Analysis and Design of Multifunctional Agricultural Landscapes

A Graph Theoretic Approach

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Dit onderzoek is uitgevoerd binnen de C.T. de Wit Graduate School: Production Ecology and Resource Conservation.

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Proefschrift
ter verkrijging van de graad van doctor
op gezag van de rector magnificus
van Wageningen Universiteit,
Prof. dr. M.J. Kropff
in het openbaar te verdedigen
op woensdag 21 mei 2008
des namiddags te half twee in de Aula

André Jellema (2008)

Analysis and Design of Multifunctional Landscapes: A Graph Theoretic Approach
PhD thesis Wageningen University. - With references. -With summaries in English and Dutch.

ISBN: 978-90-8504-883-1

Abstract

Jellema A., 2008. Analysis and Design of Multifunctional Landscapes: A Graph Theoretic Approach.

This thesis focuses on the development of quantitative methodologies for the evaluation of landscape functions and their interactions in multifunctional agricultural landscapes. In current methodologies, ecological and landscape functions, which require an approach at landscape scale in stead of field or farm scale, are poorly represented. This thesis focuses on the spatial coherence of hedgerow networks for ecological functions and landscape character for perception of landscape identity, and on their integration in a multifunctional and multiscale trade-off analysis. Graph theory, currently emerging in landscape ecology, provided the basis for new methodologies. By developing new methods based on this theory, it became possible to develop descriptors for spatial coherence in networks of linear landscape elements, which often occur in agricultural landscapes. Landscape character was analyzed using graph theoretical regionalization. This approach allows to delineate homogeneous regions in spatial data patterns for the classification of landscapes, rather than using predefined analysis units, as commonly applied in other methods. The two methodologies can be applied in spatial planning processes to direct conservation measures or to analyze and map human perceptions of landscapes. To investigate the interactions between landscape functions at field, farm and landscape scale, a generic analytical framework is presented. This framework is based on a heuristic search method which iteratively improves a set of landscape plans and allows the optimization of complex spatial functions. The concept of Pareto optimality is applied to the direct optimization of the trade-off surface between different landscape functions. The final set of Pareto optimal solutions reveals the window of opportunities for regional development and can be used to support landscape planning discussions. For each of the solutions a spatially explicit image of the future landscape can be presented based on a quantitative scientific model. All research methodologies developed in this thesis have been illustrated with case studies in the Northern Frisian Woodlands.

Keywords: multifunctional agriculture, spatial planning, hedgerow, connectivity, landscape character, graph theory, region growing, optimization, Pareto optimality.

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Chapter 1

General introduction

1.1 A multifunctional perspective on agriculture

Speaking about the 'multifunctionality' of agriculture is acknowledging that agriculture provides multiple services for society in addition to the service of food and fiber production (OECD, 1998). These additional services can be defined broadly and have an economic, social or environmental dimension. Agriculture contributes to:

- The viability of rural communities, providing employment and catalyzing economic activities such as supply and processing industries and service providing companies.
- Landscape values, including supporting cultural-historical landscapes, natural habitats, openness, silence and darkness;
- Environmental health, including clean water and air, land conservation and the sustainable management of renewable resources.

Beside these more regional services, agriculture may also provide services at a national or global level such as food security, food safety, food quality, flood control and CO_2 reduction. It is important to note that the concept of multifunctionality does not imply that these services are provided automatically as inevitable outcomes of any and all farming systems. The outcomes vary widely based on the agricultural practices, farm size, farm location (by country, eco-region and local environment) and the interactions between these variables (De Vries, 2000). These additional services of agriculture are also referred to as non-commodity goods, public goods or positive externalities.

The concept of multifunctionality has its origin in the sustainability dialogue of the early nineties and is now accepted, after the political upheavals in the WTO context, as an analytical framework to operationalize sustainable development (Le Cotty et al., 2005, Figure 1). For a more detailed description of the history of multifunctionality, see Box 1. Sustainable development is a normative concept that aims to "meet the needs of the present without compromising the ability of future generations to meet their own needs" (WCED, 1987). The multifunctional perspective on agriculture helps to identify activities and functions that can be utilized to obtain these societal demands within sustainability thresholds. The strength of this analytical framework is the focus on integration and the development of possible synergies between functions (Knickel and Renting, 2000).

The multifunctional perspective on agriculture is seen as a solution to the current problems in the rural areas of the EU (EC, 2000; O'Conner et al., 2006). The Common Agricultural Policy (CAP) over the past 50 years has led to continuous modernization, up-scaling and intensification of farming systems (Wesley et al., 1989). Nowadays this agricultural model is no longer viable, because of trade-liberalization (Costantini et al., 2007), decreasing prices and increasing costs (Van der Ploeg et al.,

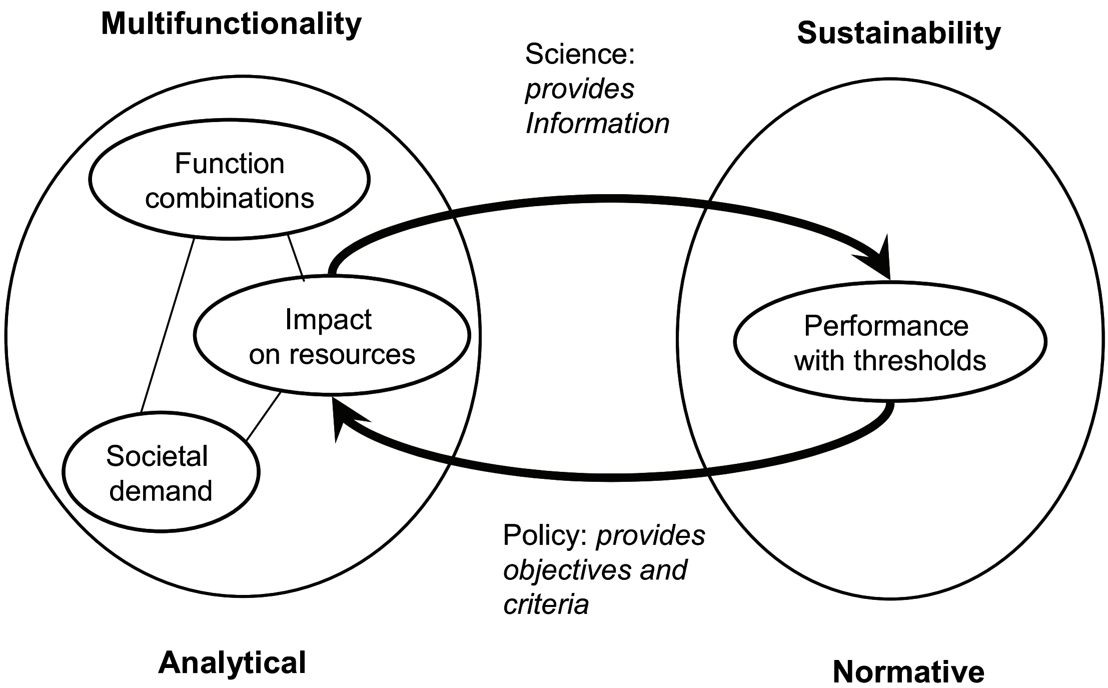

Figure 1. Formalization of links between multifunctionality and sustainability (source: Le Cotty et al., 2005).

2000), environmental pollution and biodiversity loss (Stoate et al., 2001) and concerns about the public health (Smith et al., 2004). In areas far from the economic centers this crisis led to land abandonment, disrupting social and economic structures (Vos and Meekes, 1999). On the other hand at the fringes of these economic centers there is an increased demand for land to build houses, infrastructural and leisure facilities driving up the prices and restricting the possibilities for large scale intensive agricultural practice (Antrop, 2000; Antrop, 2002). The urban sprawl causes a public concern about the loss of landscape qualities like openness, quietness, scenic beauty, cultural history, biodiversity and rural village live (Frouws, 1998). This continuing crisis in the agricultural sector and the urbanization of Europe can be seen as a threat to agriculture, but also as a chance for the development of new farming practices (Van der Ploeg and Renting, 2000; O'Conner et al., 2006).

1.2 Regional development of multifunctional agriculture

Although the development of multifunctional agriculture often starts as a bottom-up process driven by individuals, many of the new functions of agriculture cannot be realized or managed at the traditional farm or field scale (Cumming et al., 2006; Gottfried et al., 1996). Functions such as landscape esthetics (Hendriks et al., 2000; Gibon, 2005), nature conservation (Geertsema, 2002; Tscharntke et al., 2005), or water management (Mtetwa and Schutte, 2002; Ulen and Kalisky, 2005) depend on large

Box 1. The history of multifunctionality.

The notion of multifunctionality in agriculture has emerged in the 1980s and has spread in the 1990s (Le Cotty et al., 2005). It entered the political arena when it was referred to in the Agenda 21 documents of the Rio Earth Summit of 1992, "particularly with regard to food security and sustainable development" (UNCED, 1992), but has gained particular importance during the international negotiations on trade liberalization organized by the World Trade Organization (WTO). In preparation of the Doha Round the European Union (EU) launched a series of statements (CEC, 1997; CEC, 1998; CEC, 1999; CEC, 2001) in which the multifunctional character of agriculture was used as an argument to continue its domestic support programs building a "European Model of Agriculture" (Potter and Burney, 2002; Swinbank, 2002). In the view of the opponents, multifunctionality was seen as no more than a smokescreen for the continuation of protectionist agricultural policies and resistance to further trade liberalization. Nowadays, the WTO contention has switched gradually from the legitimacy of multifunctionality to the best policy approach to address the non-trade concerns of agriculture (Sakuyama, 2005), focusing on the search for none-trade distorting policy measures (Anderson, 2000; Schmitz and Moss, 2005). A considerable contribution to this agreement was made by the Organization for Economic Cooperation and Development (OECD) by proposing a working definition on multifunctionality in a consensus seeking report (Sakuyama, 2005).

According to this working definition, key elements of multifunctionality in agriculture are the existence of multiple commodity and non-commodity outputs and the fact that some of these outputs exhibit the characteristics of externalities, or side effects, which are freely accessible and non-exclusive (OECD, 2001). As a result markets do not exist or function poorly and outputs are difficult to value in economic terms (Randall, 2007) and to manage politically (Hall et al., 2004). Nowadays the multifunctionality of agriculture is an accepted concept to discuss sustainable development within and outside the EU (Le Cotty et al., 2005).

Gibon, 2005), nature conservation (Geertsema, 2002; Tscharntke et al., 2005), or water management (Mtetwa and Schutte, 2002; Ulen and Kalisky, 2005) depend on large scale patterns at a landscape, a regional or catchment scale. To realize these functions farmers need to collaborate with other farmers in the region and as a result new social structures may arise such as farmer study groups advising on farming practice and environmental cooperatives formulating common goals for their regions (Brunori and Rossi, 2000; Holloway et al., 2006; Franks and Mc Gloin, 2007). Regional landscape structures should provide services for which there is a demand. To further embed their plans into the region, farmers do not only need to interact with other farmers, but also with non-agricultural stakeholders such as: local governments, non-agricultural residents, land owners, NGO's and waterboards (Glasbergen, 2000). Each of these stakeholders has its own agenda and perspective on the region. So the question is how do these regional plans become established.

Nowadays, modern policy making has moved away from a top-down decision making towards the introduction of regional governance (Friedmann, 1993). Regional governance is a communal learning and decision making process between stakeholders in which they share their perspectives and have to develop a common vision on regional development within the boundaries of national and international policies (Haughton and Counsell, 2004; Pinto-Correia et al., 2006). However, due to the complexity of the matter none of the stakeholders will have a complete overview of the issues involved. The search for synergies between land use functions involves the integration of knowledge from different scientific domains (Van Mansvelt, 1997) at multiple spatial and temporal scales (Knickel and Renting, 2000). Scientists can contribute to the development of multifunctional agriculture by structuring the complexity of reality and by grounding a value-laden discussion in an understandable scientific perception of reality (Tait, 2001). In this context, future studies (Faucheux and Hue, 2001) using a goal oriented approach (Von Wiren-Lehr, 2001), environmental modeling (Bolte et al., 2007) and systems theory (Kropff et al., 2001) provide a powerful means to study the interactions between land use functions and to communicate the consequences of management options (Loevinsohn et al., 2002; Walker, 2002). Therefore, there is a need for spatial explicit knowledge systems operating at multiple scales which provide insight in the interactions between land use functions.

1.3 A goal-oriented approach to land use planning

A goal oriented approach (Von Wiren-Lehr, 2001; Rossing and Groot, 2004; Rossing et al., 2007) is an analytical approach to decision making based on the comparison of the state of a land use system to a set of explicit objectives in 4 steps: In the first step case-specific objectives are defined in dialogue with the stakeholders, determining system boundaries and relations between the system components (Kropff et al., 2001). In the second step indicators are developed for the defined objectives as measurable properties of the system. In the third step an evaluation strategy is adopted to assess the sustainability of the current or future systems. Which strategy is adopted strongly depends on the questions being raised as will be discussed in more detail below. In the last step the theoretical outcome of the assessment is communicated to the stakeholder, which may lead to an adaptation of the sustainability goals, indicators or evaluations made and the reiteration of the evaluation cycle described above. The goal oriented approach facilitates a balanced decision making process by making objectives and the mental models of the stakeholders explicit and by evaluating the consequences of their desires (Pahl-Wostl and Hare, 2004).

Depending on the questions raised different evaluation strategies can be adopted: a predictive approach and an explorative approach (Van Ittersum et al., 1998). In a predictive study, different scenarios of policy measures are developed and their effectiveness to meet the predefined objectives is evaluated using a set of indicators. These indicators which can be based on simple expert rules or can comprise the application of complex simulating models. Following the predictive approach only a small number of the future solutions is provided. In the explorative approach the best combination of policy measures is matched using an optimization technique, providing the maximum contribution to the predefined objectives. By systematically varying the objectives the boundaries of the set of feasible solutions can be revealed and used for decision making (Groot et al., accepted). However, due to the complexity of the optimization process, explorative models often operate on simplified representations of reality. The two evaluation strategies described above have their own niche in land use planning processes (Van Keulen, 2007). The predictive approach is often used to analyse the current situation or to answer 'what if' questions for the development of specific policy measures. The power of explorative approach is to open a wide perspective of possible future developments, including innovative developments that are viable from a systems point of view, but disconnected from current trends and developments (Rossing et al., 1997). This characteristic makes the explorative approach potentially valuable in participative planning processes searching for compromises between different development options (Van Ittersum et al., 1998).

Explorative approaches applied to agriculture are traditionally focussed on the evaluation of economic, agronomic and environmental aspects of farming (Zander and Kächele, 1999; Ten Berge et al., 2000; Dogliotti, 2003; Van der Ven et al., 2003). Social and landscape functions are often omitted (Rossing et al., 2007). In this thesis I will contribute to the development of goal-oriented land use studies by developing a generic analytical framework capable of integrating multiple scale interactions between land use objectives, including the landscape scale, using an explorative approach. To evaluate these landscape functions indicators are needed at the relevant scale. For practical reasons I focussed on the development of indicators for the functions of biodiversity conservation and landscape quality.

1.4 Evaluating biodiversity conservation and landscape character

To evaluate the functioning of a landscape the relation between the landscape configuration and landscape processes needs to be established (Turner, 1989; Wu and Hobbs, 2002; Turner, 2005; Schröder and Seppelt, 2006).

The biodiversity conservation potential of a landscape can be established by relating properties of the landscape to the survival of species. Species survival in the landscape is traditionally studied using a patch oriented view on the world (McArthur and Wilson, 1967; Levins, 1970; Forman and Gordon, 1986; Pulliam, 1988; Hanski, 1994; Forman, 1995). Patches are relatively homogeneous areas of habitat where fundamental ecological processes take place. Spatial relations are expressed between the patches rather than within patches and linear habitat elements are seen as corridors, conduits of fluxes, facilitating the movement of individuals from one patch to the next. Based on this paradigm landscape ecology produced a plethora of computerized methods for measuring the spatial structure of landscapes, varying from simple geometrical indicators or landscape indexes (McGarigal and Marks, 1995; Gustafson, 1998; Cardille et al., 2005), metapolulation models (Levins, 1970; Hanski and Ovaskainen, 2003), source sink models (Pulliam, 1988; Keagy et al., 2005; Runge et al., 2006) to individual based models (Jepsen et al., 2005; Breckling et al., 2006; Grimm et al., 2006). However not all landscapes fit such a patch oriented view of the world (Campbell Grant et al., 2007). In agricultural landscapes linear habitat elements such as canals hedgerows and field margins are the carriers of biodiversity (Marshall and Moonen, 2002; Grashof-Bokdam et al., 2005). For species restricted to these habitats, the world is composed of a more or less continuous network of linear elements, varying in extension, density and quality. Patches and corridors cannot be identified, neither structurally nor functionally. Therefore patch-based evaluation models cannot be applied to evaluate the ecological functioning of this type of landscapes. In this thesis I will contribute to the development of new methodologies for the evaluation of the spatial coherence of linear habitat networks by using the mathematical framework of the graph theory, as will be explained below.

The character of a landscape is defined as the presence, variety and arrangement of different landscape features (Swanwick and Consultants, 2002). The character of a landscape determines the appearance of a landscape, makes it stand out from other landscapes and gives a sense of place to the people inhabiting the landscape (Stedman, 2003). The quality of the landscape character is determined by evaluating the difference between the observed patterns in the landscape and a reference image. A reference image of the landscape can be based on expert qualifications (the objectivist model), such as readability of the landscape (Hendriks et al., 2000), cultural history (Macinnes, 2004; Antrop, 2005) or a mental model of human perception (Stamps III, 2004) (the subjectivist model) (Lothian, 1999; Daniel, 2001). To support spatial planning spatial analysis tools like remote sensing and Geographical Information Systems (GIS) are applied to locate, characterize and evaluate landscapes in a quantitative way using predefined analysis units (Peccol et al., 1996; Palmer and Roos-

Klein Lankhorst, 1998; Farjon et al., 2002; Scott, 2002; Geertsema, 2003; Ayad, 2005; De la Fuente de Val et al., 2006). The selection of the observation scale is a critical step in these methods and may severely bias the outcome of the pattern analysis. The size and shape of the analysis units can severely bias the measured outcome (Openshaw and Tayler, 1981; Jelinski and Wu, 1996; Dark and Bram, 2007). In literature this is called the modifiable area unit problem or MAUP. In this thesis we take a different approach, rather than determining spatial units in advance, we will use graph theory to adapt the spatial analysis units to the pattern of landscape features.

1.5 Graph theoretical analysis of spatial data patterns

In the course of this study, I discovered that graph theory offers good opportunities to develop generic flexible tools to evaluate landscape patterns. Graph theory is a mathematical theory which uses a conceptual model of pair wise relations between objects to solve mathematical problems (Bondy and Murty, 1977; Newman, 2003). A graph in this context refers to a set of points or nodes and a set of edges that connect pairs of nodes (Figure 2). The graph exhibits an interesting property for landscape studies, because in contrast to other data formats such as the vector of raster format (Longley et al., 2005), the spatial relations between the objects in the landscape can directly be modeled and analyzed (Theobald, 2001). The application of graphs for spatial data analysis is scarce, but applications are diverse. Graphs are used to: find the shortest path between two locations (Zhao and Cheng, 2001), analyze stream networks (Calinescu et al., 2006), analyze topological relations (De Almeida et al., 2007), register spatial data (Trias-Sanz and Pierrot-Deseilligny, 2004), spatial data mining (Zimmermann et al., 2004) and map generalization (Jiang and Claramunt, 2004).

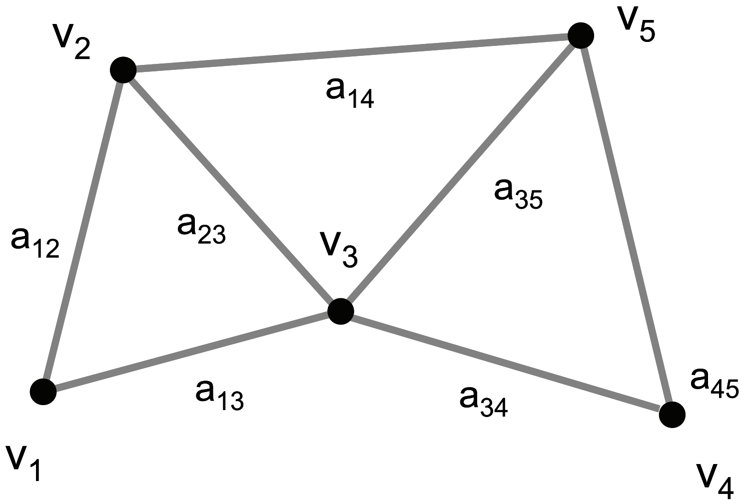

Figure 2. A graph G consisting of a set of 5 nodes $\{v_1, v_2, v_3, v_4, v_5\}$and a set of 7 edges $\{a_{12}, a_{13}, a_{14}, a_{23}, a_{34}, a_{35}, a_{45}\}$.

The application of graph theory in landscape studies was first introduced by Cantwell and Forman (1993) to evaluate the ecological functioning of habitat patterns. However the concept was not picked up widely before the ground breaking paper of Urban and Keitt (2001). Nowadays a number of different approaches can be recognized to: descriptively characterize landscape patterns (Cantwell and Forman, 1993; Forman, 1995); prioritize key patches and corridors (Urban and Keitt, 2001; Jordan, 2003); analyze the permeability of the landscape (Van Langevelde, 2000; Urban and Keitt, 2001; Fall et al., 2007); determine the shortest paths through the landscape (Drielsma et al., 2007); and simulate population processes (Franc, 2004; Roberts et al., 2006). All authors mentioned above applied graph theory to patch-based networks and in this thesis I extent their application to the evaluation linear habitat networks.

Graphs are also used for the analysis of spatial patterns in an image or for image segmentation (Shi and Malik, 2000; Pavan and Pelillo, 2003; Marfil et al., 2006; Sharon et al., 2006). By grouping neighboring similar pixels in homogeneous spatial clusters or regions, optical patterns can be delineated into identifiable objects. In landscape studies this type of methodology has been proposed to delineate patches and landscapes using high resolution imagery (Burnett and Blaschke, 2003). However many features of the landscape cannot be read directly from the spectral information on an aerial photograph but are interpreted and are stored in a GIS. In this thesis I will broaden the scope of graph theoretical image analysis by generalizing it to other types of spatial data formats to assess landscape character.

1.6 Case study area

All research methodologies developed in this thesis have been illustrated with case studies in the Northern Frisian Woodlands (Figure 3). The study area has been selected because of the social dynamics in the region. Farmers in the Northern Frisian Woodlands are pioneers in the development of multifunctional agriculture and regional collaboration for environmental objectives (Renting and Van der Ploeg, 2001). This development has been followed and supported by researchers from Wageningen University (Van der Ploeg, 2000; Renting and Van der Ploeg, 2001; Groot et al., 2003; Wiskerke et al., 2003; Groot et al., 2006a). Nowadays the farmers are working on a regional plan to change institutional arrangements in favor of more self governance to improve the economic, environmental, ecological and landscape values of the Northern Frisian Woodlands (Anonymous, 2005). These developments provide an interesting background for the development of this thesis. For details about the study area and it's developments see Box 2.

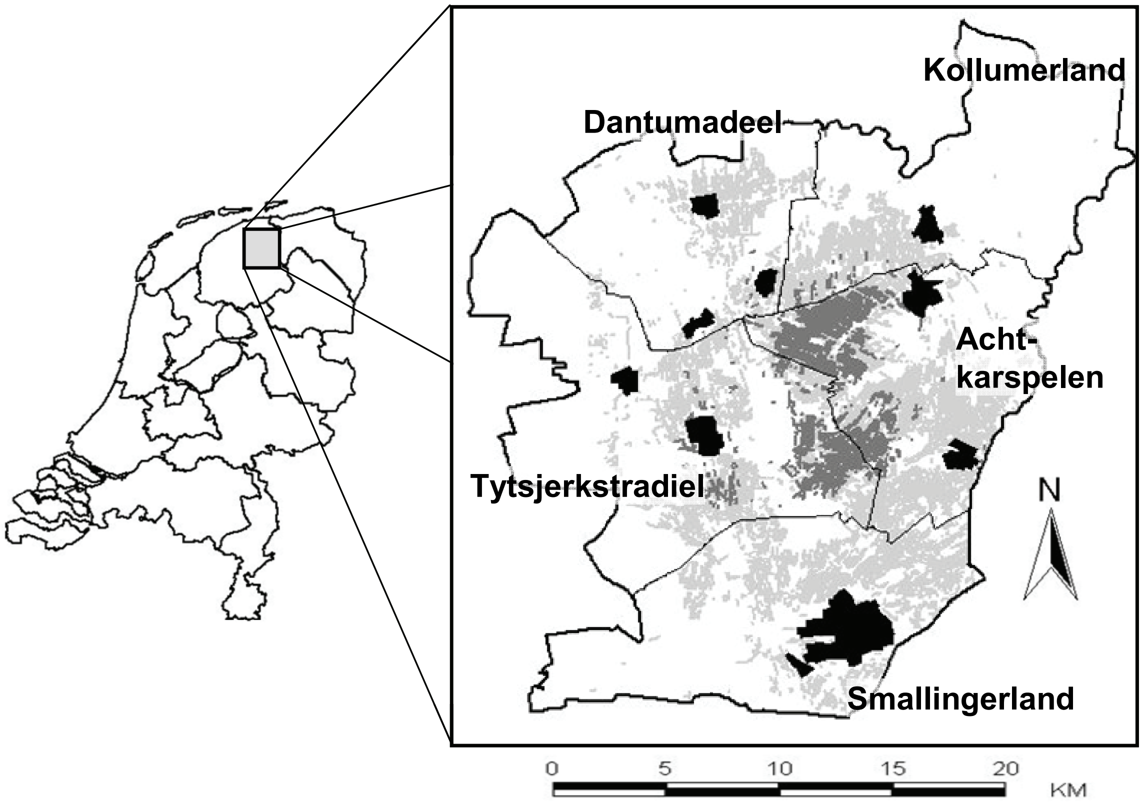

Figure 3. The five municipalities of the Northern Frisian Woodlands located in the North of the Netherlands. Legend: towns and borders in black, hedgerows in dark grey, 'singels' in light grey.

1.7 Objectives and thesis outline

In this thesis I develop a generic analytical framework capable of analyzing multiple spatial scale interactions between land use objectives, including the field, farm and landscape scale and contribute to the development of new methodologies to assess functioning of the agricultural landscape, focussing on the spatial coherence of ecological networks and landscape character, using graph theory.

The objectives of this thesis are:

- to develop a generic analytical framework capable of analyzing multiple spatial scale interactions between land use objectives, including the landscape scale;
- to develop generic indicators for the evaluation of land use objectives at the landscape scale, focusing on spatial coherence of linear habitat networks and landscape character;
- to explore the possibilities to apply the graph theoretical framework in landscape studies.

To achieve these objectives the following research questions have been investigated:

(1) How can a conceptual model for a generic framework to study the interactions between land use functions at multiple spatial scales be developed?
(2) How can such a conceptual framework be implemented technically?
(3) How can spatial coherence of linear habitat networks in agricultural landscapes be measured in a generic and ecological relevant way?
(4) How can characteristic regional landscape patterns be measured in a quantitative and transparent way?
(5) What is the best graph pyramid segmentation algorithm to analyze spatial patterns?
(6) How can indicators for ecological coherence and landscape character be integrated into the analysis framework?

These questions have been addressed in the following 6 chapters (Figure 4):

Chapter 2 "*Towards an integrative approach for the design and analysis of multifunctional agricultural landscapes*" presents a conceptual model for the design and analysis of multifunctional landscapes at multiple spatial scales based on a short review and integration of current methodologies and approaches in landscape ecology and production ecology, addressing research question 1.

Chapter 3 "*Exploring multi-scale trade-offs between nature conservation, agricultural profits and landscape quality. A methodology to support discussions on land use perspectives*" presents the technical implementation of the conceptual model and the proof of concept in a near real case study in the Frisian Woodlands, addressing research question 2.

Chapter 4 "*On connectivity in linear habitat networks using a graph theoretical model*" presents a generic framework to evaluate spatial coherence of habitat networks consisting of linear elements using graph theory, addressing research questions 3.

Chapter 5 "*Landscape character assessment using region growing techniques in Geographical Information Systems*" presents a methodology to analyze spatial patterns in the landscape to make characteristics of the landscape quantifiable and discussable, addressing research question 4.

Chapter 6 "*Evaluation of 52 graph pyramid segmentation algorithms for regionalization of spatial data*" presents the methodological foundation for the methodology used in Chapter 5. In this chapter a systematic comparison of different graph pyramid segmentation algorithms has been made to compare and to identify their strengths and weaknesses, addressing research question 5.

Chapter 7 "*Exploring trade-offs in a hedgerow landscape: redesigning an agro-ecological zone*" presents a real case study in the Frisian woodlands, integrating different landscape functions in the explorative design framework to evaluate a sketch design of an agro-ecological zone in the Frisian Woodlands made by an NGO, addressing research question 6.

Chapter 8 "*General discussion*" discusses and integrates the main findings of the different chapters.

