from class B to class A. This is not the case for the arrows presented in the synoptic fuzzy transition graphs (Figure 7-2 - Figure 7-9)

Table 7-1 Case study areas for the analysis of landscape development in dry coastal dune areas

Name	General characteristic	Extent (appr.)
Meijendel case study area	The Meijendel case study area is a complex of parabolic dunes approximately three km from the coast. It is a dynamic, spatially diverse secondary dune complex. Small, confined valleys are mainly covered with shrubs and woods. South exposed slopes have an open dry dune grassland cover and North exposed slopes are covered with stable dune grassland or shrubs. A relative high amount of active blowouts occur during the time interval of study (1990 – 2001). Nowadays (2010), the majority of blowouts are stabilized.	40 ha
Kabelpad case study area	The Kabelpad case study area consists mainly of a set of blowouts, including the deflation and accretion zones. Some remnants of stable dune grassland and shrubs are present. This complex of blowouts has been studied in detail by Jungerius and Van der Meulen (1997)	1.6 ha
Bierlap case study area	The Bierlap case study area is part of an extensive middle dune valley, covered with woods and stable dune grassland. During the 19th century it was in agricultural use. Since 1990 the area is grazed by cattle and horses (De Bonte et al.; 1999). The Bierlap has been chosen as a case study area for the dominance of *Calamagrostis epigejos,* an indicator for grass encroachment. Vegetation of the case study area consists mainly of grassland and some, mainly isolated, *Crataegus monogyna* shrubs or trees.	4.5 ha
Parabolic dune case study area	The Parabolic dune case study area is located in the lee of a typical parabole dune. The case study area is characterised by a slightly undulating relief and dominance of *Hippophae rhamnoides.* The shrubs grow vigorously to heights over 2m.	0.65 ha


Case study areas projected on 1990 image
Kabelpad case study area
Parabole dune case study area
Bierlap case study area
Meijendel case study area
N
W
E
S
300
0
300
600
Meters


Case study areas projected on 1995 image
Kabelpad case study area
Parabole dune case study area
Bierlap case study area
Meijendel case study area
N
W
E
S
300
0
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600
Meters

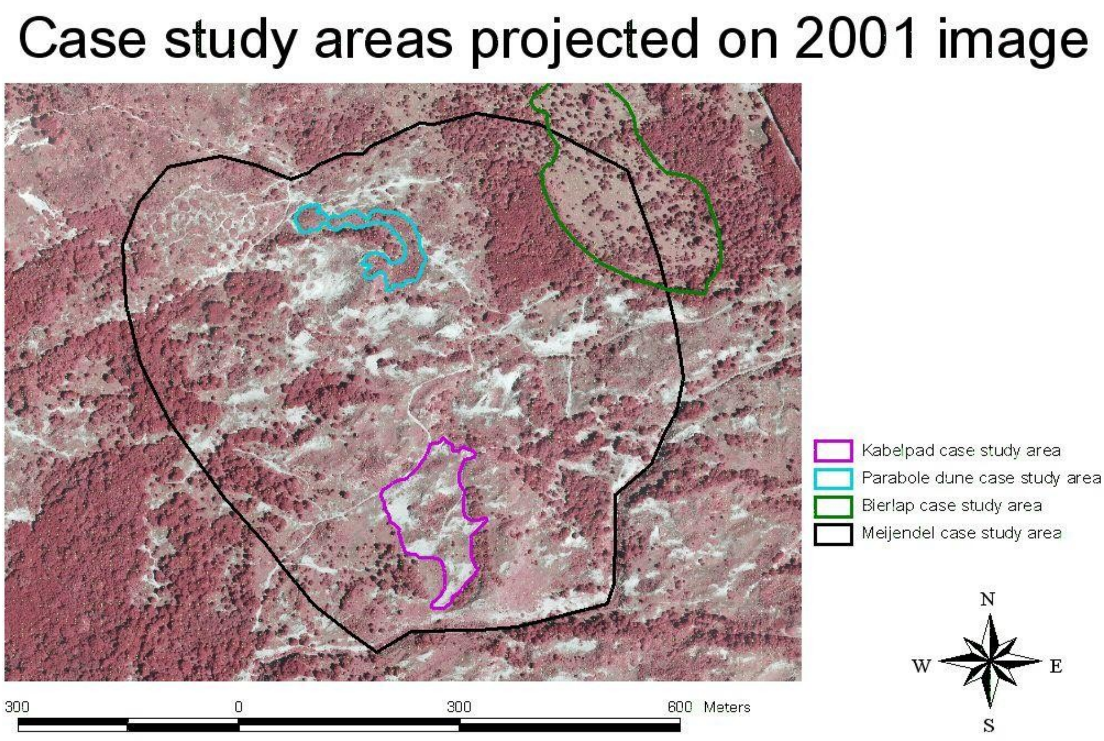

Figure 7-1 Case study areas projected on the images of 1990, 1995 and 2001.

7.4 Results

To understand the results presented in the following sections it is important to be familiar with the semantic transition typology and its ecological implication as presented in section 6.4.1. Proportional transition is a clear path of natural transition or succession that can be explained by normal vegetation succession theory and presented in a succession/replacement diagram: 'a' is followed by 'b' etc.. Inverse proportional transition is supplementary to proportional transition. When high membership values of an image interpretation class (representing a certain vegetation class) precede high membership values of a specified other class, as is the case with proportional transition, the membership values of remaining preceding image interpretation classes must be low resulting in inverse proportional transition. In the case of indifferent transition the presence or absence of a vegetation type is caused by other factors than the system itself.

Furthermore, it is important to realise that the results presented focus primarily on the semantics of the transitions and not on quantifying the transitions. As concluded in Chapter 6, synoptic fuzzy transition tables and synoptic fuzzy transition matrices must be interpreted qualitative. This is caused by the algorithms used to combine sequential fuzzy vegetation structure maps (see Formula 6-6, Formula 6-7 and Formula 6-8). A consequence of the algorithms used is that the calculated total extent of a fuzzy class at t+1 of the transition t → t+1 does not equal the total extent of a fuzzy class at t+1 of the transition t+1 → t+2.

7.4.1 The Meijendel case study area

The dry dune grasslands, as observed in the Meijendel case study area (Table 7-2, Figure 7-2 and Figure 7-3), show a clear division in dynamic and stable dunes. Dynamic dunes are represented by sand (cc1), sparse grass vegetation (fc2) and a mixture of herbs, moss and grey sand (fc3), and are related to each other by proportional transition. This statement is valid for transitions towards a higher degree of organisation from sand to a mixture of herbs, moss and grey sand (primary succession) as well as degradation from a mixture of herbs, moss and grey sand towards bare sand (regression). The stable vegetation types represented in class fc4 (high grass with ectorganic material), fc6 (stable dune grassland) and cc7 (shrubs and wood) are also related to each other by proportional transition. From the data presented, it can be observed that the relation between dynamic and stable dunes is by inverse proportional transitions. This means that these two opposing states of the landscape are the result of classic primary succession or regression within their state of instability or stability and the transition from a dynamic landscape to a stable landscape or vice versa is the result of an, until now, not recognised process. Inverse proportional succession means that the state emerges slowly with low membership values until a threshold is passed and the state becomes dominant (high membership values) and transitions are proportional. The disappearance of a state is also a threshold process: the state slowly declines until a threshold is passed, transitions become inverse proportional and the overall state changes into an inverse state of dynamic or stable dunes. A comparable process has been described by Koppel et al.

(2002) where the threshold is explained by an interaction between surface water availability, plant cover and herbivore grazing.

The landscape development described can be interpreted as the hysteresis effect where the threshold in the trajectory from dynamic to stable landscape is at another distribution of membership values than the threshold in the trajectory from stable to dynamic. According to Glenn-Lewin et al. (1992) hysteresis occurs when two or more landscape equilibria coexist due to, for instance, climate change. From the data presented it can be concluded that in the case of a small-scale dynamic ecosystem the coexistence of multiple equilibria is normal. In this case: stable and dynamic states of the dry dunes coexist and there is no dominance of one of the states. According to the results presented in section 7.4.2, 7.4.3 and 7.4.4 it can be hypothesised that due to external factors (climate change, atmospheric deposition, change in herbivory) a dominant equilibrium situation can develop. This statement must be checked analysing the special cases of landscape development presented in the following sections.

Comparing the transition diagram of the period 1990-1995 with the period 1995-2001 the general trend is towards more instability in transitions. More classes emerge or decline due to indifferent transitions. This can be an indication that the landscape is deviating from its equilibrium characterised by the coexistence of stable and dynamic states. The overall trend in the Meijendel case study area is towards a higher portion of stable states (fc4, fc6, cc7) of the landscape and a less coherent occurence of semantic transition types. This hints towards stability-instability phases and episodic landscape evolution as described by Brunsden & Thornes (1979) and is in line with the landscape model presented by Van Haperen (2009). Whether this is caused by natural internal processes or man-induced external processes (grazing by large herbivores) cannot be concluded from the data of the Meijendel case study area. The transition tables and diagrams of the special cases of landscape development can perhaps give an indication.

Apart from the general trends observed in the Meijendel case study area some detailed observations on the Meijendel case study area can be made. The transition from open dune grassland with mosses, herbs, grasses and patches with exposed grey sand (fc3) to stable dune grassland (fc6) is proportional and the opposite transition is inverse proportional during the time interval 1990-1995. During the next five years both transitions are inverse proportional: 'natural' primary succession towards a climax situation changes in a more incessant development with threshold effects. This brings on the situation that for the observer the landscape seems to be stable over a long time-span until, unexpectedly, a new state of the landscape emerges.

The transition from stable, species rich dune grassland (fc6) to high, grass dominated vegetation (grass encroachment) is indifferent: an indication that the process is initiated by external factors. The majority of the transitions from or to a stable, moss dominated vegetation structure (fc5) are indifferent. Knowing that this vegetation structure type is characterised as a species poor, lime poor variant of grey dunes it can be questioned whether soil profile development towards decalcified situations with unfavourable humification as well as rejuvenation of this state of the landscape must be interpreted as an external factor. This class was introduced in the classification system because *Campylopus introflexus* dominated vegetation was considered as a threat (Van Boxel et al., 1997; Kettner-Oostra & Sýkora, 2004). Nowadays, this moss is less invasive as evidenced by less dominance in the case study area, It is seldom found with 100% membership value.

It could be expected that the transition towards bare sand (cc1) is indifferent: the development of blowouts is mainly caused by external dynamics. From the diagrams presented this cannot be concluded. This observation is confirmed by the material presented for the Kabelpad case study area and further discussed in the following section.

7.4.2 Aeolian dynamics

The overall impression of the synoptic transition tabletransition table (Table 7-3) and diagrams (Figure 7-4 and Figure 7-5) of the Kabelpad case study area is basically similar to the table and diagrams of the Meijendel case study area. Transitions in the dynamic, as well as the stable dunes are proportional and the transition from dynamic to stable and vice versa are inverse proportional. In the complex area with blowouts of the Kabelpad case study area there are two equilibrium states: dynamic and stable. It is not surprising that the dynamic equilibrium state is better represented in the case study area: the area was selected for its aeolian dynamics.

However, the overall trend in the dynamic area is towards states with a higher level of organisation, mainly class fc3. The state of bare sand (cc1) declines and the transition towards bare sand is confined to small changes in accumulation zones, the deflation zones tend towards stabilization. This is confirmed with the data at hand: transitions towards bare sand only occur through proportional transition from vegetation typical for blown-in sand (fc2) or partly stabilised grey dunes (fc3) meaning that the latter two states must have a certain level of dominance before the state of bare sand can develop. The transition towards class fc2 is indifferent which can be interpreted as external aeolian dynamics induced by surfaces of bare sand. The transition from class fc2 to class fc3 is indifferent in the period 1990-1995 and proportional in the period 1995-2001. This can be interpreted as a trend towards rapidly declining external dynamics, 'normal' primary succession becomes dominant. Further, it can be seen that, mainly in the 1995-2001 period the inverse proportional transition from dynamic dune grassland (fc3) to stable, species rich, dune grassland (fc6) is important and results in a high presence of class fc6. This is a favourable state from a biodiversity point of view. It must be kept in mind that in this trend towards stability this state is only a phase in the proportional transition towards grass- or shrub-dominated vegetation types. Therefore the transition from dynamic dune grassland towards stable dune grassland must always be possible to preserve species rich dune grassland. A dominance of stable dune grassland is a threat for the maintenance of species rich dune grassland: eventually it will develop towards shrub or, with prolonged atmospheric deposition, grass encroachment.

Table 7-2 Synoptic fuzzy transition tables of the Meijendel case study area (black: crisp transition, green: proportional transition, orange: indifferent transition, red: inverse proportional transition)

		overall			
t	t+1	90-95		95-01	
		∑(90)	∑(95)	∑(95)	∑(01)
cc1	cc1	3,5%	3,2%	1,5%	1,5%
fc2	cc1	0,5%	1,0%	0,1%	0,4%
fc3	cc1	0,5%	1,1%	0,3%	0,5%
fc4	cc1	0,1%	0,3%		0,1%
fc5	cc1				
fc6	cc1		0,1%		
cc7	cc1			0,1%	0,1%
cc1	fc2	1,7%	0,6%	2,3%	0,8%
fc2	fc2	1,2%	0,9%	0,8%	0,7%
fc3	fc2	1,8%	1,2%	2,4%	1,2%
fc4	fc2	0,9%	0,8%	0,3%	0,4%
fc5	fc2	0,1%	0,1%	0,1%	0,1%
fc6	fc2	0,5%	0,4%	0,2%	0,2%
cc7	fc2	0,2%	0,1%	0,5%	0,2%
cc1	fc3	2,4%	1,3%	2,9%	1,6%
fc2	fc3	2,6%	3,6%	1,5%	2,2%
fc3	fc3	6,2%	6,9%	6,6%	5,0%
fc4	fc3	4,1%	4,1%	1,6%	2,1%
fc5	fc3	2,2%	1,9%	0,7%	0,7%
fc6	fc3	3,8%	3,9%	1,5%	1,4%
cc7	fc3	1,0%	0,2%	1,4%	0,4%
cc1	fc4	0,5%	0,1%	0,6%	0,2%
fc2	fc4	1,3%	0,8%	0,9%	1,0%
fc3	fc4	3,9%	2,8%	4,1%	4,4%
fc4	fc4	5,0%	3,9%	3,4%	5,2%
fc5	fc4	2,3%	1,2%	1,4%	1,8%
fc6	fc4	4,6%	3,6%	4,0%	4,6%
cc7	fc4	2,0%	0,9%	4,7%	2,6%
cc1	fc5	0,1%		0,2%	0,1%
fc2	fc5	0,3%	0,2%	0,3%	0,4%
fc3	fc5	1,6%	1,3%	3,0%	2,1%
fc4	fc5	1,7%	1,6%	1,0%	1,5%
fc5	fc5	2,0%	1,3%	1,1%	1,1%
fc6	fc5	2,1%	1,9%	1,3%	1,3%
cc7	fc5	0,7%	0,3%	1,0%	0,3%
cc1	fc6	0,2%	0,1%	0,8%	0,2%
fc2	fc6	0,8%	0,7%	1,2%	1,3%
fc3	fc6	3,0%	2,9%	7,1%	6,3%
fc4	fc6	4,3%	4,2%	3,9%	5,8%
fc5	fc6	2,2%	1,6%	2,1%	2,8%
fc6	fc6	4,3%	4,2%	4,8%	5,3%
cc7	fc6	1,5%	0,6%	4,4%	1,5%
cc1	cc7			0,1%	0,1%
fc2	cc7	0,2%	0,7%	0,2%	0,4%
fc3	cc7	1,1%	4,4%	0,7%	2,3%
fc4	cc7	3,2%	6,7%	1,8%	3,9%
fc5	cc7	1,6%	2,9%	0,8%	1,9%
fc6	cc7	2,9%	7,0%	1,1%	2,9%
cc7	cc7	13,0%	12,2%	19,1%	19,2%

		overall			
t	t+1	90-95		95-01	
		∑(90)	∑(95)	∑(95)	∑(01)
cc1	cc1	3,5%	3,2%	1,5%	1,5%
cc1	fc2	1,7%	0,6%	2,3%	0,8%
cc1	fc3	2,4%	1,3%	2,9%	1,6%
cc1	fc4	0,5%	0,1%	0,6%	0,2%
cc1	fc5	0,1%		0,2%	0,1%
cc1	fc6	0,2%	0,1%	0,8%	0,2%
cc1	cc7			0,1%	0,1%
fc2	cc1	0,5%	1,0%	0,1%	0,4%
fc2	fc2	1,2%	0,9%	0,8%	0,7%
fc2	fc3	2,6%	3,6%	1,5%	2,2%
fc2	fc4	1,3%	0,8%	0,9%	1,0%
fc2	fc5	0,3%	0,2%	0,3%	0,4%
fc2	fc6	0,8%	0,7%	1,2%	1,3%
fc2	cc7	0,2%	0,7%	0,2%	0,4%
fc3	cc1	0,5%	1,1%	0,3%	0,5%
fc3	fc2	1,8%	1,2%	2,4%	1,2%
fc3	fc3	6,2%	6,9%	6,6%	5,0%
fc3	fc4	3,9%	2,8%	4,1%	4,4%
fc3	fc5	1,6%	1,3%	3,0%	2,1%
fc3	fc6	3,0%	2,9%	7,1%	6,3%
fc3	cc7	1,1%	4,4%	0,7%	2,3%
fc4	cc1	0,1%	0,3%		0,1%
fc4	fc2	0,9%	0,8%	0,3%	0,4%
fc4	fc3	4,1%	4,1%	1,6%	2,1%
fc4	fc4	5,0%	3,9%	3,4%	5,2%
fc4	fc5	1,7%	1,6%	1,0%	1,5%
fc4	fc6	4,3%	4,2%	3,9%	5,8%
fc4	cc7	3,2%	6,7%	1,8%	3,9%
fc5	cc1				
fc5	fc2	0,1%	0,1%	0,1%	0,1%
fc5	fc3	2,2%	1,9%	0,7%	0,7%
fc5	fc4	2,3%	1,2%	1,4%	1,8%
fc5	fc5	2,0%	1,3%	1,1%	1,1%
fc5	fc6	2,2%	1,6%	2,1%	2,8%
fc5	cc7	1,6%	2,9%	0,8%	1,9%
fc6	cc1		0,1%		
fc6	fc2	0,5%	0,4%	0,2%	0,2%
fc6	fc3	3,8%	3,9%	1,5%	1,4%
fc6	fc4	4,6%	3,6%	4,0%	4,6%
fc6	fc5	2,1%	1,9%	1,3%	1,3%
fc6	fc6	4,3%	4,2%	4,8%	5,3%
fc6	cc7	2,9%	7,0%	1,1%	2,9%
cc7	cc1			0,1%	0,1%
cc7	fc2	0,2%	0,1%	0,5%	0,2%
cc7	fc3	1,0%	0,2%	1,4%	0,4%
cc7	fc4	2,0%	0,9%	4,7%	2,6%
cc7	fc5	0,7%	0,3%	1,0%	0,3%
cc7	fc6	1,5%	0,6%	4,4%	1,5%
cc7	cc7	13,0%	12,2%	19,1%	19,2%

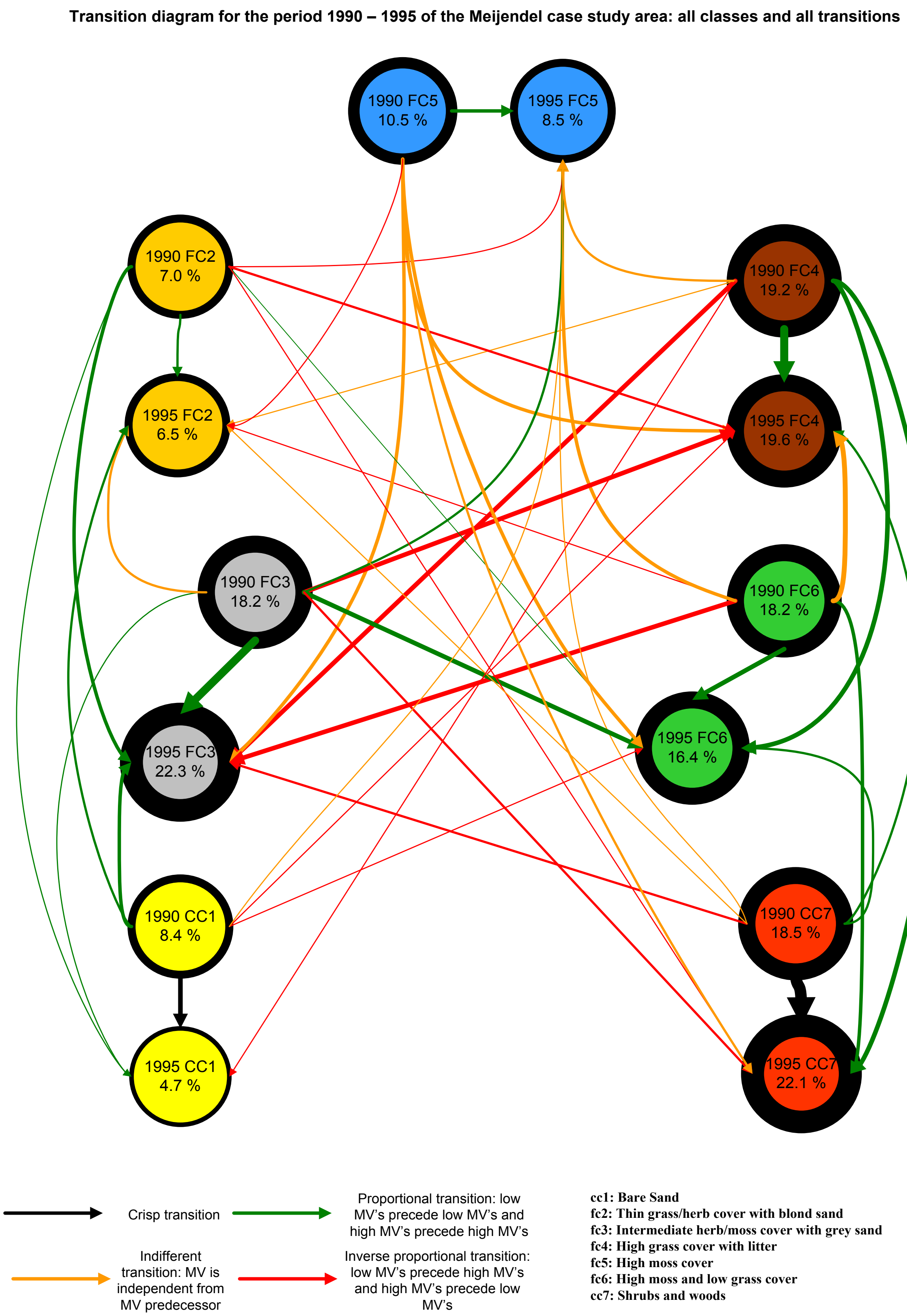

Figure 7-2 Synoptic fuzzy transition diagram of the Meijendel case study area: 1990-1995

Transition diagram for the period 1995 – 2001 of the Meijendel case study area: all classes and all transitions

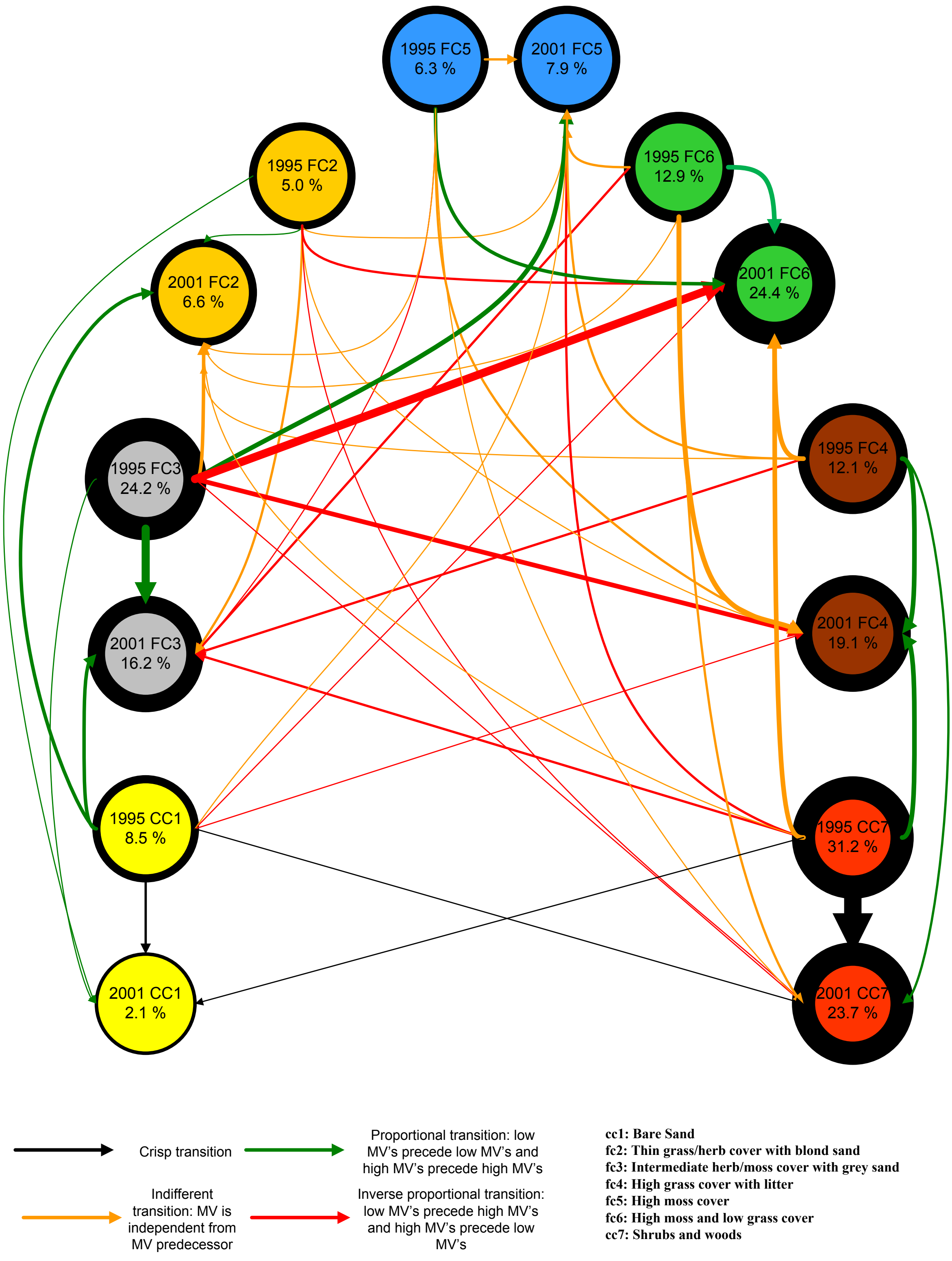

Figure 7-3 Synoptic fuzzy transition diagram of the Meijendel case study area: 1995-2001

Table 7-3 Synoptic fuzzy transition tables of the Kabelpad case study area (black: crisp transition, green: proportional transition, orange: indifferent transition, red: inverse proportional transition)