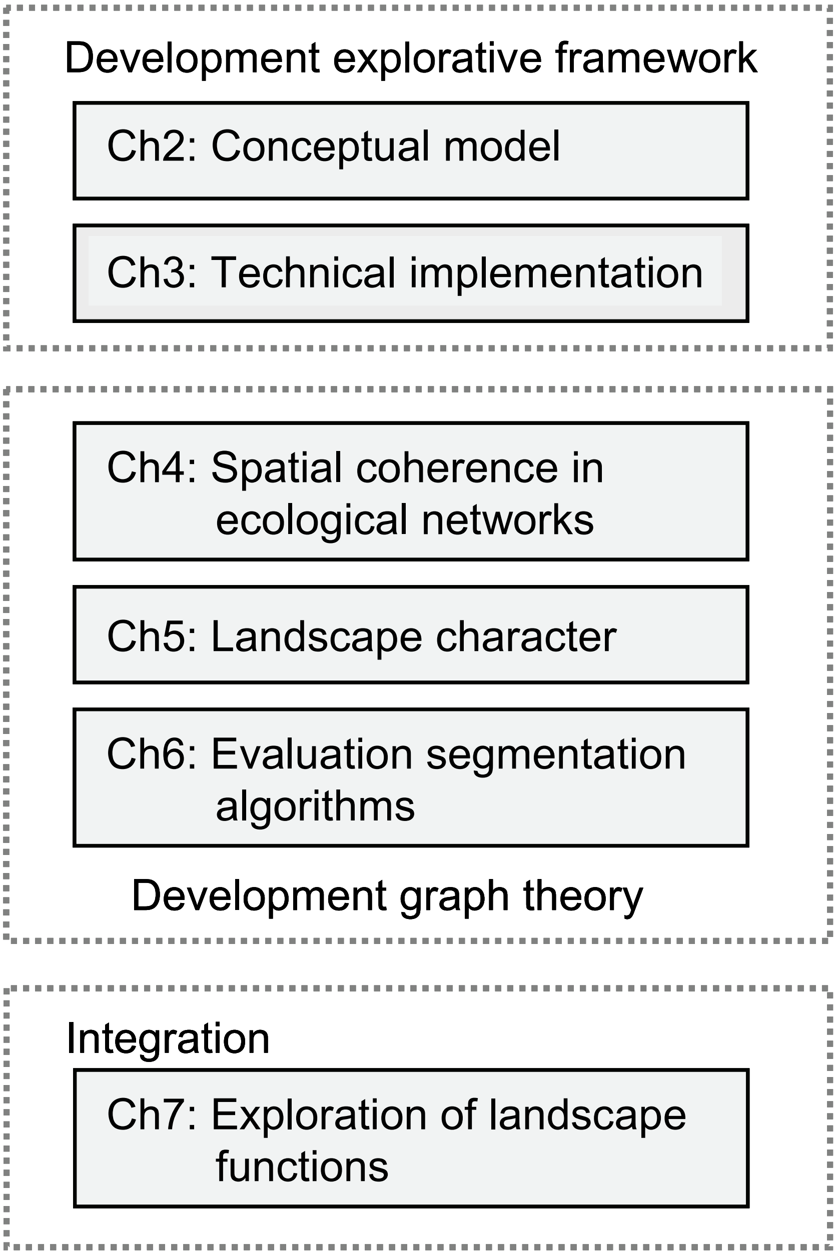

Figure 4. Thesis outline.

Box 2. The Northern Frisian Woodlands.

The Northern Frisian Woodlands comprise a dairy farming area in the north of the Netherlands, comparable to the Bocage landscapes in Brittany and Normandy in France (Baudry et al., 2001), containing the densest hedgerow network of the Netherlands with a total length of over 3000 km (Dijkstra et al., 2003). The pattern of fields reflects a history of peat reclamation. Settlements have developed along the roads on the transition between wet and dry lands and agricultural fields were reclaimed in the perpendicular direction from the roads. Hedgerows in the landscape had the function of property boundary, cattle fence, cattle feed, shade provision, wind break, erosion protection, water management, timber and fire wood production (De Boer, 2003). Nowadays they are highly appreciated for their cultural historical and biodiversity value, have resulted in the status of National Landscape by the Dutch government (Anonymous, 2006). In this area typically 3 different types of cultural historic landscapes are identified: the 'Dykswâl' landscape (Figure 5A) is characterized by fields bordered by trees with oak and birch on earthen banks; the 'Singels' landscape (Figure 5B) is characterized by fields bordered by alder trees along canals and ditches which were planted or emerged by succession; and the 'open' landscape (Figure 5C) which is characterized by their wetness and the absence of trees. The farmers of the Northern Frisian Woodlands have a long tradition of farming in a landscape of trees and the management of small landscape elements. This became only detrimental after the Dutch government announced the 'ecological guideline' in the early 1990's (Renting and Van der Ploeg, 2001), an environmental law to counter the negative effects of ammonia deposition on small landscape elements, stipulating that animal husbandry in the direct environment of valuable landscape elements should be severely limited. Implementation of this guideline would have frozen the agricultural development of the Northern Frisian Woodlands and resulted in a strong feeling of injustice by the farmers who had maintained the landscape for such a long time. After a long period of negotiation the farmers proposed a deal in which they committed themselves to maintain and improve the environmental and ecological value of the landscape elements on the conditions that the hedgerow elements would not be considered as 'acid sensitive objects'. The deal has resulted in the birth of the first environmental co operations of the Netherlands VEL (Vereniging Eastmar's Lândsdouwe) and VANLA (Vereniging Agrarisch Natuur en Landschapsbeheer Achtkarspelen). Nowadays six environmental cooperatives including VEL & VANLA within the region have joint forces to conserve and improve the landscape and farmers income in the cooperative of the Noardlike Fryske Wâlden (NFW), consisting of 800 farmers, covering 50.000 ha (Anonymous, 2005). The joint effort of the farmers has resulted in a strong reduction in nitrogen surpluses (Groot et al., 2006a), better maintenance and the creation of new hedgerows, 'singels' and other landscape elements, a higher income for the farmers from environmental schemes, agri-tourism, cost reduction and *a better social cohesion within the area (Renting and Van der Ploeg, 2001). Nowadays the farmers are working on a regional plan to change institutional arrangements in favor of more self governance to improve the economic, environmental, ecological and landscape values of the Northern Frisian Woodlands (Anonymous, 2005).*

A

B

C

Figure 5. The characteristic landscape types of the Northern Frisian Woodlands: the 'Dykswâl' landscape (A), the 'Singels' landscape (B) and the 'open' landscape (C).

Chapter 2

Towards an integrative approach for the design and analysis of multifunctional agricultural landscapes

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Based on: *Proceedings of the 6th European Symposium of the International Farming Systems Association*, Vila Real, Portugal, 2004, pp. 293-302.

Abstract

Multifunctionality is seen as one of the solutions to society's demand for new functions in the rural areas and the problems with the unsustainability of the agricultural sector in the European Union. In contrast to the traditional agricultural functions of providing income, employment and food, these new functions can not be managed at a single field or a farm. Planning of functions such as nature conservation, and landscape esthetics can only be achieved when the landscape is considered as a whole. We present an outline of a methodology based on concepts and insights from production ecology and landscape ecology, that should enable us to explore the opportunities for multifunctional agriculture, balancing objectives at three spatial scales: field, farm and regional scale. The focus of this chapter is on the integration of agricultural production and nature conservation, while aiming for flexible adaptation to other functions. Explorative design and habitat networks are used to generate and evaluate landscape prototypes. Landscape prototypes are spatially explicit images of multifunctional agricultural landscapes based on scientific models. Another important output of the approach are trade-off curves between the different functions. We discuss the implications of our approach for landscape ecological and agronomic research.

Keywords: multifunctional agriculture, explorative design, optimization, habitat networks, biodiversity, trade-offs.

2.1 Introduction

Multifunctionality is seen as one of the solutions to society's demand for new functions in the rural areas and the problems with the unsustainability of the agricultural sector in the European Union (OECD, 1999; Vos and Meekes, 1999; EC, 2000; OECD, 2001). In answer to this demand agriculture can provide different kinds of services in addition to the traditional services of the production of food, and fibers, employment and income. Farmers and agricultural production systems can contribute to a healthy environment, biodiversity and landscape esthetics (Vereijken, 1998). In contrast to the traditional products of agriculture, these additional services cannot be provided at a single field or farm, but need to be considered at a landscape level. For example, biodiversity protection schemes on single farms were not found to enhance biodiversity (Kleijn et al., 2001), while modeling studies at the regional scale showed that spatial clustering of protective measures leads to substantial increase in survival probablities of plant species (Geertsema, 2002); water levels, water tables and water quality can only be managed at a regional (catchment or polder) scale (Barendregt et al., 1993); spatial coherence is an important factor determining the quality of landscape experience in agricultural areas (Hendriks et al., 2000). Therefore policy makers, planners and individual farmers interested in the multifunctionality concept have to consider the land use at field and farm level within the spatial configuration of the landscape as a whole.

In this chapter we present a framework with which we explore opportunities for multifunctional agriculture by balancing objectives at three different spatial scales: the field scale, the farm scale and the landscape scale. The framework is based on the concepts of explorative design and ecological networks and focuses on objectives related to agricultural production and nature conservation. The methodology is aimed at easy adaptability to other functions. By presenting the conceptual basis, as yet without proof-of-concept, we aim to stimulate thinking on methodologies to bridge the agriculture-nature divide.

2.2 Explorative design

Explorative design is a modeling approach to identify future-oriented land use systems based on quantitative insight in resource use of crops of animals and the way it is affected by farm management (Dogliotti, 2003). The methodology originated in the Theoretical Production Ecology group at Wageningen University (De Wit et al., 1988), and has meanwhile been taken up and extended for conservation issues by others, e.g. Zander (2003).

The explorative design methodology starts by generating a large number of alternative land use activities at the field scale in a systematic manner (Figure 1).

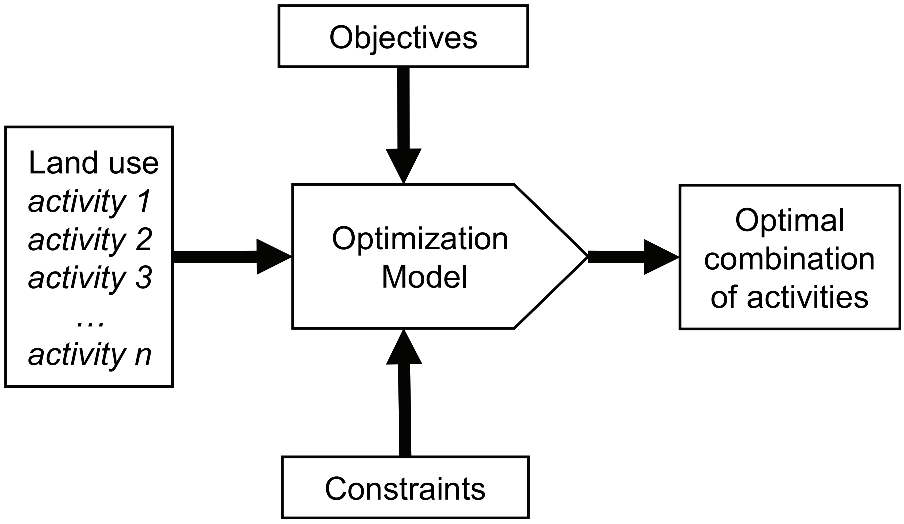

Figure 1. Schematic representation of the explorative design methodology.

Depending on the region, a number of potential crops and management strategies are defined. Each combination of crop and management strategy results in a so-called 'land use activity', which is quantified in terms of all inputs and outputs relevant to evaluate objectives and constranits. The input-output coefficients are the quantitative description of the relation between the necessary inputs for the land use activity and the outputs and are derived from physical, chemical, physiological and ecological knowledge at soil, field and crop level, and farm economic information (Van Ittersum and Rabbinge, 1997). Land use activities may be derived from current agricultural practice, but new activities can be devised using expert knowledge or computer models. In this way innovative land use systems may be developed. The explorative design methodology can be applied at the farm, regional or national scale and is usually implemented using linear programming as a method to find the optimal solution.

The explorative design approach can support decision making by benchmarking the various options of land use by calculation of trade-off curves (Rossing et al., 1997). Technically, these trade-off curves are created by systematically varying the different objectives for the study area and re-running the linear programming model.

2.3 Habitat networks

A collection of suitable habitat patches embedded in a matrix of non-habitat linked by the dispersal of species is called a habitat network (Opdam, 2002). The habitat network is an important concept for species conservation in a fragmented landscape. The basic idea is that the dispersal between the patches enhances species survival in the network as a whole, due to the possibility of recolonization after local extinction in one the patches. The effectiveness of the habitat network to protect a species from extinction depends on the habitat quality, the spatial arrangement and the resistance of the landscape matrix between the patches.

Generic rules for the design of a habit network, relating species survival to the configuration of the habitat networks are difficult to establish. Measuring the population dynamics in the field is time consuming, every studied landscape providing only a single observation (Vos et al., 2001b). An alternative way to develop a set of generic rules is the application of spatially explicit population dynamic model (Opdam et al., 2002). A spatially explicit population dynamic model is a computer model, which calculates the dynamics of a population in a virtual or realistic landscape taking into account key species characteristics. To obtain reliable results these models should be calibrated using field observations. By systematically altering the network configurations, the relation between the population dynamic behavior of the model and network configuration can be studied. Examples of such an approach can be found in Frank and Wissel (1998) and Verboom et al. (2001). In the literature a wide variety of spatial population dynamic models is available (Czárán, 1998). Wiegand et al. (1999) consider spatially explicit models superior for evaluating the configuration of habitats.

2.4 Synthesis

To integrate the concept of habitat networks into the explorative design methodology two important steps need to be taken:

(1) The explorative design methodology has to be made spatially explicit.

(2) The relation between land use activities and the survival of a population to be conserved has to be expressed in terms of input-output coefficients.

Making the explorative design methodology spatially explicit can be realized by linking the optimization model to a GIS environment. By introducing every landscape element from the GIS environment as a separate variable in the optimization model, a land use activity can be allocated for each of the landscape elements during the optimization process.

The relation between land use activities and population survival can not be expressed in input-output coefficients per hectare. Extent, spatial configuration and neighbouring land use activities and co-determine habitat suitability for species.

In landscape ecological literature heuristic optimization algorithms are used to solve this problem. In these algorithms spatial rules or simple population dynamic models are used to evaluate the complete habitat configuration for each optimization step. Examples can be found in Cabeza (2003) and Groeneveld (2003) who both base their evaluation rules on the Incidence Function model (Hanski, 1994). In this model the chance of survival for a species in a habitat network is determined by the extinction and colonization chances of relatively isolated sub-populations living in the network. Interaction between sub-populations consists of relatively rare colonization events.

In agricultural landscapes semi-isolated populations are difficult to identify. Small landscape elements like single trees, hedgerows, field margins and canals are the main carriers of biodiversity (Kleijn, 1997; Grashof-Bokdam and Van Langevelde, 2005). Many of these elements are too small to support a population in isolation. However several small landscape elements located sufficiently close to each other might support a population consisting of sub-populations which exchange individuals. Linear landscape elements may be so large that they contain several sub-populations. To evaluate population survival in these type of habitat networks mechanistic models are needed, for example spatially explicit individual based models which describe population dynamics on the basis of spatially explicit behavior. Such models are as yet part of fundamental scientific work and their data requirements precludes use in the context of explorative design.

Therefore, we propose a different approach, combining an optimization model and a network generator. The network generator will be used to generate a large number of habitat networks differing in habitat configuration and ecological value. The optimization model will be used to select one of the habitat networks and to optimize this network for agricultural production. Which of the generated habitat networks will be selected and how this network is optimized depends on the predefined land use objectives. The selected habitat network will be used as a constraint for the selection of appropriate land use activities. In the section below this approach will be explained in more detail.

2.5 Landscape prototyping

The landscape prototyping methodology consists of three components:

(1) A GIS environment.
(2) A network generator.
(3) An optimization model.

2.5.1 The GIS environment

In agricultural areas the dominant landscape features consist of production fields and linear elements like hedgerows, canals and field margins. Therefore we have conceptualized the landscape in the GIS environment by polygons and lines, the polygons representing the fields, the lines representing the linear landscape elements (Figure 2). In our conceptual model of the landscape 3 spatial levels are recognized:

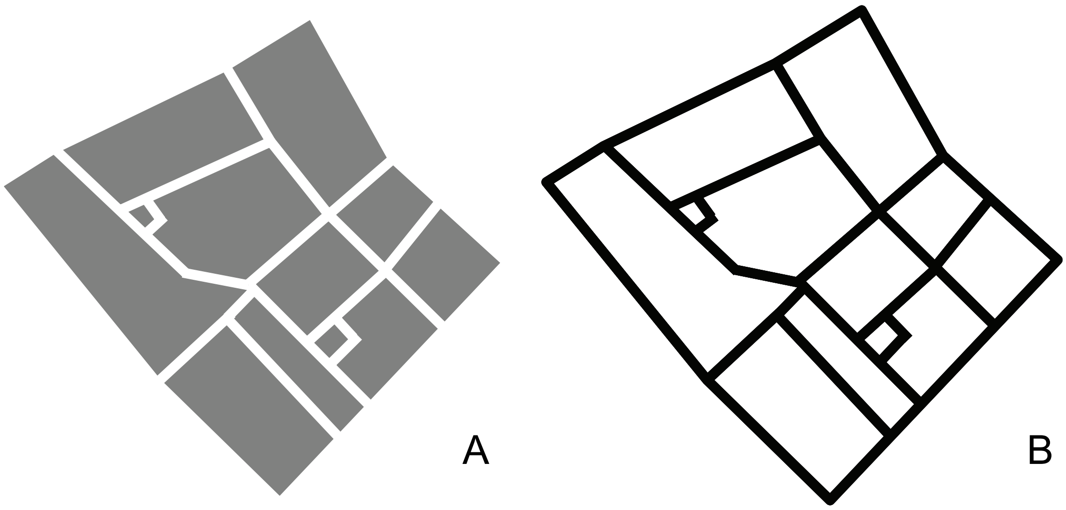

Figure 2. Conceptual landscape model. A: Polygons representing agricultural fields; B: Lines representing linear elements like hedgerows, field margins or canals.

the field level consisting of the individual fields and linear elements, the farm level consisting of the agglomerations of those landscape elements belonging to the same farm and the landscape level consisting of all elements in the landscape. Within each of the landscape elements different land use activities may occur. A land use activity can be a particular crop rotation or a meadow, but also a windbreak, a hedgerow or a channel. Each of the land use activities can be described in terms of habitat quality for a particular species. We assume that all land use activities can be divided into a limited number of habitat quality categories. In our conceptual landscape model a land use activity can have an effect, positive or negative, on the habitat quality of neighboring landscape elements. For example the application of fertilizer may have a negative effect for the habitat quality for certain plants in a neighboring hedgerows, on the other hand the growth of a wheat crop can have a positive effect on the habitat quality of the same hedgerow for mice. This conceptual landscape forms the basis for the design and optimization of multifunctional landscapes.

2.5.2 The network generator

The concept for the development of a network generator can be found in production ecological literature. Dogliotti et al. (2003) describe a software tool called 'ROTAT' generates alternative crop rotations based on agronomic criteria. The program combines crops from a predefined list to generate all possible rotations. The full factorial number of possible combinations of crops is limited by a number of filters controlled by the user. These filters are designed to eliminate crop successions that are

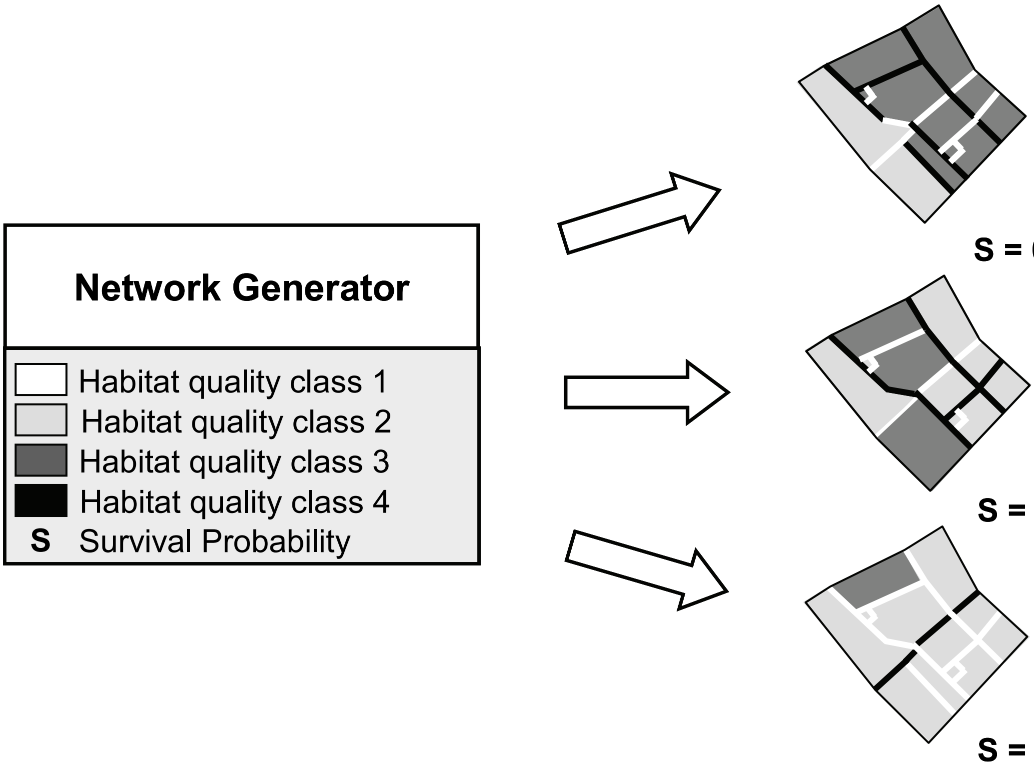

Figure 3. The network generator is used to configure a set of habitat configurations with different survival probabilities for the target species.

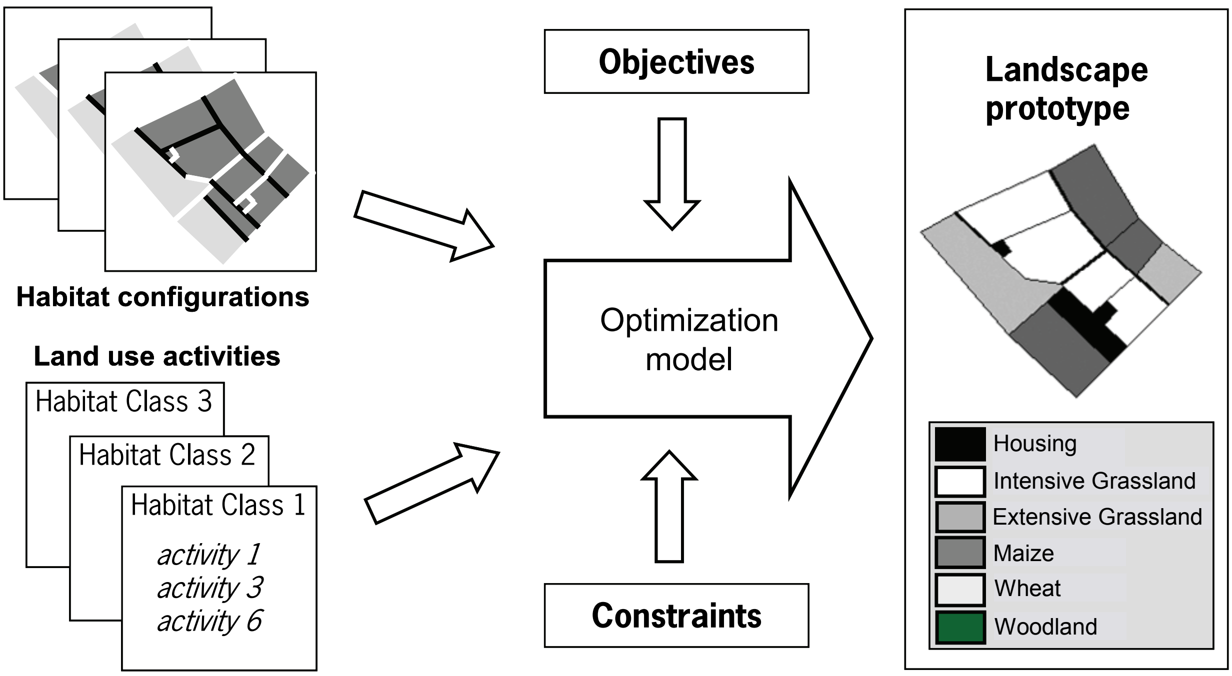

Figure 4. An optimization algorithm is used to select one of the generated habitat networks and to optimize the agricultural activities. Which network is selected and how the agricultural production is optimized is depending on predefined objectives and constraints.

agronomically not feasible or for farm-specific reasons not practical or desirable. The filters are based on timing, sequence and frequency constraints for crop cultivation techniques and on farm-specific feasibility and applicability. These filters represent expert knowledge in a quantitative and explicit way.

Habitat networks can be generated by fixing the topology of a landscape and systematically varying the habitat quality of the different landscape elements (Figure 3). Ecological rules can be used to filter all infeasible or undesirable combinations. For ecological networks these criteria could be expressed in total habitat area constraints, connectivity constraints, patch size constraints, habitat quality constraints, etc. Using a network generator in this way a large set of habitat networks can be generated varying in ecological value and habitat configuration. The generated network configurations are input for the optimization model.

2.5.3 Optimization model

In the second step of the landscape prototyping methodology the optimization algorithm is used to select one of the habitat networks and to optimize the land use within this network for agricultural production (Figure 4). The habitat network is used as a constraint for the optimization of land use. All the land use activities are divided in a limited set of habitat classes. Within each of the habitat classes the land use is optimized. Which of the habitat networks is selected and how the production is optimized depends on the predefined objectives and constraints

In the optimization model four types of constraints will be formulated: Landscape constraints, adjacency constraints, farm constraints and field constraints (Figure 5).

- Landscape constraints are constraints at landscape level, for example the minimal ecological value of a landscape.
- Adjacency constraints are constraints on the land use in the neighboring landscape element, for example on the usage of pesticides or the cultivation of a certain crop
- Farm constraints are constraints at farm level, for example the minimum income of a farm or the maximum labor use.
- Field constraints are constraints at field level, for example the minimum habitat quality of a land use activity in a specific landscape element.

The basis for such a model can be derived from existing farm optimization models (Ten Berge et al., 2000; Dogliotti, 2003; Van der Ven et al., 2003).

2.6 Expected results and perspectives

The expected results of the methodology are landscape prototypes and trade-off curves (Figure 6). Trade-off curves reveal the interaction between different land use

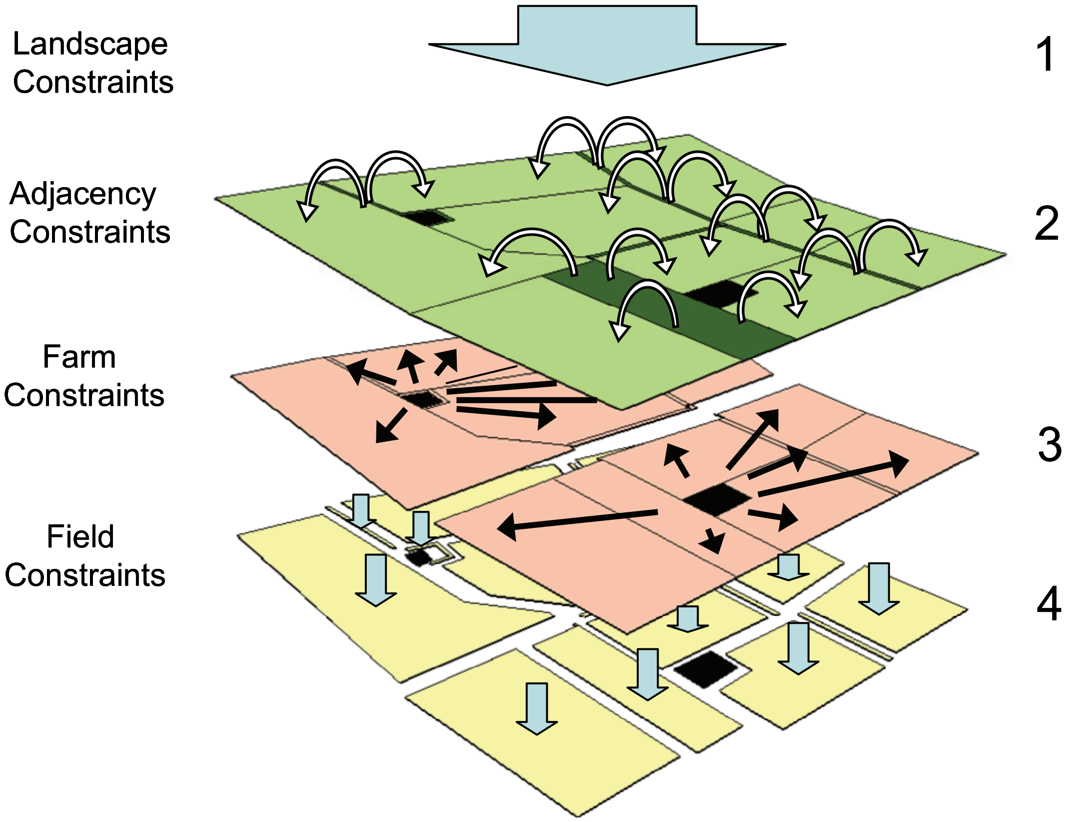

Figure 5. In the optimization model objectives and constrains can be formulated at different integration levels, indicated by arrows.