		Kabelpad			
t	t+1	90-95		95-01	
		∑(90)	∑(95)	∑(95)	∑(01)
cc1	cc1	12,4%	13,7%	3,4%	3,8%
fc2	cc1	1,0%	2,1%	0,4%	0,9%
fc3	cc1	0,8%	2,0%	0,6%	1,2%
fc4	cc1	0,2%	0,6%		0,1%
fc5	cc1				
fc6	cc1		0,2%		0,1%
cc7	cc1				
cc1	fc2	6,4%	2,7%	7,4%	2,7%
fc2	fc2	3,2%	2,2%	1,6%	1,5%
fc3	fc2	2,5%	2,3%	4,0%	2,2%
fc4	fc2	1,0%	1,1%	0,3%	0,4%
fc5	fc2	0,1%	0,1%	0,1%	0,1%
fc6	fc2	0,2%	0,3%	0,2%	0,2%
cc7	fc2	0,1%		0,1%	
cc1	fc3	9,0%	5,8%	9,6%	6,1%
fc2	fc3	7,2%	9,0%	3,3%	5,2%
fc3	fc3	7,9%	11,0%	10,8%	9,3%
fc4	fc3	3,7%	5,0%	1,6%	3,0%
fc5	fc3	0,7%	0,8%	0,8%	1,0%
fc6	fc3	1,6%	2,6%	1,4%	1,9%
cc7	fc3	0,4%	0,1%	0,5%	0,2%
cc1	fc4	2,2%	0,5%	1,1%	0,3%
fc2	fc4	3,8%	2,1%	1,3%	1,1%
fc3	fc4	4,7%	3,1%	4,2%	3,6%
fc4	fc4	3,4%	2,7%	1,9%	3,1%
fc5	fc4	0,7%	0,5%	1,0%	1,3%
fc6	fc4	1,7%	1,6%	2,3%	2,7%
cc7	fc4	0,5%	0,2%	1,2%	0,7%
cc1	fc5	0,4%	0,1%	0,8%	0,3%
fc2	fc5	1,5%	1,2%	1,0%	1,3%
fc3	fc5	2,6%	2,4%	5,5%	4,3%
fc4	fc5	1,4%	1,7%	1,3%	2,5%
fc5	fc5	0,7%	0,8%	1,3%	1,6%
fc6	fc5	1,1%	1,5%	1,5%	2,0%
cc7	fc5	0,2%	0,1%	0,4%	0,1%
cc1	fc6	1,0%	0,3%	2,4%	0,7%
fc2	fc6	2,8%	2,2%	2,5%	2,8%
fc3	fc6	3,8%	3,6%	9,9%	8,5%
fc4	fc6	3,0%	3,2%	2,9%	5,9%
fc5	fc6	0,7%	0,6%	2,1%	2,9%
fc6	fc6	1,6%	2,0%	3,4%	5,0%
cc7	fc6	0,4%	0,2%	1,3%	0,5%
cc1	cc7	0,1%	0,1%	0,1%	0,1%
fc2	cc7	0,2%	0,5%	0,1%	0,3%
fc3	cc7	0,4%	1,6%	0,4%	1,3%
fc4	cc7	0,9%	2,2%	0,6%	1,7%
fc5	cc7	0,5%	0,9%	0,5%	1,1%
fc6	cc7	0,7%	2,0%	0,5%	1,4%
cc7	cc7	0,8%	0,9%	2,4%	2,7%

		Kabelpad			
t	t+1	90-95		95-01	
		∑(90)	∑(95)	∑(95)	∑(01)
cc1	cc1	12,4%	13,7%	3,4%	3,8%
cc1	fc2	6,4%	2,7%	7,4%	2,7%
cc1	fc3	9,0%	5,8%	9,6%	6,1%
cc1	fc4	2,2%	0,5%	1,1%	0,3%
cc1	fc5	0,4%	0,1%	0,8%	0,3%
cc1	fc6	1,0%	0,3%	2,4%	0,7%
cc1	cc7	0,1%	0,1%	0,1%	0,1%
fc2	cc1	1,0%	2,1%	0,4%	0,9%
fc2	fc2	3,2%	2,2%	1,6%	1,5%
fc2	fc3	7,2%	9,0%	3,3%	5,2%
fc2	fc4	3,8%	2,1%	1,3%	1,1%
fc2	fc5	1,5%	1,2%	1,0%	1,3%
fc2	fc6	2,8%	2,2%	2,5%	2,8%
fc2	cc7	0,2%	0,5%	0,1%	0,3%
fc3	cc1	0,8%	2,0%	0,6%	1,2%
fc3	fc2	2,5%	2,3%	4,0%	2,2%
fc3	fc3	7,9%	11,0%	10,8%	9,3%
fc3	fc4	4,7%	3,1%	4,2%	3,6%
fc3	fc5	2,6%	2,4%	5,5%	4,3%
fc3	fc6	3,8%	3,6%	9,9%	8,5%
fc3	cc7	0,4%	1,6%	0,4%	1,3%
fc4	cc1	0,2%	0,6%		0,1%
fc4	fc2	1,0%	1,1%	0,3%	0,4%
fc4	fc3	3,7%	5,0%	1,6%	3,0%
fc4	fc4	3,4%	2,7%	1,9%	3,1%
fc4	fc5	1,4%	1,7%	1,3%	2,5%
fc4	fc6	3,0%	3,2%	2,9%	5,9%
fc4	cc7	0,9%	2,2%	0,6%	1,7%
fc5	cc1				
fc5	fc2	0,1%	0,1%	0,1%	0,1%
fc5	fc3	0,7%	0,8%	0,8%	1,0%
fc5	fc4	0,7%	0,5%	1,0%	1,3%
fc5	fc5	0,7%	0,8%	1,3%	1,6%
fc5	fc6	0,7%	0,6%	2,1%	2,9%
fc5	cc7	0,5%	0,9%	0,5%	1,1%
fc6	cc1		0,2%		0,1%
fc6	fc2	0,2%	0,3%	0,2%	0,2%
fc6	fc3	1,6%	2,6%	1,4%	1,9%
fc6	fc4	1,7%	1,6%	2,3%	2,7%
fc6	fc5	1,1%	1,5%	1,5%	2,0%
fc6	fc6	1,6%	2,0%	3,4%	5,0%
fc6	cc7	0,7%	2,0%	0,5%	1,4%
cc7	cc1				
cc7	fc2	0,1%		0,1%	
cc7	fc3	0,4%	0,1%	0,5%	0,2%
cc7	fc4	0,5%	0,2%	1,2%	0,7%
cc7	fc5	0,2%	0,1%	0,4%	0,1%
cc7	fc6	0,4%	0,2%	1,3%	0,5%
cc7	cc7	0,8%	0,9%	2,4%	2,7%

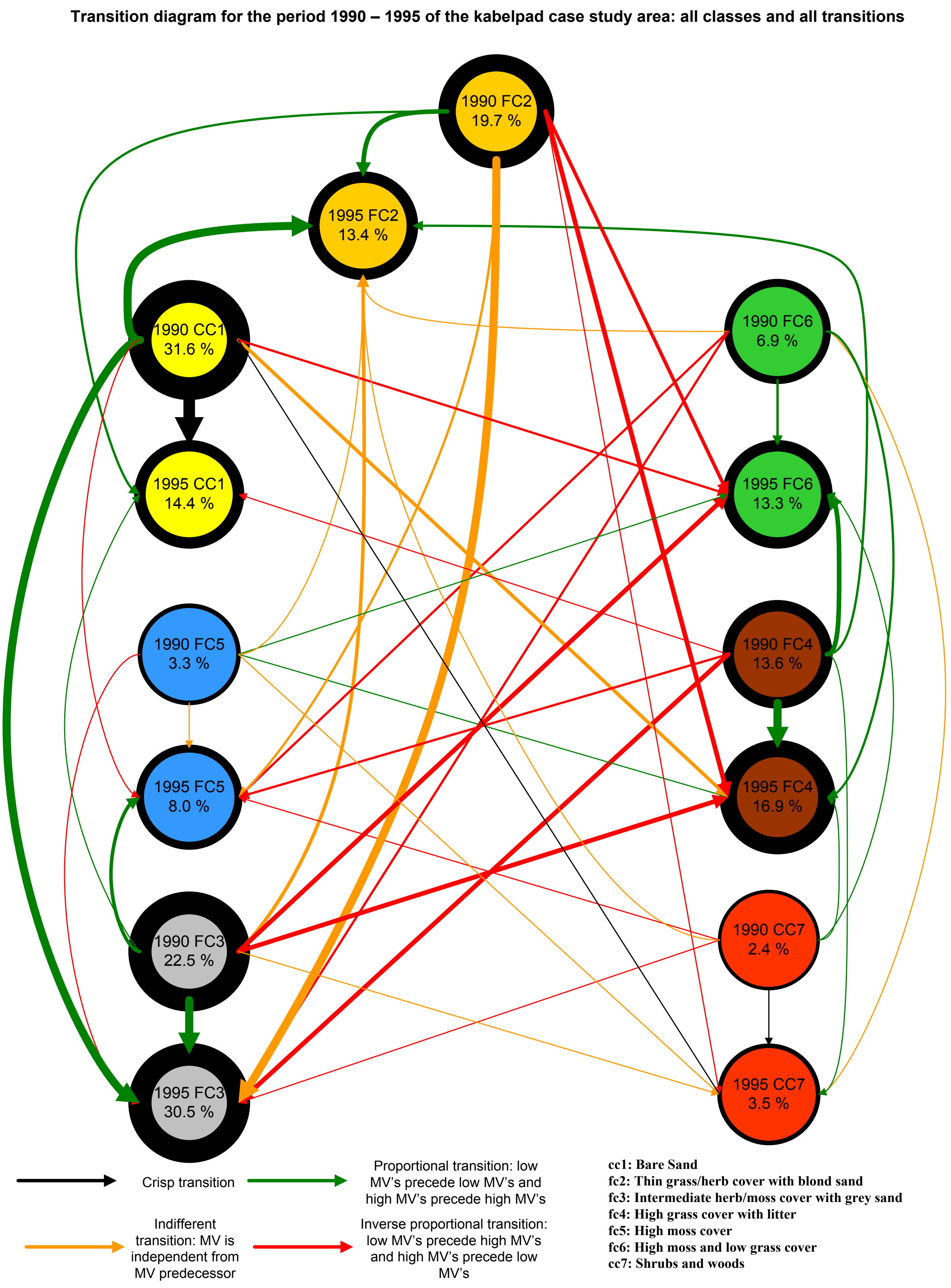

Figure 7-4 Synoptic fuzzy transition diagram of the Kabelpad case study area: 1990-1995

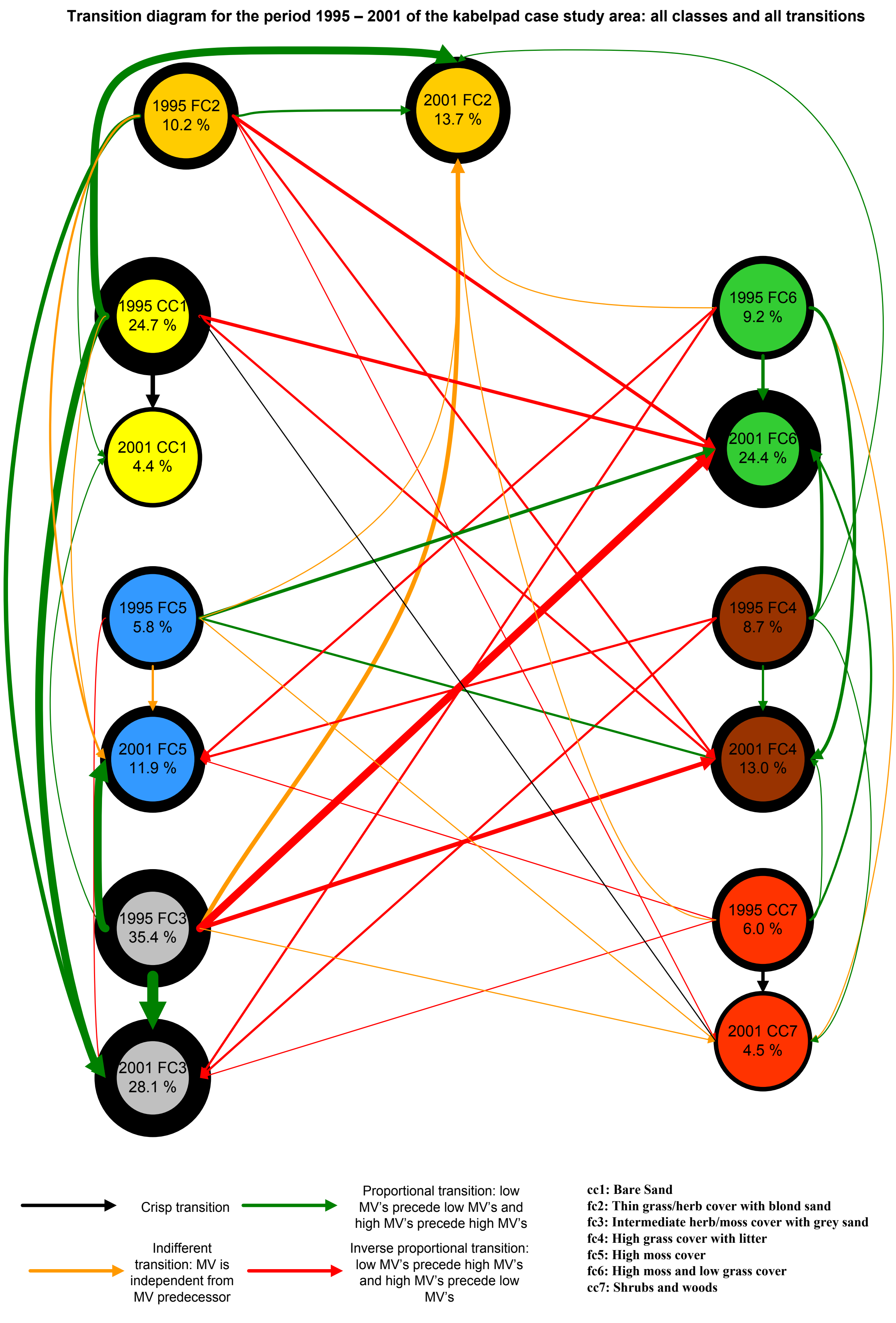

Figure 7-5 Synoptic fuzzy transition diagram of the Kabelpad case study area: 1995-2001

7.4.3 Grass encroachment

The synoptic transition table and transition graphs of the Bierlap case study areas (Table 7-4, Figure 7-6 and Figure 7-7) show vegetation development caused by predominant indifferent succession. The Bierlap case study area used to be dominated by high grass with dead ectorganic material (fc4) (De Bonte et al., 1999). After the introduction of cattle and horses in 1990, De Bonte et al. (1999) report a significant decline of high grass dominance. However, this observation is not supported by the data presented; from 1995 to 2001 it even increases.

When analysing the transitions between the stable states of the Bierlap case study area, the following observations can be made. Stable dune grassland without ectorganic material (fc6) is well represented in the area by indifferent auto-transition and indifferent transition from high dune grassland with dead ectorganic material (fc4). Therefore it can be concluded that class fc6 is, partly, maintained by external factors: grazing by large herbivores. In both periods studied, stable dune grassland without ectorganic material (fc6) also developed by inverse proportional transition from shrubs and woods. From the observed transition type and analogous to the interpretation of the Meijendel case study area and the Kabelpad study area data, shrubs and woods (cc7) and stable dune grassland without ectorganic material (fc6) are interpreted as two separate equilibrium states of the Bierlap case study area. A dominant equilibrium state does not seem to develop.

The most important observation for the evaluation of grazing by cattle and horses are the dynamics of stable dune grassland with ectorganic material (fc4). The transition from shrubs and trees (cc7) to fc4 is interpreted as part of the natural multi-trajectory characteristics of a stabilised dry dune area. The external factor responsible for the mutual indifferent transitions between class fc4 and fc6 is most likely grazing. Because the analysis of the Bierlap case study area is only carried out for the situation after grazing with large herbivores was introduced, it is difficult to formulate general conclusions on the temporal dynamics of grass encroachment in general. However, from the data presented it can be concluded that the development of stable dune grassland with ectorganic material (fc4) from other types of dune grassland is not caused by changes in the internal organization of the system. This conclusion can be interpreted as a confirmation of the results presented by Veer and Kooijman (Veer and Kooijman, 1997; Veer, 1997; Kooijman et al., 1998; Kooijman and Besse, 2002) who describe the importance of Nitrogen and Phosphor as external factors in dune grassland dynamics.

In the case study area a multi trajectory development between some stable states is observed though the occurrence of mainly indifferent transitions suggest an overall instable system where equilibrium states (shrubs and woods and stable dune grassland without ectorganic material) are out of balance.

7.4.4 Shrub encroachment

The synoptic fuzzy transition table (Table 7-5) and synoptic fuzzy transition diagrams (Figure 7-8 and Figure 7-9) representing the dynamics of the parabolic dune case study area show a resemblance with landscape development as observed in the Meijendel case study area as well as the Bierlap case study area. One, stable, equilibrium state that consist of shrubs and trees (cc7) and high grass with dead ectorganic material (fc4) seems to be obvious. When stable, species rich dune grassland (fc6) is also assigned to this stable state there are indications that this state is out of balance. The situation is similar to the Bierlap case study area: transitions from and towards class fc6 are indifferent, in the 1990-1995 period the shrubs are not involved in the transitition, in the period 1995-2001 the transition from shrubs towards stable short dune grassland (fc6) becomes important. This is interpreted as an effect of grazing by large herbivores. Furthermore, it can be observed that proportional transition within the stable state of the dune landscape becomes less significant, this is interpreted as an indication of increasing instability of the system.

Despite the fact that stable dune grassland is an important element in the parabolic dune case study area, shrubs (cc7) tend towards dominance. This is mainly caused by proportional transition from different stable states. Inverse proportional transition from dynamic states towards shrubs is negligible. Therefore, it can be concluded that in the parabolic dune case study area the development of *Hippophae rhanmoides* shrub is a natural process of increasing internal organization within the system.

Table 7-4 Synoptic fuzzy transition tables of the Bierlap case study area (black: crisp transition, green: proportional transition, orange: indifferent transition, red: inverse proportional transition)

		Bierlap			
t	t+1	90-95		95-01	
		∑(90)	∑(95)	∑(95)	∑(01)
cc1	cc1				
fc2	cc1				
fc3	cc1				
fc4	cc1				
fc5	cc1				
fc6	cc1				
cc7	cc1				
cc1	fc2				
fc2	fc2				
fc3	fc2		0,1%	0,1%	0,1%
fc4	fc2	0,2%	0,1%	0,1%	0,1%
fc5	fc2				
fc6	fc2	0,1%	0,1%	0,2%	0,1%
cc7	fc2	0,2%	0,1%	0,4%	0,1%
cc1	fc3				
fc2	fc3	0,1%	0,1%	0,1%	0,1%
fc3	fc3	1,2%	1,2%	1,1%	1,3%
fc4	fc3	5,2%	2,5%	2,3%	1,8%
fc5	fc3	0,2%	0,1%	0,2%	0,2%
fc6	fc3	3,9%	2,2%	3,2%	1,8%
cc7	fc3	4,3%	1,0%	2,4%	0,6%
cc1	fc4				
fc2	fc4	0,2%	0,3%	0,1%	0,2%
fc3	fc4	1,8%	2,8%	2,7%	5,6%
fc4	fc4	8,0%	5,8%	6,4%	9,0%
fc5	fc4	0,4%	0,4%	0,8%	1,4%
fc6	fc4	6,2%	5,3%	9,3%	8,9%
cc7	fc4	7,7%	3,1%	9,2%	5,0%
cc1	fc5				
fc2	fc5				
fc3	fc5	0,2%	0,3%	0,2%	0,3%
fc4	fc5	1,3%	0,7%	0,5%	0,4%
fc5	fc5	0,2%	0,2%	0,1%	0,1%
fc6	fc5	1,2%	0,7%	0,7%	0,4%
cc7	fc5	1,7%	0,7%	1,2%	0,3%
cc1	fc6				
fc2	fc6	0,2%	0,3%	0,1%	0,2%
fc3	fc6	1,8%	3,8%	2,9%	5,6%
fc4	fc6	7,9%	8,6%	6,6%	8,3%
fc5	fc6	0,4%	0,5%	0,9%	1,5%
fc6	fc6	6,2%	7,9%	9,6%	8,2%
cc7	fc6	7,2%	3,3%	8,9%	3,0%
cc1	cc7				
fc2	cc7	0,1%	0,7%		0,1%
fc3	cc7	1,1%	4,8%	0,4%	1,9%
fc4	cc7	3,1%	7,2%	1,5%	3,7%
fc5	cc7	0,9%	2,2%	0,6%	1,3%
fc6	cc7	2,7%	7,2%	1,5%	3,4%
cc7	cc7	24,1%	25,8%	25,1%	24,8%

		Bierlap			
t	t+1	90-95		95-01	
		∑(90)	∑(95)	∑(95)	∑(01)
cc1	cc1				
cc1	fc2				
cc1	fc3				
cc1	fc4				
cc1	fc5				
cc1	fc6				
cc1	cc7				
fc2	cc1				
fc2	fc2				
fc2	fc3	0,1%	0,1%	0,1%	0,1%
fc2	fc4	0,2%	0,3%	0,1%	0,2%
fc2	fc5				
fc2	fc6	0,2%	0,3%	0,1%	0,2%
fc2	cc7	0,1%	0,7%		0,1%
fc3	cc1				
fc3	fc2		0,1%	0,1%	0,1%
fc3	fc3	1,2%	1,2%	1,1%	1,3%
fc3	fc4	1,8%	2,8%	2,7%	5,6%
fc3	fc5	0,2%	0,3%	0,2%	0,3%
fc3	fc6	1,8%	3,8%	2,9%	5,6%
fc3	cc7	1,1%	4,8%	0,4%	1,9%
fc4	cc1				
fc4	fc2	0,2%	0,1%	0,1%	0,1%
fc4	fc3	5,2%	2,5%	2,3%	1,8%
fc4	fc4	8,0%	5,8%	6,4%	9,0%
fc4	fc5	1,3%	0,7%	0,5%	0,4%
fc4	fc6	7,9%	8,6%	6,6%	8,3%
fc4	cc7	3,1%	7,2%	1,5%	3,7%
fc5	cc1				
fc5	fc2				
fc5	fc3	0,2%	0,1%	0,2%	0,2%
fc5	fc4	0,4%	0,4%	0,8%	1,4%
fc5	fc5	0,2%	0,2%	0,1%	0,1%
fc5	fc6	0,4%	0,5%	0,9%	1,5%
fc5	cc7	0,9%	2,2%	0,6%	1,3%
fc6	cc1				
fc6	fc2	0,1%	0,1%	0,2%	0,1%
fc6	fc3	3,9%	2,2%	3,2%	1,8%
fc6	fc4	6,2%	5,3%	9,3%	8,9%
fc6	fc5	1,2%	0,7%	0,7%	0,4%
fc6	fc6	6,2%	7,9%	9,6%	8,2%
fc6	cc7	2,7%	7,2%	1,5%	3,4%
cc7	cc1				
cc7	fc2	0,2%	0,1%	0,4%	0,1%
cc7	fc3	4,3%	1,0%	2,4%	0,6%
cc7	fc4	7,7%	3,1%	9,2%	5,0%
cc7	fc5	1,7%	0,7%	1,2%	0,3%
cc7	fc6	7,2%	3,3%	8,9%	3,0%
cc7	cc7	24,1%	25,8%	25,1%	24,8%

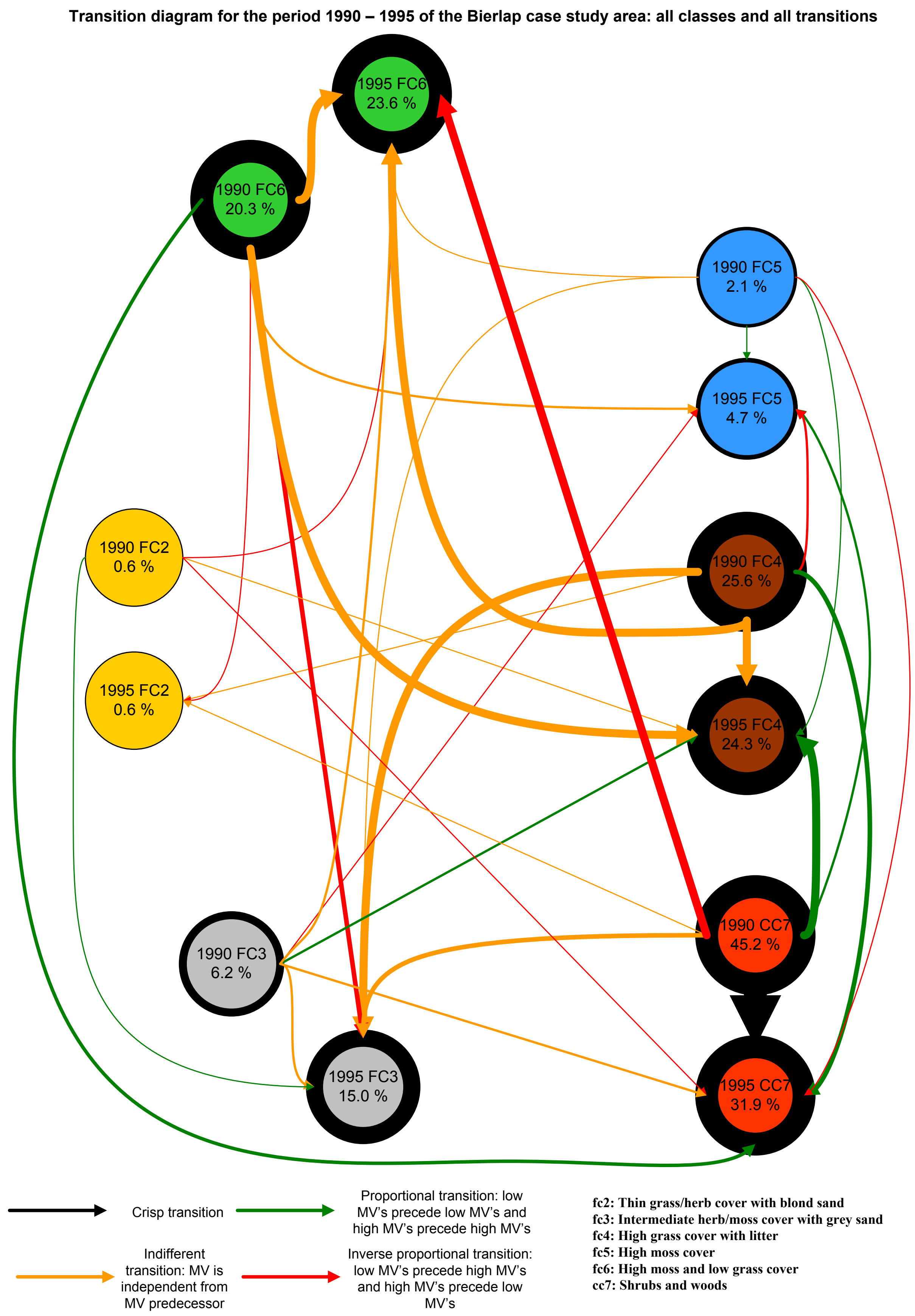

Figure 7-6 Synoptic fuzzy transition diagram of the Bierlap case study area: 1990-1995

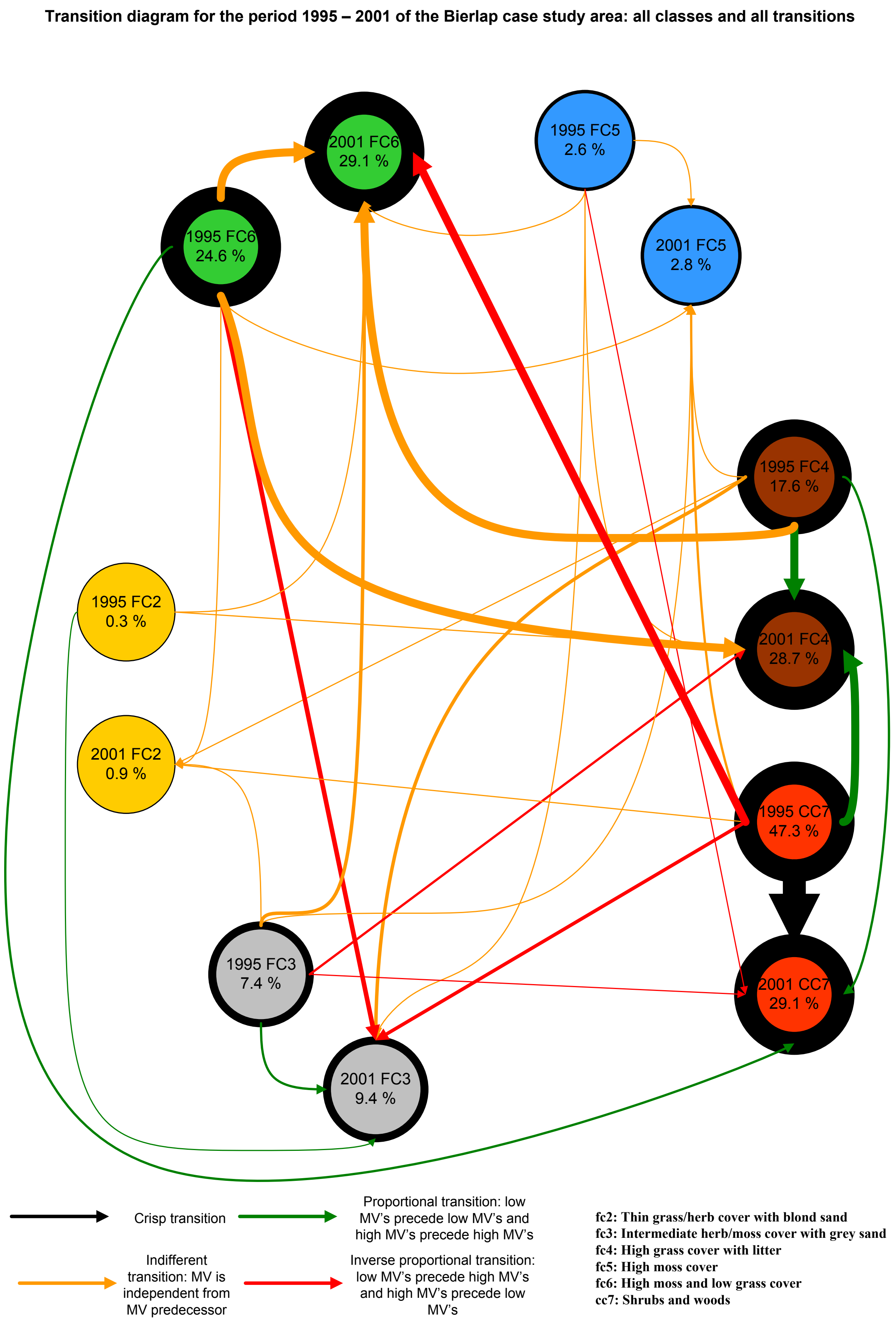

Figure 7-7 Synoptic fuzzy transition diagrams of the Bierlap case study area: 1995-2001

Table 7-5 Synoptic fuzzy transition table of the Parabolic dune case study area (black: crisp transition, green: proportional transition, orange: indifferent transition, red: inverse proportional transition)

		Parabole dune			
t	t+1	90-95		95-01	
		∑(90)	∑(95)	∑(95)	∑(01)
cc1	cc1				
fc2	cc1				
fc3	cc1		0,1%		
fc4	cc1				
fc5	cc1				
fc6	cc1				
cc7	cc1				
cc1	fc2				
fc2	fc2	0,1%	0,1%		
fc3	fc2	0,3%	0,2%	0,1%	0,1%
fc4	fc2	0,3%	0,2%	0,1%	0,1%
fc5	fc2	0,1%	0,1%	0,1%	
fc6	fc2	0,2%	0,2%	0,1%	
cc7	fc2	0,1%		0,5%	0,1%
cc1	fc3				
fc2	fc3	0,3%	0,3%	0,1%	0,1%
fc3	fc3	2,3%	2,1%	1,0%	0,6%
fc4	fc3	3,5%	2,6%	1,0%	0,7%
fc5	fc3	3,4%	1,7%	1,2%	0,6%
fc6	fc3	4,4%	3,0%	1,1%	0,7%
cc7	fc3	0,9%	0,2%	2,6%	0,6%
cc1	fc4			0,1%	
fc2	fc4	0,3%	0,3%	0,2%	0,3%
fc3	fc4	2,7%	2,6%	2,8%	4,3%
fc4	fc4	6,0%	4,6%	3,9%	6,1%
fc5	fc4	4,2%	2,0%	4,6%	4,8%
fc6	fc4	6,5%	4,8%	5,1%	6,2%
cc7	fc4	2,2%	0,8%	9,0%	4,6%
cc1	fc5				
fc2	fc5	0,1%	0,1%	0,1%	0,1%
fc3	fc5	1,8%	2,5%	1,5%	1,3%
fc4	fc5	4,9%	5,0%	1,4%	1,4%
fc5	fc5	4,4%	3,0%	2,5%	1,6%
fc6	fc5	5,5%	5,6%	1,8%	1,4%
cc7	fc5	2,0%	0,8%	3,4%	0,9%
cc1	fc6			0,1%	
fc2	fc6	0,2%	0,2%	0,3%	0,3%
fc3	fc6	2,5%	2,9%	3,7%	4,8%
fc4	fc6	5,8%	5,2%	4,3%	5,8%
fc5	fc6	4,3%	2,7%	5,6%	5,3%
fc6	fc6	6,5%	5,6%	5,8%	6,0%
cc7	fc6	2,0%	0,6%	8,9%	3,3%
cc1	cc7				
fc2	cc7	0,2%	0,5%	0,1%	0,2%
fc3	cc7	2,1%	7,2%	0,8%	3,1%
fc4	cc7	5,8%	10,9%	2,9%	6,6%
fc5	cc7	3,1%	4,8%	3,1%	5,9%
fc6	cc7	5,1%	11,5%	2,4%	5,8%
cc7	cc7	5,8%	4,9%	17,4%	16,2%

		Parabole dune			
t	t+1	90-95		95-01	
		∑(90)	∑(95)	∑(95)	∑(01)
cc1	cc1				
cc1	fc2				
cc1	fc3				
cc1	fc4			0,1%	
cc1	fc5				
cc1	fc6			0,1%	
cc1	cc7				
fc2	cc1				
fc2	fc2	0,1%	0,1%		
fc2	fc3	0,3%	0,3%	0,1%	0,1%
fc2	fc4	0,3%	0,3%	0,2%	0,3%
fc2	fc5	0,1%	0,1%	0,1%	0,1%
fc2	fc6	0,2%	0,2%	0,3%	0,3%
fc2	cc7	0,2%	0,5%	0,1%	0,2%
fc3	cc1		0,1%		
fc3	fc2	0,3%	0,2%	0,1%	0,1%
fc3	fc3	2,3%	2,1%	1,0%	0,6%
fc3	fc4	2,7%	2,6%	2,8%	4,3%
fc3	fc5	1,8%	2,5%	1,5%	1,3%
fc3	fc6	2,5%	2,9%	3,7%	4,8%
fc3	cc7	2,1%	7,2%	0,8%	3,1%
fc4	cc1				
fc4	fc2	0,3%	0,2%	0,1%	0,1%
fc4	fc3	3,5%	2,6%	1,0%	0,7%
fc4	fc4	6,0%	4,6%	3,9%	6,1%
fc4	fc5	4,9%	5,0%	1,4%	1,4%
fc4	fc6	5,8%	5,2%	4,3%	5,8%
fc4	cc7	5,8%	10,9%	2,9%	6,6%
fc5	cc1				
fc5	fc2	0,1%	0,1%	0,1%	
fc5	fc3	3,4%	1,7%	1,2%	0,6%
fc5	fc4	4,2%	2,0%	4,6%	4,8%
fc5	fc5	4,4%	3,0%	2,5%	1,6%
fc5	fc6	4,3%	2,7%	5,6%	5,3%
fc5	cc7	3,1%	4,8%	3,1%	5,9%
fc6	cc1				
fc6	fc2	0,2%	0,2%	0,1%	
fc6	fc3	4,4%	3,0%	1,1%	0,7%
fc6	fc4	6,5%	4,8%	5,1%	6,2%
fc6	fc5	5,5%	5,6%	1,8%	1,4%
fc6	fc6	6,5%	5,6%	5,8%	6,0%
fc6	cc7	5,1%	11,5%	2,4%	5,8%
cc7	cc1				
cc7	fc2	0,1%		0,5%	0,1%
cc7	fc3	0,9%	0,2%	2,6%	0,6%
cc7	fc4	2,2%	0,8%	9,0%	4,6%
cc7	fc5	2,0%	0,8%	3,4%	0,9%
cc7	fc6	2,0%	0,6%	8,9%	3,3%
cc7	cc7	5,8%	4,9%	17,4%	16,2%

Transition diagram for the period 1990 – 1995 of the Parabolic dune case study area: all classes and all transitions

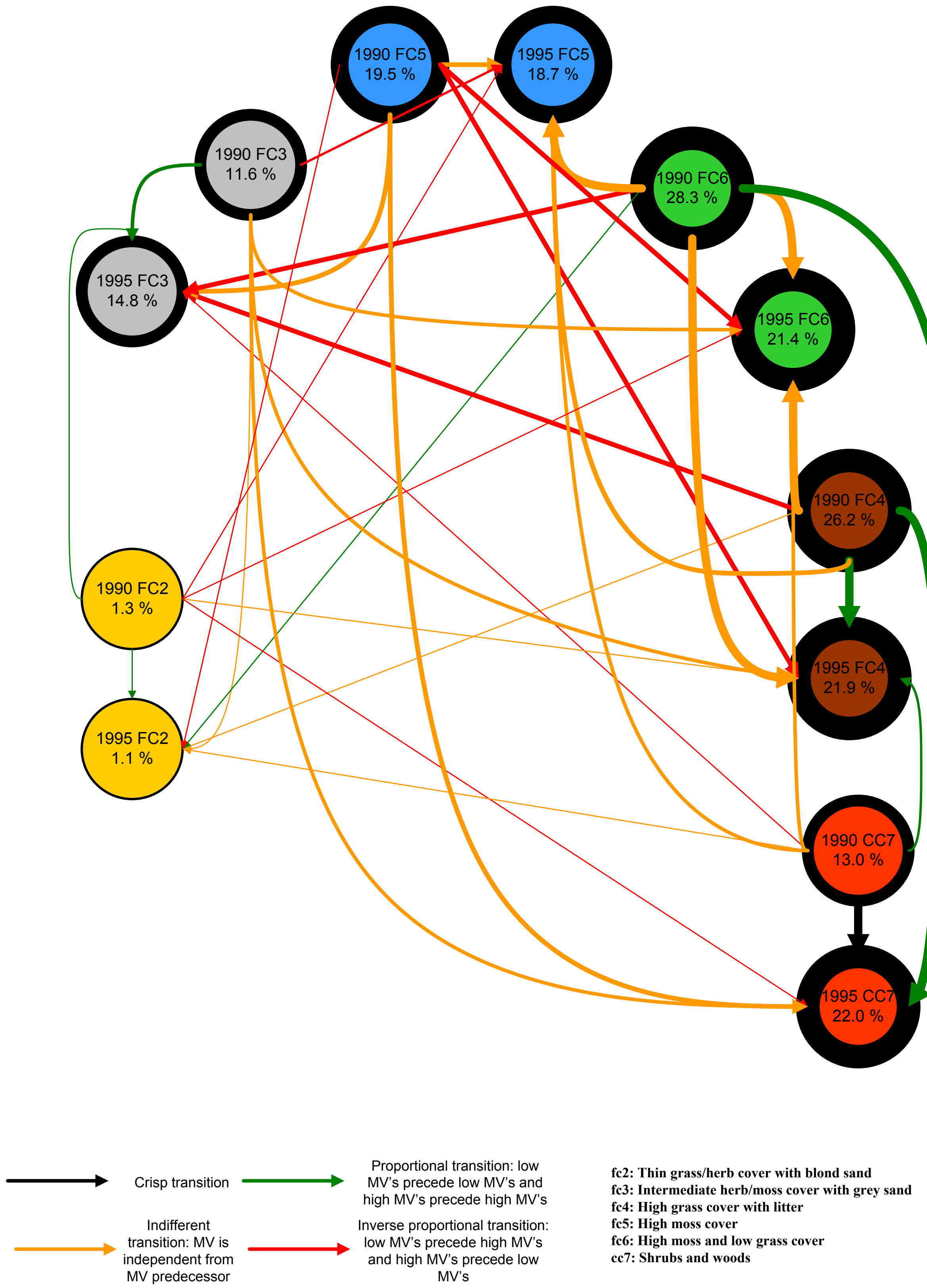

Figure 7-8 Synoptic fuzzy transition diagram of the parabolic dune case study area: 1990-1995

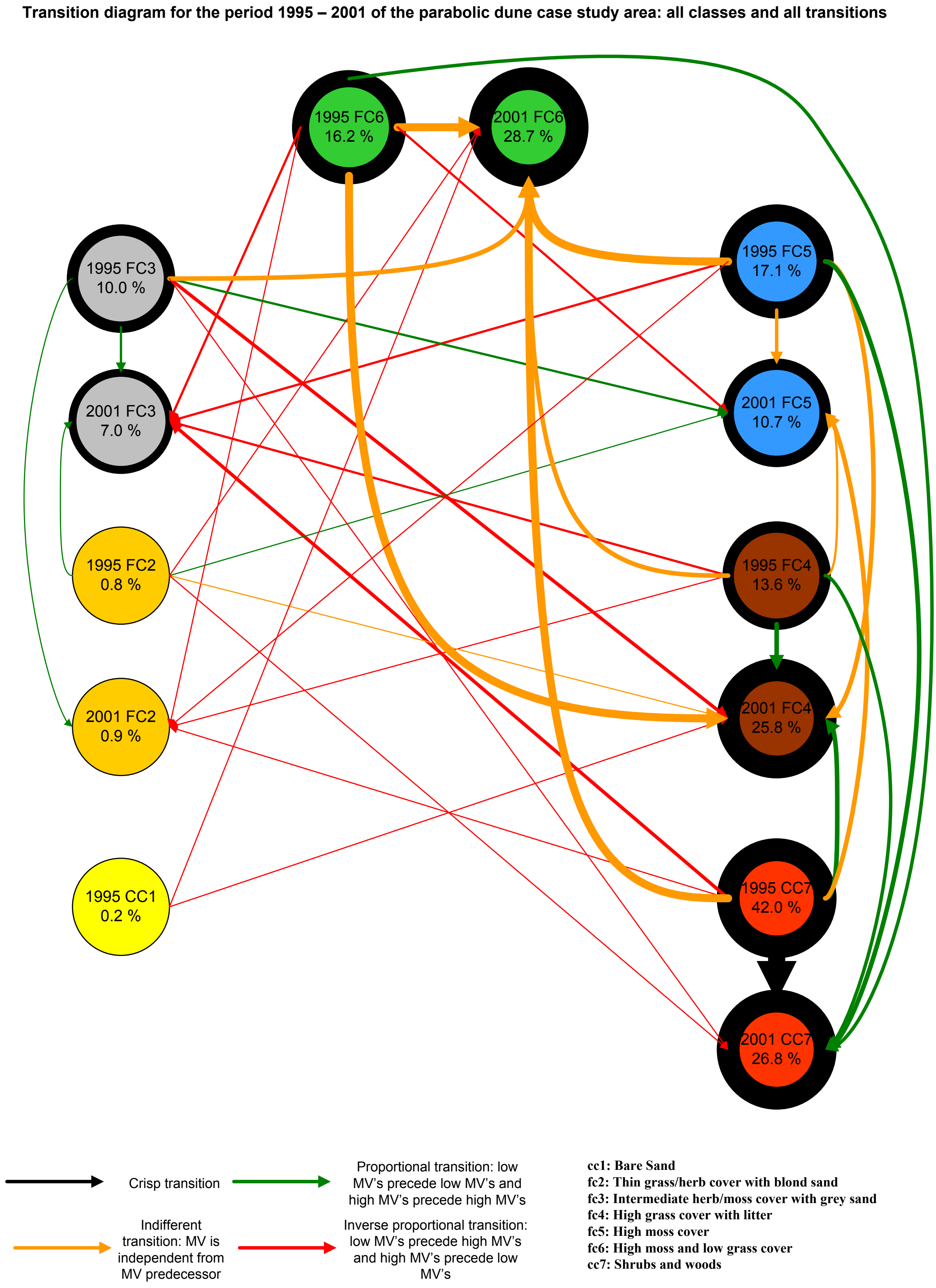

Figure 7-9 Synoptic fuzz transition diagram of the parabolic dune case study area: 1995-2001

7.5 Discussion

The Meijendel case study area is a relative large area with a good representation of all possible states of a dry dune area. It is striking that nearly every possible transition occurs in the Meijendel case study area and that the majority of opposing transitions (the transition from class B to class A is opposed by the transition from class A to class B) are semantically equal. Moreover, the construction of a transition diagram according to the rules described in section 7.3.1 is, in general, possible for both time intervals. This is interpreted as a confirmation of the basic conceptual assumption: landscape development in a small-scale dynamic ecosystem is a multi-trajectory process where the transitions have diverse, though explicable, characteristics. The development of small-scale dynamic ecosystems is not chaotic though chance elements are surely part of the process as a whole.

Conclusive models of vegetation development are presented in Figure 7-10 - Figure 7-13. The arrows indicate semantic transition types to and from individual classes as well as semantic transition types to and from groups of classes. Grouped classes represent stable or dynamic (equilibrium) states of the landscape.

A general model for vegetation development in dry coastal dunes is presented in Figure 7-10: two equilibrium states that change after a threshold is passed where a hysteresis effect is the explanation of the relative stability of the two equilibrium states. Within the equilibrium states, proportional transitions are dominant. This general model can be applied to the dynamic dry dune area as a whole, when applying this model to selected parts of the area some comments can be made.

The Kabelpad case study was selected for its aeolian activity. From the results presented it is clear that the case study area is primarily typical for a stabilizing dry dune area after aeolian activity. The model that is developed for this area (Figure 7-11) is nearly similar to the general model, the only difference is found in the transition between the class typical for fresh blown-in sand (fc2) and dynamic grey dunes (fc3). This is the effect of aeolian activity with a low intensity so the vegetation cover remains intact but the species composition is influenced.

When examining the models of vegetation development in dune areas with grass encroachment (Figure 7-12) and shrub encroachment (Figure 7-13) the general model is only partly recognized. This is caused by the fact that classes typical for dynamic dry dunes are rare in these areas: grass and shrub encroachment are processes in stable dune areas. The implication of the position of class fc6 in both models is important. Stable dune grassland with a short turf is generally accepted as an important state from a nature conservation point of view (Veer & Kooijman, 1997). From the models presented it can be concluded that this state only develops by indifferent and inverse proportional succession in areas with grass and shrub encroachment and managed by grazing with large herbivores. Although the favoured vegetation type has a positive trend, the observed imbalance of the system as a whole, due to grazing, is not favourable.

This observation cannot be generalised because it is based on relative small case study areas of one coastal dune area (see Table 7-1). However the approach presented in this chapter is promising and it is recommended to apply it to more dune areas and time-intervals. The main shortcoming of the analysis presented is the fact that no comparison can be made between grazed and not-grazed areas. General observation is that the vegetation structure of the Meijendel case study area, including the Kabelpad and Parabolic dune case study areas, is only slightly influenced by grazing and the Bierlap case study area is considerably influenced by grazing.

From the models of vegetation development presented in Figure 7-10 - Figure 7-13 it can be concluded that the optimal situation for a dry coastal dune area is the co-existence of two equilibrium states composed of several vegetation structure types (dynamic states and stable states). The dynamics of this optimal situation are according to the multi-trajectory model. This means that any vegetation structure can be replaced by any vegetation structure with the limiting condition that states within the two equilibrium states change proportional and changes between the two equilibrium states are inverse proportional. Now it can be questioned whether stabilizing processes like grass and shrub encroachment, as well as destabilizing processes like grazing by large herbivores and aeolian activity, are positive for the multi trajectory character of dry dune ecosystems. This is discussed in the following section where the results are interpreted for their relevance in terrain management.

In Chapter 5, a conceptual model is presented for the dry coastal dunes; they are represented as a spatio-temporal-semantic dynamic space. The integration of this model with the results presented in this chapter result in the observation that the diagonal line in Figure 5-3, representing the decrease in temporal dynamics, combined with the increase in semantic complexity and spatial complexity or vice versa is, in term of landscape development, not a continuous process. The centre of the three-dimensional space presented in Figure 5-3 is crucial in the development of dry coastal dunes. This centre is found between grey dunes (fc3) and stable dune grassland (fc6). So, at a medium level of temporal dynamics, spatial complexity and semantic complexity the system can alternate from dynamic to stable or vice versa. The underlying or initiating mechanism is not recognised though level of organisation, characterized by the number and intensity of positive and negative feed-back relations, is crucial. At this point proportional transition in dynamic states, initiated by positive feedback mechanisms, changes in proportional transition in stable states initiated by negative feedback mechanisms. Major difficulty in recognising the mechanism is the fact that the temporal dynamics, in contrast to the spatial and semantic complexity, are not observed as a continuum. The time lag of five years between the photos, makes it impossible to determine whether proportional transitions that take place within an equilibrium state are direct or have transient states. Increasing the frequency of orthophoto production is not practical for reasons of organization and costs. It is therefore recommended to use sequential relevée information for study of the temporal continuum and find indications for the mechanism that causes the (inverse proportional) transition from dynamic to stable and vice versa. As hypothesized in section 7.4, it is most likely a hysteresis effect though the effect is not confirmed.

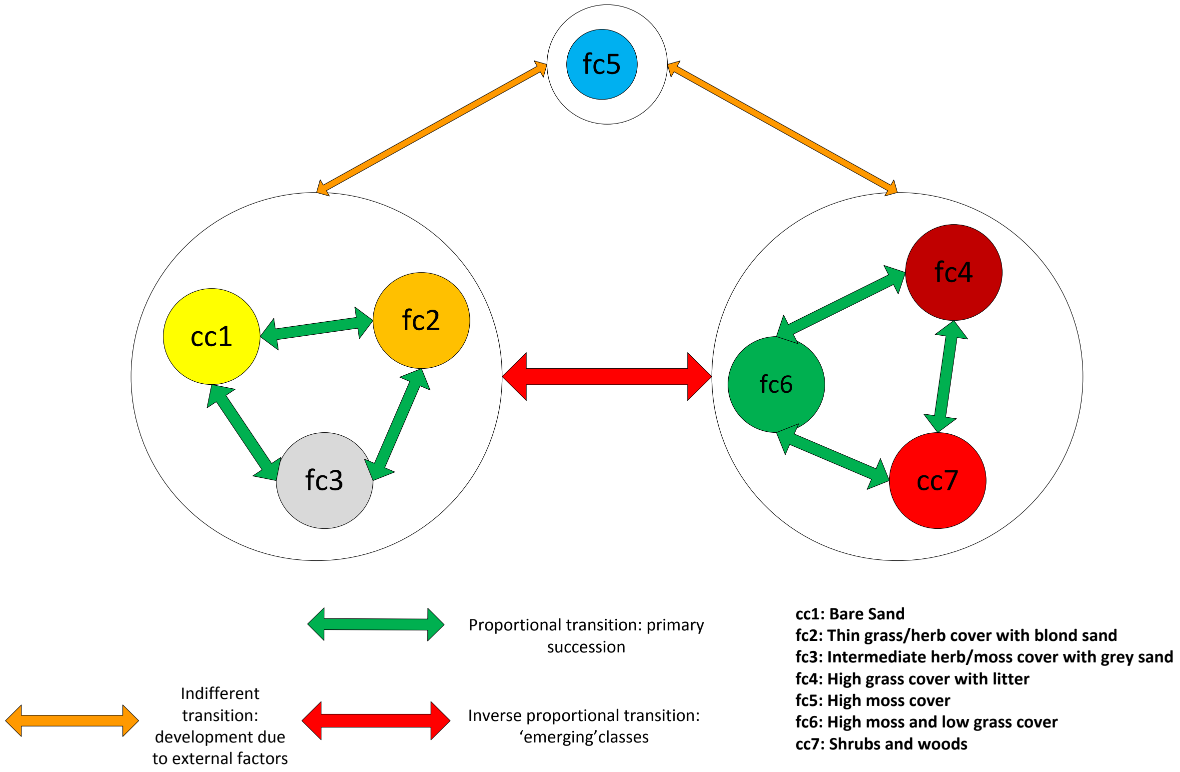

Figure 7-10 General model of vegetation development in dry coastal dunes

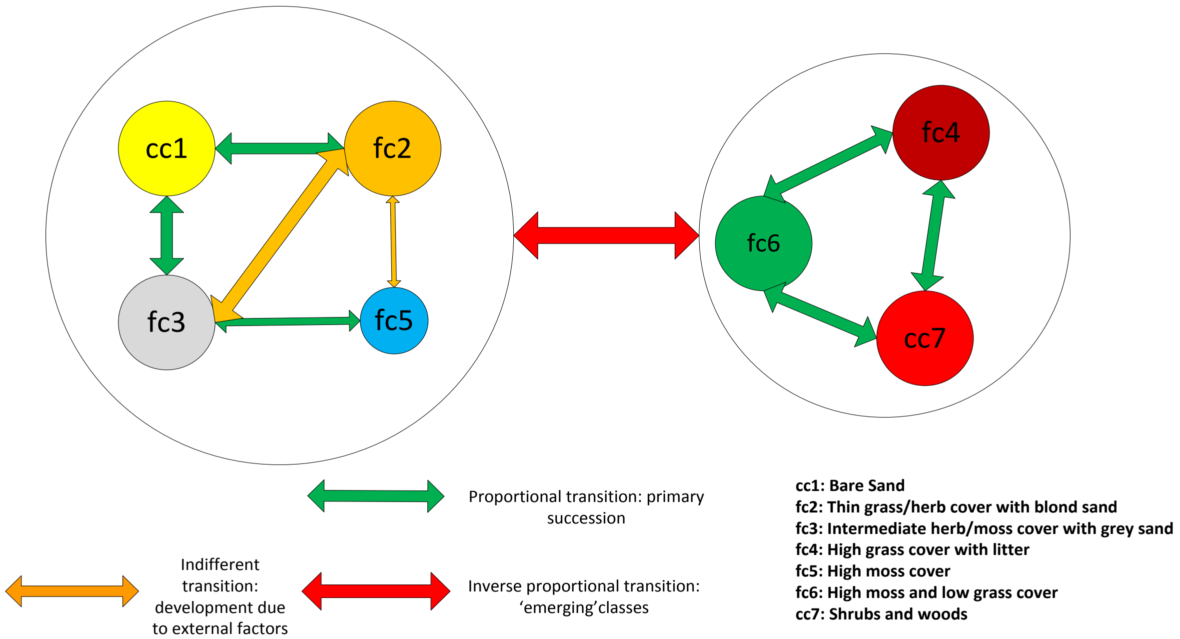

Figure 7-11 Model of vegetation development in a stabilizing dune area after aeolian activity

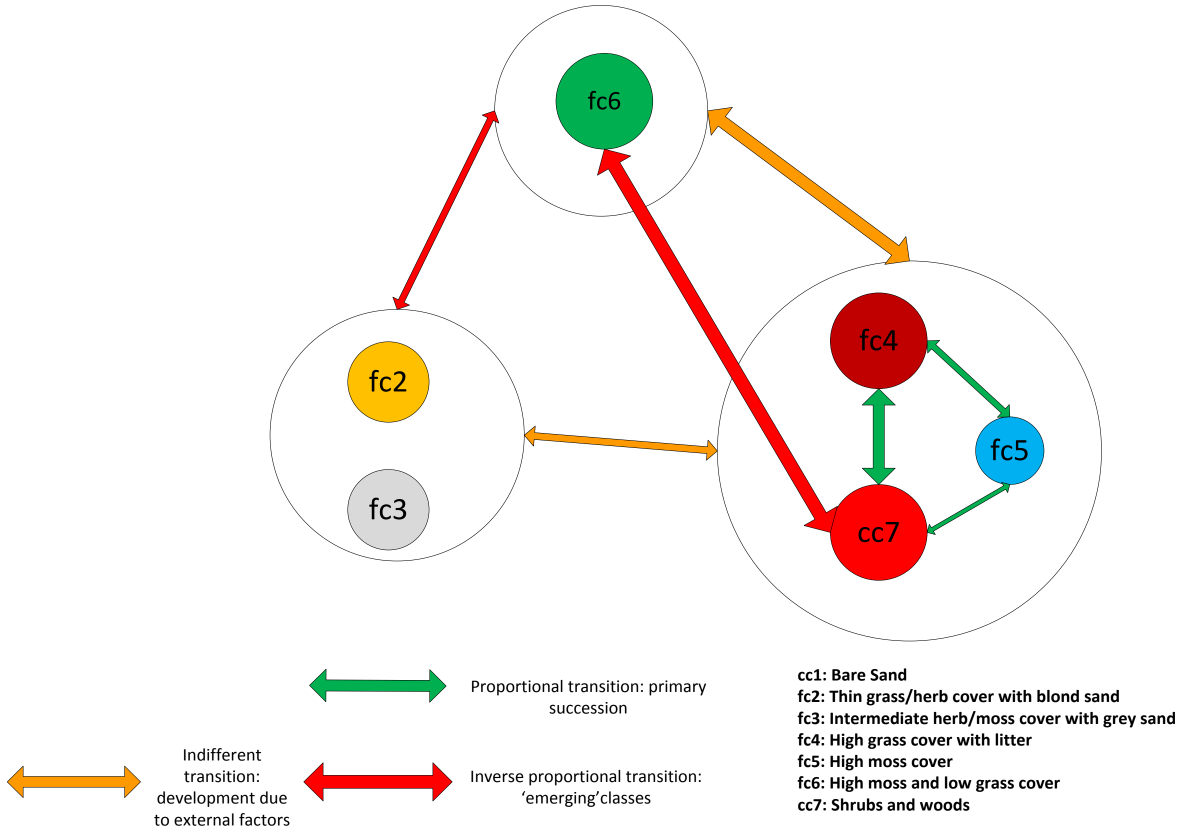

Figure 7-12 Model of vegetation develoment in a dune area with grass encroachment