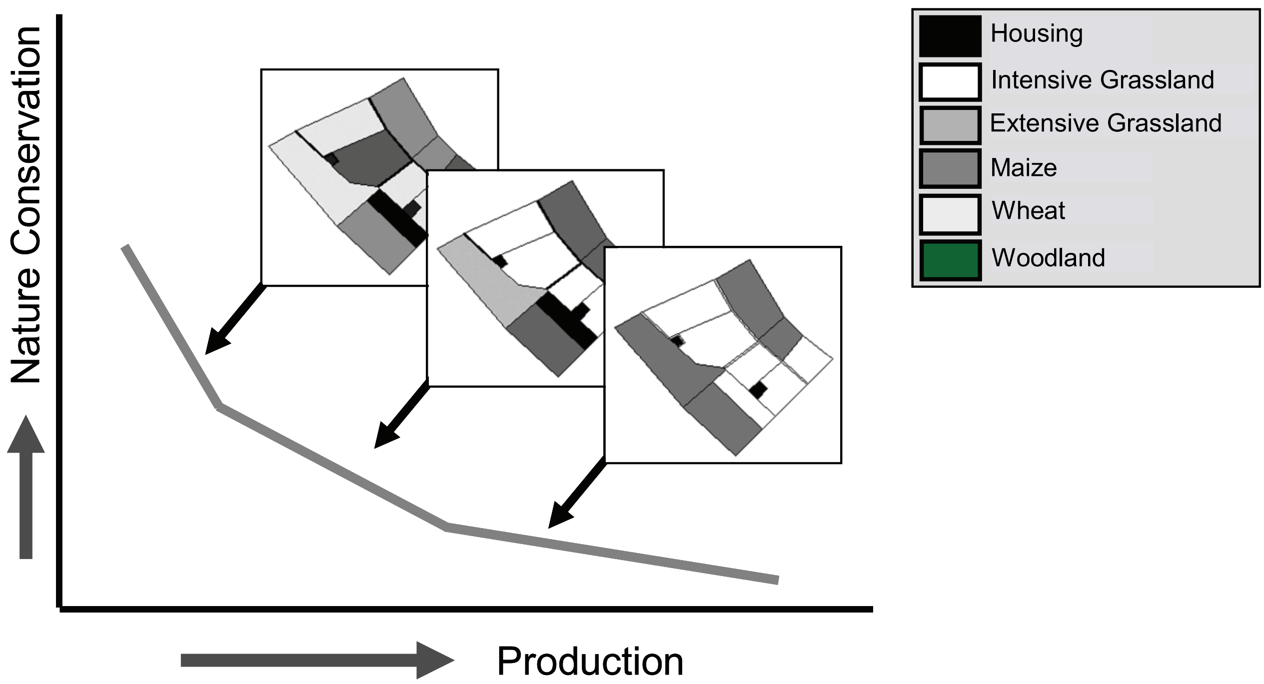

Figure 6. Imaginary trade-off between production and nature along with selected landscape prototypes. The figure is meant to illustrate the approach proposed in the chapter.

objectives and the contours of the window of opportunities for multifunctional agriculture. Landscape prototypes are spatially explicit images of multifunctional agricultural landscapes based on scientific insights. These outputs may be used to deepen and visually enhance the discussion about multifunctional agriculture.

Chapter 3

Exploring multi-scale trade-offs between nature conservation, agricultural profits and landscape quality – a methodology to support discussions on land use perspectives

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Published in: *Agriculture, Ecosystems and Environment* 120 (2007): 58-69.

Abstract

Intensively managed agricultural areas in North-Western Europe have been undergoing a shift from solely production oriented use to provision of multiple services and functions. Design and assessment of multifunctional agricultural landscapes could be supported by exploration of trade-offs between financial returns from agriculture, landscape quality, nature conservation and environmental quality. This chapter presents the Landscape IMAGES methodology for spatially explicit exploration of options for multifunctional agriculture in landscapes at a scale of a few km². The framework has been developed to support discussions and inform decision making by local and regional policy makers, land owners and land managers. Other relevant stakeholders could include non-governmental organizations representing nature conservation and environmental protection objectives.

The structure of the Landscape IMAGES framework prototype is elaborated and its functioning is illustrated with a near-real example of a grassland-dominated landscape with hedgerows bordering the fields. In this landscape, four objectives are being pursued by adjusting land use intensity and hedgerow presence: 1. acceptable agronomic yields for farms, 2. diversification of the botanical composition of fields and hedgerows, 3. variation in plant communities in the fields and half-openness of the landscape, and 4. reduction of nutrient losses to the environment. For exploration of the trade-offs between multiple objectives a heuristic search method (i.e., differential evolution) is employed, which yields a large range of alternative, acceptable configurations of the landscape. The framework provides explicit insight in the trade-off between the objectives and is implemented in a visual application that enables the comparison of alternative options. The method can be applied to a range of spatially explicit land use and nature allocation problems and will further evolve as a result of anticipated interactions with stakeholders.

Keywords: multifunctional agriculture, discussion support, learning, optimization, nature conservation, landscape, scales

3.1 Introduction

3.1.1 Context and rationale

Over the last two decades, attention in policy, land use planning and research directed at intensively managed agricultural areas in North-Western Europe has shifted from production to provision of multiple services and functions by agriculture (Vos and Meekes, 1999). Such multifunctional land use issues are for example maintenance or improvement of landscape structure, sustainable management of renewable natural resources, preservation of biodiversity and contribution to socio-economic viability of rural areas (OECD, 2001). A normative interpretation of multifunctional agriculture (MFA) was adopted by the European Union and used in its Agenda 2000 agricultural reform, by recognizing and encouraging the range of services provided by farmers and advocating a multi-sectoral and integrated approach to the rural economy. In a number of European countries the notion of MFA has become embedded in legislation, in others it is used in relation with notions such as sustainable development and rural development (Kröger and Knickel, 2005).

The increased attention for MFA can be attributed to a combination of many sometimes interacting factors, of which sufficient or even surplus production capacity, increased environmental awareness and other new societal demands such as the need for recreational area are the most pronounced. Due to the changes in land use objectives for the involved stakeholders, the decision making process concerning land use at different scales has become to a large degree a spatial planning process, integrating issues of agricultural production and its side-effects (nutrient losses, deterioration of food webs) at field and farm scales, and nature conservation, environmental protection and landscape quality at the regional/catchment scale.

To achieve an integrated view on the required adjustments and innovation in landscapes and land use systems where complex, uncertain and value-laden issues occur, systems approaches that integrate various issues, stakes of social actors, disciplines and scales are indispensable. This type of work is characterized by a multi-disciplinary approach to problem solving, involving both technical and social sciences, and a high degree of stakeholder participation (Gough et al., 1998; Bland, 1999). Potential stakeholders range from the actual land owners and land managers to local residents and citizens, the latter mostly represented by governmental and non-governmental organizations such as nature conservation and environmental protection groups. Also local and national policy makers have a strong stake.

The resulting complexity in both land use planning issues and stakeholder interactions necessitates the use of supporting methodologies and models to inform stakeholders and policymakers, to design alternatives and to explore scenarios for the future. The role of model-based support systems should be sought in contributions to: (i) learning of stakeholders by providing a 'learning laboratory' wherein the learning cycle can be completed rapidly and the possibility of reflection on the results is offered (McCown, 2002) and (ii) widening the perspective or 'frame' of multiple stakeholders involved in discussions about natural resource management and planning on problems and their potential solutions (Sterk et al., 2005), so-called 'reframing' (Kaufman and Smith, 1999; Bouwen and Taillieu, 2004). The approach of 'discussion support systems' as proposed by Nelson et al. (2002) aims to contribute to learning and dialogue between stakeholders about development options (Hansen, 2005), by addressing issues of common interest, and explicit examination of the consequences of different objectives and preferences (Struif Bontkes and Van Keulen, 2003). Therefore, an integrated analysis of multifunctional agricultural land use systems involves an assessment of various performance criteria of the systems. The exploration of development options involves the determination of the trade-offs between the performance criteria or objectives.

3.1.2 Related work

Existing spatially explicit, future-oriented land use exploration approaches applied to agricultural landscapes dominated by cropping or grassland systems have focussed primarily on agro-ecological aspects of production, hydrology and nutrient loss abatement (O'Callaghan, 1995; Van Huylenbroeck, 1997; Seppelt and Voinov, 2002; Wang et al., 2004; Matthews et al., 2006). From the perspective of landscape ecology considerable attention has been paid to the analysis of species distribution in relation to agricultural landscape structure (e.g. Brooker, 2002) and effects of changes in landscape structure have been evaluated in scenario studies (e.g., Dolman et al., 2001; Münier et al., 2004; Prato, 2005). Approaches for combined optimization of agricultural land use and landscape elements configuration to improve habitat quality and nature conservation value are scarce (Wossink et al., 1999; Van Langevelde et al., 2002; Groeneveld, 2004). In contrast, in agro-forestry a considerable body of experience with multi-criteria planning of forest management in relation to habitat suitability has been developed over the last years (e.g., Store and Kangas, 2001). Moreover, these approaches have been applied in a participatory manner with stakeholders (Kangas et al., 2005; Mendoza and Prabhu, 2005). A recent broad inventarisation of existing approaches, tools and frameworks for multifunctionality of agriculture in the European Union carried out in the MultAgri project commissioned by the EC revealed that (Kröger and Knickel, 2005):

- More holistic conceptual and analytical frameworks are required that address multifunctionality of agriculture.

- Integrative research tools and tool combinations are needed to better assess the wider effects of programs aiming for improved multifunctionality of agriculture.
- More attention is necessary for education and training in inter- or trans-disciplinary work and the development and practical application of integrated assessment methods and tools.

3.1.3 Objectives

In this chapter we present a spatially explicit, GIS-based land use optimization methodology named Landscape IMAGES (Interactive Multi-goal Agricultural Landscape Generation and Evaluation System). This approach combines agronomic, economic and environmental indicators with biodiversity and landscape quality indicators. The chapter focuses on the method of combination of multiple objectives and their spatially explicit evaluation at different hierarchical levels, rather than the technical aspects of the heuristic trade-off exploration methodology. A near-real implementation of the prototype framework is applied to a case study area in the Netherlands, which is described in section 2. The structure of the proposed framework and its specifications is introduced in section 3. Results of explorations are presented and analysed in section 4. In section 5, the degree to which the developed methodology meets the demands for modelling frameworks supporting participatory approaches are discussed and some potential applications are described.

3.2 Case study

The region of the Northern Frisian Woodlands, The Netherlands, is characterized by a small scale landscape on predominantly sandy soils with dairy farming as the prevailing land use activity. On some farms a limited proportion of up to 5% of the area is used for forage maize production, while the rest of the area is occupied by permanent grassland, rotationally grazed and mown. The fields with an average size of 2 ha are often surrounded by hedgerows. The average grazing season lasts 6 months from May to October. Grazing systems range from day and night grazing to restricted and zero grazing. The bio-physical farm and field characteristics and the societal demands as articulated in regulations to maintain landscape and land use have limited the possibilities to convert to large scale agriculture in the past.

In the Northern Frisian Woodlands environmental cooperatives founded by farmers play an important role at regional level to realize a vital regional economy, attractive leisure and residence areas, a clean environment and maintenance of landscape and biodiversity (Renting and Van der Ploeg, 2001; Stuiver and Wiskerke, 2004; Anonymous, 2005). The initiatives of the environmental cooperatives are supported by local, regional and national governments, and farmers and landscape management organizations. The strengthening of landscape and nature values in combination with agricultural practice is being pursued by an array of measures, for instance (Anonymous, 2005):

- Application and improvement of nature conservation packages offered by national landscape management programs for extensively used grasslands and for linear landscape elements such as hedgerows.
- Improvement of the ecological connectivity of the landscape by strategic allocation of linear landscape elements.
- Protection of meadow birds and adjustment of the grassland management patterns to encourage nesting and nest hatching.

The environmental cooperatives and other local stakeholders have solicited scientific support to evaluate proposed adjustments in the design and assessment of landscape and agricultural land use practices. Various stakeholder groups have different questions:

- Farmers are interested in exploration of the opportunities for cost-efficient intensive farming in a landscape of small fields surrounded by hedgerows. One of the questions is to which extent parts of hedgerows can be removed without jeopardizing the typical character of the landscape. Another issue relates to possible contributions to nature, landscape and economic goals by differential management of fields close to and far from farm buildings.
- Farmers' environmental cooperatives are looking for insight in the additional value of their joint actions on the quality of the abiotic environment and the landscape.
- Landscape management organizations require insight in the effects of 'good practices' in hedgerow management on biodiversity and returns from farming.
- Policy developers at regional and national scale would benefit from information about the effectively of investments into nature conservation.

The selected case study area of 232 ha enclosed by roads is presented in Figure 1. The majority of fields in this area belong to three farms, denoted A, B and C. Some relevant characteristics of the field configuration for each farm are listed in Table 1. A gradient in soil fertility was assumed in the case study area (Figure 1), related to the nitrogen delivery capacity by the soil. This gradient was hypothetical with the purpose to illustrate the capability of the framework to deal with spatial variations in bio-physical circumstances. The ranges in nitrogen delivery capacity by the soil used here are actually observed in the case study area.

Figure 1. Landscape of the case study area with fields for farms A, B and C and buffer fields. Numbers indicate the soil fertility level (0=140, 1=150, 2=160, 3=170, 4=180 kg N per ha). Circles with letter indicate the position of the farm houses and stables for the farms.

Table 1. Characteristics of the farms located in the case study area and included in the exploration.

Characteristic	Farm A	Farm B	Farm C
Number of fields	16	16	21
Average area per field (ha)	2.62	2.93	1.70
Average distance of fields from farm yard (m)	690	703	650
Average soil fertility level [a]	0.63	1.55	3.41
Minimum proportion of grazed grass dry matter	0.40	0.25	0.35

[a] Relates to nitrogen delivery capacity of the soil, with the following levels: 0=140, 1=150, 2=160, 3=170, 4=180 kg N per ha.

A gradient in soil fertility was assumed in the case study area (Figure 1), related to the nitrogen delivery capacity by the soil. This gradient was hypothetical with the purpose to illustrate the capability of the framework to deal with spatial variations in bio-physical circumstances. The ranges in nitrogen delivery capacity by the soil used here are actually observed in the case study area.

3.3 Methodological framework of landscape IMAGES

3.3.1 Conceptual model

The assessment of the performance of a given territory of any scale can be based on multiple criteria, such as economic returns, nature value, landscape identity and environmental quality indicators. When the occupation or use of the territory is heterogeneous, the area can be compartmented into discrete spatial units to arrive at land units with homogeneous activities. For a territory at landscape scale these activities on land units can for instance be the cultivation of a particular crop on a field or the presence of a hedgerow on a field border. The various activities make different contributions to the performance criteria and the activities of spatial units may interact with respect to the performance criteria. Consequently, different configurations of activities result in different values of the performance criteria, which can be positively correlated, but can also be conflicting. Insight into the relationships between the performance criteria in dependence of allocation of activities to land units offers input for choices considering the use of the territory. Interesting configurations of allocated activities are those that perform as good as possible when all the performance criteria are considered.

The exploration of the trade-offs between performance criteria or objectives can be formulated as a multi-objective design problem, which can be generally stated as follows:

$$\text{Max } \mathbf{U}(\mathbf{x}) = (\, U_1(\mathbf{x}), U_2(\mathbf{x}), \ldots , U_k(\mathbf{x})\,)^T \tag{1}$$

$$\mathbf{x} = (x_1, x_2, \ldots ,x_n)^T \tag{2}$$

Subject to i constraints:

$$g_i\,(\mathbf{x}) \leq h_i \tag{3}$$

where $U_1(x),...,U_n(x)$ are the objective functions that are simultaneously maximized or minimized, and $(x_1,...,x_n)$ are the (integer) decision variables that represent the activities allocated to the n spatial units. The decision variables can take on a predescribed array of values, $\mathbf{x} \in S$, where S is the solution or parameter space. Constraints (Equation 3) can arise from the problem formulation, for instance by limitations on the inputs or outputs related to the activities.

The allocation of discrete activities to the spatial units makes the problem ‘NP hard’: no algorithm exists that guarantees that the exact k-dimensional trade-off surface is obtained under all circumstances, because the dimensionality of the problem, and therefore the computational difficulty, grows faster than any polynomial in the number of decision variables. Heuristic techniques such as genetic algorithms (GAs) and evolutionary strategies (ESs) can be employed to obtain approximations of the trade-off surfaces by a population of solutions, each representing a configuration of activities for the territory. GAs and ESs are adaptive search techniques based on the principles of natural evolution. Genetic operators for reproduction, selection, mutation and crossover (the latter only in GAs) are applied to a randomly generated population of solutions to improve its average performance criteria generation by generation (Bergey and Ragsdale, 2005). During this iterative process, solutions are selected for each new generation on the basis of Pareto optimality. A set of Pareto optimal solutions consists of solutions that are not dominated by other solutions, when all objectives $U_1(x),...,U_n(x)$ are considered. Using this concept the solutions can be ranked as follows (Goldberg, 1989):

1. The Pareto optimal sub-set is established.
2. This sub-set receives the highest rank and is removed from contention.
3. The procedure is repeated until all solutions have been ranked.

3.3.2 Production activities and agro-ecological relations

For the present case study the territory at landscape scale was compartmented into land units (Figure 1) representing agricultural fields (polygons) and field borders (lines

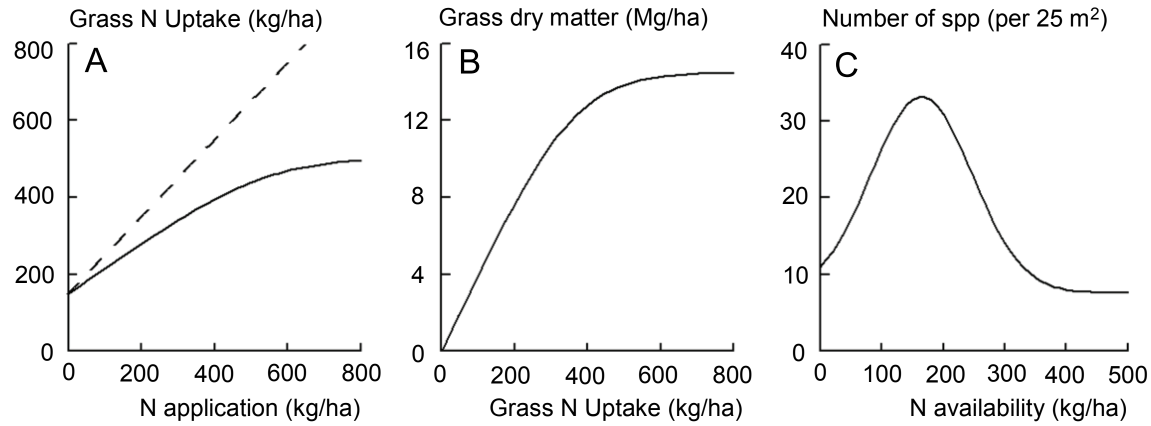

Figure 2. Agro-ecological relations between (A) fertilizer N application and grass N uptake (solid line) and total N availability (dashed line), (B) N uptake and biomass production, and (C) total N availability and plant species number in grasslands.

coinciding with polygon borders). Agricultural production activities were allocated to the fields, and field borders could be occupied by a hedgerow or remain unoccupied. An agro-ecological engineering approach was used to design production activities, which are defined as the cultivation of a crop or vegetation and/or management of a herd in a particular physical environment, completely specified by its inputs and outputs (Van Ittersum and Rabbinge, 1997). The inputs and outputs are fully determined by the physical environment, the plant and animal types and the applied production techniques. Therefore, the production activities were derived from factorial combination of *design criteria* (Hengsdijk and Van Ittersum, 2002) that explicitly characterize the physical environment (here: soil fertility), type of plants and animals (vegetation and herd) and production techniques (fertilizer application and harvesting regime). An overview of the design criteria and the variants per criterion is given in Table 2. Combinations of variants were filtered for agronomic feasibility. A total of 535 production activities were generated, between 98 and 114 per soil fertility level.

The inputs and outputs of the production activities were calculated from simplified empirical agro-ecological relations (Figure 2). The relations between fertilizer N application rate and N uptake in grass (Figure 2A) and between N uptake and dry matter yield (Figure 2B) were derived from the results of cutting and grazing experiments (Snijders et al., 1987; Lantinga et al., 1999), using an expolinear equation (cf. Groot et al., 2003). The intercept in Figure 2A represents the N available from delivery by the soil and was determined by the soil fertility level (see Table 2).

Productive grassland area was corrected for the presence of hedgerows, which were assumed to have a width of 10 m. Compared to a harvesting regime of only mowing, the annual N uptake and dry matter yield under harvesting regimes that

Table 2. Design criteria and the variants for each criterion as implemented for engineered grassland based dairy farming systems.

Attribute	Design criterion	Number of variants
Production environment	Soil fertility	5 levels, 140, 150, 160, 170 and 180 kg N per ha
Production technique	Fertilizer application	11 levels of fertilizer application: 0, 25, 50, 75, 100, 125, 150, 200, 250, 300, 350 kg N per ha
	Harvesting regime	Valid combinations of 0 to 5 grazing periods, 0 to 5 mowing cuts and 3 dates of first harvest (before 1 June, 1-30 June, 1 July or later)

included grazing were reduced dependent on the number of grazing cuts, because of larger harvest losses and sward deterioration under grazing (Lantinga et al., 1999). Three periods for the first harvest were defined: before 1 June, between 1 June and 1 July, and after 1 July. The length of growth periods of the grass was calculated from the harvesting regime, i.e. the number of mowing and grazing cuts throughout the growing season and the date of first harvest.

From the dry matter yield and the length of growth periods for individual cuts the production of energy for lactation (1 kVEM = 6.9 MJ net energy for lactation; Van Es, 1978) was estimated. The associated milk production was calculated assuming an energy requirement of 0.85 kVEM per kg milk for cows producing 8000 kg milk per annum and a replacement rate of 25% according to Dutch feeding standards (Anonymous, 1997).

The relations between available nutrients and plant species diversity (Figure 3C) are derived from experimentally obtained relationships between grassland productivity and species diversity (Bakker, 1989; Oomes, 1992), combined with the production curves in Figures 2A and 3B. For borders occupied with hedgerows the same relation was used with the average nutrient availability of the adjacent fields as independent variable.

3.3.3 Production activity allocation problem

In the model agricultural production activities on the fields and hedgerows adjacent to the fields are allocated, taking into account spatial heterogeneity and spatial interactions. The model seeks to:

- maximize gross margin from agricultural production (U_P),
- minimize loss of nutrients to the environment (U_E),
- maximize nature value of fields and borders (U_N),

- maximize variation the landscape in terms of species presence and hedgerow allocation, i.e. half-openness (U_L),

subject to (see end of this section):
- limits to nutrient input,
- proportion of herbage grazed.

On the basis of the outputs of the production activities, the objective function values U_i were quantified as presented in Equations 4-7.

$$U_P = \sum_f \left(R_f + S_f - C_f\right) \tag{4}$$

where R_f is the returns from production for field f (€), S_f is the subsidies for field f (€), C_f is the variable costs for field f (€).

As indicator for the economic performance of farms gross margin was adopted (U_P; Equation 4), which is more sensitive to changes in farm management than total farm results, which also include fixed costs (Ondersteijn et al., 2003). The returns from production per field R_f were calculated directly from the milk production and the milk price (€0.35 per kg milk). Costs per field C_f were separated into costs related to production and transport costs. Costs for production were restricted to costs for harvesting by grazing or mowing and fertilizer costs. Transport costs associated with grazing and mowing management depended on the travel distance between farm yard and the field, the travel velocity and the frequency of visits to a field under particular management. The applicability of agri-environmental subsidies to individual fields was assessed on the basis of plant species abundance, and harvesting and fertilization regimes. The financial revenues from nature agri-environmental schemes (€254 or €1154 per ha) were added to the value of the objective function for economic results, U_P (Equation 4).

The species abundance in the grass swards and hedgerows (U_N) was used as an indicator for nature conservation value (Equation5). For borders not occupied with hedgerows S_b=0 was used. As a consequence, increases in both hedgerow length and species numbers in hedgerows resulted in an increase in U_N.

$$U_N = \frac{\sum_f \left(S_f \cdot A_f\right)}{\sum_f A_f} + 4 \cdot \frac{\sum_b \left(S_b \cdot A_b\right)}{\sum_b A_b} \tag{5}$$

where S_f is the number of species on field f (per ha), A_f is the area of field f (ha), S_b is the number of species in border b (per ha), A_b is the area of border b (ha).

Landscape quality (U_L) was equated to variation in the landscape (Equation 6). $VAR(S_{f,i})$ was calculated as the variance of the species number for each field and its adjacent fields. This evaluation at field neighborhood level precluded high appreciation of landscapes with varying but clustered species numbers per field. $VAR(S_{f,i})$ is a measure of the heterogeneity of the landscape in terms of the variation in colors and growth forms in grasslands (Stobbelaar et al., 2004). Hedgerows strongly influence the perception of landscapes by breaking up landscapes, providing diversity, perspective and pattern (Oreszczyn and Lane, 2001). In particular irregularity in the hedgerow pattern in landscapes is often highly appreciated. On the one hand hedgerows enclosing fields offer a sense of mystery and intimacy, while on the other hand the landscape should not be completely closed but offer overviews over the patchwork of fields (Oreszczyn and Lane, 2001; Weinstoerffer and Girardin, 2000). Therefore, the second term in Equation 6 was included as a measure of half-openness of the landscape.

$$U_L = \sum_f \left(VAR(S_{f,i}) + 10 \cdot (0.5 - ABS(\frac{\sum_{f,h} A_{f,h}}{\sum_{f,b} A_{f,b}} - 0.5))^2 \right) \quad (6)$$

where $VAR(S_{f,i})$ is the variance of species number on i fields adjacent to field f, $A_{f,h}$ = is the area of hedgerows around field f, $A_{f,b}$ is the area of borders with and without hedgerows around field f.

The loss of nutrients (U_E, Equation 7) was directly derived from the agro-ecological relations in Figure 2A by calculating the difference between uptake and availability of N.

$$U_E = \sum_f E_f \quad (7)$$

where E_f nitrogen loss from field f (kg N).

The majority of fields in the case study landscape belong to farms A, B and C (Figure 1). The farm level represents an administrative level between landscape and fields, where the management decisions are taken. The values of the objective functions U_P, U_N, U_L and U_E were aggregated per farm and for the whole landscape of the case study area. In this chapter, the results of the optimizations are evaluated after aggregation to the landscape scale, unless indicated otherwise. Fields in the landscape that are not used by farms A, B or C were treated as buffer fields and were not included in the calculations of U_i. To these fields a random land use activity was allocated during the initialization of the model, which was not modified during the optimization.

Farm level constraints were set for the average fertilizer application rate and the proportion of herbage that needs to be available for grazing. Maximum N application was fixed at 325 kg N per ha for all farms. This value was derived from the maximum allowed slurry N application of 250 kg N per ha, with an expected apparent recovery of 70%, and additional artificial fertilizer application of 150 kg N per ha. The minimum proportion of grazed herbage for each farm (Table 1) was calculated on the basis of the length of the grazing season (145 or 200 days) and the grazing system (day and night or only day grazing).

3.3.4 Pareto-based differential evolution

Exploration of the trade-offs between objectives was performed with a multi-objective implementation of the evolutionary strategy algorithm of differential evolution (DE) developed by Storn and Price (1997). Currently, DE is widely used in the research community due to its simplicity, efficiency and robustness (Bergey and Ragsdale, 2005; Mayer et al., 2005). DE involves the iterative improvement of a set of solutions or genotypes. Each allele in the genotype is a real number. In our application, the genotypes represented alternative landscapes, and the alleles were decision variables in which the land use of an individual field and the occupation of the field borders were encoded. For each of the 53 fields belonging to the three farms in the case study landscape (Figure 1), two alleles were available to encode field use (x) and border occupation (z) separately, resulting in a total of 106 alleles per genotype. To this end the allele values were converted to discrete (Lampinen and Zelinka, 1999) or binary parameters.

A detailed description of the functioning of the algorithm is provided by Lampinen and Zelinka (1999) and Xue et al. (2003), and is summarized here. The algorithm was initialized by generating a set of solutions with random values for the x and z decision variables, only constrained by restrictions imposed on the parameter set: the possible production activities on fields for x, and the number of borders per field for z. This set was improved for a predefined number of generations. Criteria to evaluate the quality of the solutions were the Pareto ranking and within the same rank the crowdedness of the portion of the solution space where the solution was located, according to the crowding metric presented by Deb et al. (2002). Selection of solutions of better ranking results in a pressure normal to the trade-off region, whereas selection of solutions in less crowded parts of the solution space exerts a pressure tangential to the trade-off region, which promotes the spread over the solution space (Khor et al., 2005).

The following procedure for improvement of the solution set was applied.

(1) Generation of a competitor for each individual solution in the set, by a combination of copying and recombination of alleles in a ratio that is governed by parameter CR.

(2) Assessing the quality of the solutions and their competitors by ranking and calculation of the crowding metric.

(3) Selection of either the original solution or its competitor for the new solution set.

To explore the extremes of the objective space, single-objective optimizations for the individual objectives were performed, also employing the DE algorithm. Here, the objective values of U_i were used as the selection criterion in step 3 (and step 2 was omitted). The performance of the algorithm is affected by four (fixed) parameters. CR (value used in this study: 0.85) denotes the probability of mutation of an allele. F (0.15) controls the amplification of the mutations. MP (10) is the multiplication factor to calculate the population size from the number of alleles in each genotype, in this case 1060. G (12,000) is the number of generations and serves as the stopping criterion. The parameter values employed in this study were derived from factorial analysis in preliminary optimization runs. Constraints are implemented as penalties to solutions that violate any of the constraints, so that these solutions will receive the lowest rank. These solutions are not selected for the next generation if a competitor has been composed that meets the constraints, and remain in the population otherwise.