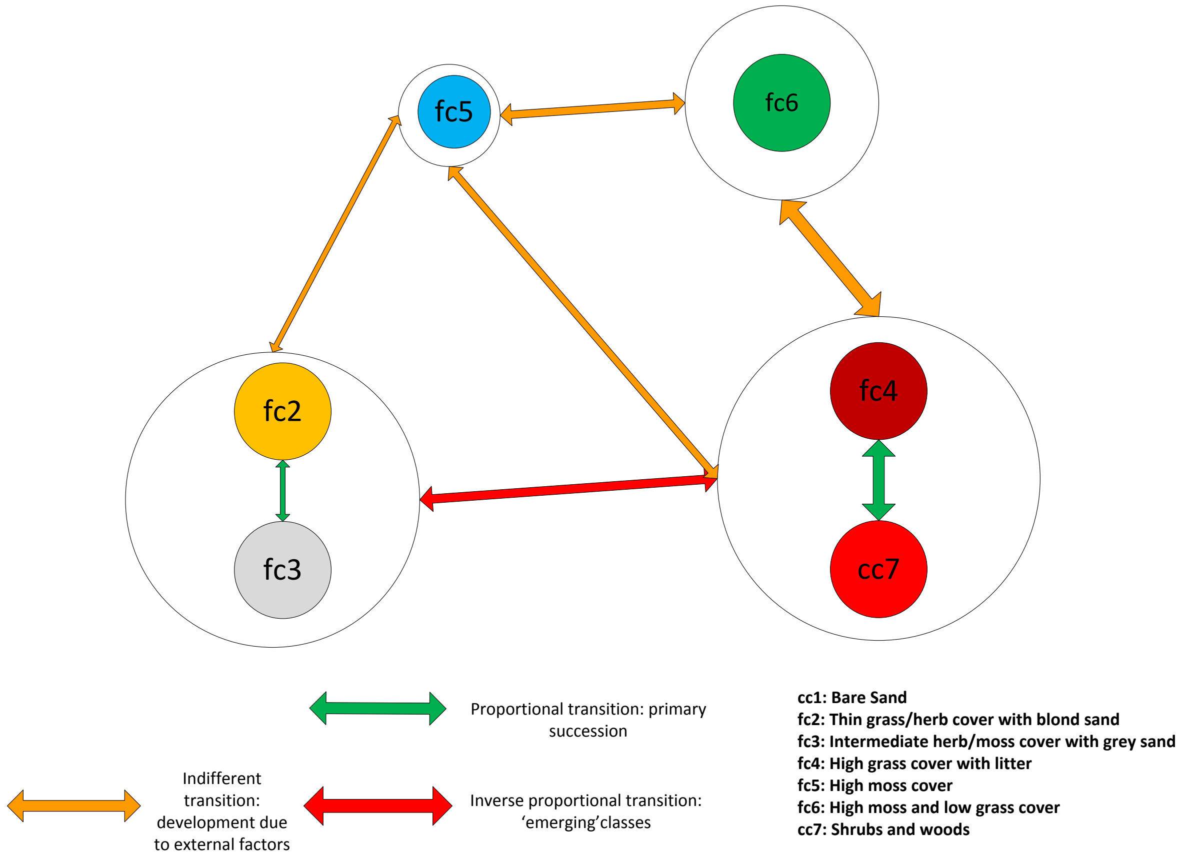

Figure 7-13 Model of vegetation development in a dune area with shrub encroachment

7.6 Conclusion and recommendations for the management of dry coastal dune grasslands

Small-scale dynamic ecosystems, dry coastal dunes in particular, are primarily self-organizing systems where the balance between abiotic and biotic processes results in a landscape with a high variation in temporal dynamics, spatial complexity and semantic complexity. The idea of non-equilibrium dynamics in vegetation as postulated by Anand (2000) seems to be obvious: vegetation dynamics alternate between determinism and turbulence. This seems to be in agreement with the Serial Landscape Model where the state of the landscape, as revealed in the spatial, temporal and semantic domain, can range from converging (deterministic) to diverging (turbulent). However, there is no conformity between stability, convergence and determinism on the one hand and dynamics, divergence and turbulence on the other hand. Dry coastal dunes are in dynamic balance between two equilibrium states: the dynamic, mainly converging state and the stable, mainly diverging state. Within these states, transitions are more or less deterministic by proportional transitions. The transition between the two states is also deterministic by inverse proportional transition. Instability of the equilibrium states is caused by indifferent transition and can be characterized as turbulent.

When translating these findings to management it has to be concluded that introduction of turbulence in small-scale dynamic ecosystems results in a landscape out of balance and the management goal is not achieved. This conclusion is especially valid for the stable equilibrium state of the landscape. Introducing large herbivores in a landscape characterized by low spatial complexity and temporal dynamics, and high semantic complexity (typical for grass encroachment), results in a landscape that is out of balance. Attention has to be paid to the establishment of a new equilibrium. When the landscape remains out of balance, a species-poor vegetation with indicators of disturbance will develop. The introduction of turbulence to achieve a dynamic equilibrium state by, for instance rejuvenation of blowouts, can be successful because this type of turbulence is non-recurrent. After tillage of the soil (Riksen, 2006), natural biotic and abiotic processes of the system are responsible for the further development.

General conclusion concerning the management of dry dunes in particular and small-scale dynamic ecosystems in general is that the aim should always be to achieve an equilibrium state of the landscape by as little prolonged turbulence as possible and as much processes of the system itself. Therefore, a sequence for the decision of management intervention is proposed.

At first, the most advisable is a non-recurrent management intervention like tillage or rejuvenation of complete dunes (Arens et al., 2004; Arens and Geelen, 2006; Riksen, 2006; Koster, 2009). Example of ecosystem restoration of another small-scale dynamic ecosystem like rivers is re-meandering (Fjorback et al., 2002; Palmer et al., 2005). These nonrecurrent management interventions are spatial, temporal and semantic radical: it effects a large area, is catastrophic and a totally new situation occurs.

When the spatial extent of the intervention is limited by other functions of the area (recreation, agriculture, etc.) and a radical intervention is not possible, a periodic intervention with an interval of at least one year should be executed. Examples in dry dunes are burning (Kettner-Oostra et al., 2006), cutting (Kutiel et al., 2000) and mowing (Veer, 1998). Only when nonrecurring radical interventions or periodic interventions are not possible, some form of constant intervention like grazing by large herbivores should be performed. Notwithstanding the constant turbulence administered to the system, resulting in a system out-of-balance, grazing by large herbivores is a widely applied management intervention in small-scale dynamic ecosystem and the data presented show satisfactory results. However it is important to realize that the results are achieved in a landscape out-of-balance.

The optimal management intervention in small-scale dynamic ecosystems is doing nothing. However, when external factors like atmospheric deposition or high mortality of herbivores that are natural part of the system (rabbits in coastal dunes) bring the system out-of-balance there should be intervention. When referring to the manager's framework presented in chapter 2 (Figure 2-1), it can be concluded that in small-scale dynamic ecosystems interventions have to be reverse to the sequence presented in Figure 2-1. In large, mainly self-supporting ecosystems, the intervention (when necessary) should be digging and in small, highly managed ecosystems, the intervention can be grazing.

8 SYNTHESIS AND CONCLUSIONS

8.1 General

In this thesis, an unified concept for the spatial, temporal and semantic characteristics of a small-scale dynamic ecosystem is given. Several techniques are developed and used to describe dry coastal dunes, which are highly representative for such dynamic systems. These techniques are each typical for the perception of one of the three domains as presented in the Serial Landscape Model (Chapter 1). Fuzzy image interpretation as first presented by Droesen (1999) is applied in the description of the *spatial* domain (Chapter 2). For the accuracy assessment of its results a new technique, based on the crisp image interpretation error matrix (Foody, 2002), is proposed and applied (Chapter 3). For the description of the *semantic* domain, techniques for digital image interpretation (Lillesand et al., 2008) and multivariate techniques for vegetation science (Jongman et al., 1995) are combined (Chapter 4). Hierarchy theory, a general accepted concept in Landscape Ecology, led to the combination of the *spatial* domain (fuzzy image interpretation) with the *semantic* domain at an expected higher level of organization (landscape guided stratification) (Chapter 5). This induced the development of a new landscape ecological concept for small-scale dynamic ecosystems (Figure 5-3). For the description of the *temporal* domain, a new technique had to be developed (Chapter 6). The sequential analysis of fuzzy image interpretation maps with fuzzy transition graphs, tables and diagrams led to the recognition of, semantically distinctive types of transition. Based on the techniques developed, the integration of processes and their semantic implications were presented in Chapter 7. From this short enumeration of techniques applied and developed in the detailed landscape ecological analyses it is clear that significant advances in landscape research can be achieved by the application of new techniques.
This conclusion was drawn before by, for instance, Turner & Gardner (1991), Golley (1987) and Farina (2006) though their focus is on numeric spatial methods like digital image interpretation, GIS and spatial indices. This thesis shows that the combination of different numerical methods applied in spatial, temporal or thematic research leads to an improvement of landscape ecological research. The integration of these methods can only succeed when a sound concept is used. From the results presented in Chapter 7 and its general implications for the management of small-scale dynamic ecosystems it can be concluded that the procedure of alternate development of concepts and techniques for understanding the structure and functioning of the landscape is successful: it generates new and challenging perspectives. These perspectives relate to further comprehension of landscape development, advances in landscape perception and the establishment of science-based landscape management. The concepts, techniques and actual understanding of the case study area demonstrate the multi-disciplinary character of landscape ecology.

The conclusions presented in the preceding chapters have their implications in three aspects of landscape ecology. First, the actual functioning of a specific type of landscape, dry coastal dunes, is better understood and results in new management perspectives; this is further elucidated in section 8.2. Second, the semantic approach in understanding landscapes with typical conservation challenges, the small-scale dynamic ecosystem, is developed. Section 8.3 goes further into this matter. Last the significance of the conclusions for landscape ecology are brief discussed in section 8.4.

8.2 Dry coastal dunes, new management perspectives

From the conclusions presented in Chapter 4 and 7 it is clear that there is a temporal slight shift towards stability in the dry coastal dunes studied. This is in correspondence with other observations on the coastal dunes of The Netherlands (Kooijman & De Haan, 1995; Veer & Kooijman, 1997; De Bonte et al., 1999; Grootjans et al., 2002). Environmental dynamics direct the stabilizing effect of atmospheric deposition and high mortality of small herbivores (rabbits) in dry coastal dunes. The Meijendel case study area, which is studied for its landscape dynamics, has high environmental dynamics caused by the factors climate, geology and geomorphology, resulting in a landscape 'stable in its instability'. Wind (Arens, 1996a; Arens, 1996b), salt-spray (Sevink, 1991), high lime content of the substrate (Kooijman et al., 1998), aeolian activity and denudation by overland flow (Rutin, 1983) influence the dynamics of the dry dunes in an intricate web of cause and effect. When one or more of these influences change, the stability of the area will increase. This is very well illustrated in the coastal dunes of Voorne, where after the construction of a new harbour in front of the coast resulting in a decrease in climatic dynamics, shrubs and trees became dominant (Van der Maarel et al., 1985; Van Dorp et al., 1985). Also in areas with low relief intensity and mild climatic conditions like the Bierlap and parabolic dune case study areas the vegetation becomes more stable. It is likely that the Meijendel case study area, located approximately two km from the coast and thus subject to relative mild climatic conditions, is vulnerable to stabilisation.

When this stabilizing effect results in unfavourable vegetation types, characterised by grass and shrub encroachment, the management has to focus on re-introduction of environmental dynamics. As concluded in Chapter 7 and in accordance with the above, these dynamics should be convergent. This means: catastrophic and crisp. Management interventions similar to geomorphic dynamics are better than divergent management interventions like grazing by large herbivores. Blowouts and complete parabolic dunes have been re-activated and this gives promising results (Arens et al., 2004; Arens & Geelen, 2006). In the management and monitoring of dry coastal dunes the focus has to be on the balance between dynamics and stability, and interventions have to be regulated in accordance with this balance, which requires that a surplus of (temporary) dynamics is favoured over the continuation of stabilizing and diverging processes.

8.3 Small-scale dynamic ecosystems, a new semantic approach

Small-scale dynamic ecosystems are spatial and temporal heterogeneous. This observation is neither new nor radical. The recognition of the semantic heterogeneity has led to a better understanding of small-scale dynamic ecosystems and is a new approach. Throughout this thesis the third, semantic, domain of the Serial Landscape Model was a substantial part of the development of techniques and concepts. This launched new prospects in the understanding of the functioning of small-scale dynamic ecosystems (Chapter 7).

In the DICRANUM classification procedure (section 2.5), the image interpretation class definition, which is obtained by confronting the implication of the classes for monitoring landscapes with the image characteristics, is a purely semantic approach. The accuracy assessment of the fuzzy classification results was only possible with two premises that can be characterised as semantic (section 3.2.2). The premises define how the fuzziness of several thematic classes are distributed within a spatial element. In fact, it is assumed that the fuzzy thematic classes have a crisp spatial distribution within the spatial element. This semantic premise was also applied in the construction of transition tables and diagrams in Chapter 6. The two major semantic approaches are presented in Chapter 4 and Chapter 6 where, respectively, the ecological implications of the observed classes and transitions between the classes are elucidated.

The complexity of small-scale dynamic ecosystems made it necessary to study the semantics of the system in order to understand its dynamics. Small-scale dynamic ecosystems are a transitional form between convergent (crisp, catastrophic) landscapes and divergent (random, chance) landscapes revealed as semantic continuity. The dynamics are also semantically characterised by recognising three semantic transition types (see section 6.4.1). Although every study in landscape ecology has semantic aspects, semantics was never applied in the analysis as such.

Until now, the semantic continuous approach is only applied to dry coastal dune systems but it is advised to do so in the analysis of other small-scale dynamic ecosystems. This can be concluded from Chapter 7, where it is obvious that the integration of the temporal and spatial domains with the semantic domain can lead to new advances in the understanding of a landscape.

8.4 Landscape ecology, the need for concept development

The confrontation of numerical techniques with the ecology of the landscape led to the development of three new concepts. First, the notion of continuity in the spatial and semantic domain combined with fuzzy logic, as applied in the DICRANUM classification procedure, led to the definition of the Serial Landscape Model (Chapter 1). This is a landscape ecological concept that integrates the spatial, temporal and semantic characteristics of the landscape. Second, the comparison of fuzzy digital vegetation maps led to the development of an explanatory model for a small-scale dynamic ecosystem and the conclusion that a particular state of the landscape is a unique combination of temporal dynamics, spatial complexity and semantic complexity (Chapter 5). Last, fuzzy logic gave the opportunity to produce transition diagrams with information on the characteristics of the transitions. These results confirmed the concept that small-scale dynamic ecosystems develop according to a multi-trajectory model. The data revealed that dry coastal dunes are a type of landscape with two amalgamated equilibrium states (Chapter 7). This is a promising landscape concept for the management and conservation of small-scale dynamic ecosystems.

It can be concluded that the development and application of new techniques for the observation and analysis of landscape are vital for the advance of landscape ecology. However, this advance also has to focus on general conceptual understanding of the landscape and not only on the further specification of more sophisticated techniques. Landscape ecology, being multidisciplinary as well as autonomous (Bastian & Steinhardt, 2002), can only be innovative and applicable in landscape management when the focus is also on concept development.

9 SUMMARY

9.1 Classification of pattern and process in small-scale dynamic ecosystems; with cases in the Dutch coastal dunes

It is concluded in ***Chapter 1*** that the classic approach in landscape ecology and vegetation science is focused on the recognition of objects: thematic, spatial and temporal. In the survey and analysis of large-scale, stable landscapes, this approach is adequate. However, nature reserves often are small-scale dynamic ecosystems. These areas were not suited for reclamation and anthropogenic use. Examples of these areas are: coastal dunes, salt marshes, drift sands and rivers. The recognition and unambiguous classification of discrete spatial elements in such areas is seriously hampered by the actual spatial and thematic complexity.

This observation, combined with the availability of high-resolution digital remote sensing images and the availability of high data storage and processing speed, led to the development of the Serial Landscape Model. This model defines three domains of the landscape: the spatial domain, the temporal domain and the semantic domain. Important aspect of the model is that the combination of attributes and classes is not an instrument to describe pattern and development of the landscape, but it is an autonomous aspect: the semantics. According to the Serial Landscape Model, the small-scale dynamic landscape can be converging (discrete), diverging (random) or a continuous (fuzzy) transition between these extremes.

The aim of this thesis is the elaboration of a method to link digital data and techniques with the Serial Landscape Model. The second aim of this thesis is focused on monitoring a small-scale dynamic ecosystem with the developed techniques, the dry coastal dunes being taken as a highly suited example.

The data model and resulting classification technique are presented in ***Chapter 2***. Requirements of the monitoring program are based and defined on aspects of research, terrain management and policy. Because the complete range from convergence to divergence is found in small-scale dynamic ecosystems, fuzzy logic is the most appropriate technique to use in the classification procedure. This means that an image element (pixel) is member of multiple sets, the grade this element is member of a set being expressed in the membership value. The sets distinguished are in fact classes. By applying fuzzy logic, the semantic domain is in accordance with the character of the small-scale dynamic ecosystem. The classification procedure is further elaborated for dry coastal dunes and seven image interpretation classes are defined: two crisp and five fuzzy. In fact, the crisp classes are special cases of fuzzy classes: by definition, image elements are either full member of a class or not. In ***Chapter 2*** some classification results are presented and it is concluded that differences in terrain and material make it necessary to construct separate class functions per area and orthophoto.

So far, no technique has existed to assess the accuracy of the classification results. Such a technique for assessing was developed especially for the classification procedure and it is presented in ***Chapter 3***. The comparison of the classification results with independent ground truth, resulting in a confusion or error matrix, is a basic procedure in digital image interpretation. In order to do so with fuzzy classification results two premises are defined. Firstly, it is assumed that the membership value assigned to a class per image element is the extent that the class occurs in the image element. Secondly, it is assumed that the smallest extent a class occurs in either the image element or in the ground-truth, is correctly assigned to the image element as well as to the ground truth. Then, a confusion or error matrix with producer's accuracy, user's accuracy and overall accuracy can be calculated. The error or confusion matrices of classification results from three dune areas were combined with an analysis of the ground truth strategy. This resulted in some recommendations for field survey in support of fuzzy image interpretation. Rare classes have to be sampled in disproportional high numbers. Low membership values have to be overrepresented for classes that occur with prevalent high membership values and high membership values have to be overrepresented for classes with prevalent low membership values.

So far, classes used in the production of fuzzy vegetation structure maps have been described only by their reflection characteristics as revealed in the images. To describe the semantics in detail, field information has to be linked with the image characteristics. There is also a necessity to relate the image interpretation classes with representative units used in planning and evaluation of terrain management. In the EU these units are the habitat types according to the NATURA 2000 methodology. Both aspects are elaborated in ***Chapter 4***. The image classification procedure resulted in the construction of a radiometric feature space. Detailed field survey of relevées resulted in a phytosociologic feature space constructed with two ordination axes. For the dry coastal dune area Meijendel species groups and gradients in environmental variables (soil, geomorphology) are recognized in the phytosociologic feature space. Image interpretation classes, as defined in the radiometric feature space, are placed in the phytosociologic feature space and a semantic relation between image characteristics and landscape ecological parameters could be established. It was also possible to relate NATURA 2000 habitat types to image interpretation classes. The results led to the conclusion that in monitoring priority habitats types multiple image interpretation classes have to be defined which gives the terrain manager a good apprehension of the spatial, temporal and semantic developments within the habitat.

It was assumed that the results of the image classification would improve by stratifying the image and executing the image classification for the individual strata. This assumption is based on landscape ecological hierarchy theory. The assumption is further elaborated in ***Chapter 5***. The part of the Meijendel dune area for which digital orthophotos of 1990, 1995 and 2001 were available was classified: stratified and non-stratified. The calculated accuracies revealed that hierarchy theory is not applicable within the scope of the Serial Landscape Model. Based on this conclusion a new landscape concept was developed. In this concept, the state of the landscape is described as a combination of temporal dynamics, spatial complexity and semantic complexity. It is observed that with an increasing level of internal organization of the landscape (in the temporal domain considered as primary succession), there is a clear trend in decreasing temporal dynamics and increasing spatial and semantic complexity. Vegetation structure types distinguished as undesirable by terrain managers turn out to deviate from this trend. For example, grass encroachment can be characterized as temporarily stable, spatially homogeneous and semantically complex. A general applied intervention as grazing by large herbivores results in increasing spatial heterogeneity, which is in accordance with a more 'normal' type of internal organization of the landscape.

The description of landscape development with sequential image interpretation and construction of transition matrices and transition diagrams is a generally accepted technique, especially in surveying vegetation succession. In ***Chapter 6***, a technique is presented to construct transition matrices with fuzzy vegetation structure maps. A further topic is whether transition matrices of small-scale dynamic ecosystems are applicable as Markov models.

The combination of two sets of fuzzy maps results in a complex matrix, which is unfit for quantitative as well as a qualitative assessment. Therefore, the construction of transition matrices and transition diagrams have to be performed in successive steps. First, transition graphs of transitions between two mutual classes are constructed. These graphs are an indication for the semantic transition type. Three types are discerned. Proportional transition is characterized by the fact that a high membership value of a class is succeeded by a high membership value of another class, or, in the case of auto-transition, the same class. Inverse proportional transition is characterized by the fact that a high membership value of a class is succeeded by a low membership value of another class, or, in the case of auto-transition, the same class. Indifferent transition is revealed by the fact that there is no relation between the membership values of successive classes. Ecologically, these types can be explained as follows:

- proportional transition is natural succession with primarily an increasing level of internal organization,
- inverse proportional transition is a process of gradual appearance or disappearance of a vegetation structure type,
- indifferent transition is observed when external factors influence the system.

The transition between all classes is summarized in overall transition matrices whereby the extent of the transitions calculated is based either on the membership value of the originating class or on the membership value of the resulting class. The ratio between these two extents gives an indication for the character of the fuzzy transition: from high to low membership values or inverse.

The resulting synoptic fuzzy transition diagram of part of the Meijendel dune area gives the impression that in small-scale dynamic ecosystems any state of the landscape can change into any other state. This result is further elaborated in ***Chapter 7*** in which a multi-trajectory model of landscape development is introduced. Four cases of landscape development are further analyzed: development of a small-scale dynamic dune area as a whole, development of an area with blowouts, development of an area with grass encroachment and development of an area with shrub encroachment.

A small-scale dynamic dry dune landscape has a clear division in development. Within the open dynamic dunes, the development is according to proportional transition. This is also the case for the stable dry dunes. The transition between these two states is according to inverse proportional transition: the transition from dynamic to stable dry dunes is gradual, as well as the transition from stable to dynamic dry dunes. These conclusions can also be drawn for the areas with aeolian dynamics, grass encroachment and shrub encroachment. However, the highly valued stable, species rich, dune grassland type maintains a deviating place in the transition diagram of dunes with grass encroachment that are grazed by large herbivores. This dune grassland type only develops by indifferent or inverse proportional transitions. It is concluded that nonrecurring radical interventions should be preferred in the management of small-scale dynamic dune ecosystems,. Continuous disturbance by large herbivores is not preferred.

It is concluded in ***Chapter 8*** that the development of new concepts for landscape and landscape development, initiated by the availability of new data and procedures, also give new perspectives for studying the functioning of landscape. Therefore, it is important that, apart from the development of tools to describe landscape and evaluate interventions, there are also initiatives to perceive and describe the landscape with a conceptual approach.

9.2 Classificatie van patroon en proces in kleinschalige dynamische ecosystemen; met voorbeelden uit de Nederlandse kustduinen

In ***Hoofdstuk 1*** wordt duidelijk gemaakt dat de klassieke benadering van landschapsecologie en vegetatiekunde sterk gericht is op het herkennen van objecten: thematisch, ruimtelijk en temporeel. Bij de kartering en analyse van grootschalige, stabiele landschappen werkt deze aanpak veelal goed. Met name in natuurgebieden is er echter vaak sprake van een kleinschalig, dynamisch karakter: dit zijn veelal de gebieden die niet interessant zijn of waren voor agrarische ontginning of andere antropogene gebruiksvormen. Voorbeelden van dit soort landschappen zijn: kustduinen, kwelders, stuifzandgebieden, rivieren, etc.. Het ruimtelijk herkennen en eenduidig beschrijven van discrete eenheden in deze landschappen stuit veelal op problemen en op de werkelijke ruimtelijke en thematische complexiteit van het landschap.

Deze waarneming, in combinatie met de beschikbaarheid van hoge resolutie digitale remote sensing beelden en de algemene beschikbaarheid van hoge reken- en opslagcapaciteit, heeft geleid tot de ontwikkeling van het Serieel Landschapsmodel. In dit model wordt het landschap beschreven in drie domeinen: het ruimtelijk domein, het temporeel domein en het semantisch domein. Belangrijk is de erkenning van het feit dat de betekenis van het landschap (de semantiek) een eigenstandig aspect is en dat (combinaties) van attribuutwaarden en klassen niet enkel een instrument zijn om het patroon en de ontwikkeling te beschrijven. Zowel in het ruimtelijk, temporeel en het semantisch domein kan het landschap convergent (discreet), divergent (random) of een continue overgang daartussen (fuzzy) zijn.

Het doel van het proefschrift is het uitwerken van een methode om digitale bronnen en technieken voor landschapswaarneming te koppelen aan het landschapsecologisch concept zoals beschreven door het Serieel Landschapsmodel. Deze uitwerking is in de praktijk gebracht met behulp van digitale orthofoto's van de Nederlandse kustduinen en is de basis van het tweede doel van dit proefschrift: het bestuderen van de ontwikkeling van een kleinschalig dynamisch ecosysteem, de Nederlandse kustduinen in het bijzonder.

De uitwerking van het data model en de daaruit voortvloeiende classificatie-techniek wordt gepresenteerd in ***Hoofdstuk 2***. Randvoorwaarden hiervoor komen vooral voort uit eisen die aan een monitoringsprogramma worden gesteld door onderzoek, terreinbeheer en beleid. Omdat in kleinschalige dynamische ecosystemen het gehele scala van convergentie tot divergentie voorkomt ligt het voor de hand om fuzzy-logic toe te passen in de classificatie-procedure. Dit betekent dat een beeld element (pixel) onderdeel is van meerdere verzamelingen. De mate waarin hij onderdeel is van de verzameling wordt uitgedrukt in de membership value. In feite is een dergelijk verzameling een klasse. Door de toepassing van deze techniek is het nu mogelijk om het semantisch domein een inhoud te geven, die overeenkomt met het werkelijke karakter van een kleinschalig dynamisch ecosysteem. De classificatie-procedure wordt verder specifiek uitgewerkt voor de droge duinen waarbij zeven beeldinterpretatie klassen worden gedefinieerd, vijf fuzzy en twee crisp. De crisp klassen zijn in feite een bijzonder geval van fuzzy klassen: beeldelementen zijn per definitie 100% onderdeel van de verzameling. In dit hoofdstuk wordt een aantal resultaten van deze classificatie-procedure gepresenteerd waaruit geconcludeerd kan worden dat variatie in terrein en materiaal het noodzakelijk maakt om voor elk gebied en elke orthophoto afzonderlijke object-ruimtes te construeren.

Voor de afwijkende classificatie procedure was tot op heden nog geen validatie procedure voorhanden. Deze is in dit onderzoek ontwikkeld en wordt gepresenteerd in ***Hoofdstuk 3***. Basisprocedure is het vergelijken van het classificatieresultaat (de vegetatiestructuurkaart) met onafhankelijk opgenomen veld referenties. Voor de berekening van de betrouwbaarheid wordt een fouten-matrix opgesteld, een algemeen toegepaste methode in digitale beeldverwerking. Om dit echter te kunnen doen moet er een tweetal aannames worden gedaan. Ten eerste wordt er aangenomen dat de membership value die per klasse wordt toegewezen aan een beeldelement het oppervlak is dat deze klasse voorkomt binnen het beeldelement. Ten tweede wordt aangenomen dat het kleinste oppervlak dat een specifieke klasse voorkomt in het geclassificeerde beeldelement of in de veldreferentie juist is toegekend aan het classificatie-resultaat en de veldreferentie. Nu kan er een foutenmatrix worden berekend met de gebruikers betrouwbaarheid, de productie betrouwbaarheid en de totale betrouwbaarheid. Op basis van fouten matrices berekend voor drie classificaties van drie afzonderlijke duingebieden in 2001 en een analyse van de veldopname-strategie zijn een aantal aanvullende randvoorwaarden voor veldopname ten behoeve van fuzzy beeldclassificatie geformuleerd. Ten eerste moeten zeldzame klassen onevenredig hoog worden bemonsterd, moeten van klassen die voorkomen met een veelal hoge membership value ook lage membership values worden bemonsterd en moeten van klassen die veelal voorkomen met een lage membership value ook hoge membership values worden bemonsterd.

De klassen die zijn gebruikt in de productie van fuzzy vegetatiestructuurkaarten zijn enkel beschreven op basis van hun reflectiekarakteristieken in het beeld. Om er een echte semantische inhoud aan te geven is het noodzakelijk gedetailleerde veldinformatie te koppelen aan de beeldkenmerken. Daarnaast bestaat er de noodzaak om de beeldklassen te koppelen aan eenheden die maatgevend zijn voor de planning en evaluatie van het beheer. Binnen de EU is dat de NATURA 2000 systematiek. Beide genoemde aspecten worden uitgewerkt in ***Hoofdstuk 4***. Middels de beeldclassificatie is er een radiometrische objectruimte geconstrueerd. Met behulp van gedetailleerde veldopnamen kan er ook een phytosociologische objectruimte worden geconstrueerd op basis van een aantal berekende ordinatieassen. Met behulp van veldopnames in het duinterrein Meijendel is een phytosociologische objectruimte geconstrueerd waarin soortengroepen en gradiënten in milieuvariabelen (bodem, geomorfologie) kunnen worden herkend. Vervolgens zijn de beeldklassen, zoals gedefinieerd in de radiometrische objectruimte, afgebeeld in de phytosociologische objectruimte en kon er een semantische relatie gelegd worden tussen de beeldklassen en landschapsecologische parameters. Op basis van de NATURA 2000 habitat beschrijvingen kan er ook een relatie gelegd worden tussen beeldklassen en habitattypen. Belangrijkste conclusie uit de gepresenteerde resultaten is dat er bij het monitoren van prioritaire habitattypen naar gestreefd moet worden om per habitattype meerdere beeldklassen te definiëren. Alleen dan krijgt de beheerder een goed zicht op de

ruimtelijke, temporele en semantische ontwikkeling binnen de habitat.

Op basis van de algemene aanvaarde hiërarchie theorie is aangenomen dat resultaten van de beeldclassificatie verbeteren door het beeld te stratificeren en de strata afzonderlijk te classificeren. Deze aanname wordt verder uitgewerkt in ***Hoofdstuk 5***. Een deel van het duingebied Meijendel waarvan digitale orthofoto's van 1990, 1995 en 2001 voorhanden waren is geheel en gestratificeerd geclassificeerd. Vergelijking van de berekende betrouwbaarheid van de classificaties leidde tot de conclusie dat hiërarchie theorie niet toepasbaar is binnen het serieel landschapsmodel. Op basis van deze conclusie is een nieuw landschapsconcept ontwikkeld. In dit concept wordt de toestand van het landschap, zoals weergegeven in de combinatie van beeldklassen, gezien als een combinatie van temporele dynamiek, ruimtelijke complexiteit en semantische complexiteit. Het blijkt dat er bij toenemende mate van interne organisatie van het landschap (temporeel te beschouwen als primaire successie) een duidelijke trend is waar te nemen van afnemende temporele dynamiek en toenemende semantische en ruimtelijke complexiteit. De, vanuit het oogpunt van natuurbeheer, ongewenste vegetatiestructuurtypen blijken buiten deze trend te vallen. Vergrassing kan bijvoorbeeld gekarakteriseerd worden als temporeel stabiel, ruimtelijk homogeen en semantisch complex. Algemeen toegepaste beheersmaatregel is begrazen: hierdoor neemt de ruimtelijke heterogeniteit toe en wordt er een 'normale' vorm van interne organisatie in het landschap bereikt.

Het beschrijven van de ontwikkeling van het landschap met behulp van sequentiële beeldinterpretatie en het opstellen van transitiematrices en diagrammen is een algemeen aanvaarde techniek voor het onderzoek van vegetatiesuccessie. In ***Hoofdstuk 6*** wordt de techniek om transitiematrices op te stellen op basis van fuzzy vegetatiekaarten uitgewerkt. Ook wordt onderzocht in hoeverre transitiematrices van kleinschalige dynamische ecosystemen toepasbaar zijn als Markov model.

De combinatie van twee sets van fuzzy kaarten resulteert in een te complexe matrix om zowel kwantitatief als kwalitatief te beoordelen. Het opstellen van transitiematrices en transitiediagrammen wordt daarom in een aantal stappen uitgevoerd. In eerste instantie worden er transitiegrafieken opgesteld tussen klassen onderling. De grafiek is een aanwijzing voor het type transitie. Dit kan zijn: evenredig, een hoge membership value van een klasse wordt opgevolgd door een hoge membershipwaarde van een andere klasse; omgekeerd evenredig, een hoge membership value van een klasse wordt opgevolgd door een lage membership value en indifferent, er is geen relatie tussen de opeenvolgende membershipwaarden. Ecologisch kan dit als volgt worden uitgelegd: evenredige transitie is natuurlijke successie waarbij de mate van organisatie van het systeem toeneemt. Omgekeerd evenredige transitie is het proces als een type geleidelijk verschijnt of verdwijnt. Indifferente transitie wordt waargenomen als externe factoren het systeem beïnvloeden.

De transities tussen klassen onderling worden samengevat in overall transitie matrices waarbij het oppervlak van de transitie kan worden berekend op basis van de membership value in de uitgangssituatie of op basis van de membership value in de resulterende situatie. De verhouding tussen deze twee oppervlakten is een indicatie voor de wijze van transitie: van hoge membership value naar lage, of omgekeerd.

Het resulterende transitiediagram van een deelgebied van Meijendel geeft aan dat in kleinschalige dynamische ecosystemen alles in alles lijkt over te gaan. Dit resultaat wordt verder uitgewerkt in ***Hoofdstuk 7*** waarin het multi-ontwikkelings model wordt geïntroduceerd. Vier gevallen van landschapsontwikkeling worden uitgewerkt: ontwikkeling van een kleinschalig dynamisch duingebied als geheel, ontwikkeling van een gebied met stuifkuilen, ontwikkeling van een gebied met vergrassing en ontwikkeling van gebied met verstruweling.

Een kleinschalig dynamisch droog duinlandschap wordt gekenmerkt door een duidelijke tweedeling in ontwikkeling: het open duinlandschap ontwikkelt zich volgens evenredige transities en het gesloten duinlandschap ontwikkelt zich volgens evenredige transities. De overgang van open naar gesloten gaat geleidelijk volgens omgekeerd evenredige transitie. Ook bij stabilisatie van stuifkuilen, vergrassing en verstruweling is er een vergelijkbare ontwikkeling maar juist het hoog gewaardeerde, gesloten soortenrijke duingrasland neemt een bijzondere positie in. Vooral bij vergrassing valt op dat dit type alleen nog maar omgekeerd evenredige of indifferente transities kent. Voor het beheer wordt geconcludeerd dat in kleinschalige dynamische ecosystemen eenmalige, ingrijpende maatregelen te prefereren zijn boven continue beïnvloeding van het landschap door bijvoorbeeld begrazing.

In ***Hoofdstuk 8*** wordt geconcludeerd dat het ontwikkelen van nieuwe concepten voor landschap en landchapsontwikkeling, geïnitieerd door de beschikbaarheid van nieuwe gegevensbronnen en procedures, ook nieuwe inzichten in het functioneren van het landschap tot gevolg heeft. Daarom is het van belang dat, naast de ontwikkeling van waarnemings- en verwerkingstechnieken ten behoeve van onderzoek en evaluatie van beheer, altijd initiatief wordt genomen om op een andere, conceptuele wijze naar het landschap te kijken.

10
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11 LIST OF FRAMES, FIGURES, TABLES AND FORMULAS

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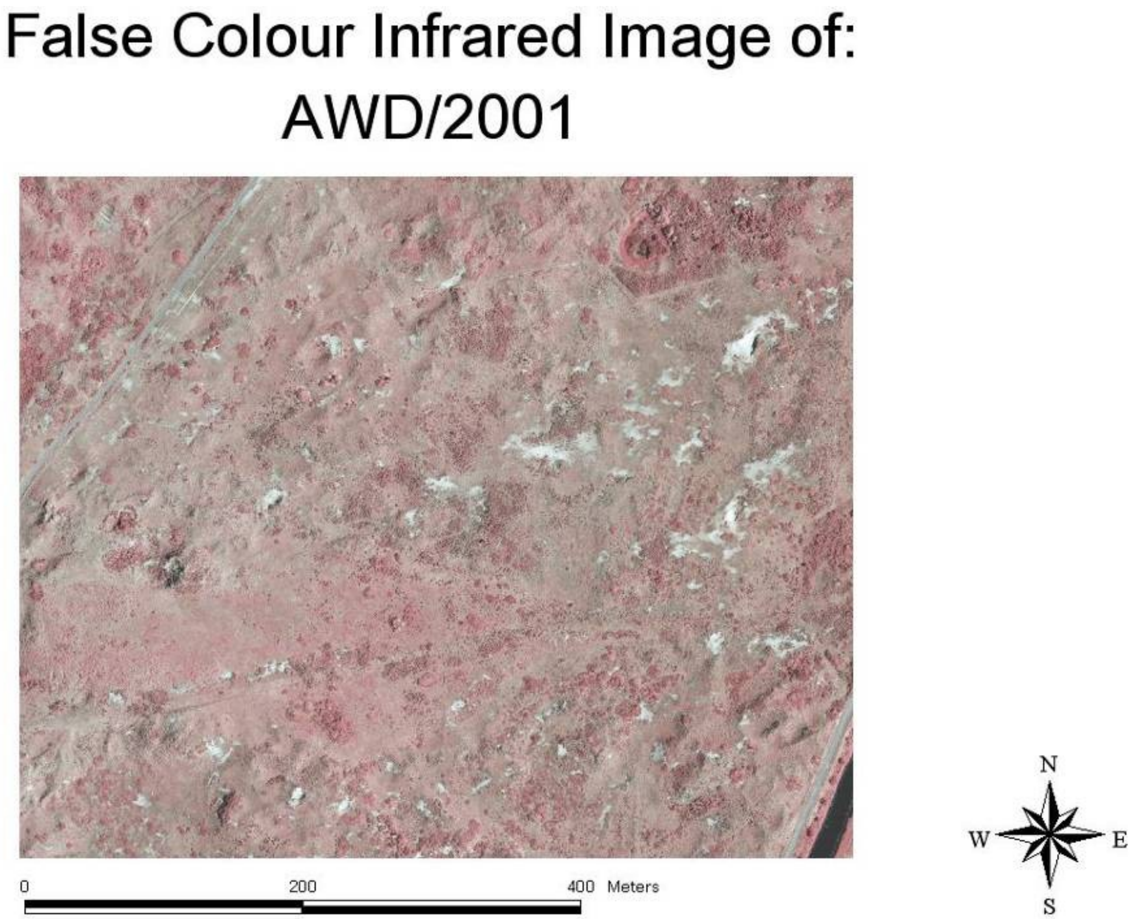
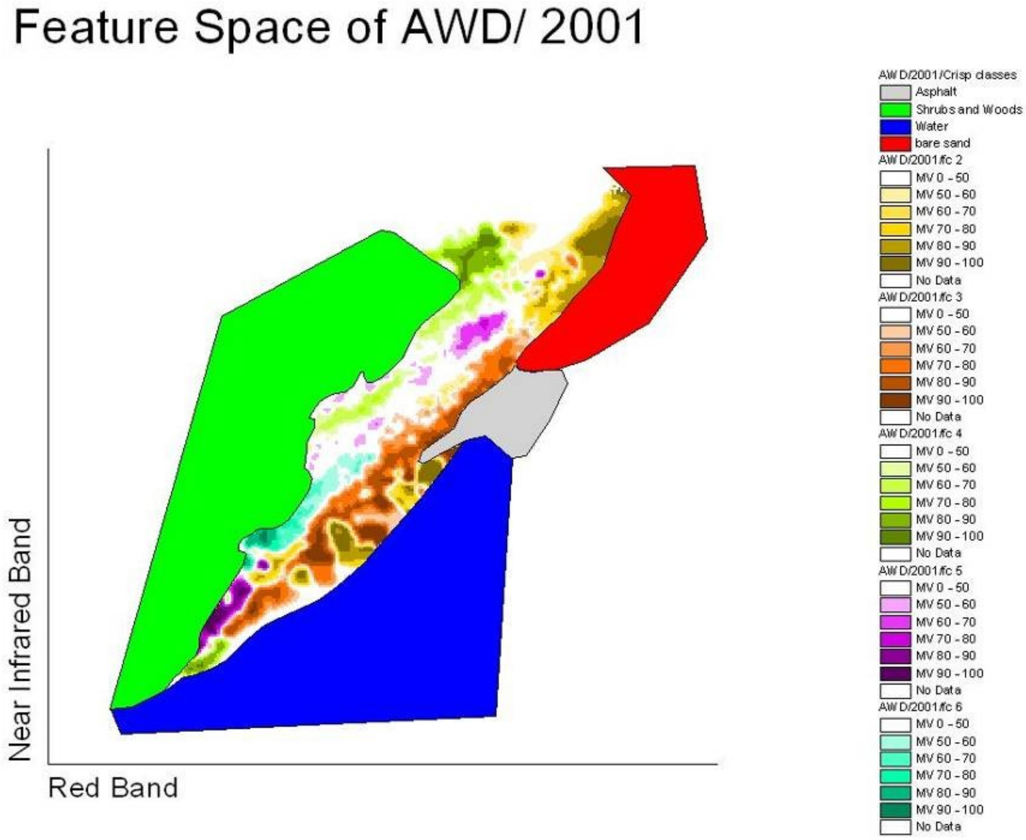
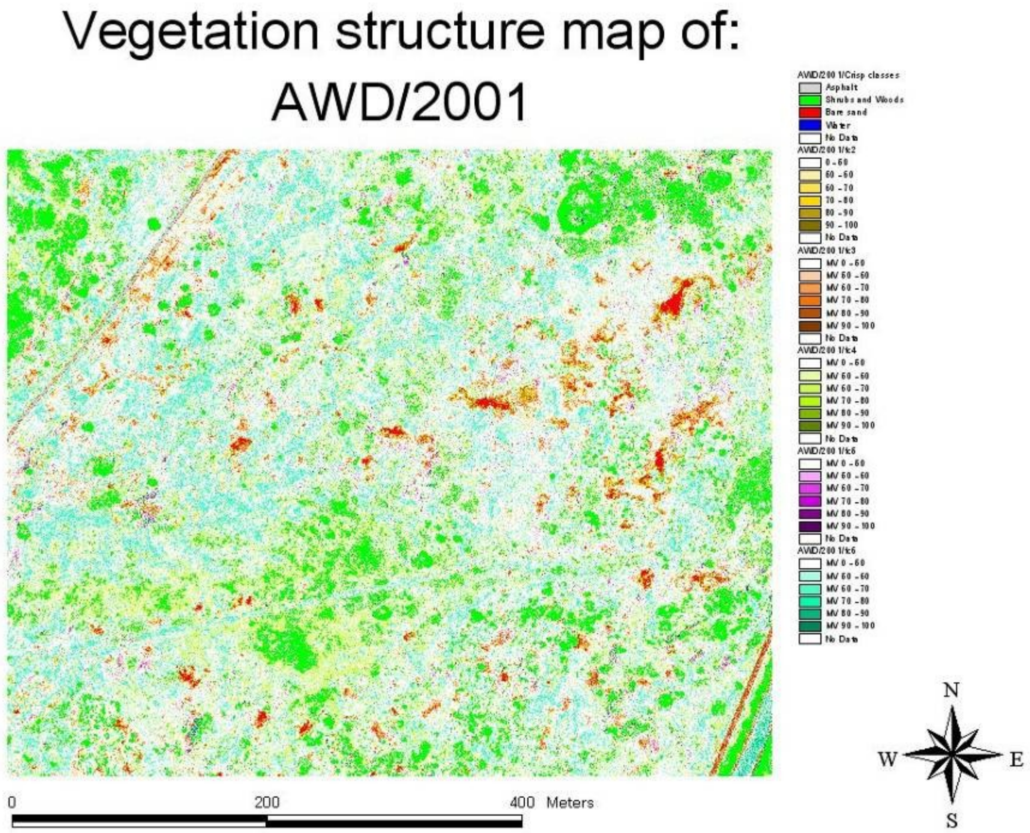
APPENDICES

Appendix A
Examples of images, feature spaces and vegetation structure maps of the sample areas presented in Chapter 2

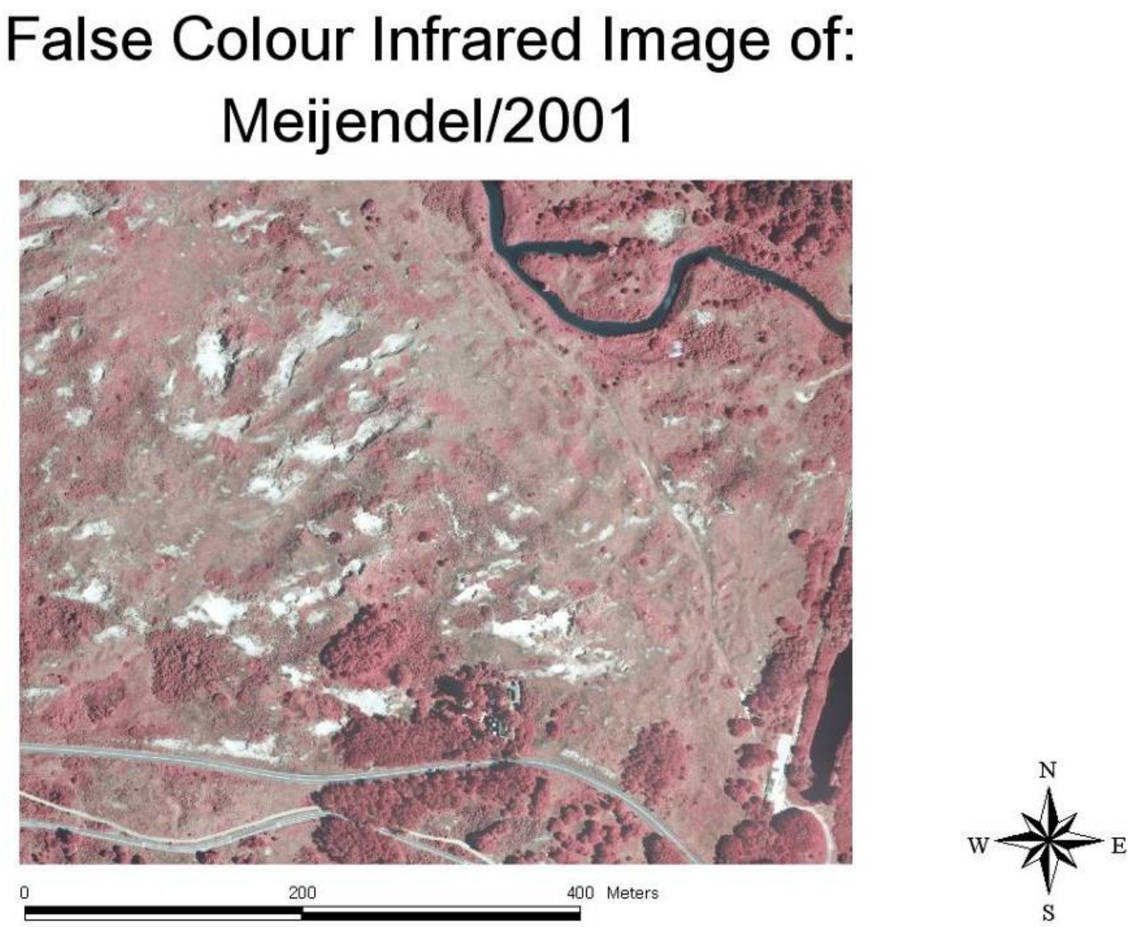
Appendix A.1 Amsterdam Water Supply Dunes



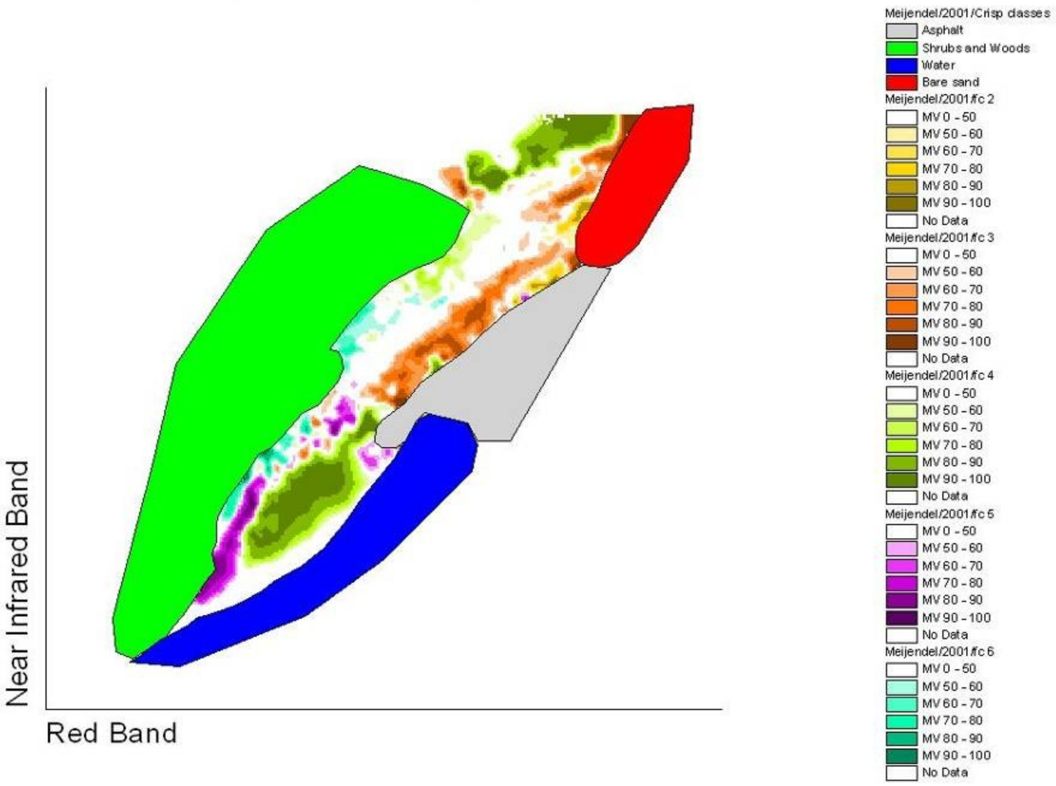

Feature Space of AWD/ 2001
Near Infrared Band
Red Band
AWD/2001/Crisp classes
Asphalt
Shrubs and Woods
Water
bare sand
AWD/2001/fc 2
MV 0 - 50
MV 50 - 60
MV 60 - 70
MV 70 - 80
MV 80 - 90
MV 90 - 100
No Data
AWD/2001/fc 3
MV 0 - 50
MV 50 - 60
MV 60 - 70
MV 70 - 80
MV 80 - 90
MV 90 - 100
No Data
AWD/2001/fc 4
MV 0 - 50
MV 50 - 60
MV 60 - 70
MV 70 - 80
MV 80 - 90
MV 90 - 100
No Data
AWD/2001/fc 5
MV 0 - 50
MV 50 - 60
MV 60 - 70
MV 70 - 80
MV 80 - 90
MV 90 - 100
No Data
AWD/2001/fc 6
MV 0 - 50
MV 50 - 60
MV 60 - 70
MV 70 - 80
MV 80 - 90
MV 90 - 100
No Data