3.3.5 Implementation

The model was implemented in the Microsoft .NET Development Environment. The landscape configuration data were directly accessed from ESRI shape files (Anonymous, 1998) with the ShapeLib.dll (URL: http://shapelib.maptools.org/). Software published on the internet by K. Deb was used to perform the Pareto ranking and to calculate the crowding distance (URL: http://www.iitk.ac.in/kangal/soft.htm)

3.4 Results

The solution sets obtained after 12,000 generations of improvement by the DE algorithm covers a large range of possible configurations of the landscape in terms of land use on fields and the placement of hedges on field borders. Replicated multi-objective optimization runs yielded similar extreme values for the four objectives (data not presented), although the distances between these extremes and those obtained by single-objective optimization were still considerable (Figure 3). However, single-objective optimizations with constraints on other objectives indicated that the trade-off

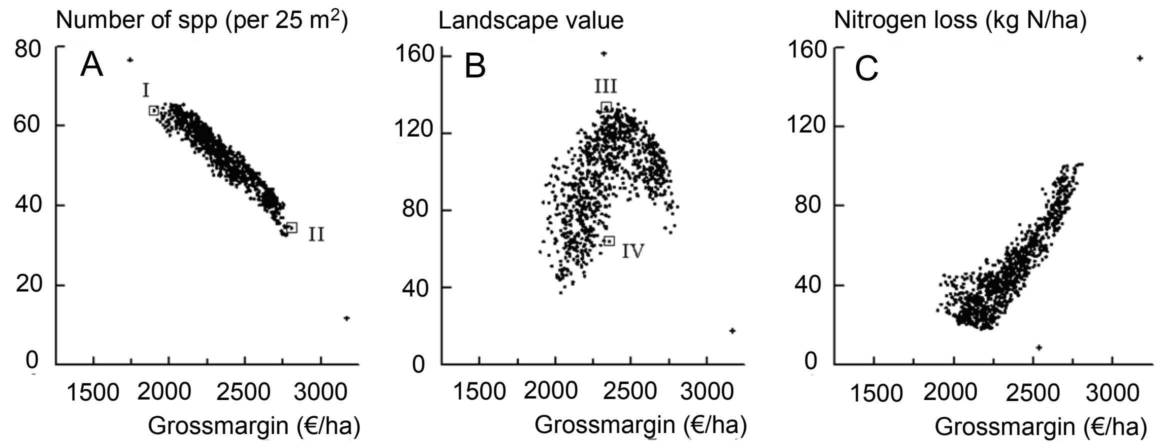

Figure 3. Landscape scale trade-off curves between gross margin (€ per ha) and nature value (A), gross margin and landscape value (B) and gross margin and nitrogen losses (kg N per ha, C) after 12,000 generations of optimization (●). Four selected landscapes are indicated (□) and numbered I-IV. Extreme solutions obtained by single-objective optimization are indicated (+).

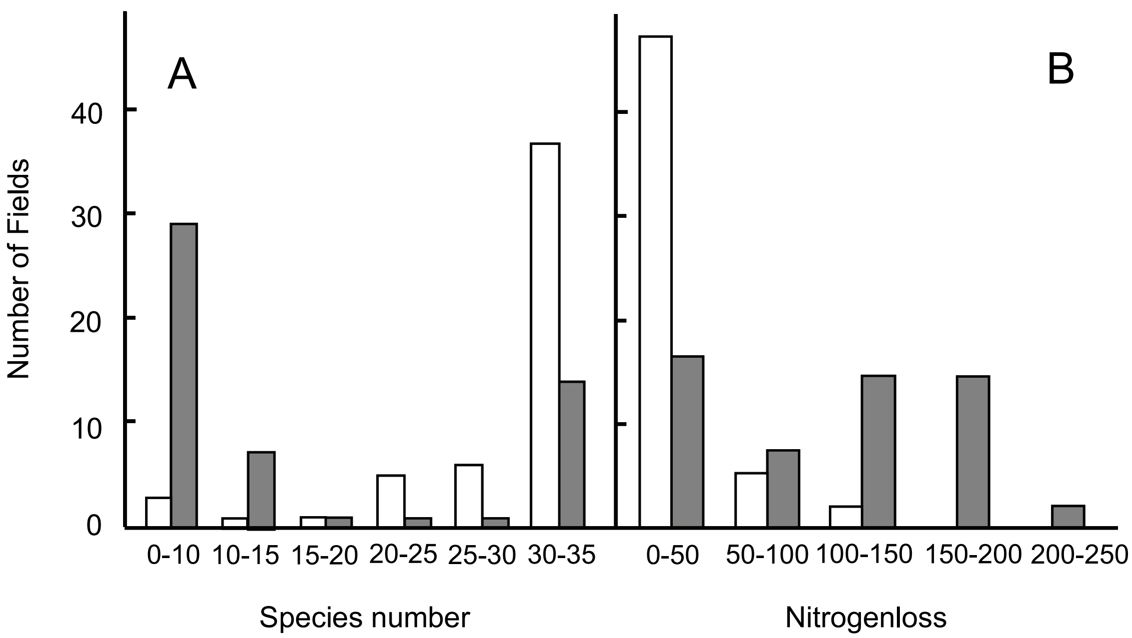

Figure 4. Frequency distributions of plant species numbers (per 25 m²; A) and nitrogen loss (kg N per ha; B) per field in optimized landscapes with high nature value (open bars; solution I in Figure 3A), high gross margin (closed bars; solution II in Figure 3A). Objective values for the solutions: I: U_P = €1898 per ha, U_N = 64.0 spp per 25 m², U_L = 58.7, U_E = 27.7 kg N per ha; II: 2806, 34.5, 81.9, 101.1.

frontier was closely approached in the multi-objective optimizations (data not presented). The results of an example solution set are presented here.

The trade-offs between the objectives at landscape scale are presented in Figure 3, which shows the non-dominated Pareto optimal set for the four objectives, graphically represented in bi-plots. The gross margin ranged from ca. €1750 to €2750 per ha. These relatively high values for grasslands originated from the calculation of true milk production, estimated from net energy for lactation in grass, and not using merely a NEL-price. Moreover, some of the costs (veterinary, reproduction, and contractor) were not included in the calculations. Landscapes I and II in Figure 3A represent extremes in the trade-off between gross margin and nature value, as found in the example solution set. The frequency distribution of species numbers in fields and nutrient loss per field for the selected landscapes show the large contrasts (Figure 4).

Landscape I (low gross margin, high nature value) is dominated by fields with production activities characterized by high species numbers (Figure 4A) and low nutrient losses (Figure 4B) as a consequence of low fertilizer inputs. Landscape II (high gross margin, low nature value) comprises more production activities where low species numbers occur (Figure 4A). However, it also contains 14 low-input fields with production activities characterized by high species numbers where agri-environmental conservation packages apply, and thus subsidies are earned. In this landscape, production activities with a wide range of nutrient loss levels per field were allocated.

For each level of satisfaction of an objective, a large diversity of alternative solutions varying in other objectives was found. For example (Figure 3B), at a certain level of gross margin larger variation in the landscape was achieved by improved spatial distribution of production activities varying in management intensities, in particular when intermediate or lower levels of gross margin would be acceptable. The larger variation in management intensity of production activities was illustrated by the spatial distribution of species abundance in fields, which reflects management intensity, and of hedge presence for selected landscapes III and IV (Figure 3B) in Figure 5. These landscapes had similar values for the other objectives.

The trade-offs between gross margin and nature value at different hierarchical levels are shown in Figure 6. The data points in Figure 6A represent the individual production activities which are defined at the field level. Combination of production activities at the farm level resulted in averaging out of extremes (Figure 6B). As a result of the requirement of a minimum proportion of grazed herbage, the land use was dominated by production activities with gross margins lower than €3000 per ha. These production activities were characterized by presence of grazing cuts, which have lower production efficiency than mowing cuts, due to lower net herbage production caused by trampling by cattle and larger herbage residues in the field after grazing.

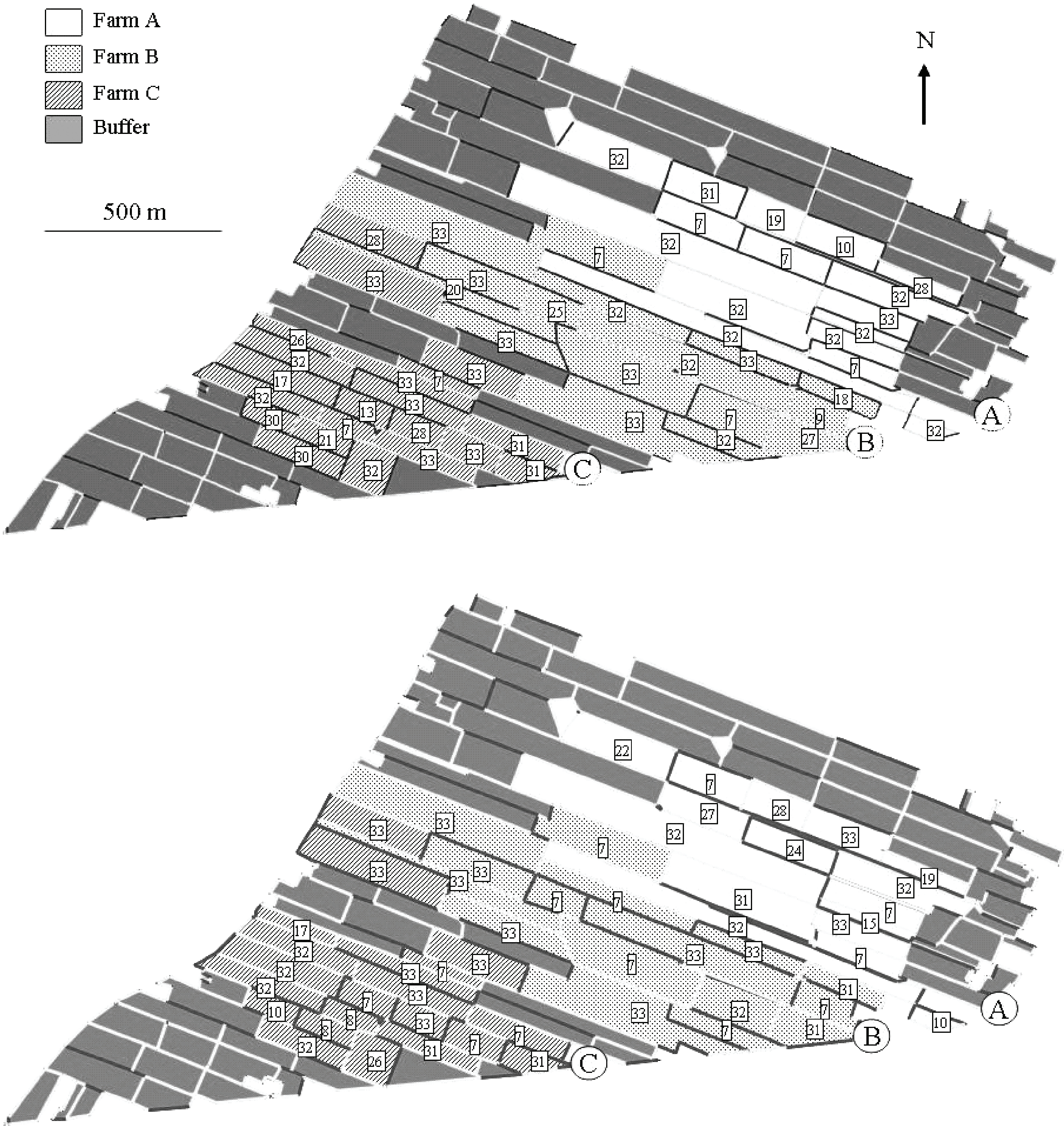

Figure 5. Plant species numbers (per 25 m²) per field and the presence of hedgerows (solid lines) in landscapes with high landscape value (A; solution III in Figure 3B) or low landscape value (B; solution IV in Figure 3B). Objective values for the solutions: III: UP = €2334 per ha, U_N = 47.6 spp per 25 m², U_L = 133.6, U_E = 49.3 kg N per ha; IV: 2355, 53.4, 64.3, 32.5. Circles with letters indicate the position of the farm houses and stables for the farms.

Differences in the ranges of objective values were observed between the farms (Figure 6B).The larger range in the number of species in fields for farm B when compared to the other farms was caused by the lower required proportion of grazed herbage for this farm (see Table 1). The shift towards higher gross margin at the same nutrient availability/species number in fields for farms B and C when compared to farm A could be attributed to the higher soil fertility levels for farms B and C. These contrasts between the farms resulted in narrowing of the ranges in objective values at landscape scale (Figure 6C), despite the fact that within the solution set species numbers in fields aggregated to farm level were highly correlated between farms. The correlation coefficients between farms determined for species numbers in fields over the whole solution set ranged between 0.75 and 0.85.

3.5 Discussion

The optimization study with the Landscape IMAGES framework demonstrated that trade-offs between multiple objectives can be effectively explored in a spatially explicit land use allocation problem. The presented future-oriented explorations, employing principles of the agro-ecological engineering approach proposed by Hengsdijk and Van Ittersum (2002), yield ex-ante assessments of land use alternatives to assist strategic decision making and to inform debates on landscape and land use planning. The possibilities for multi-scale design and evaluation of landscapes offered by the framework, enabled evaluation of spatial interactions and their implications at higher hierarchical scales (Figure 6). The solution sets contained a large range of possible configurations of the landscape in terms of land use on fields and the

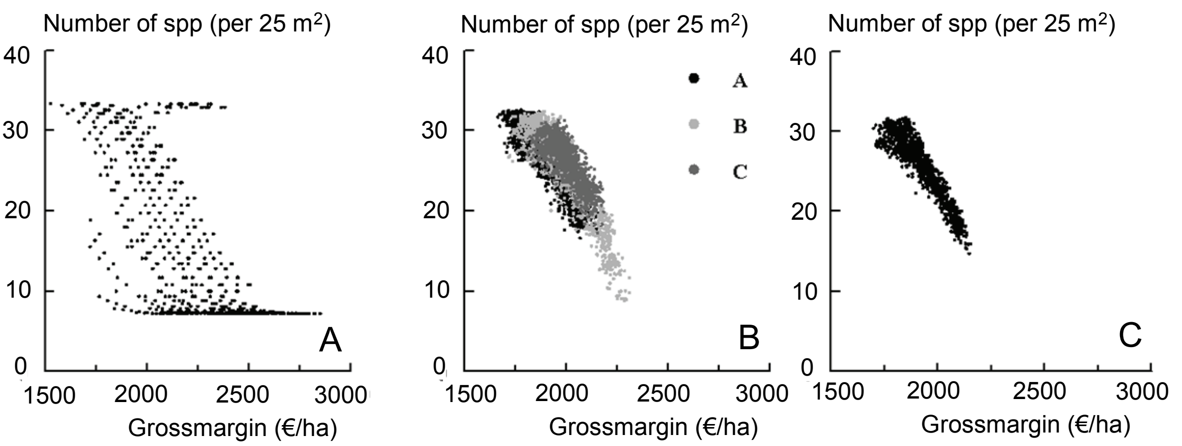

Figure 6. Relationship between gross margin of agricultural practice (including subsidies for nature conservation) and the average, area-weighed abundance of species in fields for individual fields (A), farms (B) and the whole landscape (C).

placement of hedges on field borders. At a certain satisfaction level for an objective the potential ‘window of opportunities’ to improve on other objectives by selecting different production activities could be made explicit (Figures 3-5).

The algorithm generated solutions that showed the trade-offs between four objectives across a wide range of objective values, although the extremes for individual objectives obtained in the single-objective optimization were not reached (Figure 3). This phenomenon is more frequently encountered by heuristic methods to solve multi-objective optimization problems, due to insufficient selection pressure tangential to the trade-off region (Khor et al., 2005), and is apparently only partly alleviated by the applied crowding metric-based selection. Alternative solutions to this problem could involve enriching of the initial population for the multi-objective optimization with results from single-objective optimizations. This should be considered in future research.

The framework offers the opportunity to combine knowledge from diverse disciplines, so that trade-offs between objectives proposed by these disciplines can be evaluated. Thereby, assessment and enhancement of multifunctionality of land use and landscape design could be supported. Currently, the prototype relationships implemented are still mainly focused on the ‘natural’ science approaches of agronomy, environment, ecology and landscape ecology, combined with the socio-cultural discipline of landscape identity. The possibility to define objectives and apply constraints at the different hierarchical levels of field, farm and landscape provides the possibility for incorporation of sociological concepts such as farming styles, which can be characterized by variation in their predominant objectives and constraints in farming (Van der Ploeg, 1994). These styles have been shown to relate to the way farmers manage issues of sustainability and landscape maintenance (Busck, 2002; Schmitzberger et al., 2005). Incorporation of farming styles could be achieved by defining scenarios with contrasts in objectives and constraints at farm or landscape level, combined with developing a larger set of production activities with a larger array of production techniques and related input-output coefficients.

The generated alternatives offer ample opportunities for discussions with stakeholders on various topics. The current implementation with simplified agro-ecological relations illustrated that existing stakeholder questions can be addressed. For instance, the presented results showed differences between farms in ranges in the trade-off between gross margin and species abundance (Figure 6b). This indicates that the potential room to manoeuvre can strongly depend on the bio-physical circumstances (soil fertility) and farm configuration (grazing system applied). In future versions with more elaborated agro-ecological relations, the determination of relationships between farm management practices, biodiversity and landscape identity can yield insight into the possibilities of increasing farming intensity on individual farms. By relating field and farm levels to landscape level when assessing nutrient losses and biodiversity, the added value of concerted action of farmers within environmental cooperatives can be quantified. Moreover, including hedgerow quality in the analysis will provide input for landscape management organizations to determine priorities in their management and extension programs.

The current version of the framework exhibits a number of requirements for effective model utilization in discussion support by, e.g., parameter, objective and constraint adjustment at the three relevant scales, and selection of dimensions for visualization to enable interrogation of the results. These features enable the assessment of issues of mutual interest and explicit examination of different objectives and preferences (cf. Struif Bontkes and Van Keulen, 2003). Moreover, the framework offers ample flexibility to adjust model functioning in consultation with stakeholders. Additional methods to effectively select alternatives that match the viewpoints of the respective stakeholders would further support stakeholder discussions. Some approaches are available and will be considered in our future work, for instance efficiency assessment of solutions by data envelopment analysis (Charnes et al., 1978), compromise analysis (Van Huylenbroeck, 1997) or preference ranking on the basis of the priority assigned to the objectives (Fonseca and Fleming, 1998; Anderson et al., 2005).

In future applications, the presented Landscape IMAGES framework could be applied to a range of spatially explicit land use and nature allocation problems. Some possible issues are listed below.

(1) Support of policy development on feasibility of new institutional arrangements for self regulation, such as territorial contracts, wherein groups of land users at the regional scale cooperate and conform to regulations to meet environmental and nature conservation aims (Wiskerke et al., 2003). This requires evaluation of repercussions of management practices of individual land users at the regional scale.

(2) Design of nature conservation strategies focusing on the relation between landscape structure and biodiversity. For example, mosaic management of grasslands at landscape or regional level could offer meadow birds like the black-tailed godwit (*Limosa limosa*) the required variation in sward herbage mass and development stage (Terwan and Guldemond, 2002).

(3) The framework currently addresses hierarchical levels of field – farm – landscape, but can be applied to larger territories and higher hierarchical levels of for instance landscape – region – country. The compartmentation of the territory should then consist of larger land units such as landscapes and larger landscape structures of a few km², and nature of the production activities and design criteria should be adjusted (cf., Van Ittersum et al., 1998).

To evaluate the above mentioned issues 1 and 2, the Landscape IMAGES framework will be further developed in cooperation with stakeholders in the Northern Frisian Woodlands. The questions of stakeholders and available scientific knowledge and data form the basis for formulation of appropriate quantitative relations for the generation of production activities. These can be implemented in the integrating model for a specific case study area.

Acknowledgements
The study was carried out as part of the project 'Multifunctional Agriculture: From Farm Practice to Farm Design and Institutional Innovation' in the MFA program financed by the boards of WUR and INRA. Thanks are due to Ted Lefroy, Patrick Smith and Leslie Brooker of CSIRO Sustainable Ecosystems in Perth, Australia, for stimulating discussions on design of agricultural landscapes during a sabbatical leave of Walter A.H. Rossing. The visit was made possible by a financial contribution of the OECD Co-operative Research Program: Biological resource management for Sustainable Agricultural Systems.

Chapter 4

On connectivity in linear habitat networks using a graph theoretical model

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Submitted to: *Ecology*

Abstract

Connectivity in a network of linear habitat elements, as often found in agricultural or riverine landscapes, cannot be described or analyzed adequately using traditional ecological methods which are based on a patch oriented view on the world. In this chapter an alternative model is proposed, by approximation of a spatially continuous mental model of connectivity using discretization of space and graph theory. The new graph theoretical model for connectivity is a generic model: it bridges the patch oriented and the linear element oriented views on landscapes; it allows a consistent interpretation of connectivity at different spatial levels, including the concepts of link, patch and landscape connectivity; and it provides an analysis framework for the many different indicators of connectivity developed in ecology, including structural as well as functional measures. The applicability of the graph theoretical model is demonstrated in a case study in a hedgerow landscape in the Netherlands. Four graph theoretical measures, i.e. degree, closeness, core value and betweenness, are applied to diagnose the functioning of the network and to predict the effect of connectivity on local species distribution, species spread, vulnerability of the network for fragmentation and importance of habitats for the total network coherence. Results indicate that raised species densities and biodiversity as often observed at the intersections of networks and considered to be characteristic for linear habitat networks may be explained as an emergent property of connectivity relations within the network. The results further showed that linearity of the network affects species distribution opportunities only for specific dispersal capacity capacities of species. For species with a limited dispersal capacity, the linear character strongly determines the functioning of the network, whereas for species with a large dispersal capacity the linear network as a whole may function as a strongly interconnected patch. We conclude that the new graph theoretical model as proposed may contribute to the better understanding of ecological processes in linear habitat networks.

Keywords: connectivity, graph theory, linear habitat, ecological network, hedgerow network, dendritic network, landscape connectivity, patch connectivity

4.1 Introduction

The concept of connectivity was introduced in ecology by Merriam (1984) and is defined as the degree to which the landscape facilitates the movement of individuals, determined by the interaction between the landscape and species behavior (Taylor et al., 1993). Strongly interconnected landscapes enable species to forage over multiple habitats (Kozakiewicz, 1995; Steffan-Dewenter and Tscharntke, 1999), may rescue local populations from going extinct (Brown and Kodric-Brown, 1977; Hanski et al., 1996; Hill et al., 2002), allow recolonization of habitats after extinction of local populations (Levins, 1970; Marshall and Moonen, 2002) and limit inbreeding by supporting exchange of genes between local populations (Frankham, 1995; Shirley and Sibly, 2001; Vos et al., 2001a; Coulon et al., 2004). Therefore connectivity is considered one of the key factors determining species survival (Taylor et al., 1993) and an important aspect in nature conservation and spatial planning (Haig et al., 1998; Hoctor et al., 2000; Brooker, 2002; Bruinderink et al., 2003; Opdam et al., 2006). Information about the strength and the importance of connections can be used directly in conservation efforts to prevent the adverse effects of fragmentation of habitat (Fahrig, 1997; Fahrig, 2003)

Connectivity in the landscape is generally studied using a conceptual model of patches of natural or semi-natural habitats in a network configuration (McArthur and Wilson, 1967; Levins, 1970; Forman and Gordon, 1986; Hanski, 1994; Forman, 1995). Patches are relatively homogeneous areas of habitat where fundamental ecological processes take place, often conceptualized as point processes. Spatial relations are expressed between the patches rather than within patches and linear habitat elements are seen as conduits of fluxes ('corridors'), facilitating and directing the movement of individuals from one patch to the next. As pointed out by Campbell Grant et al. (2007), not all landscapes fit such a patch oriented view of the world. For habitat networks mainly consisting of linear habitat elements the patch-based concept is not appropriate as it is difficult to distinguish patches and corridors, both structurally and functionally. Examples of such networks include river systems consisting of linear, reticulated or branched structures of interconnected river arms (Fisher, 1997), agricultural landscapes containing a net of field margins, hedgerows or canals (Marshall and Moonen, 2002; Grashof-Bokdam et al., 2005), cave systems of interconnected tunnels (Pipan and Culver, 2007) and road networks providing a ecological mesh of road margins (Christen and Matlack, 2006). These linear habitat networks are also referred to as dendritic networks (Fagan, 2002; Campbell Grant et al., 2007). We prefer the term linear habitat network, which in contrast to the dendritic network does not contain any implicit assumption on the spatial configuration of the linear habitat elements. For species restricted to such a linear habitat network, the world is composed of a maze of linear habitat with variable degree of continuity. Population processes are taking place within the linear elements. The movement of individuals may be either within or between the different branches of linear elements rather than between patches, following the linear structure or crossing the matrix.

To structure thinking about spatial relations in linear habitat networks, the patch-based model needs to be replaced by a new conceptual model. In this chapter we explore how graph theory can be used for such a model. A graph is a mathematical way of describing a structure by a set of points (nodes), connected by a set of lines (edges). The node set represents the different elements of the structure and the edge set represents the relations between these elements (Bondy and Murty, 1977; Newman, 2003). In a habitat network the habitat elements can be represented by a set of nodes and the connections between the habitat elements by a set of edges. In literature, three alternative conceptualizations of linear habitat networks have been proposed using graph theory (Figure 1; Fagan, 2002; Campbell Grant et al., 2007). The first proposition is to represent a linear habitat network by conceptualizing it as an interconnected chain of segments, each segment being represented by a node and the connections between the segments by a set of edges (Fagan, 2002; Figure 1A). In this model the one-dimensional character of the linear habitat network is emphasized, however branching and interactions between different linear network elements are omitted. In a second model each linear element is represented by a single node and the relations among the linear elements by a set of edges (Fagan, 2002; Figure 1B). The network representation is now equivalent to the conceptual model of the patch network. This model emphasizes the branching nature of the network by introducing edges between the linear elements, but it ignores the linear character of the network elements. The third model describes a linear habitat network by representing the distal points of linear habitat elements as nodes and the elements themselves as edges,

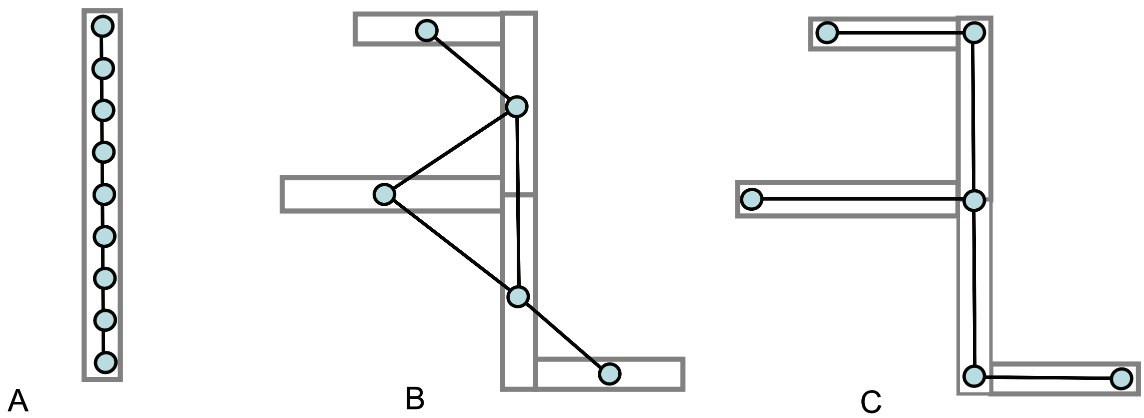

Figure 1. Three graph theoretical models for linear habitat networks: A: chain of sections, B: interconnected patches, C: a network of flows.

similar to a road or a flow network (Campbell Grant et al., 2007; Figure 1C). In this model the unique ecological characteristics of joints between linear habitat elements such as increased biodiversity are emphasized, but relations between the network elements that pass through the matrix and spatial relations within linear elements are not expressed. Another major problem with this representation is that in graph theory nodes and edges have different functions: nodes represent the objects of interest and the edges express the relations between these objects. In the representation of Campbell Grant et al. (2007) edges and nodes both represent habitat elements as well as the relations between the habitat elements. It can be concluded that no graph theoretical model exists to describe and analyze linear habitat networks taking into account the linear character of the network, within and between habitat connectivity relations and the appropriate application of the graph theoretical concepts of edges and nodes.

The objective of this chapter is to present a new graph theoretical model combining the strengths of the models presented above and to demonstrate how graph theory can be used to evaluate the ecological functioning of these linear networks. We will arrive at this model by approximation of a generic conceptual model of connectivity. The conceptual model allows connectivity to be expressed consistently at different spatial scales, integrates different notions of connectivity commonly applied in ecology and bridges between the patch-oriented and the linear element-oriented views. To demonstrate the applicability of the graph theoretical approximation of this model, a case study is performed in a hedgerow landscape in the Netherlands. Graph theoretical indicators derived from social sciences are used to evaluate the importance of the different habitat elements for the ecological functioning of the network. The chapter concludes with a discussion on the contribution of the proposed approach to the ongoing debate on connectivity and graph theory.

4.2 Theoretical framework

4.2.1 A conceptual model for connectivity at multiple scales

In the patch-oriented view spatial relations within a patch are generally omitted. By conceptualizing a patch as a single object or a node implicitly the mean field assumption of ideal mixing is applied. This assumption implies that the degree of connectedness of two patches is independent of the current location of an individual in the patch, it's point of exit and it's point of entry into the new patch. This assumption will never be true, but is especially flawed in linear habitat networks, due to the elongated shape of the network elements. A general model of connectivity is expressed by Equation 1:

$$C = \int_x \int_y s(x,y) \int_{x'} \int_{y'} d(x',y') g((x,y),(x',y'),L) \quad dx \quad dy \quad dx' \quad dy' \tag{1}$$

where g((x,y),(x’,y’),L) defines connectivity between two locations (x,y) and (x’,y’) in landscape L as a function of the interaction between habitat configuration, the species characteristics and of the landscape in between. Functions s(x,y) and d(x’,y’) are heavyside functions, which define the starting points (x,y) and destinations points (x’,y’) of interest respectively and assume the value 1 for points of interest and 0 otherwise. Equation 1 was inspired by Skelsey et al. (2005) who used a similar equation to describe plant pathogen dispersal. Depending on which sources and destinations are considered relevant, measures of connectivity are obtained at multiple scales resulting in link connectivity (Vos et al., 2001a), local connectivity (Moilanen and Hanski, 2001) and landscape connectivity (Tischendorf and Fahrig, 2000b). When s(x,y) defines all locations in a source habitat element and d(x’,y’) defines all locations in a destination habitat element, Equation 1 describes link connectivity or the ease with which an organism moves from one habitat element to another.