Vegetation structure map of:
AWD/2001
0
200
400 Meters
N
W
E
S

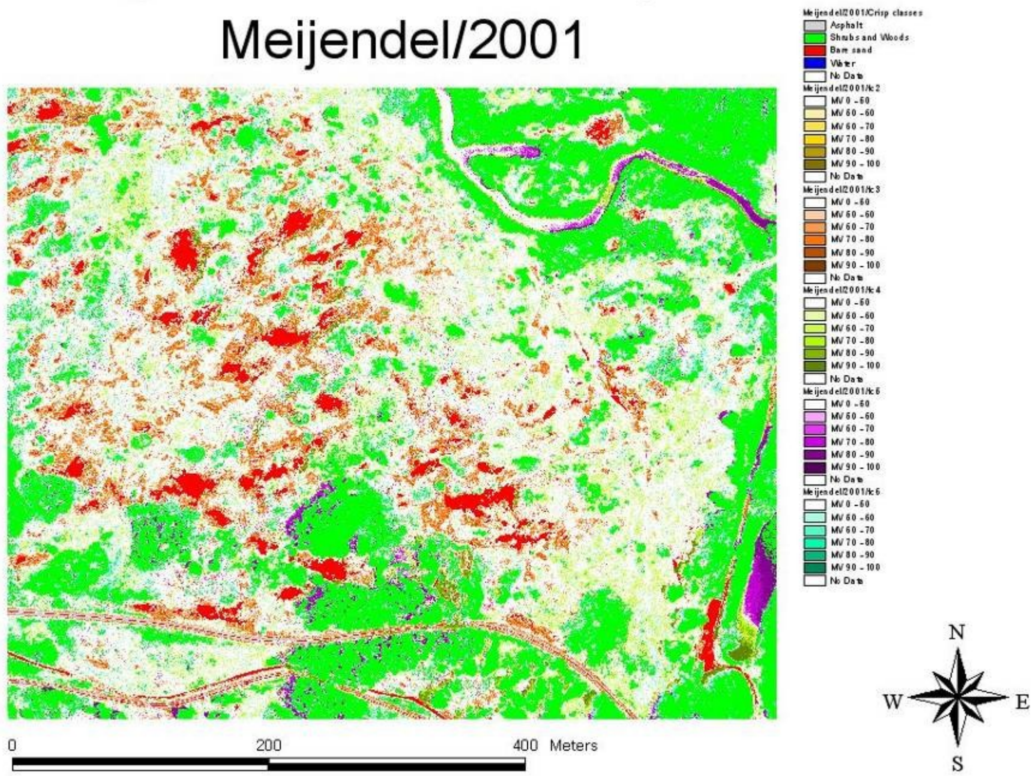
Appendix A.2 Meijendel/Berkheide



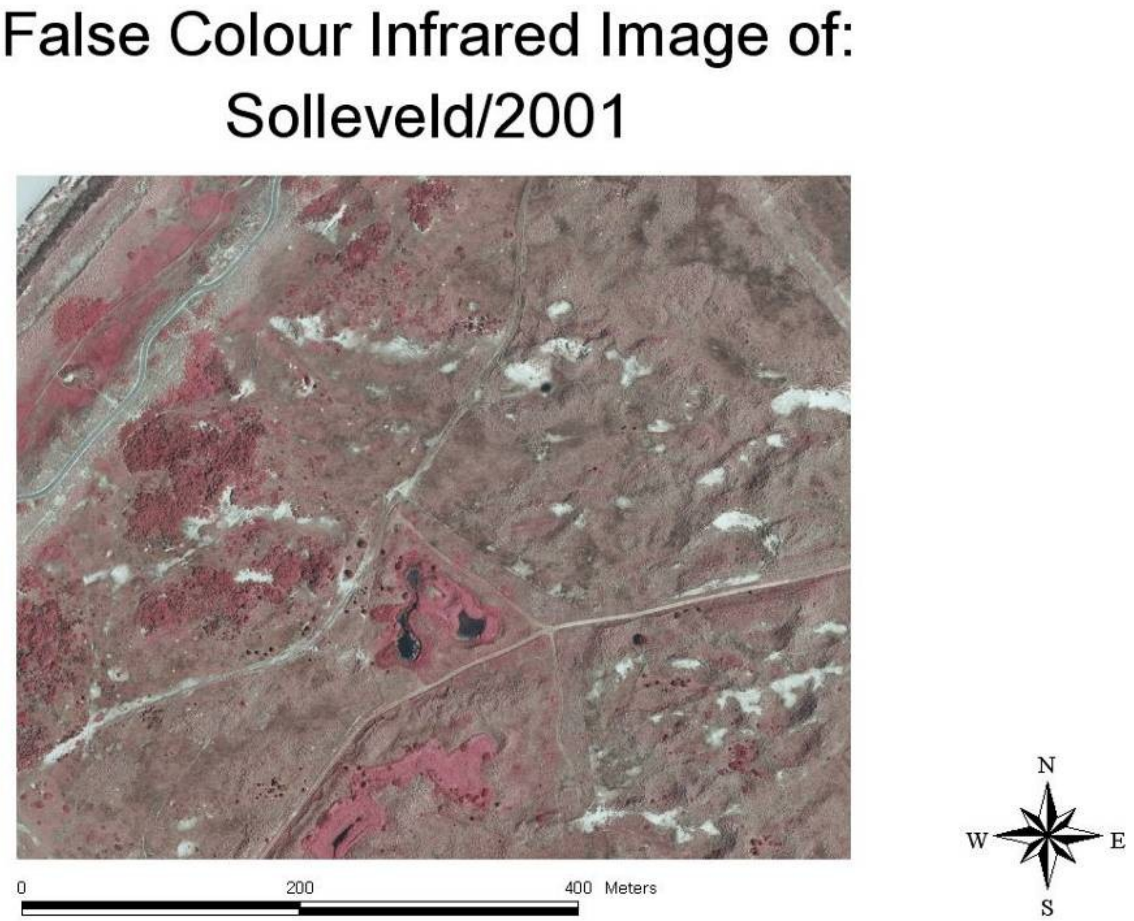
Feature Space of Meijendel / 2001

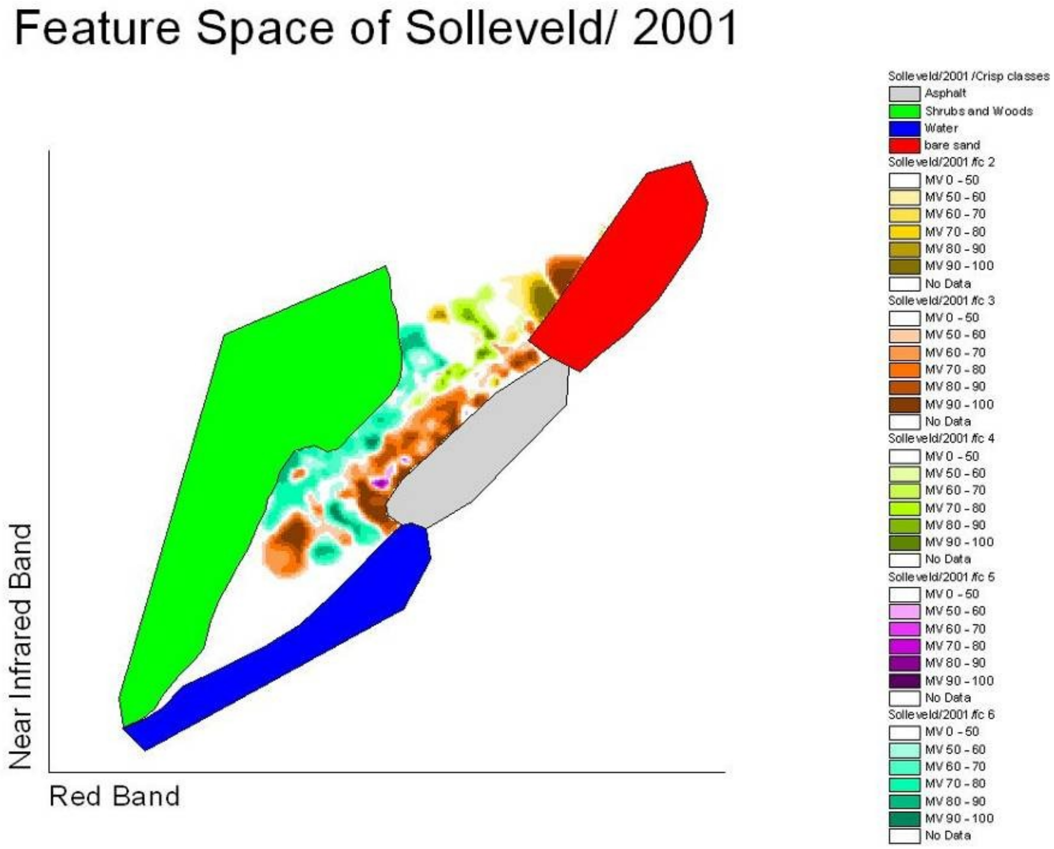


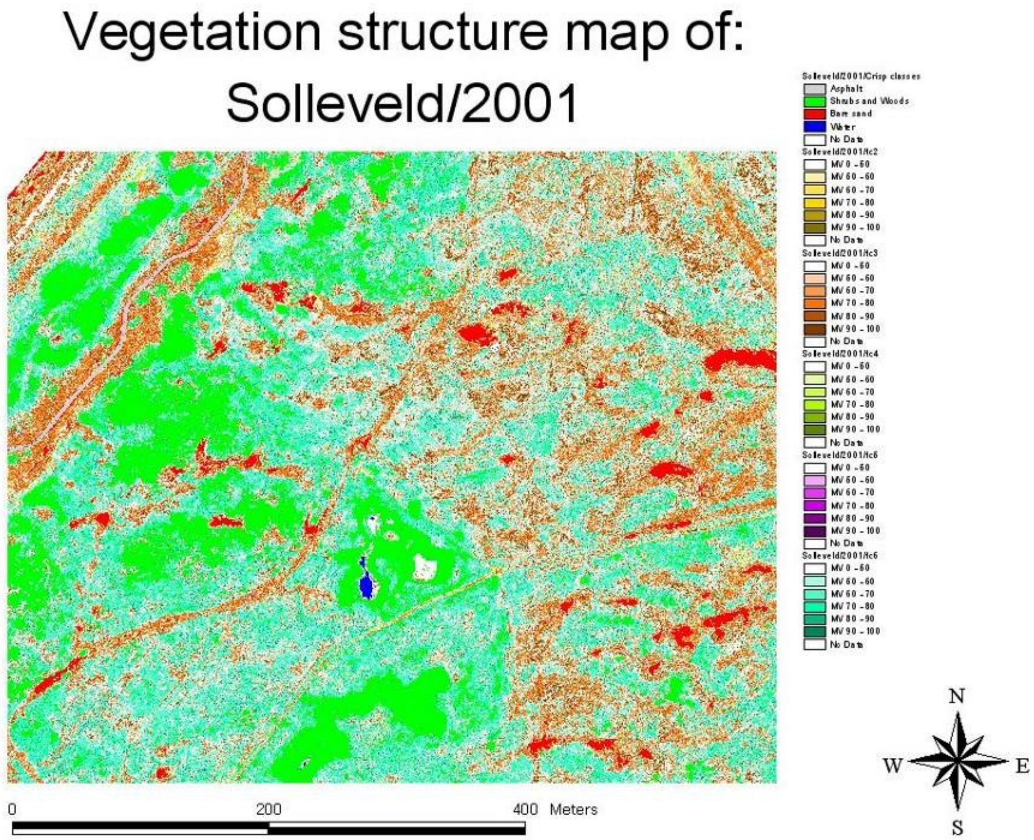
Vegetation structure map of:
Meijendel/2001



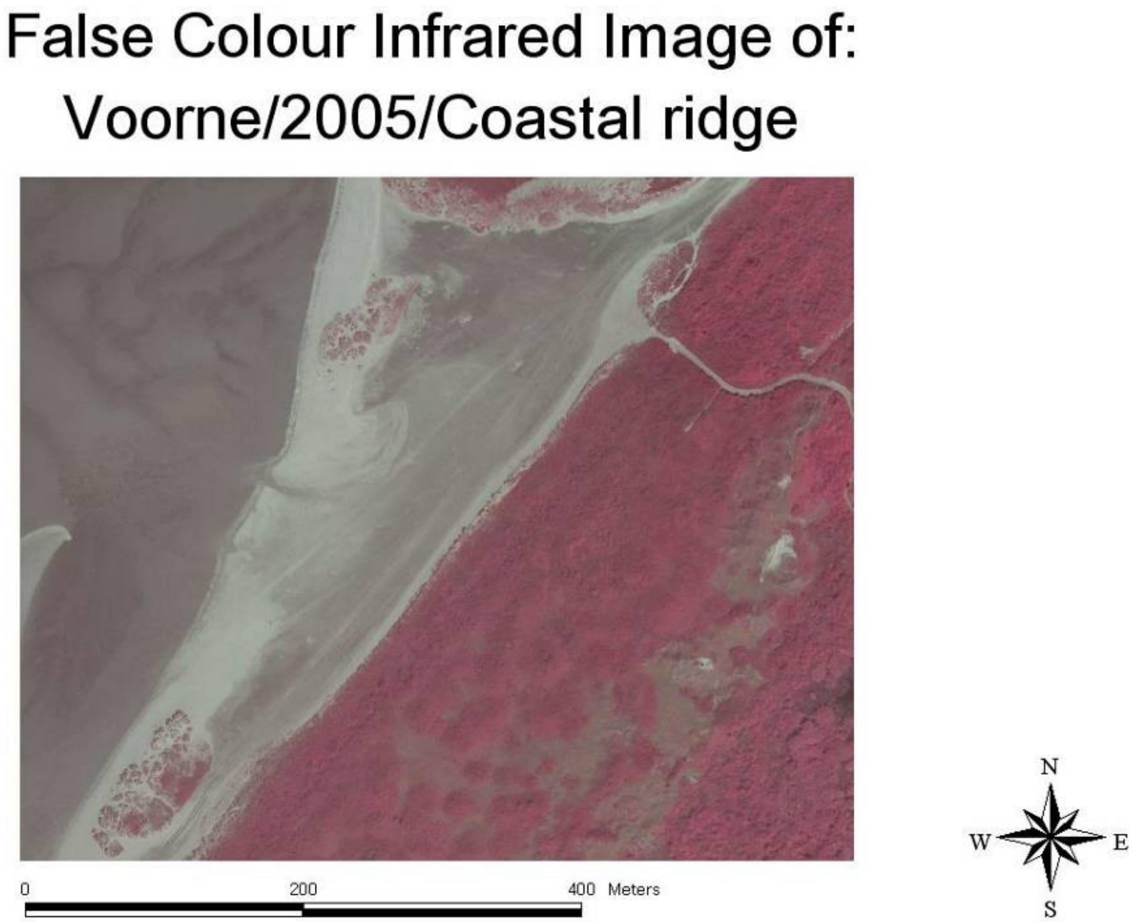
Appendix A.3 Solleveld

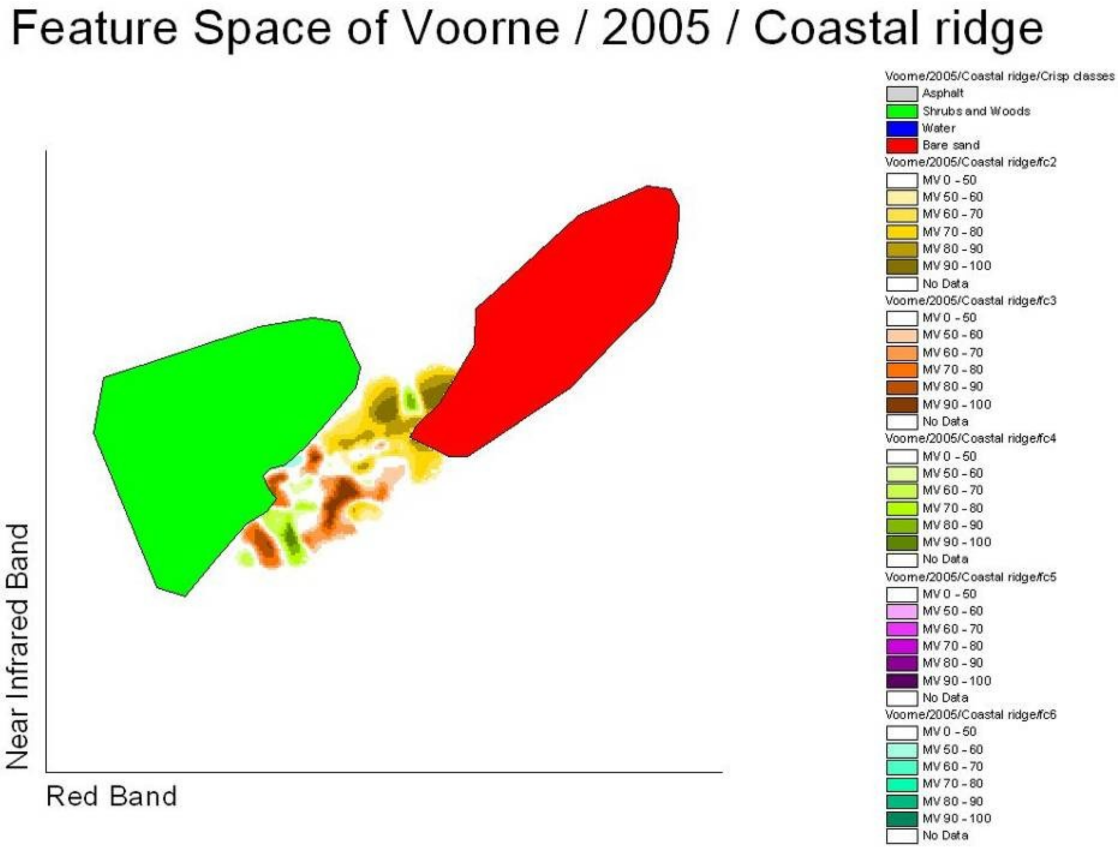


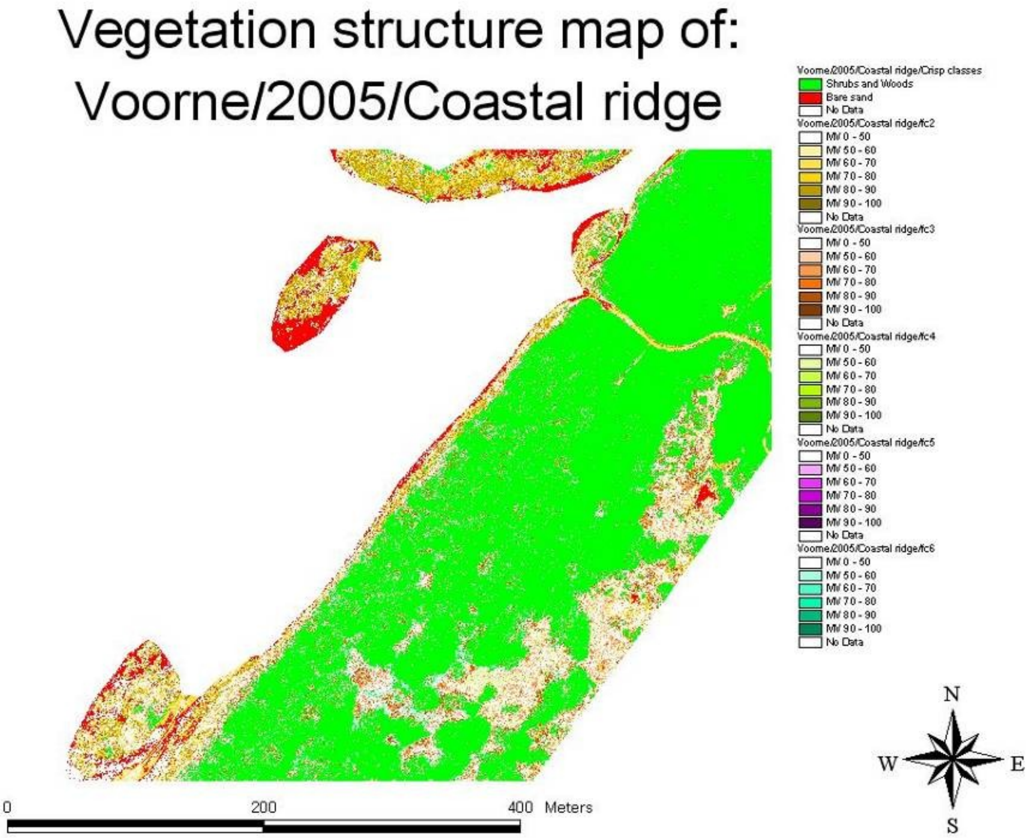

Feature Space of Solleveld/ 2001
Near Infrared Band
Red Band
Solleveld/2001 /Crisp classes
Asphalt
Shrubs and Woods
Water
bare sand
Solleveld/2001 /fc 2
MV 0 - 50
MV 50 - 60
MV 60 - 70
MV 70 - 80
MV 80 - 90
MV 90 - 100
No Data
Solleveld/2001 /fc 3
MV 0 - 50
MV 50 - 60
MV 60 - 70
MV 70 - 80
MV 80 - 90
MV 90 - 100
No Data
Solleveld/2001 /fc 4
MV 0 - 50
MV 50 - 60
MV 60 - 70
MV 70 - 80
MV 80 - 90
MV 90 - 100
No Data
Solleveld/2001 /fc 5
MV 0 - 50
MV 50 - 60
MV 60 - 70
MV 70 - 80
MV 80 - 90
MV 90 - 100
No Data
Solleveld/2001 /fc 6
MV 0 - 50
MV 50 - 60
MV 60 - 70
MV 70 - 80
MV 80 - 90
MV 90 - 100
No Data


Vegetation structure map of:
Solleveld/2001
Asphalt
Shrubs and Woods
Bare sand
Water
No Data
0
200
400 Meters
N
W
E
S

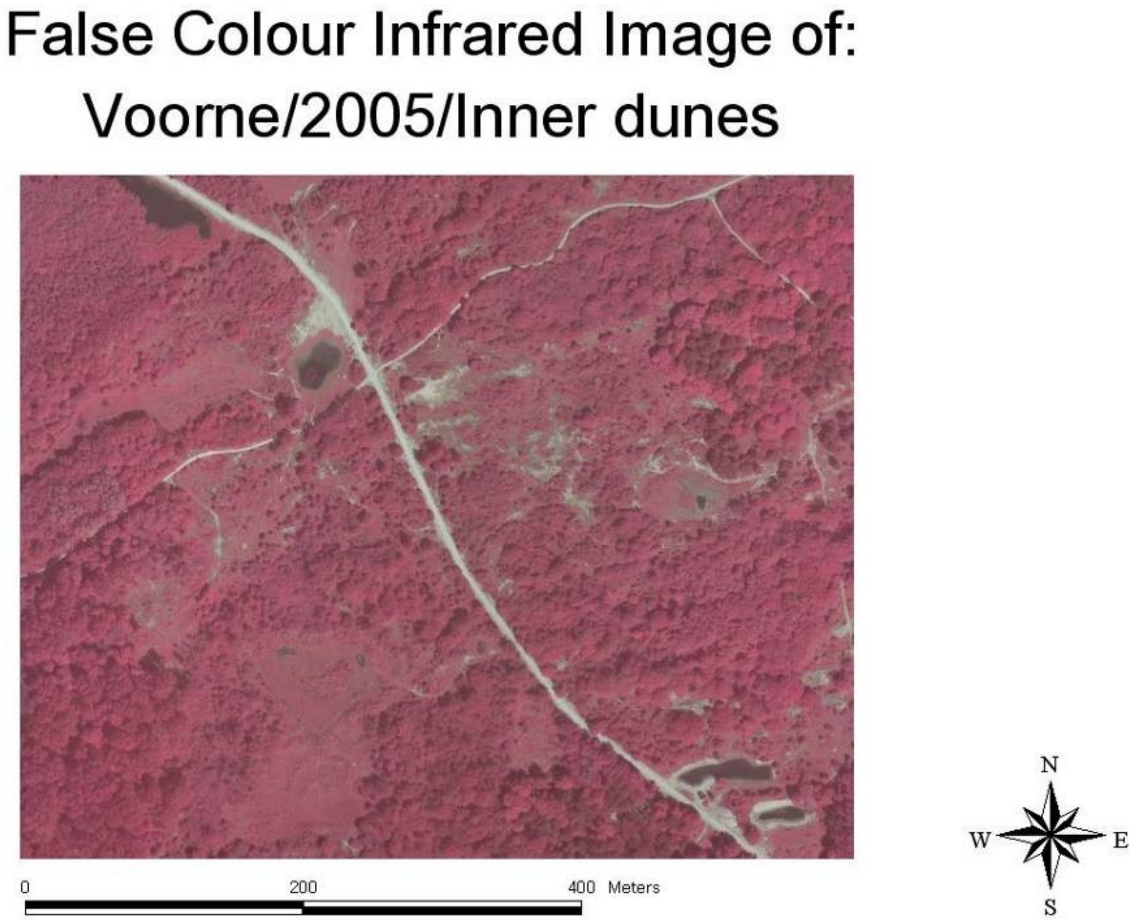
Appendix A.4 Voorne: coastal ridge



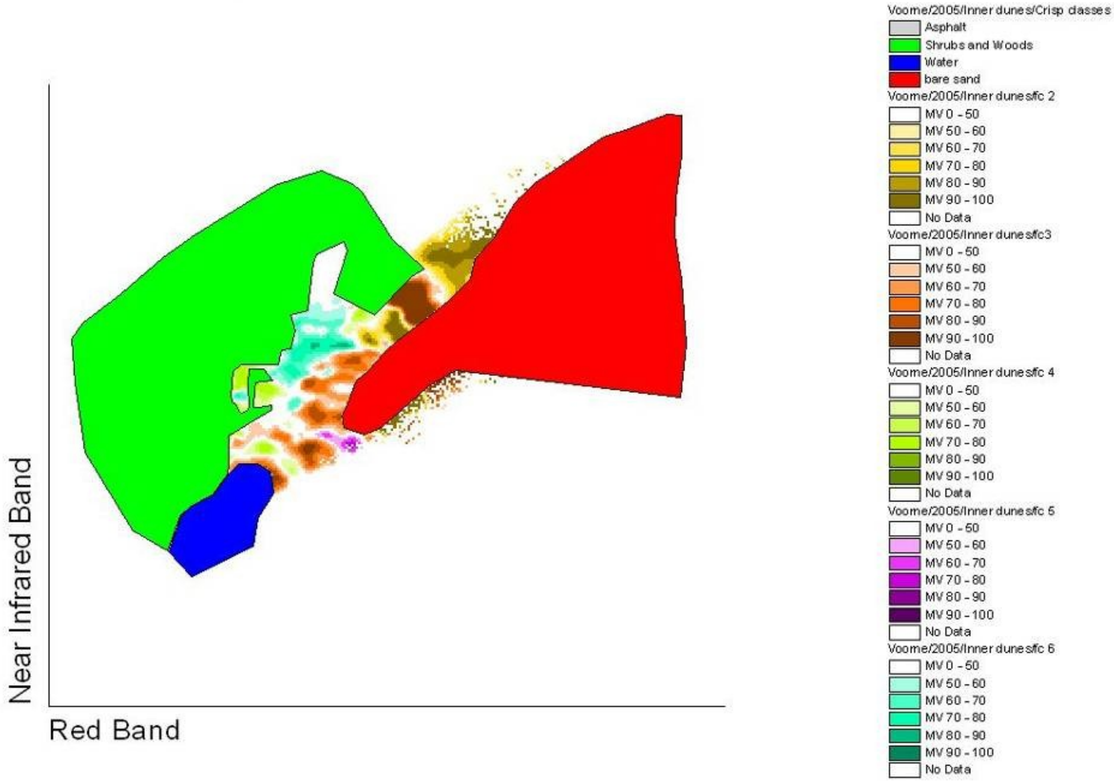

Feature Space of Voorne / 2005 / Coastal ridge
Voorne/2005/Coastal ridge/Crisp classes
Asphalt
Shrubs and Woods
Water
Bare sand
Voorne/2005/Coastal ridge/fc2
MV 0 - 50
MV 50 - 60
MV 60 - 70
MV 70 - 80
MV 80 - 90
MV 90 - 100
No Data
Voorne/2005/Coastal ridge/fc3
MV 0 - 50
MV 50 - 60
MV 60 - 70
MV 70 - 80
MV 80 - 90
MV 90 - 100
No Data
Voorne/2005/Coastal ridge/fc4
MV 0 - 50
MV 50 - 60
MV 60 - 70
MV 70 - 80
MV 80 - 90
MV 90 - 100
No Data
Voorne/2005/Coastal ridge/fc5
MV 0 - 50
MV 50 - 60
MV 60 - 70
MV 70 - 80
MV 80 - 90
MV 90 - 100
No Data
Voorne/2005/Coastal ridge/fc6
MV 0 - 50
MV 50 - 60
MV 60 - 70
MV 70 - 80
MV 80 - 90
MV 90 - 100
No Data
Near Infrared Band
Red Band


Vegetation structure map of:
Voorne/2005/Coastal ridge
Voorne/2005/Coastal ridge/Crisp classes
Shrubs and Woods
Bare sand
No Data
Voorne/2005/Coastal ridge/fc2
MV 0 - 50
MV 50 - 60
MV 60 - 70
MV 70 - 80
MV 80 - 90
MV 90 - 100
No Data
Voorne/2005/Coastal ridge/fc3
MV 0 - 50
MV 50 - 60
MV 60 - 70
MV 70 - 80
MV 80 - 90
MV 90 - 100
No Data
Voorne/2005/Coastal ridge/fc4
MV 0 - 50
MV 50 - 60
MV 60 - 70
MV 70 - 80
MV 80 - 90
MV 90 - 100
No Data
Voorne/2005/Coastal ridge/fc5
MV 0 - 50
MV 50 - 60
MV 60 - 70
MV 70 - 80
MV 80 - 90
MV 90 - 100
No Data
Voorne/2005/Coastal ridge/fc6
MV 0 - 50
MV 50 - 60
MV 60 - 70
MV 70 - 80
MV 80 - 90
MV 90 - 100
No Data
N
W
E
S
0
200
400 Meters

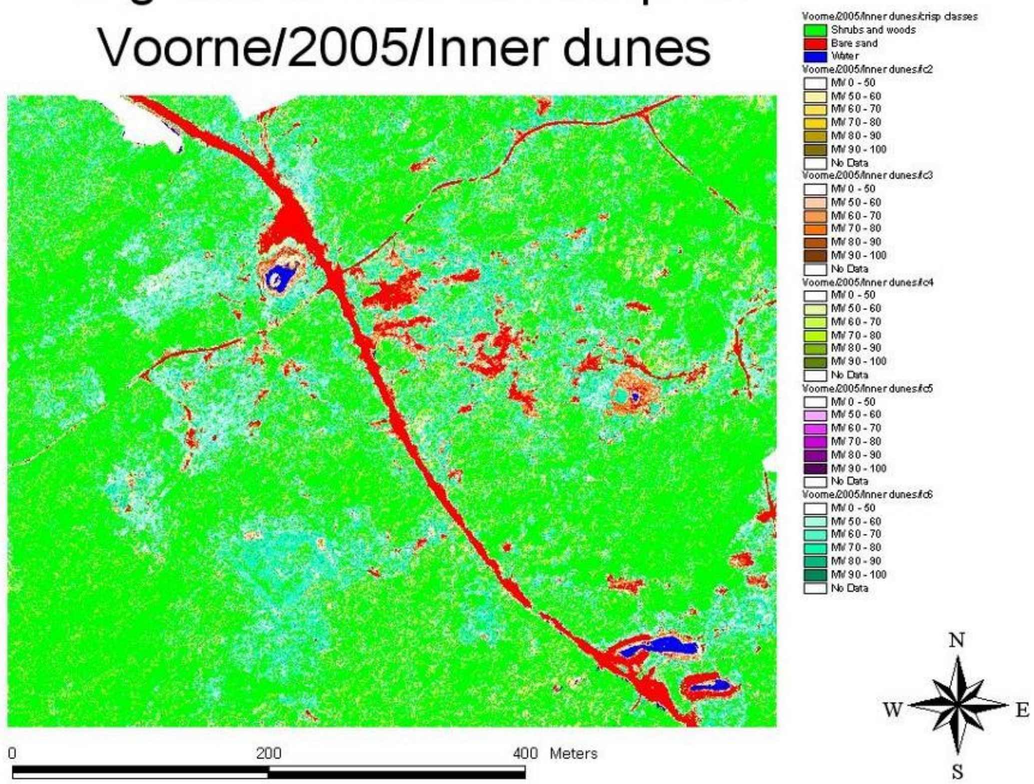
Appendix A.5 Voorne: inner dunes



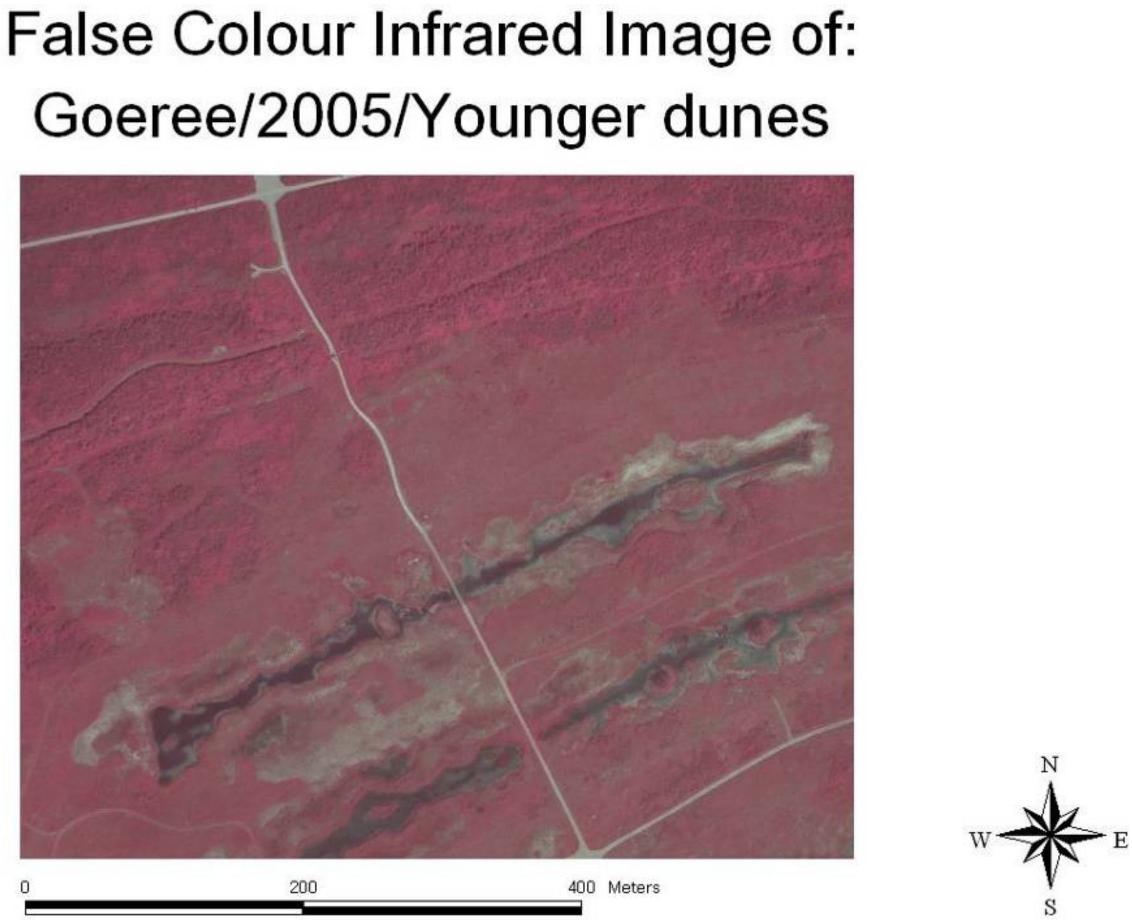
Feature Space of Voorne / 2005 / Inner dunes