When s(x,y) defines all source locations in the landscape and d (x’,y’) defines all possible destinations in a single habitat element, C describes local connectivity. Local connectivity expresses the degree of interconnectness of a habitat element with the rest of the landscape and is often used by metapopulation ecologists to describe colonization chance or the immigration rate into a habitat element. When all habitat locations in the landscape are assumed to be source locations as well as destination locations, Equation 1 expresses the landscape connectivity or the ease with which organisms can move through the landscape as a whole.

In ecology there are different ways to express function g((x,y),(x’,y’),L), the connectivity between two points in landscape L. Goodwin (2003) distinguishes between structural and functional connectivity measures. Structural measures are connectivity indicators based on geometric characteristics of the landscape such as the Euclidian distance between habitats or derivations thereof (Moilanen and Nieminen, 2002; Winfree et al., 2005). Functional measures are connectivity indicators based on understanding of the interaction between species and landscape in terms of behavior and survival. Such interaction may be derived either empirically by capture-recapture, genetic analysis or radio tracking (Charrier et al., 1997; Vos et al., 2001a; Kindlmann et al., 2004) or mechanistically by simulating the movement of individuals through the landscape (Schippers et al., 1996; Tischendorf et al., 1998; Goodwin and Fahrig, 2002). The two categories of connectivity may be seen as development stages in ecological knowledge, with structural connectivity being simpler to deal with, but functional connectivity being more relevant to understanding pattern development and species survival. Function g((x,y),(x',y'), L) may represent any type of connectivity measure.

4.2.2 A graph theoretic approximation

By conceptualizing the landscape as a graph, Equation 1 can be approximated by spatial discretization. A spatial graph G (V,A,W) is a mathematical structure defined by a set of n nodes $V=\{v_1, v_2, \dots v_n\}$, an adjacency matrix A^{nxn} with the elements $a_{ij} \in \{0,1\}$ indicating whether v_i is connected to v_j ($a_{ij} = 1$) or not ($a_{ij} = 0$) and a matrix of weights W^{nxn} with elements $w_{ij} \in \Re^+$. A linear habitat network can be described as a graph by conceptualizing each linear element as a number of smaller units of equal size, here denoted as segments and by representing each of these segments by a node (Figure 2A and B). Each node v_i is described by coordinates (x_i, y_i), the connection between two nodes v_i and v_j by an edge a_{ij} and the connectivity between the nodes by a weight w_{ij}. The connectivity relation between two points does not need to be symmetric. Asymmetric connectivity relations (Drew and Eggleston, 2006), due to prevailing wind directions, water currents or slopes, may be implemented by defining the network as a digraph, a graph where $w_{ij} \neq w_{ji}$. Now, using the discretized version of Equation 1, link connectivity between segments *i* and *j* (w_{ij}), local connectivity of segment *j* ($w_{.j}$), and landscape connectivity ($w_{..}$) can be expressed by scaling from the segment level as a one-to-one relation, a one-to-many relation, and a many-to-many relation.

$$w_{ij} = g(v_i, v_j, L) \tag{2}$$

$$w_{.j} = \sum_{i \in I} w_{ij} \tag{3}$$

where I represents the collection of all source segments in the landscape, and

$$w_{..} = \sum_{j \in J} w_{.j} \tag{4}$$

where J represents the collection of all destination segments in the landscape. The analysis of spatial relations does not need to be restricted to the smallest spatial units in the landscape. For example when A represents all nodes in (linear) element a and B represents all nodes in (linear) element b, Equation 5 can be used to describe and analyze the linear habitat network at element level (Figure 2C):

$$w_{ab} = \sum_{j \in B} \sum_{i \in A} w_{ij} \tag{5}$$

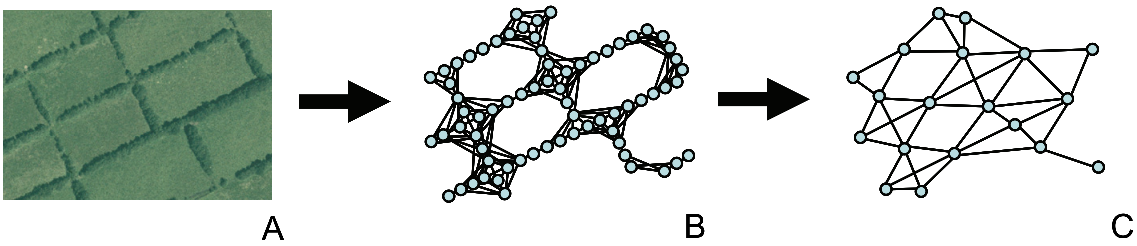

Figure 2. Graph theoretical approximation of a continuous linear habitat network: A. Linear habitat network of hedgerows in the Frisian Woodlands, the Netherlands; B. Graph theoretical approximation of the hedgerow network by discretizing hedgerows in segments of equal length, the connections between the segments are dependent on the dispersal capacity of the species under consideration; C. Graph theoretical up-scaling of the representation in B to the level of landscape elements. Each hedgerow element in the network is represented by a single node and the connectivity relations between the nodes are derived from the underlying connectivity structure at segment level.

By scaling up from segment level to the level of entire linear habitat elements information on the spatial configuration at the lower (segment) scale is used to characterize connectivity at a higher (element) scale. The result is a graph with fewer edges and nodes, which offers computational advantages. The price to be paid is the loss of information of the connectivity relations within the habitat element.

Using the graph theoretical model the continuous model of connectivity can only be approximated. Discretization of space introduces an error in the calculation of connectivity relations between the different parts of the landscape, the size of the error depending on the segment size or the grain of the network representation δ (Wu, 2004). The optimal grain to describe connectivity relations in a network may be determined by trial and error. By systematically increasing the segment size of the network and calculating the landscape connectivity of the network using function $g(v_i, v_j, L)$, a segment size can be determined which influences the calculation results only very little. This procedure is similar to the approximation of a time step in the numerical integration of time dependent differential equations (Leffelaar, 1999).

4.2.3 Network analysis

Now that we have defined our graph theoretical model for a linear habitat network, graph theoretical measures can be used to evaluate the functioning of the network. In this section we will introduce 4 indicators, degree, core value, betweenness and closeness, commonly applied in social sciences (Freeman, 1977; Wasserman and Faust, 1995; Newman, 2008), which can be used to evaluate the importance of a node for the functioning of the network and explain their ecological relevance (Table 1).

Table 1. Graph theoretical indicators of node importance and their ecological relevance.

Graph theoretical indicators	**Ecological relevance**
Degree	Local species distribution, population densities, biodiversity
Core value	Vulnerability for fragmentation elsewhere in the network
Betweenness	Importance for the spatial coherence of the network as a whole
Closeness	Species spread through the network, invasions

The *degree* of a node is defined as the sum of (weighted) edges connected to it (Newman, 2008). Nodes with more connections tend to have more influence on the network and are in turn more affected by the network (Figure 3A). Individuals dispersing randomly through the network are more likely to arrive in nodes with a high degree than in nodes with a low degree due to the larger number of entry points. Therefore population density and biodiversity at locations with a high degree is likely to be higher than in locations with a low degree due the higher immigration or colonization chances. In addition nodes with a high degree also contribute more to the local distribution of species in the network due to the large number of exit points than nodes of low degree. In our graph theoretical framework concepts of degree and local connectivity are the same (Equation 3).

Closeness and *betweenness* measure the influence of a node on the network as a whole. *Closeness* expresses the average distance of the node to the rest of the network and is based on the graph theoretical concept of geodesic network path (Dijkstra, 1959). A path in a network is defined by a sequence of nodes which can be visited by following the edges from one node to another. The sum of edges of a path is denoted as the path length. A geodesic path is the path between a specified pair of nodes with the smallest path length. The closeness of a node is defined as the mean geodesic path length of the node to all reachable nodes in the network (Sabidussi, 1966; Wasserman and Faust, 1995):

$$Cl_i = \sum_{j \in V/i} \frac{p_{ij}}{n-1} \tag{6}$$

where Cl_i is the closeness of node i and p_{ij} the length of the geodesic path between nodes i and j. Following Equation 6 nodes with a *low* closeness value are more central in the network and as a result exert more influence on the network. Individuals starting from nodes with a low closeness value can quickly reach the rest of the network. On the other hand nodes with high closeness values are likely to be the last to be arrived once a new species or a disease has entered the network.

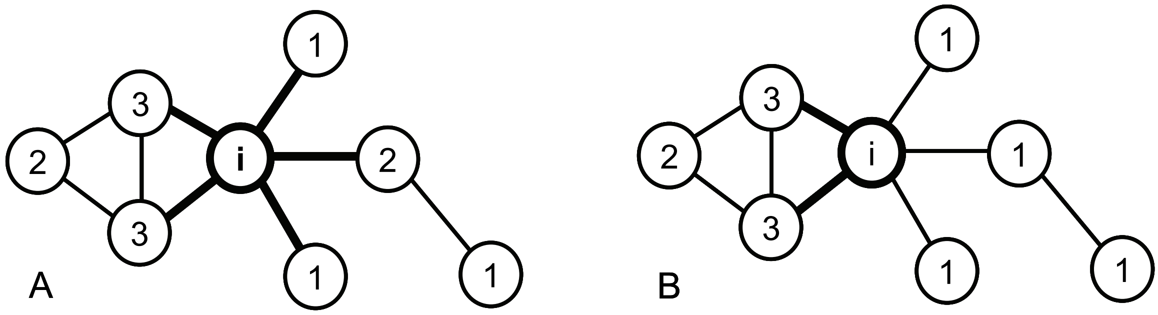

Figure 3. Schematic representation of the graph theoretical measures degree (A) and core (B) in a network of nodes (circles) and edges (lines). Node i has 5 edges attached to it (A, indicated by fat lines) resulting in a degree of 5. Only two edges need to be removed to disconnect the network that node i is part of (B, indicated by the fat lines), resulting in a core value of 2. Degree and core of each node is indicated in the circles in A and B, respectively.

Betweenness expresses the importance of the node for connections between other nodes in the network and is calculated as the fraction of geodesic paths between all other nodes in the network which includes the node under consideration (Bavel, 1948; Freeman, 1977).

$$b_i = \left\langle \sum_{s \in V/i} \sum_{t \in V/i} \frac{\pi_{st}(i)}{\pi_{st}} \middle| s \neq t \right\rangle \tag{7}$$

where b_i is the betweenness of node i, $\pi_{st} \in \{0,1\}$ indicates whether there is a geodesic path between nodes s and t and $\pi_{st}(i) \in \{0,1\}$ indicates if this path passes through node i. Betweenness is a crude measure of the control of node i over the flow between the other nodes in the network. From an ecological perspective nodes with high betweenness are important for keeping the network connected as a whole. Conservation or protection efforts are best directed at nodes with high betweenness, because habitat degradation at these locations does not only have a local effect but more importantly affects the spatial cohesion of the network as a whole.

Core value (Seidman, 1983) expresses the minimum number of other nodes that need to be removed to disconnect the node from the rest of the network and expresses the vulnerability of a node for network degradation. From an ecological perspective the core value of a node can be seen as a measure of sensitivity of a node to fragmentation processes. The higher the core value of a node the less likely it is to be affected by loss of connectivity or habitat destruction at other locations in the network.

The core value of a node can be calculated by an iterative pruning process. In each round nodes with the smallest degree are removed from the network, decreasing the degree of adjacent nodes. The core value of a node equals the degree of the node upon its removal (Figure 3B).

4.3 Connectivity in the Frisian Woodlands

4.3.1 Description of the area and approach

To illustrate the graph theoretical connectivity model and to demonstrate its applicability an example has been elaborated for the hedgerow landscape of the Frisian Woodlands. The Frisian Woodlands are a unique area in the Netherlands comprising a dense complex of hedgerows surrounding small pastures comparable to the Bocage landscapes in Brittany and Normandy, France. Originally the hedgerows were created as cattle fence, to mark property boundaries and to produce wood for household purposes. Nowadays they contribute to the ecological and biodiversity value of the landscape. The Frisian Woodlands are a small scale landscape, with distances between the hedgerows between 0 and 200m. Connectivity in this network is mainly an issue for poorly dispersing ground dwelling invertebrates largely confined to hedgerow habitat, such as certain species of ground beetles (Tischendorf et al., 1998; Bilde and Topping, 2004), springtails (Wiktorsson et al., 2004) and spiders (Bonte et al., 2007).

In this landscape we selected a section of the hedgerow network surrounded by roads. The roads are assumed to form impenetrable boundaries of the study area. We evaluated this section using a simple structural measure of connectivity (Equation 8).

$$g(v_i, v_j) = \begin{cases} 100/c_{\max} & if \quad d_{ij} \leq D_{cap} \\ 0 & otherwise \end{cases} \tag{8}$$

where $g(v_i,v_j)$ expresses whether two nodes are connected or not, d_{ij} expresses the Euclidian distance between node i and node j, D_{cap} is the dispersal capacity of a species expressed in meters and c_{max} defines the maximum number of connections in the network. The expression $100/c_{max}$ makes the landscape connectivity value of the network (Equation 4) independent from the grain size and scales it to a value between 0 and 100 percent.

The functioning of the hedgerow network has been analyzed using species profiles. A species profile is a theoretically defined set of species characteristics which is assumed to be representative for a particular group of species experiencing similar restrictions and opportunities within the habitat network (Vos et al., 2001b). In our case study we have defined 3 species profiles taking into account the spatial layout of the study using D_{cap} = 50m as a representative profile for poorly dispersing organisms having to follow the network structure of the Frisian Woodlands; D_{cap} = 100m as a representative profile for intermediate dispersing organisms capable of crossing small fields; and D_{cap} = 200m a representative profile for good dispersing organisms capable of crossing large fields. Although these profiles are defined very strictly, they should be seen as snapshots in a continuum of possible values for D_{cap}.

To determine the appropriate scale of the graph representation, a sensitivity analysis was performed for each species profile. The relation between grain size and connectivity was studied by repeated calculation of the landscape connectivity (Equation 4) in a representative part of the network while dividing the segment size in subsequent calculations, starting at segment size of 128m. When the absolute difference in landscape connectivity between two successive calculations was more then 5% the graph representation was considered to be too inaccurate, determining the final grain size of the network.

4.4 Results

4.4.1 Spatial resolution

In Table 2 the results of the sensitivity analysis are presented.

The landscape connectivity of the network (LC) and the relative rate of change (dLC) gradually decrease with the segment size of the graph representation for each of the 3 species profiles. For the 3 species profiles of 50 m, 100 m, 200 m, dLC was less than 5% between network representations with a grain size of 4 and 8 m, 8 and 16 m, and 16 and 32 m respectively. Apparently connectivity in the network can be represented accurately with a coarser grain size for species with a larger dispersal capacity. For convenience and comparisons between species profiles, the grain size adopted in the network evaluation for all three profiles was 8 m.

4.4.2 Network analysis

In Figures 4, 5, 6 and Table 3 the results of the network analysis for the three species profiles are presented. In Figure 4 the network for species with a dispersal capacity of 50 m, appears as highly fragmented and consists of 15 different sub networks or sub graphs. Species can only move along the linear networks, and the parallel linear habitat elements are connected via perpendicular oriented hedgerows. Nodes with the highest degree (between 28 and 31, respectively) are found at the intersections of the linear elements (Figure 4A). Based on this indicator it can be assumed that individuals matching this species profile are likely to be found more in these areas than in other

Table 2. Sensitivity analysis to determine the maximum grain size of the graph representation. By iteratively dissecting the length of the segments and calculating the landscape connectivity (LC), the relative change in landscape connectivity (dLC) between 2 iterations can be determined. If dLC<5% the graph representation is considered to be accurate enough.

Segment size (m)	D_{cap} 50 m		D_{cap} 100 m		D_{cap} 200 m	
	LC	*dLC(%)*	*LC*	*dLC (%)*	*LC*	*dLC (%)*
128	0.00451	-	0.01351	-	0.04070	-
64	0.00381	15.57	0.01186	12.23	0.03616	11.17
32	0.00342	10.35	0.01041	12.23	0.03361	7.05
16	0.00317	7.34	0.00967	7.05	0.03239	3.63
8	0.00296	6.47	0.00937	3.15	0.03176	1.92
4	0.00290	3.61	0.00919	1.94	0.03144	1.03
2	0.00287	1.09	0.00910	0.90	0.03128	0.51
1	0.00285	0.63	0.00906	0.50	0.03112	0.50
0.5	0.00284	0.51	0.00901	0.51	0.03096	0.51

parts of the network. This is in line with observations of increased biodiversity and population densities at intersections of linear networks in general (see Campbell Grant et al., 2002 for a review of the literature).

Figure 4B shows that most of the nodes in the network have low core values (7-8, respectively) and are therefore vulnerable for further fragmentation. Only one of the larger sub networks contains areas with the highest core values (14-15, respectively). This vulnerability is further stressed when comparing Figures 4B and C. Figure 4C shows that nodes with a high betweenness value, indicating that 16 to 25% of the geodesic paths are passing these nodes, are located in areas with low core values. Fragmentation of the network at these locations will not only have a local impact but has large consequences for the spatial coherence of the network as a whole. Figure 4D shows the closeness of the nodes, the average distance in dispersal steps from a node to all other reachable nodes in the network. Nodes in smaller fragments are more close, i.e. here by low closeness values in Figure 4D, than nodes in a larger fragment due to the smaller total length of the fragments. In some fragments nodes with a high closeness value are not located near the geometric centre of the network fragment. This can be explained by the fact that this species profile has to follow the linear structure of the network and the folded spatial configuration of the fragment. For species capable of dispersing up to 100m the network appears distinctly different (Figure 5). Compared to the species profile for organisms dispersing 50m the network now is much more connected, consisting of one large and four smaller sub graphs. Nodes with high degree (59-88, respectively) are found in areas where hedgerows are located close together (Figure 6A). The dispersal of individuals and therefore expected hotspots in biodiversity are more affected by the density of the

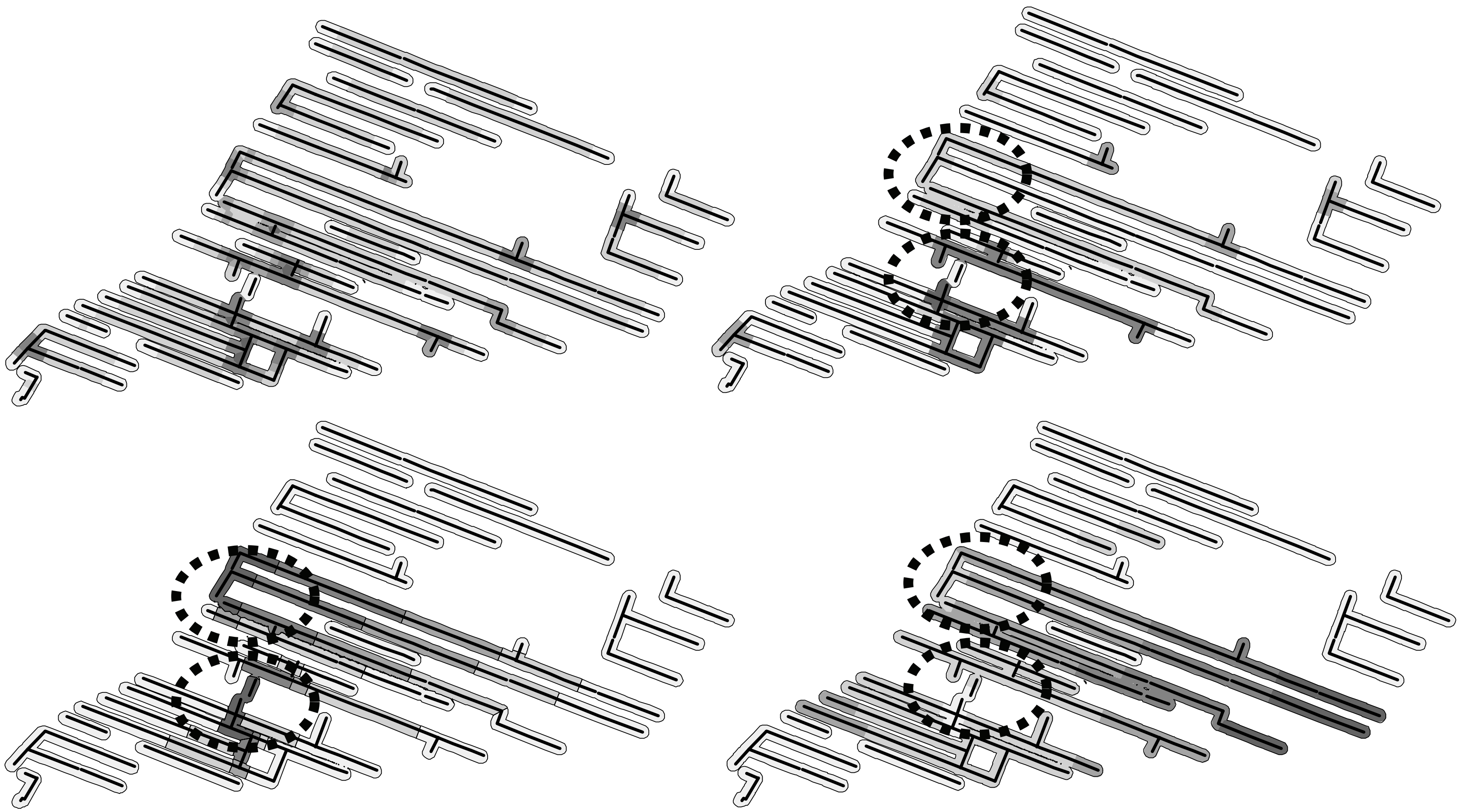

Figure 4. Network analysis for a species profile $D_{cap} = 50$ using four graph theoretical measures: Degree (A), Core Value (B), Betweenness (C) and Closeness (D). Black lines indicate the location of hedgerows, a buffer is used to visualize the dispersal capacity of the species profile and in shades of grey the values of the graph measures are indicated in 5 classes. In panels B, C and D circles indicate areas with low core value, high betweenness value and low closeness value. These areas are important for the spatial coherence of the network as a whole, are vulnerable for fragmentation and have a short average distance to the rest of the network. For quantitative information see Table 3.

Table 3. Species parameters for the graph theoretical indicators degree (*Deg.*), core value (*Core*), betweenness (*Betw.*) and closeness (*Close.*) in Figures 4, 5 and 6.

Species Profiles		**50m**				**100m**				**200m**			
		Deg.	*Core*	*Betw.(%)*	*Close.(Steps)*	*Deg.*	*Core*	*Betw. (%)*	*Close. (Steps)*	*Deg.*	*Core*	*Betw. (%)*	*Close. (Steps)*
Class 1		7-12	7-8	0-5	1.3-7.2	13-28	13-17	0-5	1.1-3.5	32-77	32-47	0-4	2-4.3
Class 2		13-17	9-10	6-10	7.3-13.4	29-43	18-22	6-11	3.6-6.1	78-122	48-62	5-8	4.4-5.1
Class 3		18-22	11	11-15	13.5-19.6	44-58	23-26	12-16	6.2-8.5	123-168	63-77	9-12	5.2-6.0
Class 4		23-27	12-13	16-20	19.7-25.8	59-73	27-31	17-22	8.6-11.1	169-213	78-92	13-17	6.1-6.8
Class 5		28-32	14-15	21-25	25.9-32	74-88	32-36	22-27	11.2-14.2	214-259	93-108	18-21	6.9-7.6

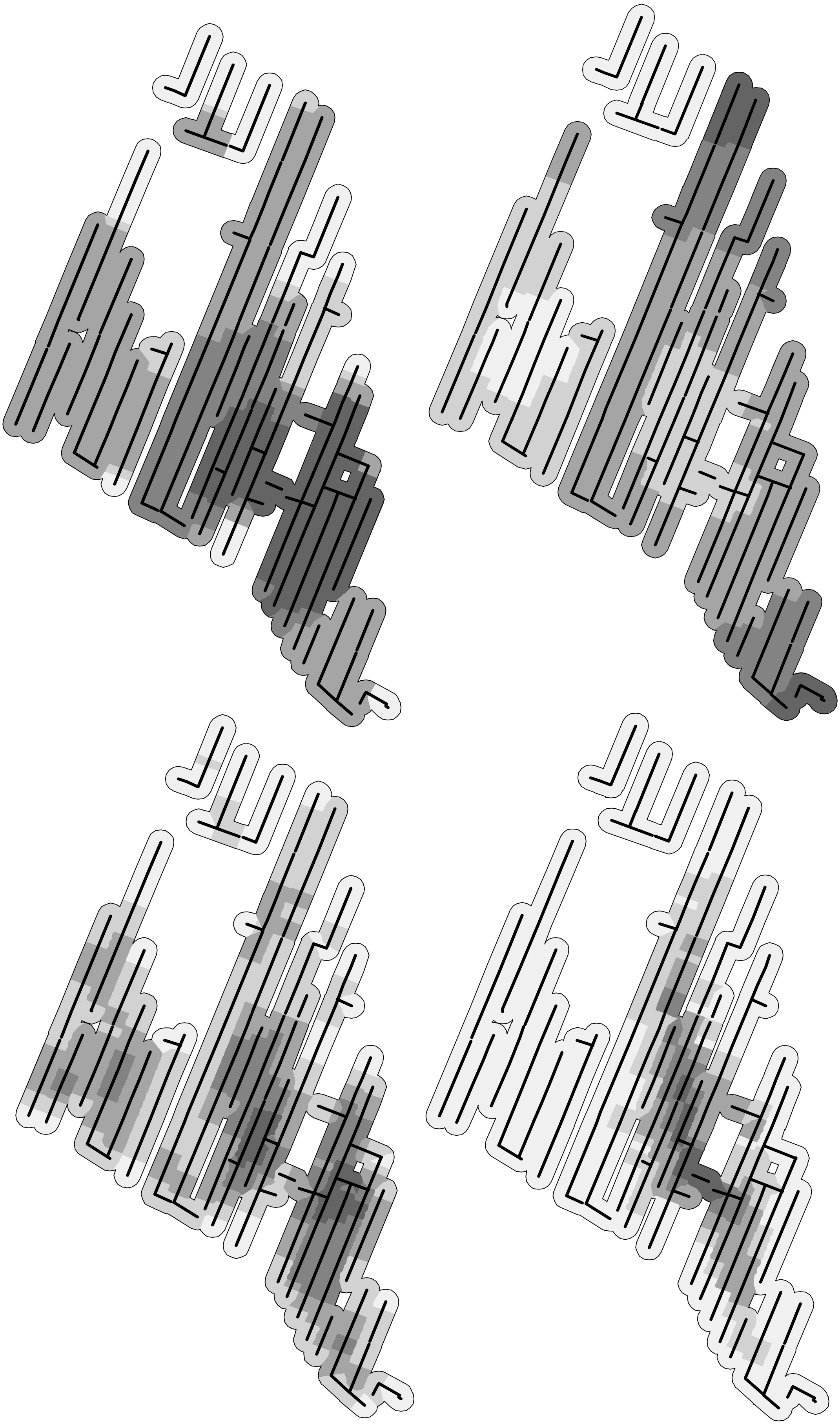

Figure 5. Network analysis for a species profile $D_{cap} = 100$ using four graph theoretical measures: Degree (A), Core Value (B), Betweenness (C) and Closeness (D). Black lines indicate the location of hedgerows, a buffer is used to visualize the dispersal capacity of the species profile and in shades of grey the values of the graph measures are indicated in 5 classes. For quantitative information see Table 3.

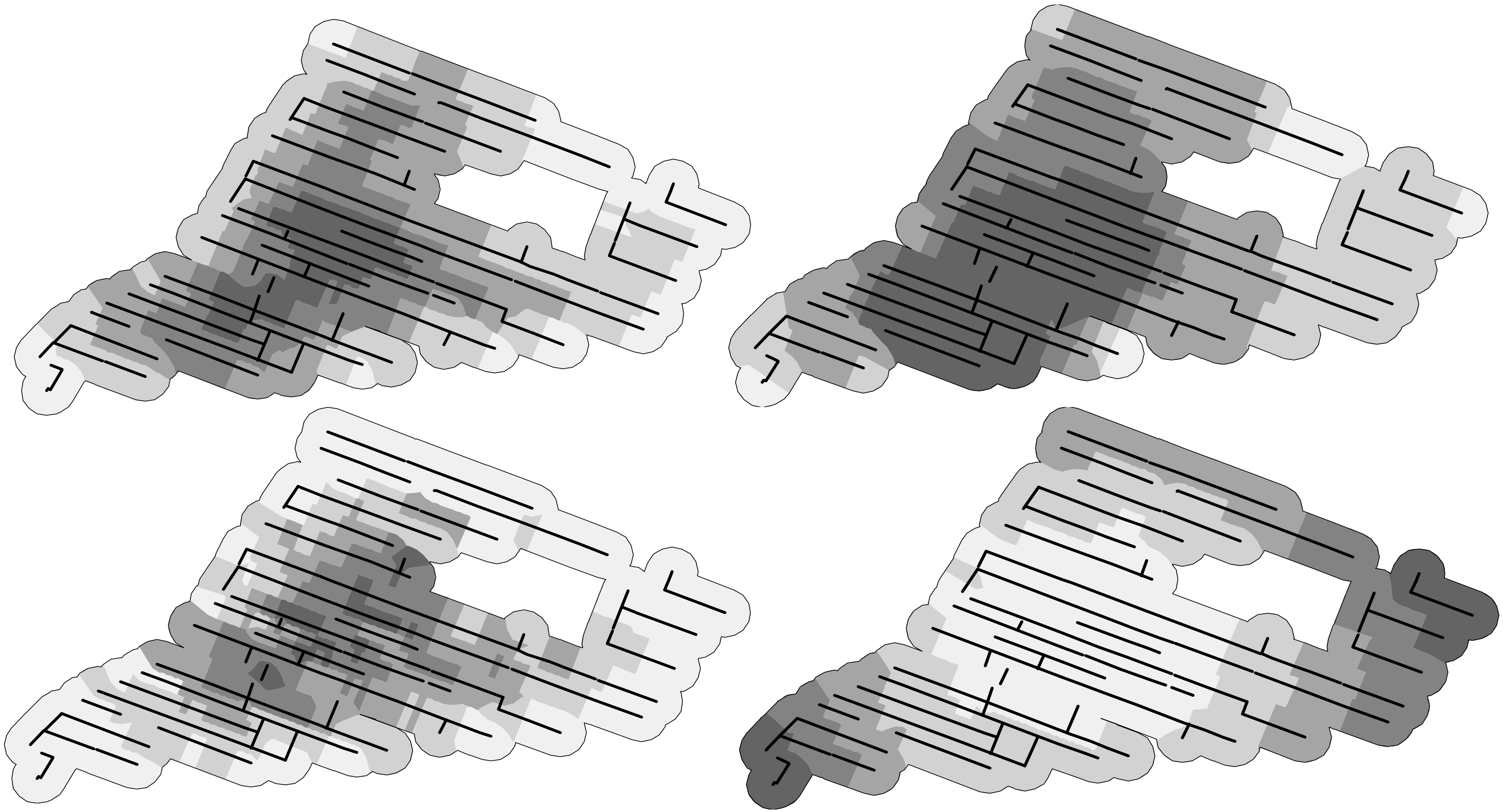

Figure 6. Network analysis for a species profile $D_{cap} = 200$ using four graph theoretical measures: Degree (A), Core Value (B), Betweenness (C) and Closeness (D). Black lines indicate the location of hedgerows, a buffer is used to visualize the dispersal capacity of the species profile and in shades of grey the values of the graph measures are indicated in 5 classes. For quantitative information see Table 3.

hedgerows than by the number of intersections. In general the core values are higher (13-36, respectively), indicating that more habitat needs to be removed before parts of the network become isolated and areas with a high betweenness value are located within the core of the network (Figures 6B and C). Although the size of the network fragments has increased the closeness of the nodes has decreased, the largest closeness value being 14.2 dispersal steps (Figure 6D).

For species capable of dispersing 200m the entire network is interconnected (Figure 6). Nodes with the largest degree, highest core and betweenness and lowest closeness are found in the centre of the network. The linear habitat network as a whole could be interpreted as a strongly interconnected single patch. Based on this analysis it can be concluded that the linear character of a network depends on the dispersal capacity of the species under consideration.

4.5 Discussion

In this chapter a new graph theoretical model has been presented to describe and analyze linear habitat networks, taking into account the linear character of the landscape elements and modeling within habitat as well as between habitat connectivity relations. We have demonstrated the applicability of this model by evaluating a hedgerow network in the Netherlands for 3 different species profiles using a simple structural measure of connectivity. In the section below we will position this new graph theoretical model in relation to the ongoing dialogue on connectivity in ecology and will discuss its applicability to analyze ecological processes in linear habitat networks.

Although there is a general agreement that connectivity between habitats is determined by the interaction between landscape and species characteristics (Merriam, 1984; Taylor et al., 1993), there are divergent opinions about the exact interpretation of the concept (Moilanen and Hanski, 2001; Tischendorf, 2001; Tischendorf and Fahrig, 2000b) and about the way connectivity should be measured (Goodwin, 2003; Tischendorf and Fahrig, 2000a). Two schools of thought may be distinguished: ecologists conceptualizing connectivity as a property of the landscape as a whole (Tischendorf and Fahrig, 2000b), other ecologist conceptualizing connectivity as a property of a habitat element (Moilanen and Hanski, 2001). For the problem we have addressed here, only the landscape-oriented approach is relevant. A main problem with the definition of connectivity as a property between habitat elements is that the total connectivity in the landscape decreases with the number of elements in the landscape (Tischendorf and Fahrig, 2000b). In the extreme case when the landscape as a whole is filled with a single patch, there can be no dispersal events between patches and the resulting connectivity will be zero, whereas in reality the landscape as a whole is interconnected. By defining connectivity as a relation between two points in space this paradox has been solved, integrating the concepts of link, local and landscape connectivity into a single conceptual framework.

In other graph applications landscape connectivity is often expressed as a function of the amount of interconnected habitat (Keitt et al., 1997; Urban and Keitt, 2001; Fall et al., 2007). We do not agree with these authors, because the notion of connectivity refers to connection rather than area. An alternative notion for the amount of interconnected habitat as a result of the dispersal capacity would be the degree of habitat clustering or the functional habitat size (Fall et al., 2007).

In our graph theoretical analysis connectivity, function g(), has been defined as a threshold function based on the maximum dispersal capacity and the Euclidean distance between two points. This function may be seen as a minimalist model for the interaction between species and landscape and can be useful if detailed ecological data is missing or to obtain a quick scan of the connectivity relations within the landscape. For a more detailed ecological analysis more ecological realism needs to be added, especially in linear habitat networks where the borders between habitat can strongly influence species movements (Charrier et al., 1997; Verboom and Huitema, 1997; Tischendorf et al., 1998; Campbell Grant et al., 2007). A simple way to include this effect of habitat type in function g() is using a cost distance function. A cost distance function scales the distance between two parts of the network according to the ease with which a species may travel through the different types of habitat. In hedgerow networks it was shown empirically that cost distance measures provide a better explanation for population distribution of ground beetles than Euclidian distance measures (Petit and Burel, 1998). The usage of cost distance functions in graph theoretical analysis has been shown by Bunn et al. (2001), Fuller and Sarkar (2006) and Fall et al. (2007). The relations between the (ecological) distance and species behavior may be further scaled using a dispersal kernel, defining dispersal densities as a function of distance. Dispersal kernels which are commonly applied are the exponential decline curve and Gaussian relations but other functions are possible (Shaw, 1995; Clark et al., 1999). To add even more ecological realism functional connectivity measures (Goodwin, 2003) may be applied based on spatially explicit individual based models of the movement of a species through the landscape (Breckling et al., 2006; Vuilleumier and Metzger, 2006; Van Den Brink et al., 2007). In this way the graph theoretical model can be seen as an integrative framework for different connectivity measures in ecology.

According to Campbell Grant et al. (2007) ecological processes in linear habitat networks are different from processes in patch networks. In their review of literature they identify a number of characteristic patterns for linear habitat networks: they concluded that the density or biodiversity at intersections of linear habitat elements is often found to be higher; dispersal through linear networks may be enhanced or delayed compared to contiguous, resulting in an increased survival or extinction of a species; and predator-prey/host-parasitoid relations may be different when compared to uniform habitats as a result of search complexity in the network. The graph theoretical model as proposed in this chapter may be applied to further analyze these characteristics. In this chapter four different graph theoretical measures have been proposed to evaluate the functioning of the network. Based on these theoretical measures it is suggested that the increase in density and biodiversity at the intersections of the linear habitat network may arise as an emergent property from the connectivity relations within the network. The results in the case study further suggest that the linear character of the habitat network depends on the dispersal capacity of the species under consideration. For species with a limited dispersal capacity, the linear character strongly determines the functioning of the network, whereas for species with a large dispersal capacity the linear network as a whole may function as an interconnected patch. Thus the patch oriented and linear element oriented view may be seen as extremes in a continuum.

The results of this research are largely theoretical, more research is needed to found the conclusions and indicators used. Beside the four graph measures as proposed, graph theory provides many other concepts and tools to analyze network relations. We consider graph theoretic process modeling such as the random walk (Lováz, 1996) and contact processes (Franc, 2004) promising to further investigate population spread and distribution through linear habitat networks. The graph theoretical model as proposed thus has the potential to significantly improve our understanding of spatial processes in linear habitat networks by providing a framework for structured thinking.

Chapter 5

Landscape character assessment using region growing techniques in Geographical Information Systems

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Accepted: *Landscape and Urban Planning*

Abstract

Landscape character is defined as presence, variety and arrangement of landscape features, which gives a landscape a specific identity and makes it stand out from surrounding landscapes. Landscape character contributes to the perceptual value of an area and is therefore important for the development of new land use functions in the country side other than the production of food and fibers. We applied an image segmentation technique, called region growing, to divide a case study area in the North of the Netherlands, stored in a GIS, into spatially continuous clusters based on the pattern of landscape features. These clusters were grouped into landscape types with a non-spatial clustering algorithm and quality was assessed using a quantitative description of a landscape ideotype. The results were analyzed for consistency and compared with expert classifications of landscapes in the case study area. The region growing algorithm was able to delineate regions in a spatial database containing landscape features such as: the field pattern, land use types and the presence and density of linear landscape elements, like hedgerows and tree lanes. The resemblance between the expert classification and the region growing result varied between 34% and 100% for the different landscape types. Differences could be explained in terms of input data and knowledge about the study area. The classification created with the region growing algorithm was more consistent throughout the study area than the expert classification.

In landscape planning region growing can be used to map and describe the character of the study area using the pattern of landscape features as a starting point, rather than predefined analysis units. By iteratively producing and discussing different maps, the methodology may be used to explore ideas and visions about landscape character as held by a group of stakeholders. Once the different landscape regions are defined, the landscape character can be described quantitatively or evaluated using a reference of an preferred landscape.

Keywords: landscape character, landscape quality, landscape planning, graph theory, region growing

5.1 Introduction

Landscape character assessment is the process of mapping, describing and evaluating a landscape on the basis of presence and arrangement of landscape features (Swanwick, 2002). Landscape features are distinctive characteristics of the landscape, which emerge from the pattern of landscape elements and their properties such as size, shape, colour and type. The character of a landscape determines its appearance, makes it stand out from other landscapes and gives a sense of place to the people inhabiting the landscape (Stedman, 2003). Landscape character assessment operates at the interface between the physical and mental dimension of the landscape (Tress and Tress, 2001): the physical dimension of the landscape is often conceptualized as a mosaic of landscape elements (Forman, 1995); the mental dimension of the landscape is reflected in the mental perception of the physical pattern in peoples minds (Lothian, 1999). Landscape character assessment makes a distinction between the more objective description of features and the subjective valuation of the landscape character depending on peoples preferences.

Landscape character and amenity values are gaining importance now that mono-functional agricultural landscapes evolve into multifunctional landscapes due to society's demand for new functions in the countryside (Vos and Meekes, 1999; EC, 2000; OECD, 2000). Multifunctional landscapes are agro-landscapes where functions like landscape aesthetics, cultural history, recreation and health care are combined with agricultural production. To support spatial planners and policy makers in thinking about these new developments, methods are needed to measure and quantify relevant landscape characteristics and to evaluate their quality.

For landscape character assessment, spatial analysis tools like remote sensing, aerial photography and Geographical Information Systems (GIS) are often employed to measure the number and distribution of different landscape features in predefined analysis units or observation scale. Spatial analysis units can be derived based on administrative boundaries, e.g. by using the protection status of the different areas (Peccol et al., 1996), based on a systems approach, by using geomorphological and soil information (Scott, 2002), based on experts by using aerial photo interpretation (Lee et al., 1999), by projecting a regular grid on the study area (Palmer and Roos-Klein Lankhorst, 1998; Farjon et al., 2002; Geertsema, 2003) or a fixed analysis window (Ayad, 2005; Brabyn, 2005; De la Fuente de Val et al., 2006). The selection of the observation scale is a critical step in these methods and may severely bias the outcome of the pattern analysis. This effect is called the modifiable area unit problem or MAUP (Openshaw and Tayler, 1981; Jelinski and Wu, 1996; Dark and Bram, 2007). In this chapter we take a different approach. Instead of determining the landscape character in predefined spatial analysis units, we will use the patterns of landscape features themselves to define spatial analysis units. We will do this by introducing a technique called region growing derived from the field of image analysis. Region growing is a segmentation technique to divide an image into regions or spatially continuous clusters based on the spectral data patterns of an image. These regions may be used to interpret an image (Benz et al., 2004) or to locate a specific object within an image (Wu et al., 2005). In this chapter a landscape is defined as a spatially continuous area characterized by its pattern of landscape features which makes it stand out from neighbouring landscapes. Using this definition and applying the region growing technique to a spatial dataset of landscape features, each region in the analysis represents a landscape, its character described by the data pattern in the region. Region growing relates to the human perception of spatial patterns by operationalizing a number of principles from the Gestalt Theory (Wertheimer, 1923; Palmer, 1992) such as proximity and similarity.

Using spatial patterns to defining homogeneous analysis units for landscape analysis is not new. Having its roots in geographical sciences (Antrop, 2004; Opdam et al., 2002) landscape ecology has a long tradition of mapping landscapes, patches, landscape elements (Forman, 1995), land units (Zonneveld, 1989) and geochores (Haase, 1989) to study the relation between landscape pattern and processes. In the early work of Carl Troll (1939) visual clues, such as shape, pattern, size, tone and texture, from aerial photographs were used in combination with thorough knowledge of the landscape system to delineate meaningful spatial entities (Zonneveld, 1989).

Nowadays a number of computerized analysis techniques have become available developed in the field of spatial statistics (Jacquez et al., 2000) and image analysis (Pal and Pal, 1993; Zhang, 2006). The application of a region growing algorithm to delineate landscapes has been proposed in ecology using high resolution imagery (Burnett and Blaschke, 2003). However many features of the landscape can not be read directly from the spectral information on an aerial photograph but are interpreted and stored in Geographical Information Systems (GIS).

In this chapter we broaden the scope of region growing by generalizing it to other spatial data formats and by implementing the region growing technique into a methodology to assess landscape character. This new methodology enables to delineate, to describe, to classify and to evaluate landscape character quantitatively based on the pattern of landscape features in a GIS. To illustrate and evaluate the methodology a case study in the Frisian Woodlands is presented. Its performance is evaluated by comparing the analysis results with a landscape character map independently created using expert knowledge. The remainder of the chapter is structured as follows: in the methodological section we will introduce the principle of region growing based on GIS data and describe the landscape character assessment methodology. Then the case study is introduced and analysis results are presented. In the final section we discuss the methodology from a technical point of view and from an application point of view for landscape planning.

5.2 Methodology

5.2.1 Region growing

Region growing is an image segmentation technique to divide or segment an image into regions or spatially continuous clusters based on the spectral data patterns of an image. The difference between two patterns is expressed by a dissimilarity function. Region growing is an iterative bottom-up optimization process, where in each round the most similar neighbouring regions are merged, minimizing the dissimilarity within regions and maximizing the dissimilarity between regions. Region growing algorithms differ from each other by dissimilarity criterion (Lehmann et al., 2005), optimization approach (Baatz and Schape, 2000) and stop criterion (Lallich, 2003; Navon et al., 2005). In this chapter we use a variation on the Fractal Net Evolution algorithm (FNE) (Baatz and Schape, 2000). This algorithm is commonly applied to segment high resolution remote sensing images (Benz et al., 2004) and has proven to give good results (Meinel and Neubert, 2003).

The typical data format for a region growing algorithm is a regional adjacency graph (RAG) (Marfil et al., 2006). A RAG = (V, A,W) is a mathematical data format in which the regions are represented by a set nodes V = $\{v_1, v_2, \ldots, v_n\}$; the adjacency between nodes by matrix A^{nxn}, where $a_{kl} \in \{0,1\}$; and the dissimilarity between nodes by a matrix of weights W^{nxn}, where $w_{kl} \in \Re^+$. The dissimilarity w_{kl} between two regions k and l is expressed as a function of the data dissimilarity w_{kl}^{data} and shape dissimilarity w_{kl}^{shape} (Equation 1):

$$w_{kl} = w_{kl}^{data} + \beta * w_{kl}^{shape} \qquad (1)$$

where β is a scaling factor between the 2 dissimilarity measures. Data dissimilarity expresses the numerical differences between the data patterns in the regions. A common way to express this difference is to express the difference in mean value (Jolion and Montanvert, 1992). In FNE a more complex measure is used by expressing the data dissimilarity as a function of the increase in standard deviation of the data values weighted by the size of the old and new regions (Equation 2):

$$w_{kl}^{data} = n_{k+l} * std_{k+l} - n_k * std_k - n_l * std_l \qquad (2)$$

where n_k is the number of data elements in region k and std_k is the standard deviation of region k. The standard deviation of the values in the data pattern can be seen as a measure of internal variation in the region. A pattern with large variation in data values has a large standard deviation and a pattern with a small variation in data values has a small standard deviation.

In FNE dissimilarity is not defined as an absolute measure of variation in the data pattern, but as the variation in pattern of the merger relative to the variation in the two individual regions separate. The consequence of this definition is that two adjacent regions with high variability have the same dissimilarity as two adjacent regions with low variability as long as the increase in variation due to region fusion is the same. This is useful because if the dissimilarity would be expressed as an absolute measure of variation, areas in the dataset with a low variability would merge more easily than areas with high variability resulting in a biased growth of regions in the dataset. In terms of landscapes the dissimilarity criterion implies that two mosaic landscapes will be considered to be as similar as two monotone landscapes as long as within each pair of landscapes the mosaic or the tone is more or less the same. Merging a monotone landscape and a mosaic landscape, two different monotone landscapes or two different mosaic landscapes on the other hand will result in a large increase in variability and therefore there will be a relatively large dissimilarity value between these landscapes. The second consequence of the data dissimilarity definition in equation 2 is that dissimilarity is measured as a function of the size of the merged regions. Small regions, including outliers, are merged more easily than large regions and as a result the region growing process tends to grow regions of similar size.

The shape dissimilarity expresses the improvement the new region makes towards the shape of a perfect circle (Equation 3).

$$w_{k+l}^{shape} = n_{k+l}(\frac{s_{k+l}}{p_{k+l}} - 1) - n_k(\frac{s_k}{p_k} - 1) - n_l(\frac{s_l}{p_l} - 1) \quad (3)$$

where s_k is the perimeter of region k and p_k is the perimeter of a circle with the same area. The shape parameter β in equation 1 is used to suppress the formation of irregularly shaped regions especially in heterogeneous data sets (Lehmann, 2005). Its value is determined by the user.

To determine which regions will be merged the local mutual best fit optimization method is used (Baatz and Schape, 2000). This is a conservative approach in which two regions A and B can merge if and only if they are each others most similar neighbour. The regions to be merged can be found as local minima in the dissimilarity matrix W. The algorithm is less greedy than other approaches, such as the local best fit method, and therefore result in fewer optimization mistakes. Furthermore, the local mutual best fit method takes into account local variation in the dataset. By considering the dissimilarity between regions in relation to the dissimilarity in the direct neighbourhood of the regions, two dissimilar regions will be merged as long as they are more similar to each other than to their other neighbours. As a result the region growing process in a data set consisting of a heterogeneous part and a homogeneous part will take place uniformly throughout the dataset. In contrast, a global optimisation procedure, that iteratively merges the two most similar regions representing the global dissimilarity minimum in the data set, will first cluster the homogeneous part of the dataset before clustering the heterogeneous part.

We implemented the algorithm in such a way that in each iteration round all local minima in the RAG are determined and merged simultaneously. This is called semi-parallel processing (Jolion and Montanvert, 1992). As a stop criterion a simple threshold value τ is used, which represents the maximum dissimilarity for merging. If the dissimilarity between two regions exceeds the threshold they can not be merged. If during an iteration no merges are possible the algorithm is terminated.

5.2.2 Region growing in GIS

In GIS typically two data formats are used: the vector format and the raster format. The vector format consists of a set of non-overlapping geo-referenced objects, represented by a polygon, a line or a point. The raster format consists of a regular grid of geo-referenced cells. In both data formats the properties of the spatial elements are described in an attribute table, which may contain categorical, ordinal, interval or ratio data values. To enable region growing the spatial data set needs to be represented as a RAG. This can be realized by representing each data element (pixel, raster cell, point or polygon) by a node, and the neighbourhood relationships between data elements by a set of edges. The next step is to express the information contained in the attributes in dissimilarity matrix W. We will do this by introducing a new matrix D2 to facilitate the calculation of matrix W during the region growing process. Matrix D2, consists of elements $d2_{kl} \in \Re^{+}$ containing the sum of the squared differences over all attributes between the data elements i in region k and the data elements j in region l, and elements $d2_{kk} \in \Re^{+}$ containing the sum of the squared differences over all attributes between all data elements i and j within a single region k (Equation 4).

$$\begin{cases} d2_{kl} = \sum_{z \in Z} \sum_{i \in K} \sum_{j \in L} \alpha^{z} (d_{ij}^{z})^{2} \\ d2_{kk} = \sum_{z \in Z} \sum_{i \in K} \sum_{j \in K} \alpha^{z} (d_{ij}^{z})^{2} \end{cases} \quad (4)$$

Variable d_{ij}^{z} expresses the numerical difference between data elements i and j for attribute z, Z is the set of all attributes, K is the set of data elements in region k and L is the set of data elements in region l. Parameter α^z is a weighting factor balancing the contribution of each attribute to the total variation in the dataset. As explained in the previous section the region growing algorithm used in this chapter minimizes the increase in variation in the dataset for each iteration. If the difference in contribution to the total variation in the data set is very large among the attributes, the region growing algorithm will mainly respond to those variables containing the largest variation. The weight α^z is calculated as the total variation of all variables in the dataset divided by the total variation of variable z, balancing the contribution of each variable to the total variation in the dataset (Equation 5).

$$\alpha^z = \frac{\sum_{q\in Z}\sum_{i\in V}\sum_{j\in V}(d_{ij}^z)^2}{\sum_{i\in V}\sum_{j\in V}(d_{ij}^z)^2} \quad \forall_z \tag{5}$$

where V is the set of all nodes in the RAG.

For continuous data the difference between two data elements can be expressed numerically as the Euclidian distance between the data values (Equation 6). If the data set consists of a single continuous attribute the standard deviation of region k std_k can be calculated using equation 7 (Appendix).

$$d_{ij}^z = \sqrt{(x_i^z - x_j^z)^2} \tag{6}$$

$$std_k = n_k \sqrt{\frac{d2_{kk}}{2}} \tag{7}$$

Substitution of equation 7 in equation 2 leads to equation 8 to calculate matrix W:

$$w_{k+l}^{data} = \sqrt{\frac{d2_{k+l,k+l}}{2}} - \sqrt{\frac{d2_{kk}}{2}} - \sqrt{\frac{d2_{ll}}{2}} \tag{8}$$

Matrix D2 can be updated in a combinatorial way using equation 9:

$$d2_{k+l} = d2_{kk} + d2_{ll} + 2 * d2_{kl} \tag{9}$$

If the dataset is very large matrix D2 can also be implemented as a sparse matrix (Duff et al., 1989), initializing $d2_{kl}$ only for those entries of adjacency matrix A, where a_{kl} = 1 or k = l. New entries $d2_{k+l,m}$ between merged regions k+1 and their neighbours m can be calculated during the growing process.

Equation 8 also enables to include data types other than continuous data into the region growing process. The resulting measure of variation is not a proper standard deviation in the statistical sense (Jongman, 1995), but still a valid measure of the variation and therefore suitable for the region growing process. In this chapter we mention the examples of directional and nominal data, as these were relevant categories in the case study.

Directional data is a special case of interval data. The difference between two angles can not be calculated by a simple subtraction of data values. For example, if the direction of line A is 15 degrees and the direction of line B is 355 degrees, the difference in angle between these two lines is 20 degrees and not 340 degrees. Therefore the difference between two angles is calculated using equation 10:

$$d_{ij}^{z} = \begin{cases} abs(x_i^z - x_j^z) & \text{if} \quad abs(x_i^z - x_j^z) \leq 90 \\ abs(x_i^z - x_j^z + 180) & \text{otherwise} \end{cases} \tag{10}$$

For nominal attributes there is no easy way to express the difference between two data values (Zhao and Karypis, 2005). For example if a nominal attribute consist of 2 classes, two data elements either belong to the same class or not. A more gradual distinction can be made if a data element would consist of several nominal variables. In a spatial dataset this can be realized by including a neighbourhood into the dissimilarity calculation, defined by a buffer operation around the data elements. The difference between two nominal data elements i and j can then be expressed as d_{ij}^{z}, the sum of the differences in relative surface area covered by the different categories divided by 2 (Equations 11 and 12).

$$d_{ij}^{z} = \sum_{k \in C^z} \frac{1}{2} * abs(rarea_{ic}^{z} - rarea_{jc}^{z}) \tag{11}$$

$$rarea_{ic}^{z} = \frac{area_{ic}^{z}}{\sum_{c \in C^z} area_{ic}^{z}} \tag{12}$$

where $rarea^{z}_{ic}$ and $area^{z}_{ic}$ are the relative and absolute area of data category c in the neighbourhood of data element i and C^z is the set of all categories of nominal attribute z.

The value assumed by d_{ij}^{z} varies depending on the data type and the original data values between: $[0, \infty]$ for continuous data, $[0,90]$ degrees for directional data and $[0,1]$ for nominal and ordinal data. Normalization of an attribute is realized by dividing the values of d_{ij}^{z} by their range. This way of normalizing data is less common than for example z-score normalization, but has proven to be effective in other forms of clustering (Milligan and Cooper, 1988).

5.2.3 Applying region growing to landscape character assessment

The objective of landscape character assessment is to describe, map and evaluate a landscape on the basis of the presence, arrangement and variability of landscape features (Swanwick, 2002). The result of such an assessment can be used for landscape planning and management. In this chapter a computerized method for landscape character assessment is presented based on the principle of region growing in a spatial data set of landscape features. Each region corresponds to a separate landscape; the character of the landscape is described by its data pattern. In Palmer (2004) it is shown that the correlation between the landscape pattern described by a GIS and the human perception of the actual landscape character is high. The methodology proposed consists of 5 steps: creation of a spatial data base, delineation of landscapes, characterization and classification of landscape character; assessment of landscape character and validation of the analysis result.

Building a spatial database

The first step in the methodology is to build a spatial database containing the distribution of the landscape features of interest and of which consists of one or more data layers. The first layer is a spatially continuous layer of data elements (raster or vector) covering the study area. This layer provides the geometrical structure for the region growing process. How smooth the region growing result will be is determined by the size of the data elements compared to the extent of the study area. Data elements which are large or very long disturb the region growing process by interconnecting data elements in different parts of the dataset. The other data layers contain the landscape features, described in continuous, directional or nominal data.

During the building of the database several considerations play a role: Which landscapes features determine the character of the study area? What are the landscape features that distinguish between the different landscapes in the study area? Which datasets are available? How can landscape features be measured in a GIS and what is the appropriate scale of measurement? By documenting the answers to these questions the process of data selection remains transparent and at least intersubjective.

Delineating landscapes

The landscapes in the database are delineated using the region growing algorithm as described in the previous sections. The final result of this algorithm depends on two user-defined parameters, the weighting parameter β and the threshold parameter τ. To determine an appropriate value for these parameters in advance is difficult. By varying these parameters a number of landscape segmentations are created from which the result best matching the data patterns may be selected based on a visual comparison with the original data. As selection criteria we propose the interpretability of the border between and the homogeneity within regions in terms. The range over which to vary the region growing parameters needs to be determined heuristically.

Characterization and classification of landscape character

The result of the region growing process is a segmentation of the dataset into regions. Each region stands for a different landscape with its own characteristic landscape pattern. The landscape character can be summarized by the mean values of the attributes. This information can be used to quantitatively describe and characterize the landscapes or as input for further analysis. To classify the regions into landscape types a 'standard' clustering algorithm, like k-means clustering or hierarchical clustering may be used (Jain et al., 1999). In this chapter a novel hierarchical clustering algorithm is introduced, derived from the region growing algorithm described in the previous section. A new graph, $G^r = (V^r, A^r, W^r)$ is defined, where V^r is a node set in which each region of the final segmentation is represented, matrix A^r is an adjacency matrix connecting all regions in the dataset ($a_{ij}^r = 1 \quad if \quad i \neq j$, and zero otherwise) and W^r is the dissimilarity matrix. Matrix W^r expresses the differences in landscape character between the regions based on data dissimilarity as expressed in Equation 2. W^r can be calculated using the regional means of the normalized data and equations 8, 4, 6, 10, 11, where $\alpha^z = 1 \quad \forall \quad z \in Z$. Iteratively, in each round the two most similar regions in the graph are grouped using the global minimum of the dissimilarity matrix W^r. Note the conceptual resemblance between region growing and hierarchical clustering, region growing can be seen as a special case of hierarchical clustering. The result is represented in a dendrogram which expresses the similarity relations between the landscapes in the study area. Using a threshold value groups of similar landscapes or landscape types can be distinguished. Similar to the region growing process, the criterion to set the threshold value is interpretability of the analysis results.

Assessment of landscape character

The degree to which a landscape resembles a desired landscape is the result of interaction between the landscape character and a set of human values. How such a judgement can be derived is topic of study elsewhere (Daniel, 2001) and is outside the scope of this chapter. Based on such an evaluation, a landscape ideotype can be defined as a quantitative description of a set of desired landscape features. The quality of the landscapes in the delineated regions can be evaluated by calculating dissimilarity w^r_{rp} , the dissimilarity between the landscape ideotype p and regions r, using equations 8, 4, 6, 10, 11. Depending on the objective of the assessment, dissimilarity w^r_{rp} may be calculated for all landscape features jointly or for each landscape feature individually. The joint dissimilarity value reveals which of the regions in the dataset have the closest resemblance to the ideotype. By assessing w^r_{rp} for each landscape feature individually, it may be identified which landscape features contributing most to overall dissimilarity. These landscape features may then be targeted by policy measures when aiming to improve the landscape character in that region.