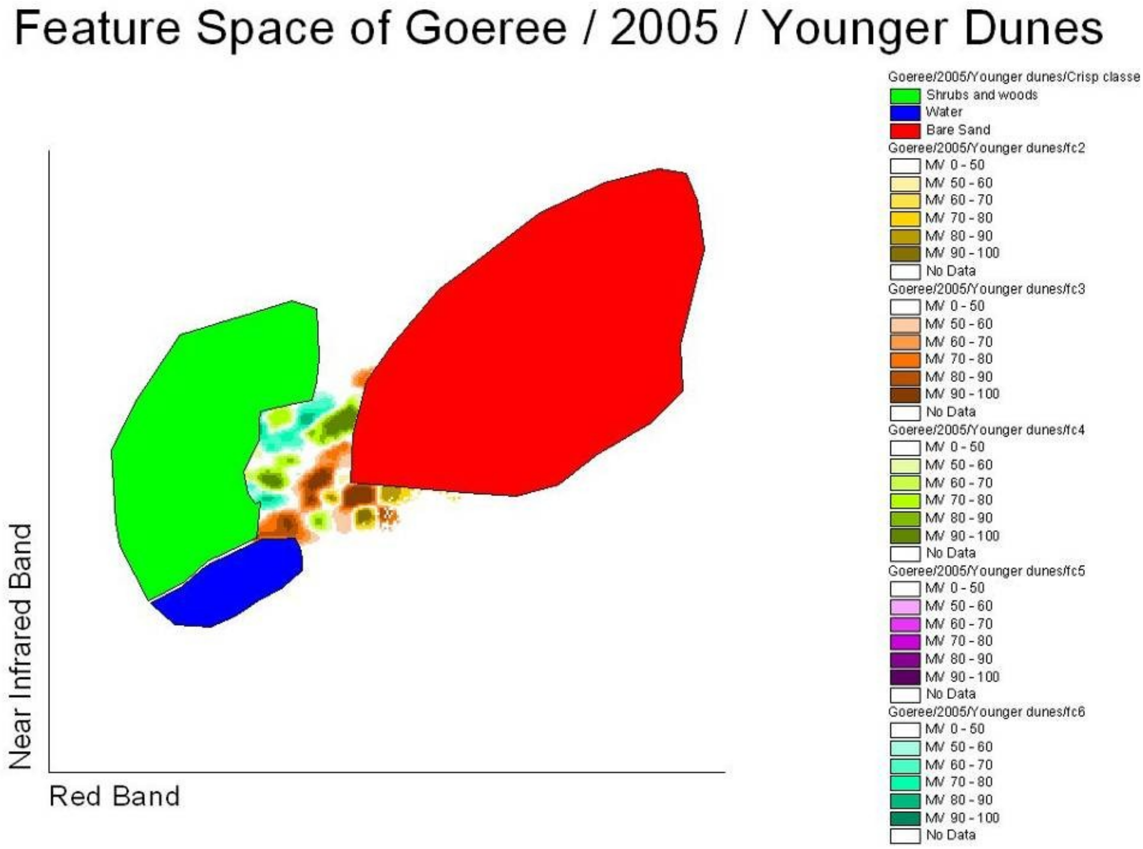


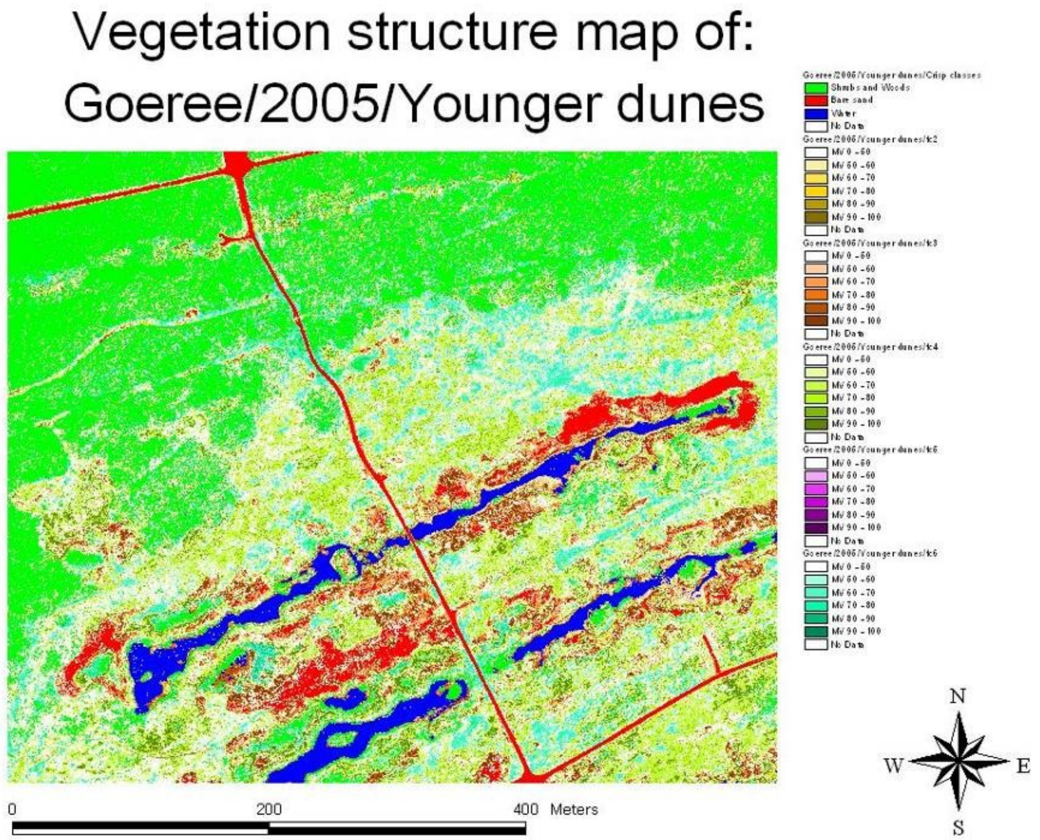
Vegetation structure map of: Voorne/2005/Inner dunes



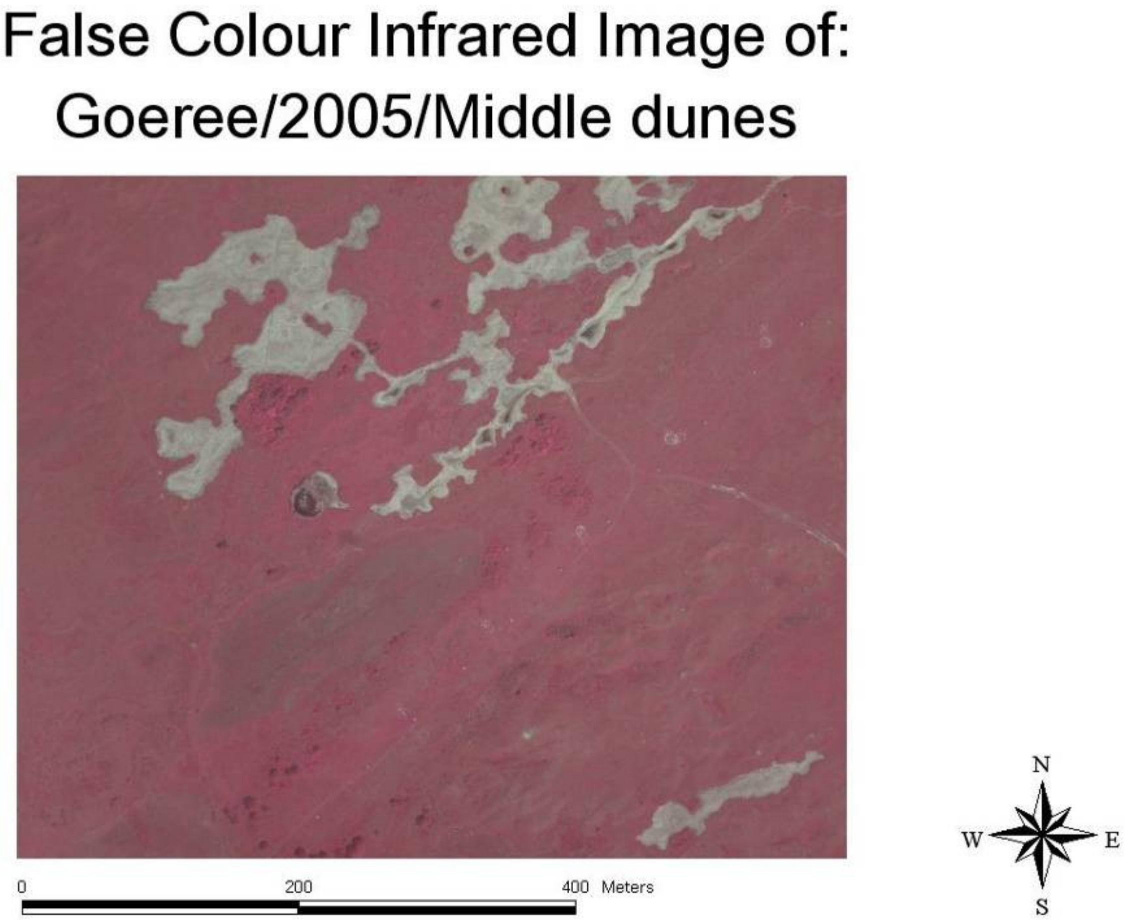
Appendix A.6 Goeree: younger dunes

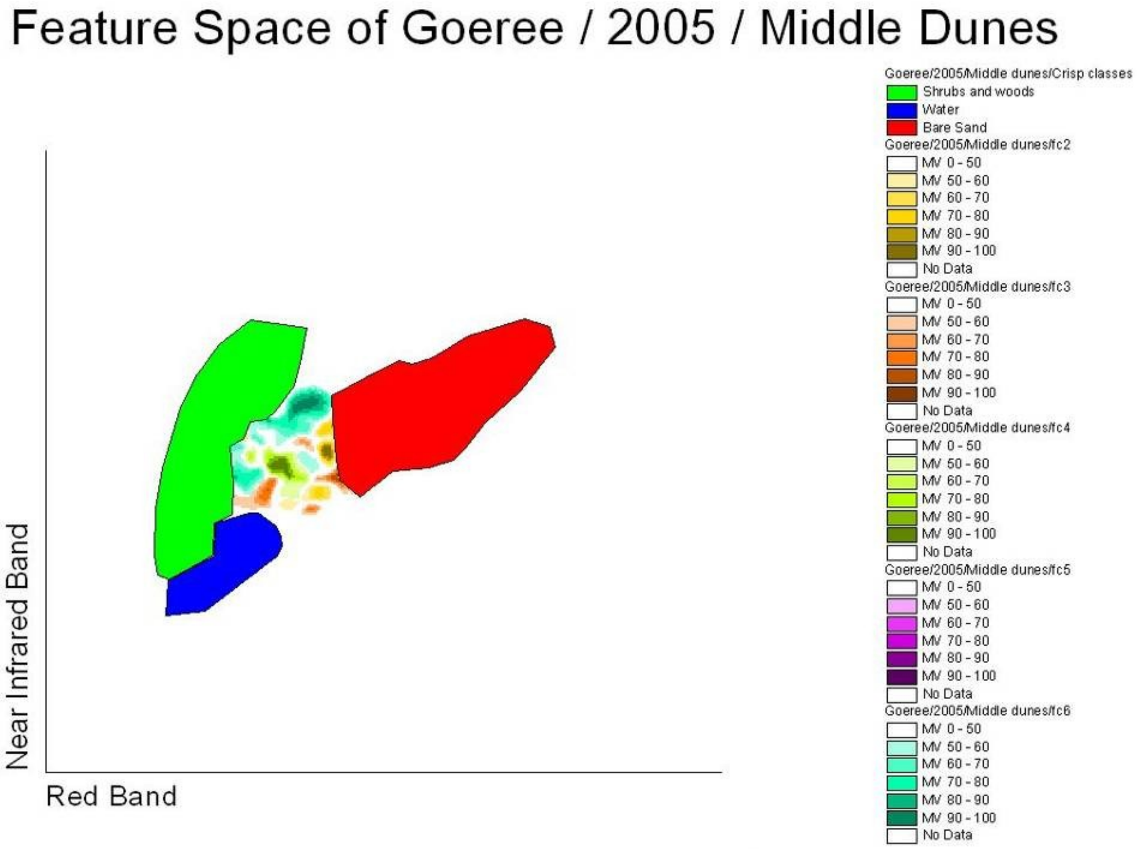


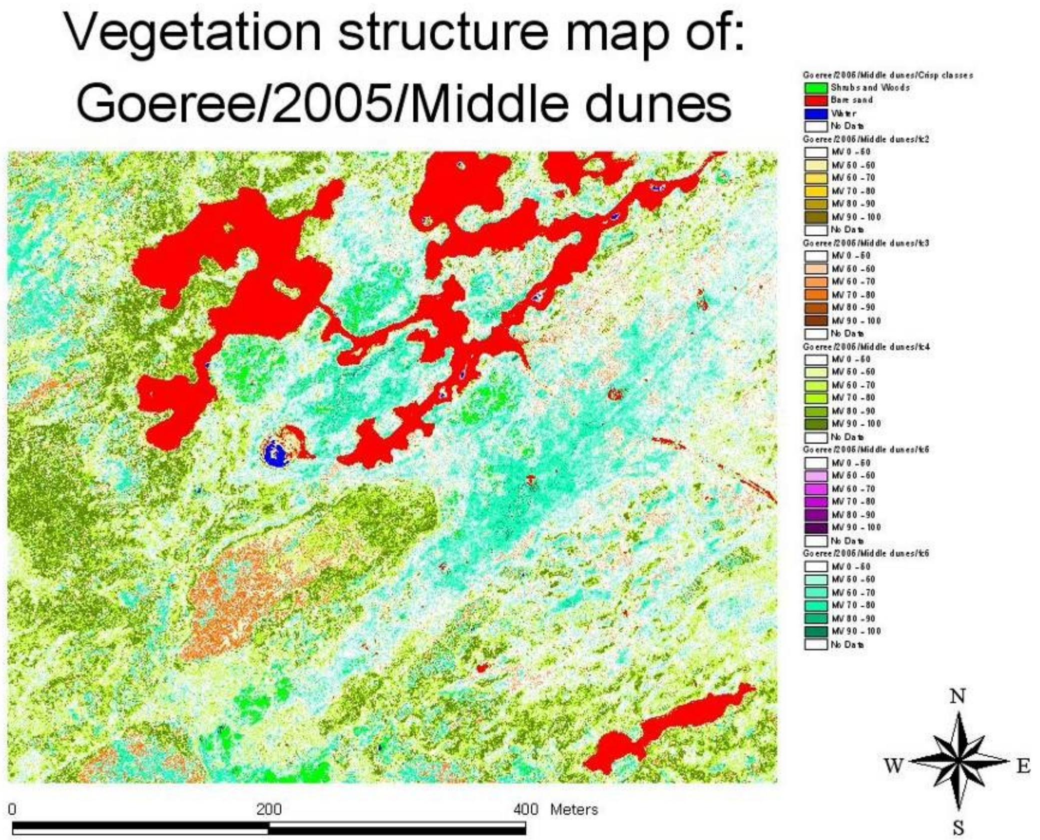

Feature Space of Goeree / 2005 / Younger Dunes
Near Infrared Band
Red Band
Goeree/2005/Younger dunes/Crisp classe
Shrubs and woods
Water
Bare Sand
Goeree/2005/Younger dunes/fc2
MV 0 - 50
MV 50 - 60
MV 60 - 70
MV 70 - 80
MV 80 - 90
MV 90 - 100
No Data
Goeree/2005/Younger dunes/fc3
MV 0 - 50
MV 50 - 60
MV 60 - 70
MV 70 - 80
MV 80 - 90
MV 90 - 100
No Data
Goeree/2005/Younger dunes/fc4
MV 0 - 50
MV 50 - 60
MV 60 - 70
MV 70 - 80
MV 80 - 90
MV 90 - 100
No Data
Goeree/2005/Younger dunes/fc5
MV 0 - 50
MV 50 - 60
MV 60 - 70
MV 70 - 80
MV 80 - 90
MV 90 - 100
No Data
Goeree/2005/Younger dunes/fc6
MV 0 - 50
MV 50 - 60
MV 60 - 70
MV 70 - 80
MV 80 - 90
MV 90 - 100
No Data


Vegetation structure map of:
Goeree/2005/Younger dunes
0
200
400 Meters
N
W
E
S

Appendix A.7 Goeree: middle dunes

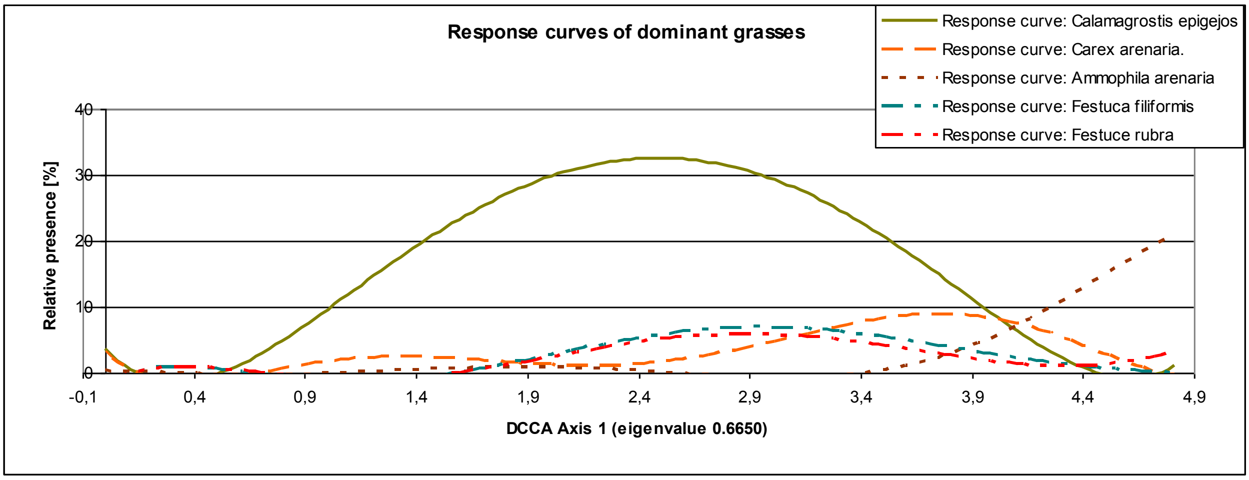



Feature Space of Goeree / 2005 / Middle Dunes
Near Infrared Band
Red Band
Goeree/2005/Middle dunes/Crisp classes
Shrubs and woods
Water
Bare Sand
Goeree/2005/Middle dunes/fc2
MV 0 - 50
MV 50 - 60
MV 60 - 70
MV 70 - 80
MV 80 - 90
MV 90 - 100
No Data
Goeree/2005/Middle dunes/fc3
MV 0 - 50
MV 50 - 60
MV 60 - 70
MV 70 - 80
MV 80 - 90
MV 90 - 100
No Data
Goeree/2005/Middle dunes/fc4
MV 0 - 50
MV 50 - 60
MV 60 - 70
MV 70 - 80
MV 80 - 90
MV 90 - 100
No Data
Goeree/2005/Middle dunes/fc5
MV 0 - 50
MV 50 - 60
MV 60 - 70
MV 70 - 80
MV 80 - 90
MV 90 - 100
No Data
Goeree/2005/Middle dunes/fc6
MV 0 - 50
MV 50 - 60
MV 60 - 70
MV 70 - 80
MV 80 - 90
MV 90 - 100
No Data

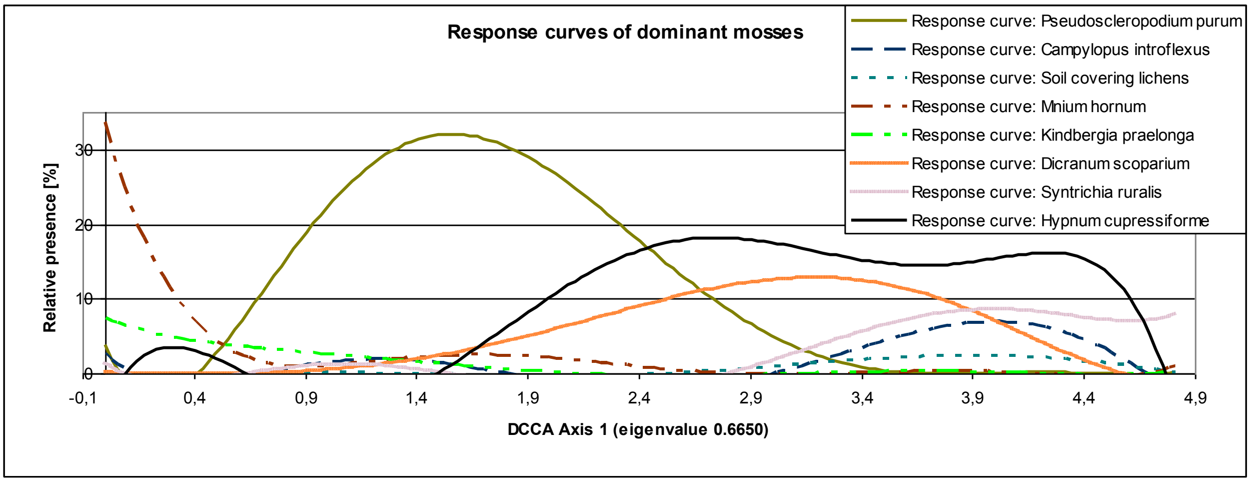

Vegetation structure map of:
Goeree/2005/Middle dunes
0
200
400 Meters
N
W
E
S

Appendix B. Response curves

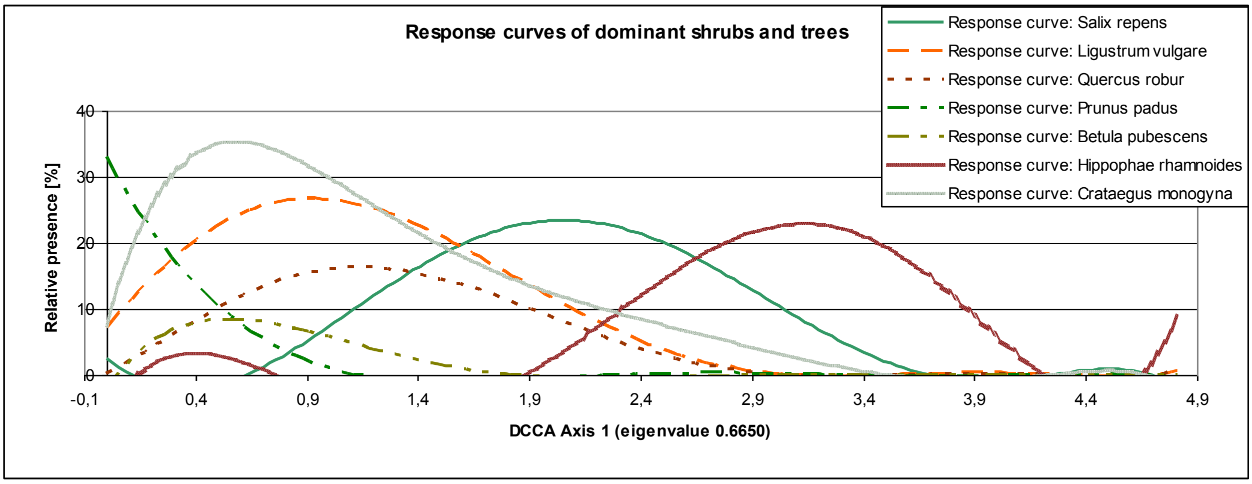
Appendix B.1 Response curves of dominant grasses on DCCA ordination axis 1



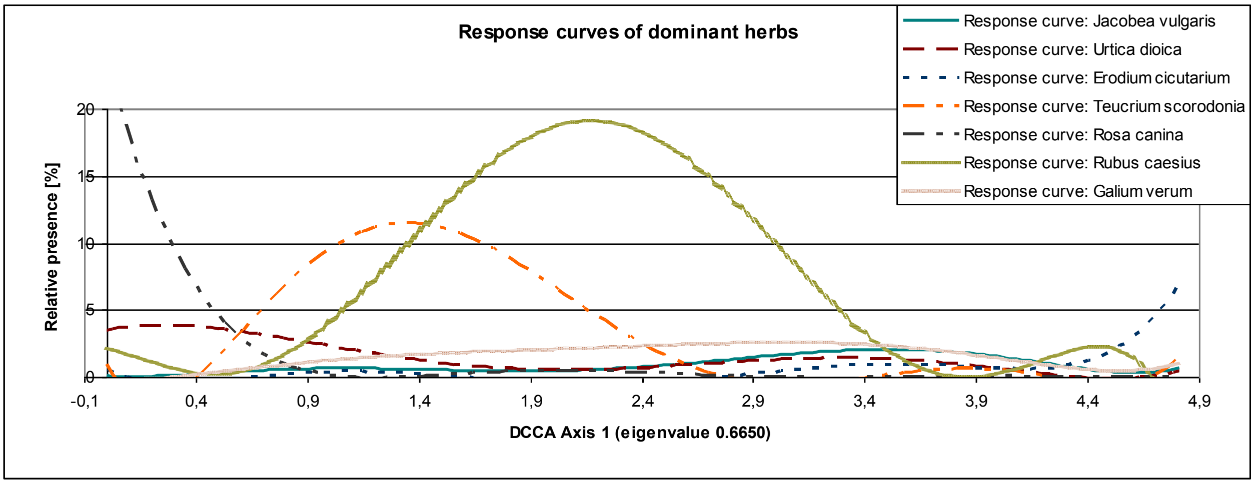
Appendix B.2 Response curves of dominant mosses on DCCA ordination axis 1