Validation of the analysis result

Validation can be defined as the substantiation to which a computer model matches the real world system and generally involves a comparison of the output data of the model with another representation of the real world system (Klein and Herskovitz, 2007). This validation can be made on the basis of a field study or by consulting a group of independent experts or residents who know the study area well. To describe the resemblance between the segmentation result and the external reference a consistency table, as commonly applied in remote sensing, is used (Lillesand and Kiefer, 1994). A consistency table is created based on the spatial overlay of a segmentation result and the independent reference dataset and consists of two parts. One part expresses the analysis consistency, the consistency with which a class in the analysis result is represented in the same class as the reference data set and the other part expresses the expert consistency, the consistency with which a reference class is represented in the same analysis class.

5.3 Case study Northern Frisian Woodlands

5.3.1 Case study description

The Northern Frisian Woodlands comprise an area in the north of the Netherlands characterized by small, elongated agricultural fields, reflecting a history of peat reclamation. Within this area 3 main landscape types can be distinguished: The '*Dykswal*' landscape consisting of fields bordered by hedgerows on wooded banks. These hedgerows traditionally had a function as cattle fence and for the provision of wood; The '*Singel*' landscape consisting of fields divided by ditches bordered on both sides by alder trees; The '*Open*' landscape consisting of fields bordered by ditches without trees (Renting et al., 2006). The typical landscape features, the biodiversity values and the small plot sizes constitute constraints for agricultural production, but offer opportunities to develop other functions like recreation and nature conservation. The landscape in The Frisian Woodlands area has recently been proclaimed a 'National Landscape' by the Dutch government emphasizing its uniqueness and importance for the Netherlands (Anonymous, 2006).

5.3.2 Building the dataset

A small scale topographical map (Top10 Vector) is used as a basis for region growing. From this map parcel polygons containing agricultural fields and building plots were used as spatial analysis unit. All linear elements, like roads and canals, were removed and small topological mistakes were corrected. To recreate a contiguous data set proximity analysis was used on the remaining 22,723 data elements and the neighbouring parcels of each parcel were determined.

To characterize the different landscapes, 6 distinctive landscape features were identified: field pattern, density of wet linear elements such as ditches and canals, density, spatial layout and composition of dry linear elements such as hedgerows, 'singels' (lines of alders along ditches), tree lines (rows of trees without undergrowth) and land use. These features were selected, because they are considered characteristic for the Frisian Woodlands (Renting et al., 2006) and because they are clearly visible in the landscape, matching the human perception of the landscape.

Field pattern was described by 3 continuous variables: parcel size, shape of the parcel and direction of the parcel. The shape of a parcel is measured as the ratio between the perimeter of the shape and the perimeter of a circle of the same area. Direction is measured as the direction of the smallest rectangle fitting around the parcel. The distribution of the wet linear elements is described by a single continuous variable, the density of wet linear elements, and calculated as the total length of wet linear elements in a buffer zone of 50 m around the parcel divided by the buffer area. Dry linear elements are an important feature of the landscape character of the Frisian Woodlands and are therefore described in using 3 attributes; density, composition and spatial layout. The density of the dry elements is determined in a similar way as the density of wet linear elements. The composition of dry linear elements is determined as a nominal variable, consisting of three classes, hedgerows, 'singels' and tree lanes. The spatial layout of dry linear elements is measured as the maximum distance between two linear elements in the direction parallel to the parcel divided by the maximum distance between two dry linear elements perpendicular to the direction of the parcel. The final landscape feature used in the analysis is land use pattern which is determined as a nominal variable. This dataset was derived from the Dutch land use map (LGN) by reclassifying the 30 land use classes to 8 more general land use classes.

5.3.3 Landscape character assessment

To find appropriate values for the shape factor β and the threshold factor τ, β was varied over a range between 0 and 0.04 in steps of 0.005 and τ over a range of 2 and 8 in steps of 0.5. Using the original data, the best matching segmentation was selected and classified. In the classification procedure directional data was excluded from the

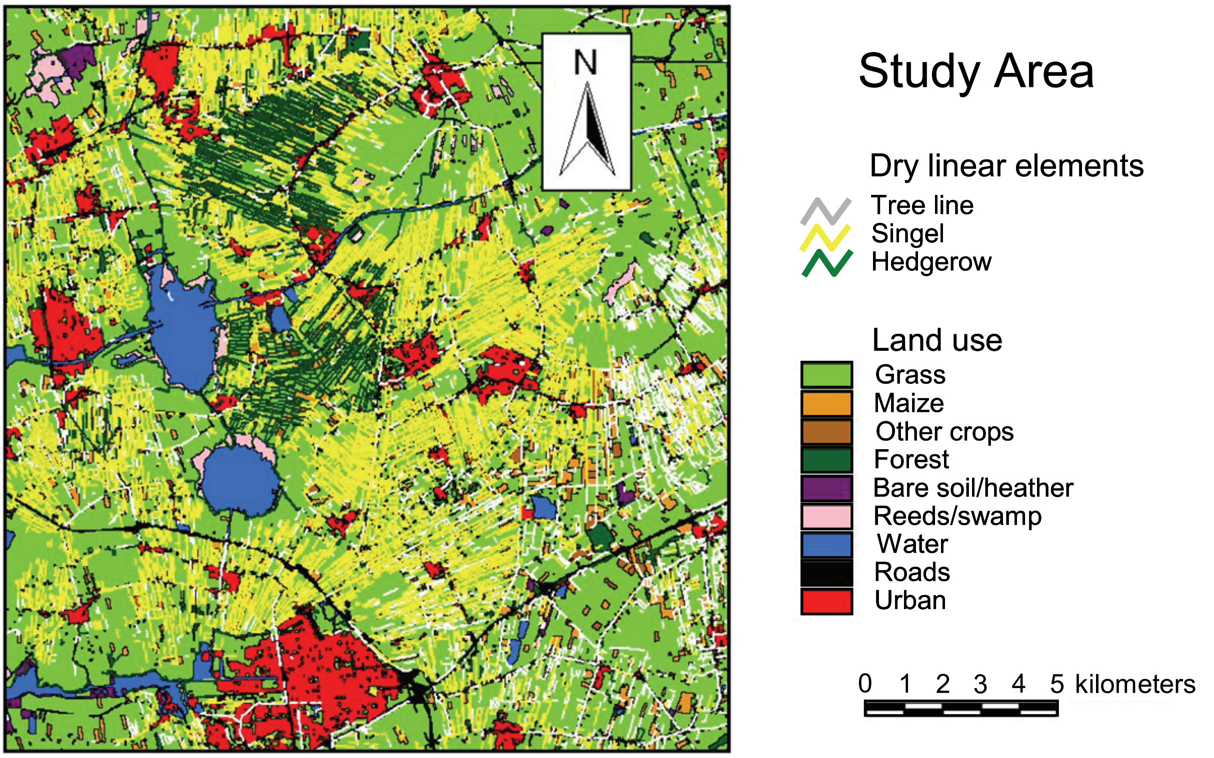

Figure 1. Overview of the spatial distribution of 2 different landscape features in the study area, dry linear elements and land use data sets.

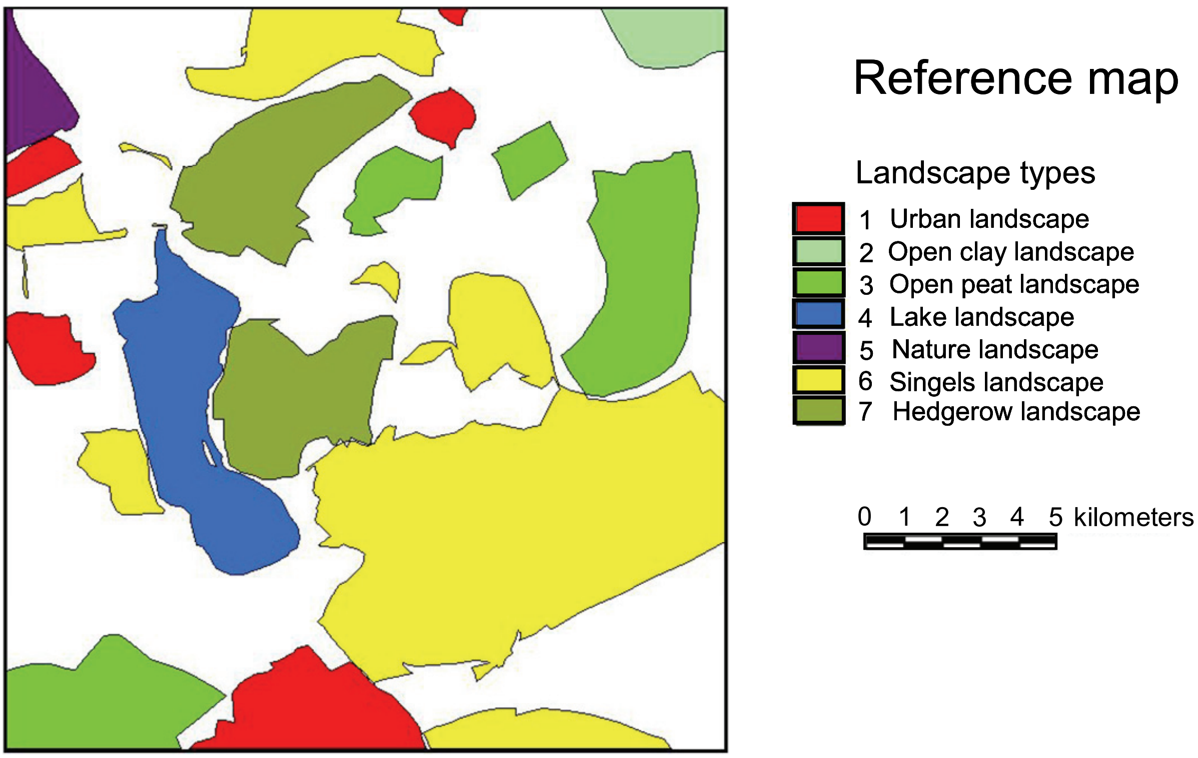

Figure 2. Reference map with the core areas of the 7 landscape types created by overlaying the maps from 4 experts.

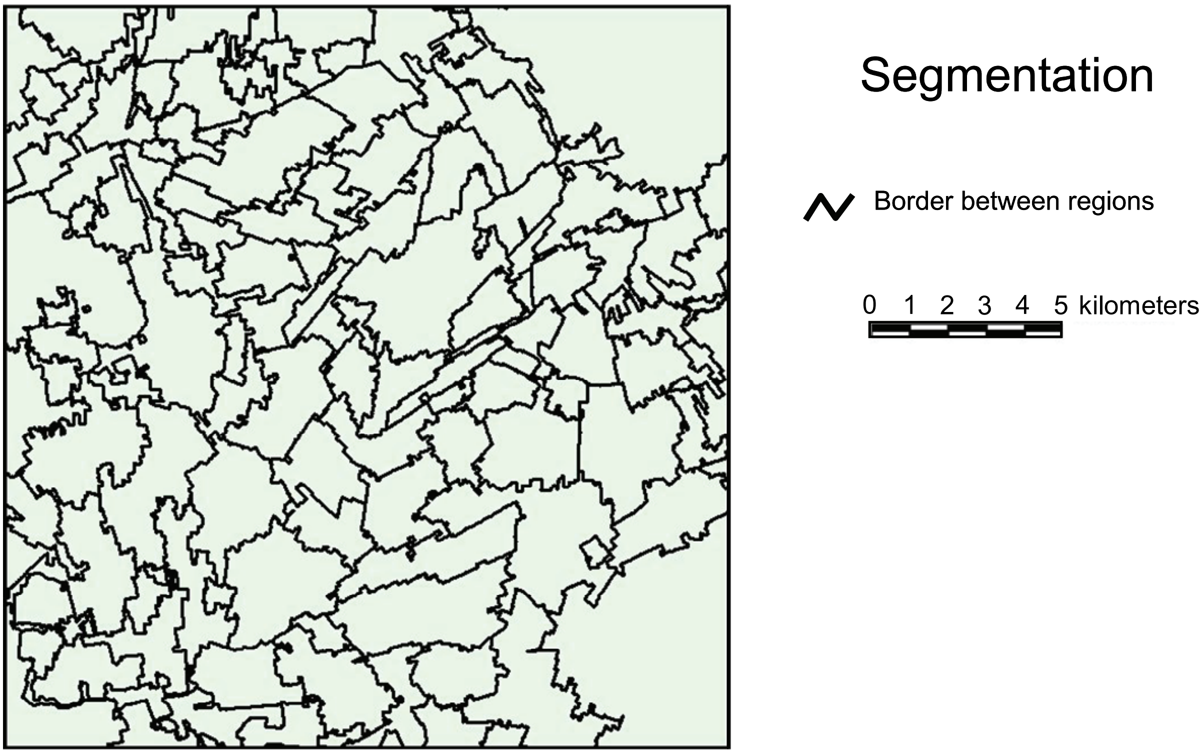

Figure 3. Region growing results, consisting of 132 regions, created by iteratively merging parcel polygons with similar landscape characteristics.

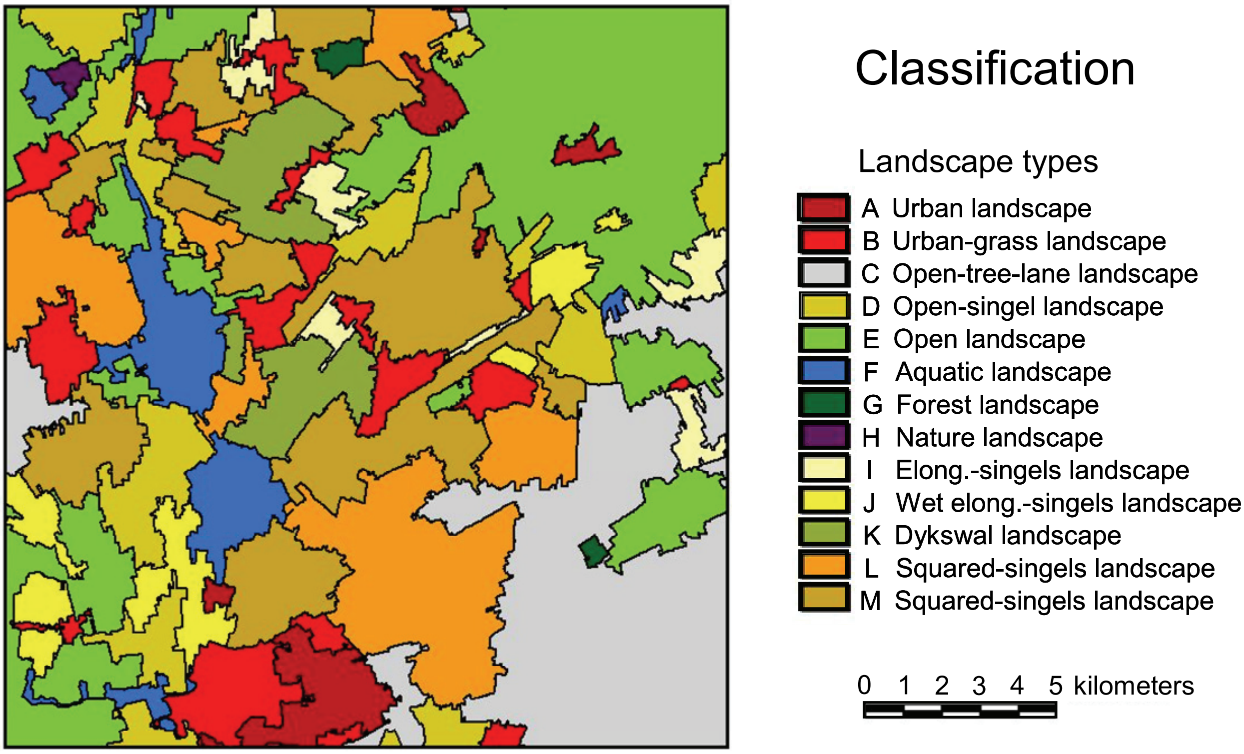

Figure 4. Classification of the study area by none-spatial clustering similar regions into landscape types.

Box 1. Quantitative description of an the landscape idiotype.

Ideotype *'Dykswal' landscape*

(1) Deviation in the field pattern direction: 0 (degrees)
(2) Dry linear element density = 0.001 m/m^2
(3) Dry linear element density = 0.5 m/m^2
(4) Dry linear elements composition:
a Tree lanes 0%, b Hedgerows 90%, c Singels 10%.
(5) Shape: 1.2 (m/m)
(6) Size = 4 (ha)
(7) Spatial layout: 1:6
(8) Land use pattern: grass 95%, maize 2.5%, wheat 2.5%

based on the policy document 'Nota Ruimte' (Anonymous, 2006).

analysis, because the average direction of the fields in a region indicates the direction of reclamation. Two landscapes oriented in a different direction can have the same dominant landscape features and therefore belong to the same landscape type. To asses the landscape character a quantitative description of the '*Dykswal*' landscape of the Frisian Woodlands (Box 1) was developed based on the policy document '*Nota Ruimte*' (Anonymous, 2006). Based on this ideotype the dissimilarity between the preferred landscape and the regions identified in the previous steps was assessed.

5.3.4 Validation of the analysis result

An external reference was created based on information provided by 4 regional experts. We asked each individual expert to create a landscape character map of the Northern Frisian Woodlands by tapping into their knowledge of the study area and focusing on visual landscape features. Each expert map was created by delineating the different landscapes in the study area on a chapter version of the top10 vector map and by describing the main characteristics of these landscapes. The landscapes on the map were delineated in such a way that together the entire study area was covered, similar to the end result of the region growing process. No predefined landscape types were provided. The interpretation of which landscapes to delineate on the map and how to characterize these landscapes was left to the expert, as long as the result was based on the presence of visual landscape features. This resulted in 4 different maps which were consistent in some parts of the study area, but very different in other parts. The maps differed in number of landscapes, their delineation and their characterization. Apparently delineation of landscapes in some parts of the study area was more straight forward than in other parts. The expert maps were simplified by reclassification to 7 classes of landscape types which allowed comparisons among the four maps. The landscape types distinguished were: *1 Urban landscape, 2 Open peat landscape, 3 Open clay landscape, 4 Lake landscape, 5 Natural landscape, 6 'Singel' landscape, 7 'Dykswal' landscape*. To create the final reference map, we only took into account those areas, which were identified consistently by at least three of the four experts. We denote these as core areas and identified them by intersecting the four expert maps (Figure 2).

5.4 Results

5.4.1 Delineation of landscapes

In the first analysis step 126 different segmentations of the study area were created. For a given shape factor β, segmentations with increasing threshold value τ were mostly perfect refinements of each other (Martin et al., 2001). Segmentations with the same threshold value but a larger shape factor demonstrated more compact and fewer regions.

The selected segmentation consisted of 132 regions varying in size from 6 to 1412 data elements and was created using a threshold value of 5 and a shape factor of 0.02 (Figure 3). Using a visual assessment, the overall match between the data and the segmentation result was good as is shown in Figure 5. Some regions are dominated by a specific landscape feature and have very distinctive borders with their neighbours: region I is dominated by urban land use, region II is dominantly open area with fields in north-west south-east direction, region III is dominantly open with fields in north south direction. Some areas consist of a mixture of features: region IV is dominantly open area with a mixture of field sizes and directions, region V is a mixture of 'singels', hedgerows and urban land use, region VI is a mixture of 'singels' and hedgerows. A mixed region can emerge because of mixed features in the region or as the result of the merging of several small regions. Some borders between regions are very clear: for example the border between region I and II or between II, III and IV. For other borders the exact location is less distinct: for example the border between VI and V or VII and V.

5.4.2 Characterization and classification of landscape character

In Figure 6 the dendrogram based on the dissimilarity W^r between the regions of the selected segmentation is presented. At each subdivision of the dataset, the attribute contributing the most to the dissimilarity between the groups is indicated. In total 13 different landscape types were distinguished using a threshold value of 0.5. This threshold value was chosen because it separates landscape types *F*, *G* and *H*. Although these 3 landscape types contain very few regions, they are very different in nature. The

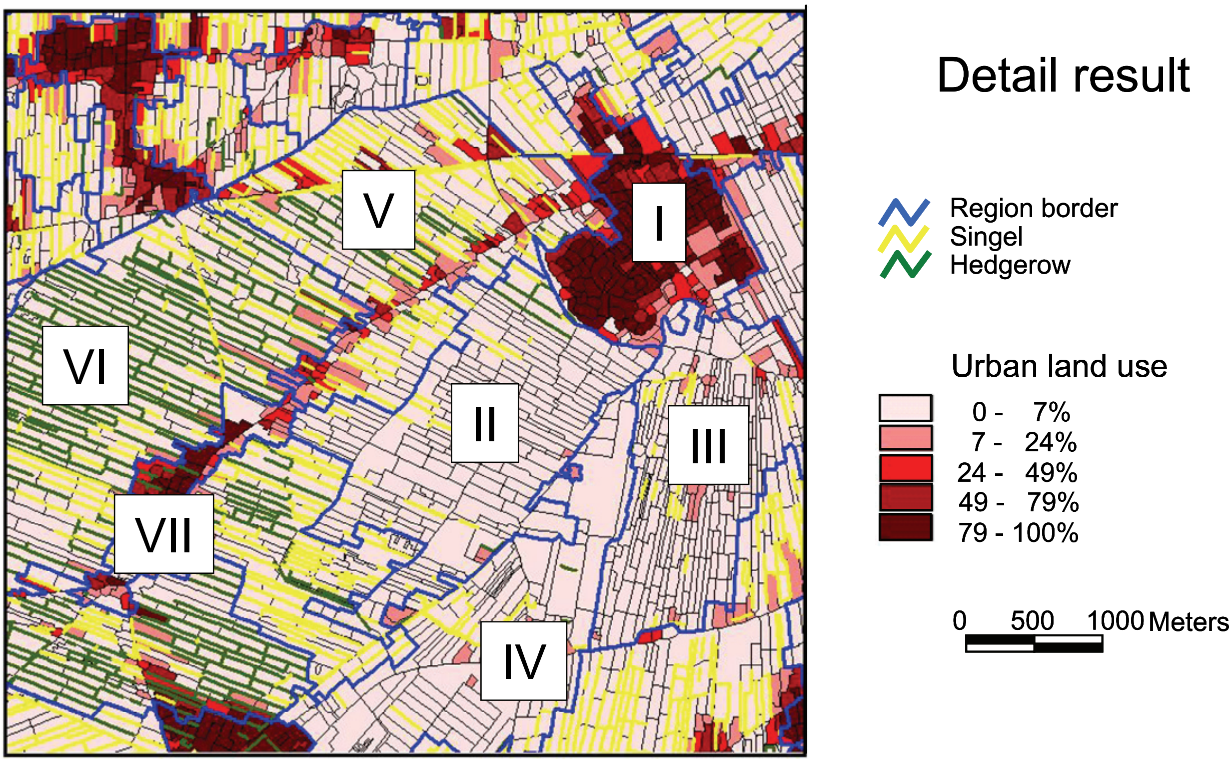

Figure 5. Detailed map of the region growing result, overlaid with the singles, the hedgerows and the field pattern and the urban land use data. Regions I to VII are explained in more detail in the text.

resulting landscape types are (Figure 4): *A Urban, B Urban with grassland, C Open with tree lanes, D Open with 'Singels', E Open no dry linear elements, F Aquatic, G Forest, H Nature, I 'Singels' wet and elongated spatial layout, J 'Singels' dry and elongated spatial layout, K 'Dykswal', L 'Singels' dry and squared layout 1, M 'Singels' dry and squared layout 2.*

5.4.3 Landscape assessment

The dissimilarity between the region and the preferred '*Dykswal*' landscape is visualized in Figure 7, showing 8 regions with a landscape character close to the preferred landscape type, region 2 has the closest resemblance to the ideotype landscape. In Table 1 the dissimilarity of the 8 regions with the preferred landscape is presented per landscape feature. Land use pattern and spatial layout are contributing most to the difference between the landscape character in the regions and the preferred landscape character, thus providing a focus for further improvement.

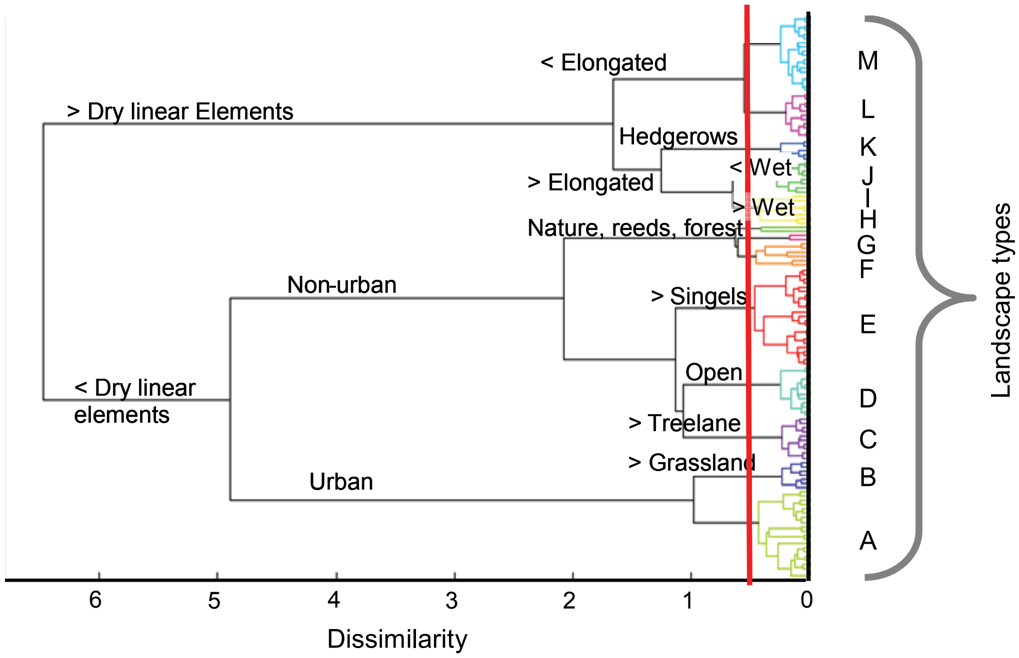

Figure 6. Dendrogram expressing the dissimilarity between different groups of regions. A dissimilarity threshold of 0.5 is used to separate 13 landscape types (*A* t/m *K*). Main characteristics of the splits in the dendrogram are indicated.

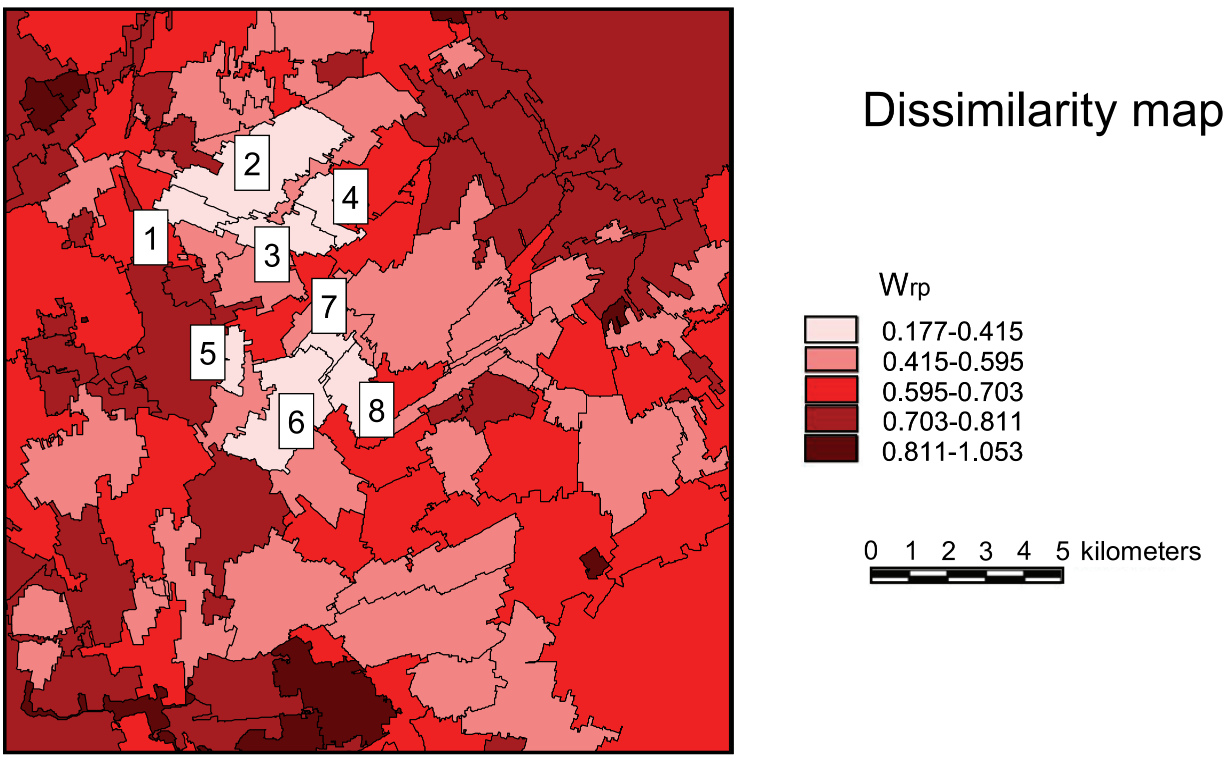

Figure 7. Dissimilarity between preferred '*Dykswal*' landscape in the Frisian Woodlands and the existing regions. Feature specific dissimilarities for region 1 - 8 are presented in Table 1.

Table 1. Total dissimilarity and dissimilarity per landscape feature between the 8 regions of Figure 5 and preferred 'Dykswal' landscape. W_{kl}^{p}= Total dissimilarity, Size = average field size, shape = average parcel roundness, WetLin = average density of wet linear elements, average density of dry linear elements, LinType =average composition of dry linear elements, Layout = average spatial layout, Land use = average composition of land use.