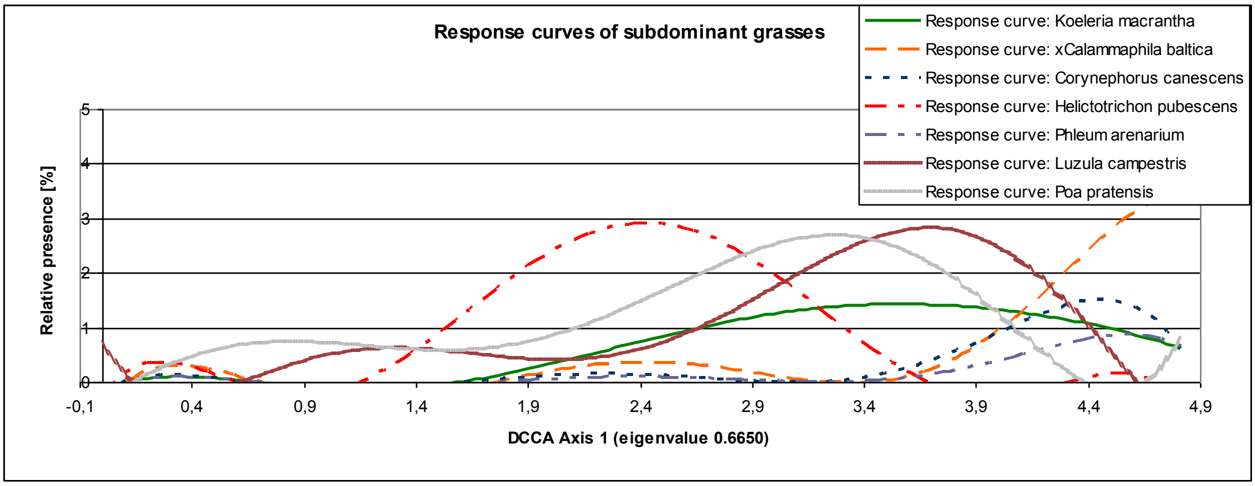
Appendix B.3 Response curves of dominant shrubs and trees on DCCA ordination axis 1



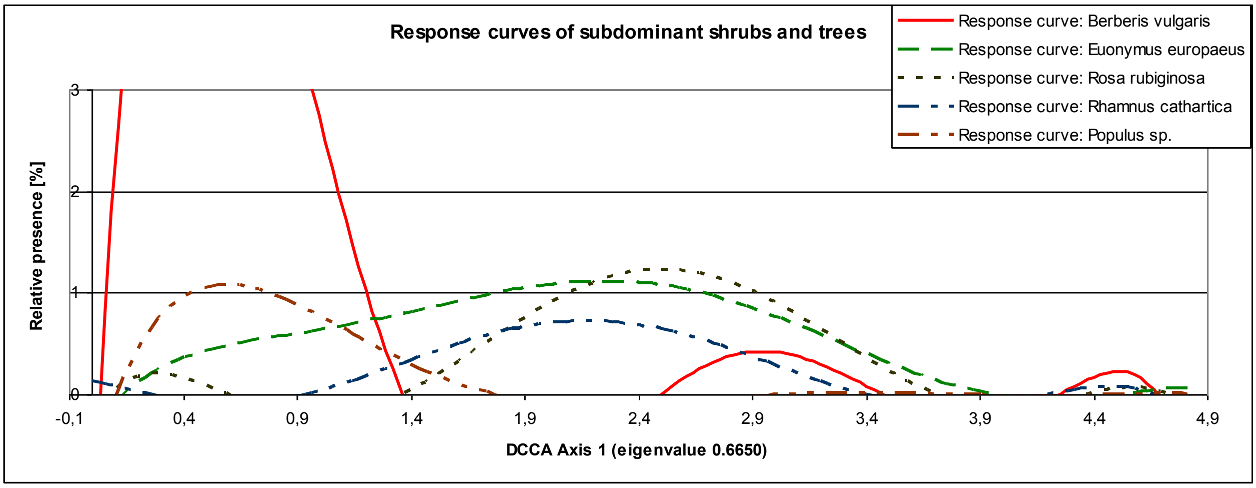
Appendix B.4 Response curves of dominant herbs on DCCA ordination axis 1



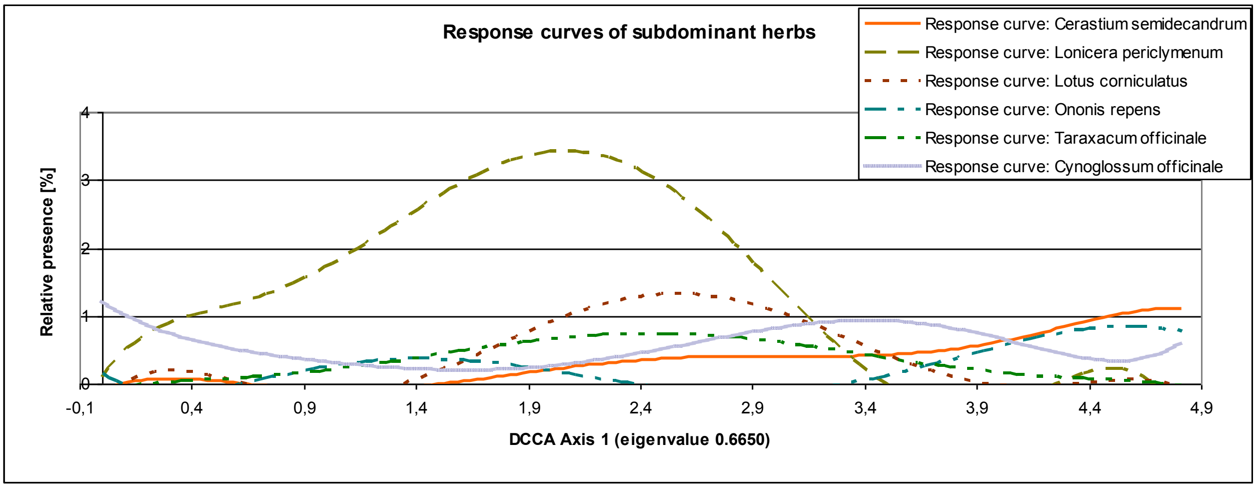
Appendix B.5 Response curves of subdominant grasses on DCCA ordination axis 1



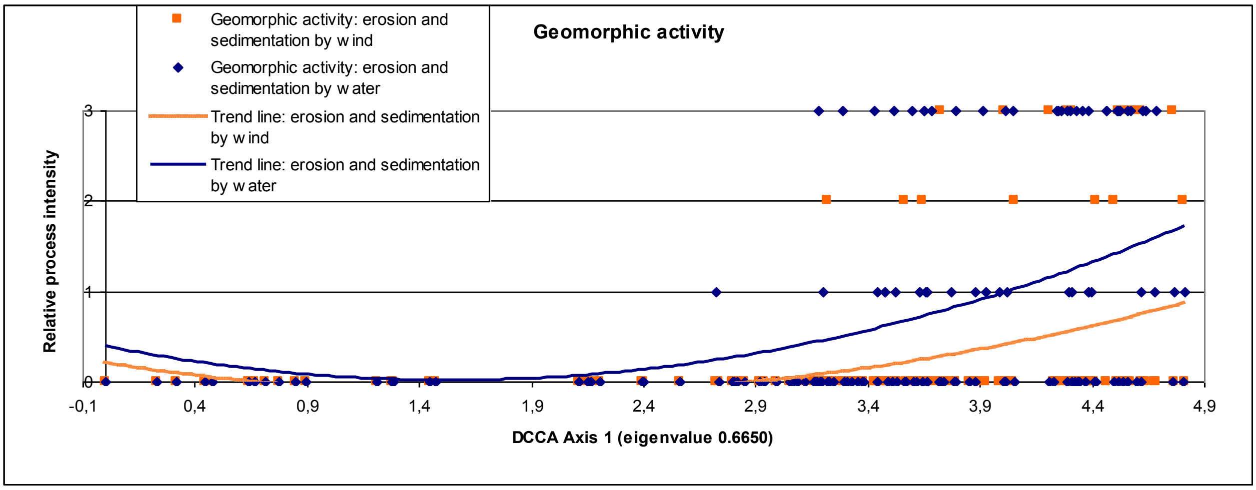
Appendix B.6 Response curves of subdominant shrubs and trees on DCCA ordination axis 1



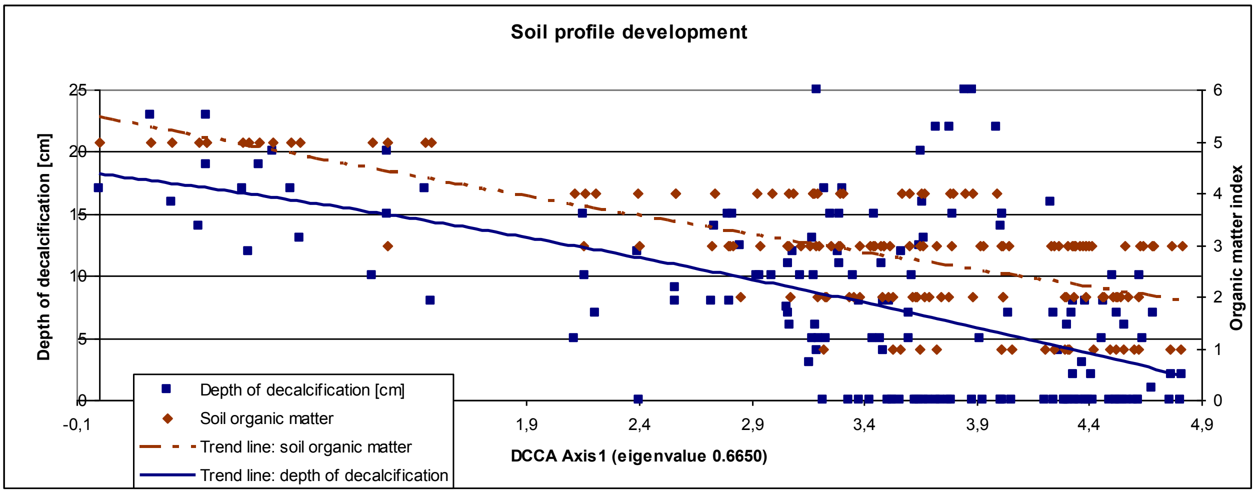
Appendix B.7 Response curves of subdominant herbs on DCCA ordination axis 1



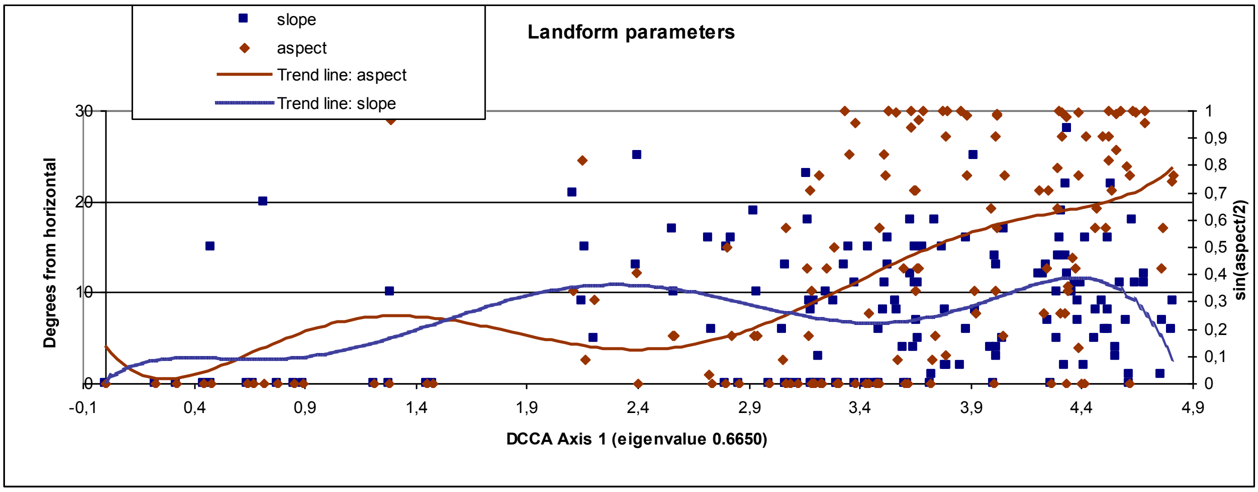
Appendix B.8 Response curves of geomorphic activity on DCCA ordination axis 1



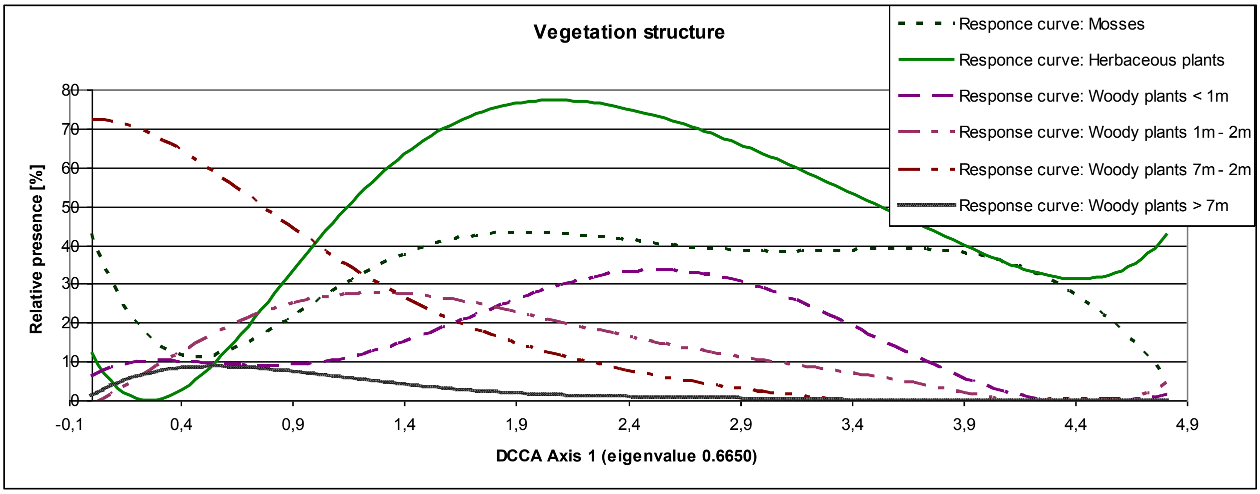
Appendix B.9 Response curves of soil profile development on DCCA ordination axis 1



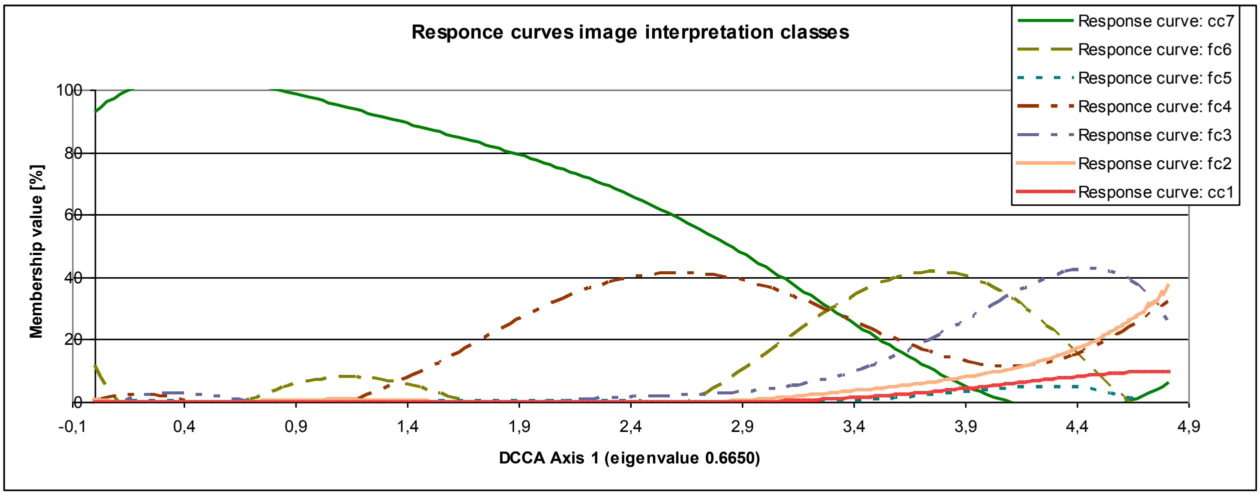
Appendix B.10 Response curves of landform parameters on DCCA ordination axis 1



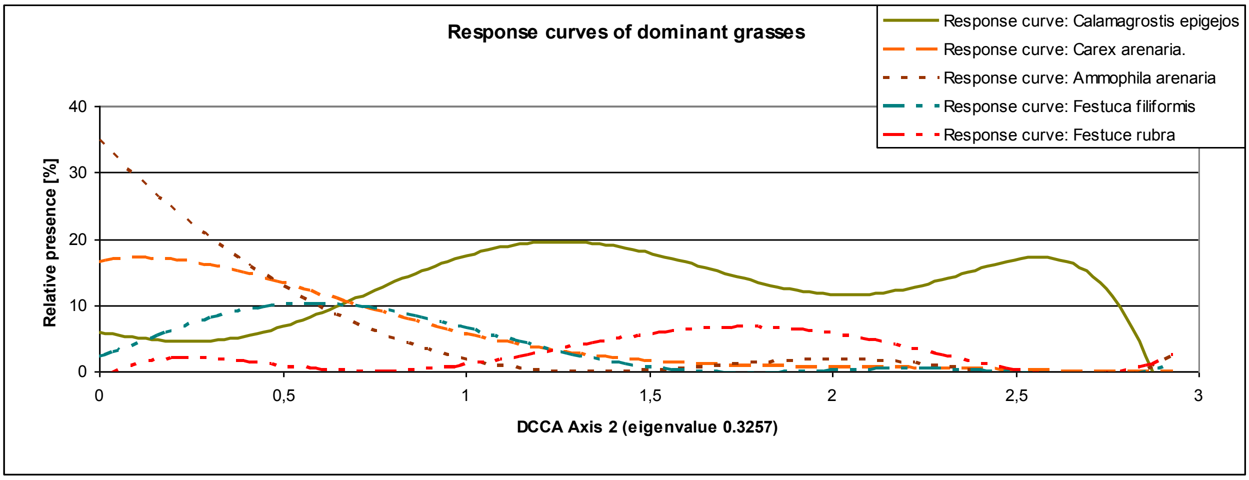
Appendix B.11 Response curves of vegetation structure on DCCA ordination axis 1



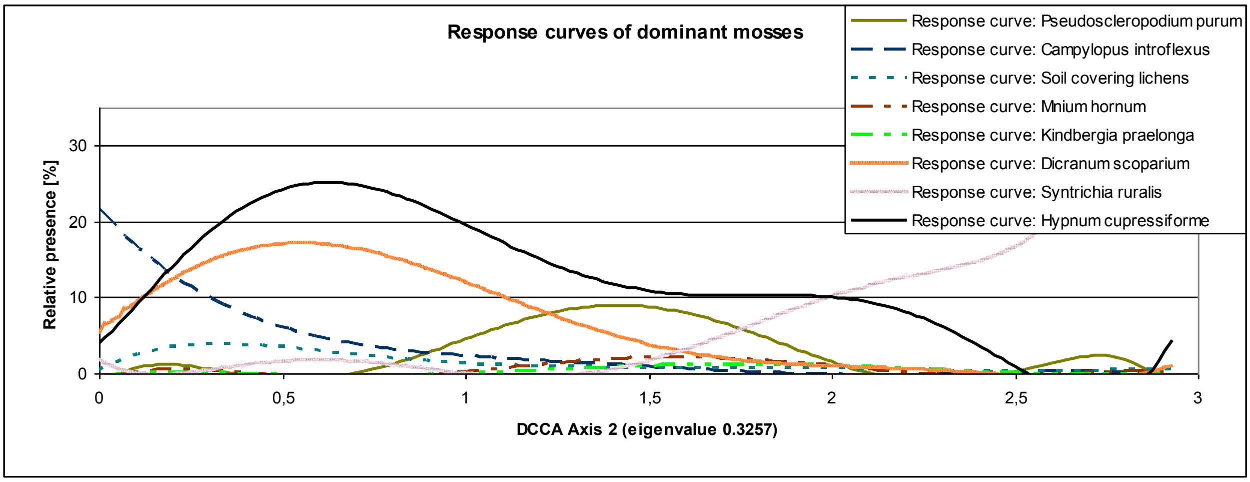
Appendix B.12 Response curves of image interpretation classes on DCCA ordination axis 1



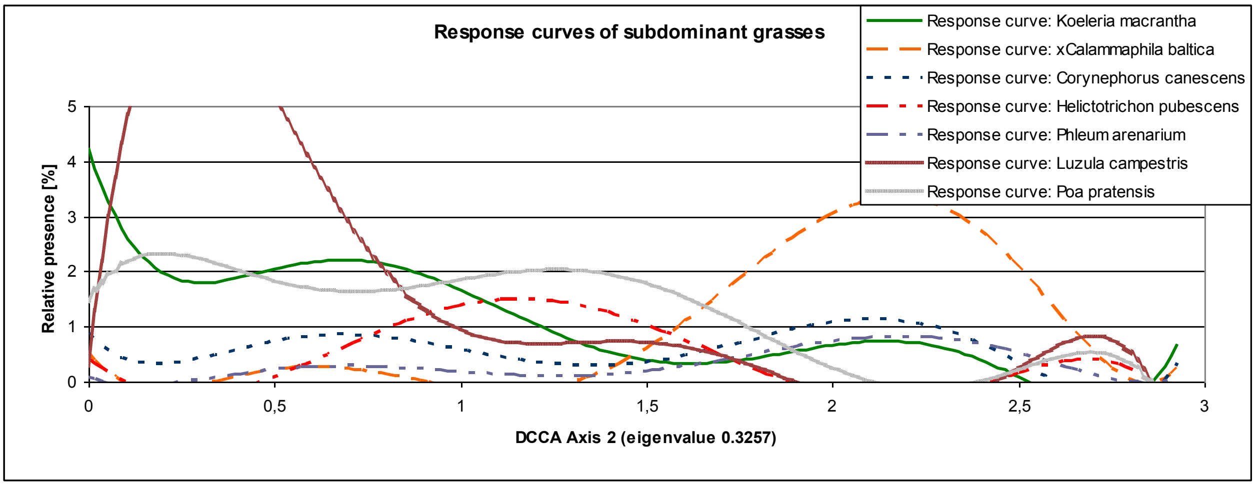
Appendix B.13 Response curves of dominant grasses on DCCA ordination axis 2



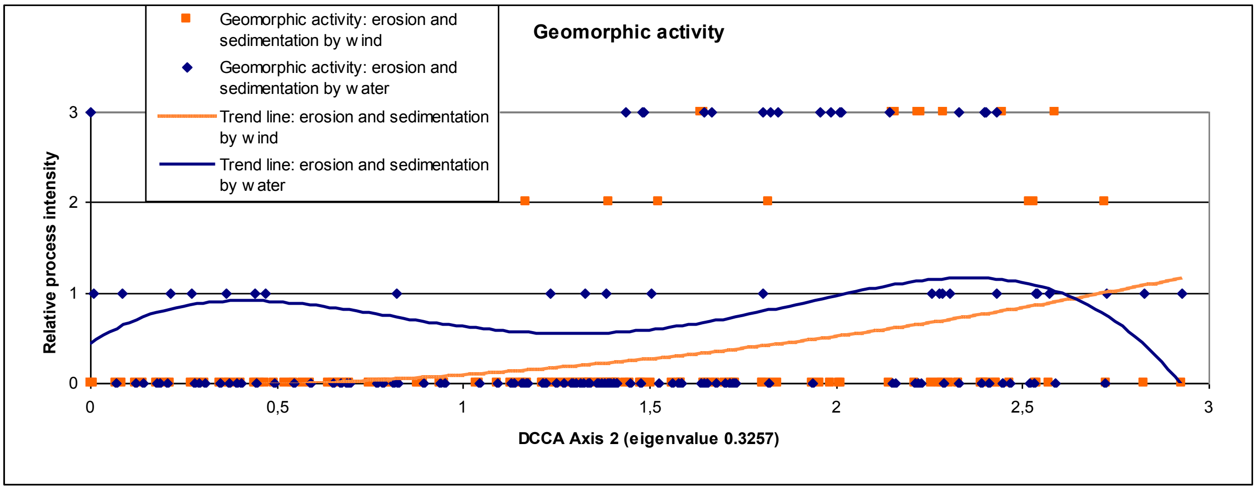
Appendix B.14 Response curves of dominant mosses on DCCA ordination axis 2



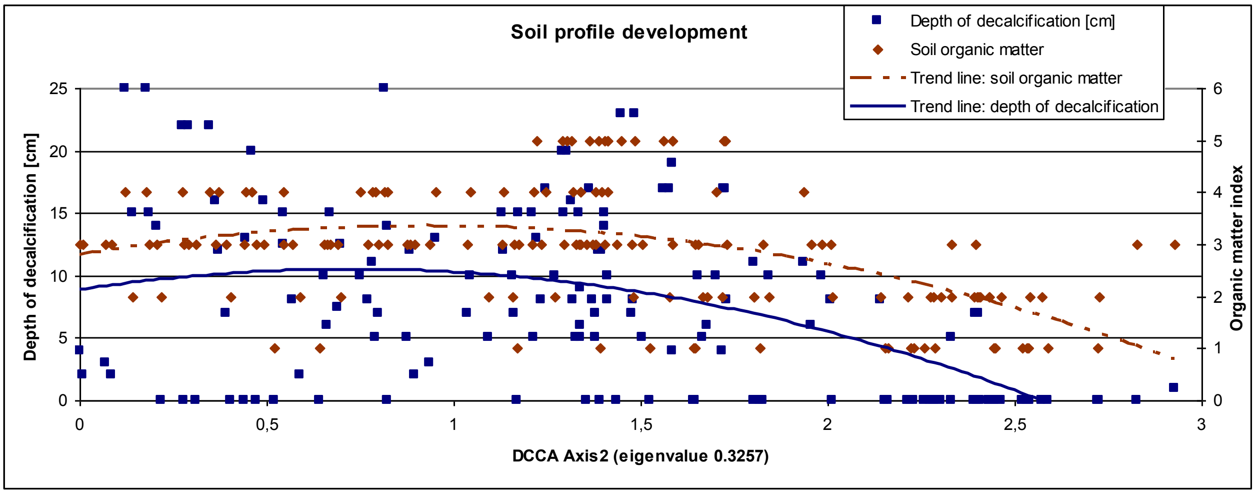
Appendix B.15 Response curves of subdominant grasses on DCCA ordination axis 2



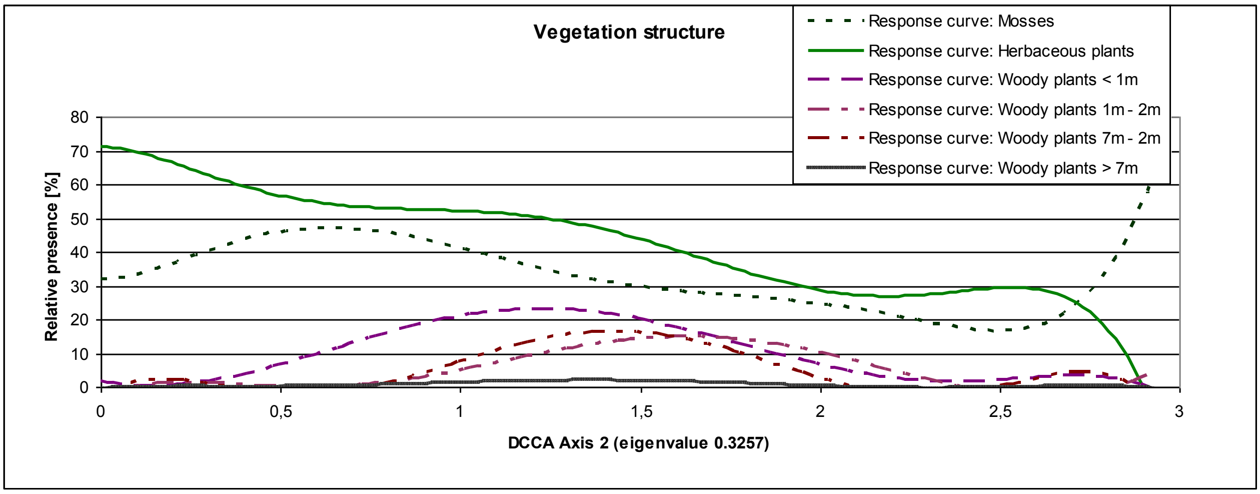
Appendix B.16 Response curves of geomorphic activity on DCCA ordination axis 2



Appendix B.17 Response curves of soil profile development on DCCA ordination axis 2



Appendix B.17 Response curves of vegetation structure on DCCA ordination axis 2



Appendix B.18 Response curves of image interpretation classes on DCCA ordination axis 2