Region ID	W_{kl}^{p}	*Size*	*Shape*	*WetLin*	*DryLin*	*LinType*	*Layout*	*Land use*
2	0.18	0.001	0.002	0.002	0.002	0.018	0.031	0.031
3	0.22	0.000	0.002	0.002	0.003	0.020	0.046	0.049
5	0.33	0.006	0.016	0.016	0.017	0.031	0.108	0.109
6	0.34	0.008	0.008	0.009	0.010	0.097	0.098	0.114
7	0.34	0.000	0.006	0.007	0.008	0.025	0.113	0.117
8	0.36	0.007	0.016	0.017	0.020	0.030	0.130	0.133
4	0.38	0.001	0.001	0.016	0.017	0.143	0.145	0.147
1	0.42	0.000	0.010	0.016	0.016	0.086	0.172	0.172

5.4.4 Validation of the analysis result

The consistency between the classification of the region growing result and the core areas of the expert map is presented in Table 2. The overlap between the two classifications was generally good. The analysis consistency is high and varies between 56% and 100%; the expert consistency is lower and varies between 34% and 100%.

The difference between these two consistency measures can be partly explained by the fact that the classification of the region growing result consists of more classes than the expert classification. Three other causes for the differences between the classifications can be identified: Lack of information among experts, lack of information in the region growing analysis and the effect of human perception. The effect of missing information can be best illustrated, by considering the *C Tree lane landscape*. None of the experts made a distinction between 'Singels' and 'Tree lanes', apparently they were not aware of this difference. As a result *C Tree lane landscape* was classified by the experts for 91% as the *6 'Singel' landscape*. Conversely, the spatial database had no information about the protective status of grasslands. As a result 65% of the expert *5 Nature landscape* is classified as *E Open landscape* in the region growing result, ever though the protective status of the grass land has an effect on the appearance of the area due to differences in management.

A comparison of the expert and the region growing landscape type '*Dykswal' landscape* illustrates how human perception of the landscape influences classification.

Table 2. Consistency table expressing the consistency with which an landscape type of the region growing analysis result overlaps with the expert landscape types (Analysis consistency) and visa versa (Expert consistency), in percent. Bold numbers indicate the most overlapping categories. For further explanation see text.

	Analysis consistency	***Region growing analysis landscape types***												
		A	B	C	D	E	F	G	H	I	J	K	L	M
Expert landscape types	1 Urban	**98**	**56**	4		1							3	1
	2 Open clay		7	6	**57**	**57**	13			13	**76**			
	3 Open peat					**14**								
	4 Lake area				28	5	**78**				2		3	3
	5 Nature					7	7		**100**					
	6 'Singel'	2	17	**91**	15	16		**100**		**75**	22		**85**	**78**
	7 Hedgerows		20				2			12		**100**	9	18

	Expert consistency	**Region growing analysis landscape types**												
		A	B	C	D	E	F	G	H	I	J	K	L	M
Expert landscape types	1 Urban	**40**	**45**	5		2							6	2
	2 Open clay		3	4	19	**61**	6			2	5		0	0
	3 Open peat					**100**								
	4 Lake area				16	9	**64**						6	4
	5 Nature				1	**65**	29		6					
	6 'Singel'		3	25	2	6		1		4	1		**32**	26
	7 Hedgerows		9				1			2		**59**	10	18

According to the consistency table, analysis landscape type *K* falls for 100% within the boundaries of expert landscape *7*. On the other hand expert class landscape type *7* matches only for 59 % with analysis landscape type *K*. Overlaying the original data shows that the experts used the description '*Dykswal*' *landscape* already when only a few hedgerows were present, whereas the clustering algorithm only classifies regions which were dominated by hedgerows as '*Dykswal*' *landscape*. Apparently for the experts the presence of a few hedgerows in the area was decisive for the characterization of the landscape. This is different for other landscape features.

Another example can be found in the lake area. According to the consistency table part of the expert *4 Lake landscape* is classified by the region growing analysis as *D Open 'Singel' landscape* and *E Open landscape*. When overlaying the original data, it can be seen that while these areas are indeed open or have a sparse distribution of singles, they are all situated around the lake. Apparently the experts perceive a zone of influence around the lake which affected their characterization of the neighbouring areas. The region growing algorithm does not make these types of distinctions between landscape features.

5.5 Discussion

In this chapter we introduced a new methodology for landscape character assessment to support spatial planning and policy development. In this methodology the pattern of landscape features has been used as a starting point for landscape character assessment using a region growing algorithm to define analysis units. In this section we will discuss the technical aspects of the methodology and the application of the methodology in spatial planning

5.5.1 Region growing in spatial data

In general it can be concluded that the region growing algorithm applied in a polygon environment, containing continuous, directional and nominal of variables performed well. In Figure 5 it is shown that the region growing algorithm produces results which are plausible when compared with the original spatial data. Each of the regions and their borders can be explained in terms of data patterns and differences in between neighbours. However, the exact location of the border cannot always be explained. This is partly due to the fact that the location of a border between landscapes is inherently fuzzy; also between human interpreters segmentation results differ (Martin et al. 2001; Figure 1). On the other hand, the region growing process introduces a bias because regions are forced to merge based on local information only. Two regions merged early in the process because of a local dissimilarity minimum can not be split later in the process when they are not the best match from a more global perspective. Using less 'greedy' criteria for merging regions such as the mutual best fit criterion (Baatz and Schape, 2000) minimizes this effect but cannot completely prevent it. An alternative is to use a top-down segmentation algorithm like the nCut (Shi and Malik, 2000), the Max-Click (Pavan and Pelillo, 2003) algorithm. However in top-down algorithms global decisions about splitting the dataset can not be corrected, at a lower scale level. A promising new development is the SWA algorithm (Sharon et al., 2006) which is a region growing algorithm using top-down sharpening rounds during the region growing process.

5.5.2 Segmentation selection

To select the best segmentation result visual overlay between the analysis results and the original data has been used. This approach introduces a subjective component into the methodology. The best segmentation result identified depends on the observer and on the way the original data is visualized. A more objective approach would be to introduce a numeric quality indicator. For image segmentation a number of indicators have been developed (Zhang, 1996; Zhang et al., 2005). In this study the application of 3 measures, the F, F1 and Q criteria, have been evaluated (data not shown), none of these measures showed a clear minimum for the 126 segmentations, but declined steadily with the threshold size. Milligan (1986) shows that developing a goodness of fit indicator based on the data values only is very challenging. Out of 30 internal indicators tested for hierarchical clustering only 5 performed well for hierarchical clustering using artificial test datasets of predefined clusters. The bottom line for segmentation evaluation is that the quality of segmentation depends on its application. Therefore, at the current state of developments, human interpretability is in our view the best test for the segmentation result. In the case study, considering Figure 5, the classification results and the validation results we showed that this criterion has been met for this application.

5.5.3 Characterization and classification

The classification of the regions was created using a hierarchical clustering algorithm adapted from the region growing algorithm. The application of the dissimilarity criterion defined in equation 2 results in a dendrogram, which has well separated classes and is therefore easily interpretable. Similar classification results can be obtained using Wards Criterion (Podani, 1989). The dissimilarity between two regions does not only depend on the increase in variation, but also on size of the groups. As a result the dissimilarity between groups of regions is much higher than between individual regions or between individual regions and groups. Therefore in the initial iterations all individual regions tend to form small groups of equal size, before merging these small groups to larger groups. The disadvantage of this criterion is that individual regions, very dissimilar from other regions will end up in a small group of dissimilar regions and are more difficult to separate. This effect can be seen for the landscape types *H*, *G* and *F*. Together they form a group each being very different from the other. However the results are better interpretable than when using more common criteria, like single linkage or average linkage (Podani, 1989).

The classification performed was an unsupervised classification and the resulting groups are depending on the data values of the data set. The resulting classification emphasizes features which are specific for the study area and locally relevant, on the other hand comparison with another unsupervised classification in a different study area is difficult. If comparison between study areas is desired a supervised classification could be used, using predefined landscape types with a quantitative description (Lillesand and Kiefer, 1993).

5.5.4 Validation

The results of the methodology have been validated using an external reference dataset based on information about the landscape character of the study area provided by local experts. The consistency between the region growing classification and the expert classification was very high for some landscape types, but not for others. Most of the differences can be explained in terms of data. More interestingly, part of the difference can be explained by the difference between the experts' view on the study area and the algorithm's 'view' on the study area: the region growing algorithm considers all landscape features with equal importance, the experts emphasise for example the presence of large water bodies and the presence of hedgerows. This provides interesting information on human perception of the landscapes and new ideas on how to measure or weigh different landscape features in the region growing algorithm. This idea will be worked out in more detail in the next section. When comparing the region growing results and the expert classification to the original data, the region growing results show a closer match, provides more details and a more consistent classification throughout the study area.

5.5.5 Contribution to planning processes

Nowadays landscape planning evolves from a top-down state led government process into a negotiation process involving different stakeholders at the regional and local level (Friedman, 1993). This process consist of 4 phases (Van Keulen, 2007): the diagnosis phase, where the current situation and problems are analyzed and described; the goal setting phase, where objectives for future development are identified; the exploration phase where chances and possible future developments are investigated and the implementation phase, where policy measures are formulated and implemented. Landscape character assessment can make an important contribution to the first and third step of the landscape planning process (Swanwick, 2002). Landscape character assessment studies are usually implemented as a professional activity for other professionals. The methodology presented in this chapter enables the active involvement of stakeholders in the process. Involvement of stakeholders in the planning process is important to build support for the plans to bridge resistance and discover hidden conflicts between visions (Luz, 2000; Buchecker, 2003), especially in multifunctional agricultural landscapes where many different stakeholders are involved. In addition stakeholders can make a large contribution towards the development of creative solutions because their diverse backgrounds.

Region growing can be used in the diagnosis phase as a tool to explore the different perceptions of stakeholders on the landscape character of the study area in a similar fashion as can be realized using mental mapping (Soini, 2001). In the first step a number of different maps need to be created based on different landscape features in the study area to trigger a discussion between stakeholders about the characterization of the landscape and borders between landscape types, revealing their specific knowledge about the study area. In an iterative process changes to the maps can be made by including or excluding data, weighting of landscape features or by using different indicators to measuring landscape features. The advantage of this approach over, for example, using a drawing board is that borders around regions will not be drawn intuitively, but are the result of explicit formulation of ideas. A stakeholder needs to state explicitly why one region is different from another region, which will be followed by a consistent implementation of these new ‘rules’ throughout the study area using the region growing algorithm. In contrast the expert classification has shown that hand drawn maps can vary a substantially in level of detail depending on where a person spends most of the time or has a particular interest. The ideal end result of this iterative improvement process will be a landscape character map of the study area based mutual understanding between the stakeholders and a transparent set of rules representing the different perceptions of the people involved.

In the exploration phase the methodology can make a contribution by quantitatively evaluating the difference between the current landscapes in the study area and desired landscape patterns as defined by the stakeholders. These results can be visualized and suitable regions for strengthening the desired landscape character can be identified. In addition it can be indicated which landscape features differ most from the desired landscape pattern, showing where and how the landscape character can most efficiently be improved.

5.6 Conclusion

Region growing enables the analysis of spatial data in a manner different from other existing analysis techniques. Spatially continuous clusters are delineated on the basis of the spatial pattern of data values in such a way that humans can relate to the regions defined. These regions can then be further analyzed and interpreted.

In landscape planning region growing can be used to map and describe the character of the study area using the pattern of landscape features as a starting point, rather than using predefined analysis units. In this way region growing can also be used to explore the visions and ideas about landscape character in the study area held by a group of stakeholders. Once the different landscape regions are defined, the landscape character can be described quantitatively and analyzed using non spatial clustering techniques or a landscape ideotype. Therefore we conclude that region growing is a useful tool for the analysis of spatial data and for the analysis of landscape character in particular.

Acknowledgements
We would like to thank Kymo Slager for patiently and diligently checking and editing 99,286 polygons, Dr. M.J.W. Jansen for his valuable math comments and four anonymous experts for their contribution to the landscape character reference map.

Chapter 6

Evaluation of graph pyramid segmentation algorithms for regionalization of spatial data in a GIS

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Submitted to: *International Journal of Geographical Information Science*.

Abstract

Regionalization is the aggregation of spatial data elements into larger contiguous regions while optimizing a certain aggregation criterion and is used to delineate objects from spatial data patterns. Many different regionalization algorithms exist, but there is a lack of comprehensive studies which compare different algorithms and there is no communal understanding on when to use which algorithm to delineate regions of a certain pattern type. This paper presents a framework to evaluate the applicability of regionalization algorithms for geo-data analysis and compares 52 graph pyramid segmentation algorithms. The evaluation framework proposed is based on a pattern generator and a set of indicators to evaluate the accuracy, sensitivity and efficiency of regionalization algorithms. Segmentation algorithms have been evaluated for their performance on 5 different data patterns consisting of two regions. The patterns differed in pattern type, data type and neighbourhood configuration. It was concluded that: (1) Regions in a continuous dataset differing in mean value but with evenly distributed heterogeneity can be accurately regionalized by many different algorithms. The most accurate algorithm was MBF-IVAR. (2) Regions contrasting in both mean value and heterogeneity in a continuous dataset can be regionalized most accurately with the algorithm MBF-ITD, and only a limited number of other algorithms performed well. (3) Regions in a continuous dataset which differ only in heterogeneity, can not be accurately delineated with the investigated type of algorithms. (4) Regions which differed in the relative density of two classes can best be delineated using the MIES-STD or MIES-VAR, but other algorithms also performed well. (5) The neighbourhood configuration has little effect on the performance of the algorithms. (6) The MBF-ITD algorithm is the most robust providing accurate regionalizations for 3 different pattern types but it is sensitive to the parameter values defined by the user and compared to other algorithms computationally intensive. The evaluation framework has proven its effectiveness in comparing 52 different algorithms. Suggestions for further research are made at the end of the chapter.

Keywords: regionalization, image segmentation, GIS, graph theory, object approach, field approach, aggregation, up-scaling

6.1 Introduction

Regionalization is the aggregation of spatial data elements into larger contiguous regions while optimizing a certain aggregation criterion (Duque et al., 2007). Regionalization has been developed independently within the fields of statistics and image analysis. In the field of statistics regionalization is also known as boundary analysis (Jacquez et al., 2000) or spatially constrained clustering (Legendre, 1987) and has been applied to minimize differences between groups, to reduce the effects of outliers and inaccuracies, to detect boundaries, or for data visualization (Duque et al., 2007). In image analysis regionalization is mostly referred to as image segmentation and is often used as a preprocessing step for the recognition of specific patterns in an image (Wu et al., 2005), to classify an image (Benz et al., 2004) or to study change between two sequential images (Wang et al., 2005).

In geo-information science regionalization is seen as the conceptual and methodological link between the object-based and the field-based representation of the world (Jacquez et al., 2000). Objects represent coherent real world spatial entities with a certain meaning, for example a building or a hilltop; fields typically represent measurements on a variable whose value varies through geographic space, for example the altitude of the earth surface. By using a regionalization methodology spatial objects can be delineated from a spatial pattern of fields (Jacquez et al., 2000; Burnett and Blaschke, 2003). In geo-information science the application of regionalization methods is mainly focused on the classification of high resolution image data, as described by for example Kartikeyan et al. (1998), Thomas et al. (2003), Gitas et al. (2004), Walter (2004), Yan et al. (2006) and Lu and Weng (2007). This has resulted in the development of specialized software packages (Meinel and Neubert, 2004; Neubert et al., 2006). Application of regionalization methods to spatial data other than from high resolution images is mainly found in ecological studies (Kent et al., 2006), for example to detect community and species distribution boundaries (Chiarello et al., 1996; Chiarello et al., 1998; Fortin et al., 2000; Fagan et al., 2003; Fortin et al., 2005; McIntire and Fortin, 2006; Arnot and Fisher, 2007) and delineate landforms (Dragut and Blaschke, 2006) or landscapes (Jellema et al., accepted).

One of the difficulties of applying regionalization as general method for spatial data analysis is the wide range of possible algorithms and approaches to choose from. Especially in the field of image segmentation the development is diverse and fast, several hundreds of publications are added to the scientific literature each year and no comprehensive survey study has been published in the last decade (Zhang, 2006). Another problem is that there is no communal understanding of what is a good regionalization algorithm. Each algorithm exhibits specific particularities and the comparison of regionalization algorithms is often restricted to just one or a few algorithms using different and often subjective criteria between studies (Zhang, 1996; Martin et al., 2001; Jolion, 2003; Meinel and Neubert, 2004; Neubert et al., 2006; Zhang et al., 2005). Consequently, there is a clear need for a framework for objective comparison of algorithms to support the selection a suitable algorithm for a given data pattern. Additionally, this requires the identification of effective indicators to assess the accuracy and performance of algorithms.

Therefore the objective of this paper is (1) to develop a framework to evaluate regionalization algorithms for their applicability in geo-data analysis and (2) to compare a large number of graph pyramid segmentation algorithms. The evaluation framework proposed is based on a pattern generator and a set of indicators to evaluate the accuracy, sensitivity and efficiency of regionalization algorithms. By using artificial data in predefined regions the response of the algorithms to variation between data patterns can be measured directly and objectively. For practical reasons we focus on the evaluation of segmentation algorithms within the family of graph pyramid segmentation algorithms (Marfil et al., 2006), excluding other commonly applied strategies, such as the ncut segmentation (Shi and Malik, 2000), dynamic programming (Xu et al., 1998), split and merge (Karatzas and Antonacopoulos, 2004), watershed algorithms (Roerdink and Meijster, 2000), Markov random fields (Sarkar et al., 2002) or fuzzy C-means (Lim and Lee, 1990). We have selected graph pyramid segmentation algorithms for a number of reasons. Following a classic region growing process of merging similar adjacent data elements the concept of graph pyramid segmentation is relatively intuitive, there is no need for mathematical approximation methods to solve the segmentation problem, relatively few input parameters are required and the algorithms can be perceived as modular, consisting of three components: a decimation scheme, a dissimilarity criterion and a stop criterion. This modular structure allowed us to combine components of algorithms found in different papers to study the main effects and their interactions. In this paper we will evaluate the full factorial combination of 4 decimation schemes with 13 dissimilarity criteria and 1 stop criterion resulting in 52 different algorithms.

The article is built up as follows: In the next section a brief overview of graph pyramid segmentation is given, discussing the different dissimilarity criteria, decimation schemes, and the stop criteria. In section 6.3, the evaluation framework, the evaluation criteria used in this paper and the experimental set-up is elaborated. The results are presented (section 6.4) and discussed (section 6.5) the light of the further development of regionalization algorithms as a spatial analysis technique.

6.2 Theoretical background

6.2.1 Graph pyramid segmentation algorithms

A graph pyramid segmentation algorithm (Marfil et al., 2006) describes the content of an image by multiple representations, or levels, with decreasing resolution following a classic iterative region growing process (Lallich et al., 2003), where level 0, or the base level of the hierarchy, consists of the original image. The graph pyramid adapts the resulting regions to the contents of the image and assures spatial consistency of topology of the regions (Meer, 1989). The hierarchical nature of the pyramid algorithm allows a reduction in the complexity of the image segmentation task and features can be processed at multiple hierarchical levels improving the segmentation result (Lehmann et al., 2005).

The basic data structure of a graph pyramid segmentation algorithm is the Region Adjacency Graph (RAG). A RAG = (V,A,W) is a mathematical data format in which each object is represented by a set nodes V = {1,…,n}, the adjacency between the objects is represented by a set of edges and the dissimilarity between the objects is described by a matrix of weights. The base level of the pyramid is defined by the image, where each pixel is represented by a node and the dissimilarities between the nodes depend on the data values of the pixels.

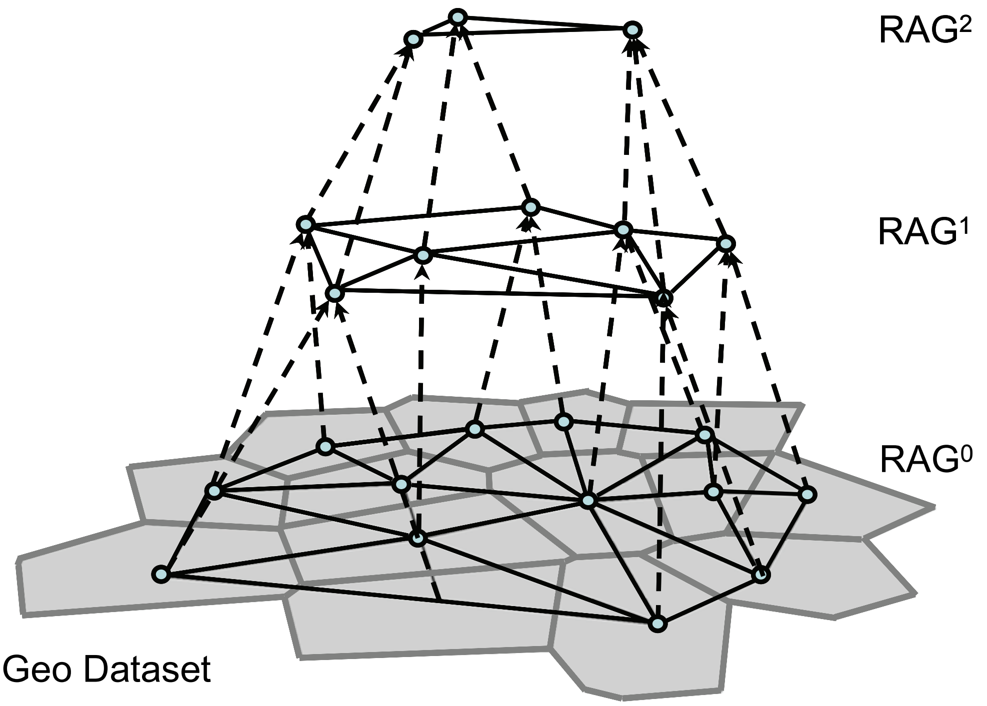

Figure 1. Graph Pyramid consisting of multiple representations of a dataset. For explanation see text.

In each iteration in the region growing process a new level of the pyramid is formed (Figure 1) following a graph decimation scheme. In the decimation scheme it is decided which nodes can potentially merge with which other nodes, structuring the segmentation process. The final decision whether two nodes will merge or not depends on the stop criterion. The decrease in number of nodes between two levels of the pyramid is called the reduction factor (Kropatsch et al., 2005) and the relation between two layers in the graph pyramid can be expressed by an additional set of edges. Each node at level h+1 (parent) is a union of a set of neighbouring nodes at level h (children) or contraction kernel (Kropatsch et al., 2005). By using the parent-child relation between nodes in subsequent layers, the original pixels at the base of the pyramid can be traced from any level of the pyramid. The decimation process is continued until the apex of the pyramid is reached. In the apex each object in the dataset is represented by a single node (Jolion and Montanvert, 1992).

6.2.2 Dissimilarity criteria

When graph pyramid segmentation is seen as an optimization process (Baatz and Schape, 2000), the dissimilarity criterion determines which characteristic of the regions is being optimized. In this paper we will focus on the application of local dissimilarity criteria, which express the difference between two adjacent regions at the same level by comparing all data values of one region with all data values of another region. In many applications the segmentation process is also guided by additional dissimilarity criteria, such as a shape dissimilarity criterion based on the shape of the regions (Baatz and Schape, 2000), a hierarchical dissimilarity criterion based on relations between layers or a global dissimilarity criterion (Lehmann et al., 2005). These types of dissimilarity criteria are not taken into consideration in this paper.

Local data dissimilarity criteria can be grouped into distance measures and heterogeneity measures (Podani, 1989). A distance measure (D-measure) expresses the data dissimilarity between two regions as function of the data distance between the elements of the regions in the data space, but does not consider within-region heterogeneity. Commonly used distance measures are the single linkage criterion (SL), defined as the minimum data distance between the members of two regions (Kropatsch and Haxhimusa, 2004) and the average linkage criterion (AL), defined as the average data distance between all members of two regions (Jolion and Montanvert, 1992).

Heterogeneity dissimilarity measures describe the difference between two regions at the basis of the variation within the regions. Heterogeneity dissimilarity measures can be split into two groups: measures describing the heterogeneity of the newly formed region (H-measures) and measures describing the increase in heterogeneity after the new region has formed (IH-measures). For each of these measures heterogeneity can be expressed as the total heterogeneity in a region, for example the sum of squares (SSQ), or as measure of average heterogeneity in a region, for example the variance (VAR). Applications of heterogeneity dissimilarity measures can be found in Baatz and Schape (2000) and Navon et al. (2005). In this paper, 3 distance measures and 10 heterogeneity measures will be evaluated (Table 1). Not all measures evaluated are currently being applied in segmentation algorithms, but are derived from other clustering methodologies to provide a more complete comparison of dissimilarity criteria.

6.2.3 Decimation schemes

The decimation scheme determines which nodes can potentially merge with which other nodes during the region growing process. The decimation scheme influences the final segmentation result (Baatz and Schape, 2000), the height of the graph pyramid (Kropatsch et al., 2005), the speed of the algorithm and computer memory usage (Jolion, 2003). In early applications decimation schemes of graph pyramids were based on a stochastic selection process (Meer, 1989). More recently data driven decimation schemes have been developed. A decimation scheme can be based on a node selection process or an edge selection process. In a node selection process during each iteration a subset of nodes from level h is selected to survive to level h+1. All non-surviving nodes are merged with one of the surviving nodes (Jolion and Montanvert, 1992). The most commonly used method to select a set of surviving nodes is to determine the maximum independent node set or MIS based on the variance in the dataset. The MIS is selected according to three rules:

(1) Surviving nodes are selected in areas with least variation in data values.
(2) The selection is maximal, no two neighbouring nodes can survive.
(3) Each non-surviving node should be in the neighbourhood of a surviving node.

This manner of node selection facilitates the creation of homogeneous regions and guarantees graph reduction throughout the image. Disadvantage of the method is the relative large number of iterations needed to finish the decimation scheme. For a comprehensive description of the algorithm see Jolion and Montanvert (1992).

An edge selection scheme selects a sub set of edges at level h which will be contracted in level h +1 by merging the associated nodes. The simplest way of edge selection is to select the edge with the smallest dissimilarity for each node (Kropatsch and Haxhimusa, 2004). This decimation scheme is similar to Borovka's algorithm to find the minimum spanning tree (Nešetřil et al., 2001) and is also called the local best fit method (BF) (Baatz and Schape, 2000). Strong points are its simplicity and the low number of iterations needed to finish the segmentation. The disadvantage is that small

Table 1. Overview of the 13 dissimilarity criteria used in the evaluations, R_k is the set of data elements and n_k the number of elements in region k and R_l is the set of data elements and n_l the number of elements in region l. The criteria STD, TD and ISTD are added as variations to the ITD dissimilarity criterion.

Distance Measures (D-measures)			
Single Linkage	**SL**	$\min(dist_{ij} \forall_{i \in Rk, j \in Rl})$	(Florek et al., 1951)
Complete Linkage	**CL**	$\max(dist_{ij} \forall_{i \in Rk, j \in Rl})$	(Sorenson, 1948)
Average Linkage	**AL**	$mean(dist_{ij} \forall_{i \in Rk, j \in Rl})$	(Sokal and Michener, 1958)
Mean Heterogeneity Measures (MH-measures)			
Mean distance in the new cluster	**DIS**	$w_{kl} = mean(dist_{ij} \forall_{i,j \in Rk \cup Rl})$	(Andersberg, 1973)
Standard deviation of the new cluster	**STD**	$w_{kl} = std(R_k \cup R_l)$	
Variance of the new cluster	**VAR**	$w_{kl} = \mathrm{var}(R_k \cup R_l)$	(Andersberg, 1973)
Absolute Heterogeneity Measures (AH-measures)			
Total deviation in the new cluster	**TD**	$w_{kl} = (n_k + n_l) * std(R_k \cup R_l)$	
Sum of squares of the new cluster	**SSQ**	$w_{kl} = ssq(R_k \cup R_l) = (n_k + n_l) * \mathrm{var}(R_k \cup R_l)$	(Andersberg, 1973)

Table 1, continued.

Relative Increase in Heterogeneity Measures (RIH-measures)			
Increase in average Distance	**IDIS**	$w_{kl} = mean(dist_{ij} \forall_{i,j \in Rk \cup Rl}) - \frac{1}{2} mean(dist_{ij} \forall_{i,j \in Rk}) - \frac{1}{2} mean(dist_{ij} \forall_{i,j \in Rl})$	(Sneath and Sokal, 1973)
Increase in standard deviation	**ISTD**	$w_{kl} = std(R_k \cup R_l) - \frac{n_k}{n_k + n_l} std(R_k) - \frac{n_l}{n_k + n_l} std(R_l)$	
Increase in variation	**IVAR**	$w_{kl} = \mathrm{var}(R_k \cup R_l) - \frac{n_k}{n_k + n_l} * \mathrm{var}(R_k) - \frac{n_l}{n_k + n_l} * \mathrm{var}(R_l)$	(Diday et al., 1982)
Absolute Increase in Heterogeneity Measures (AIH-measures)			
Increase in total deviation	**ITD**	$w_{kl} = (n_k + n_l) * std(R_k \cup R_l) - n_k * std(R_k) - n_l * std(R_l)$	(Baatz and Schape, 2000)
Increase of sum of squares	**ISSQ**	$w_{kl} = ssq(R_k \cup R_l) - ssq(R_k) - ssq(R_l)$	(Ward, 1963)

mistakes are easily introduced and will accumulate during the region growing process.number of iterations needed to finish the segmentation. The disadvantage is that small mistakes are easily introduced and will accumulate during the region growing process.

A more conservative method is to use the mutual best fit method (MBF) adapted from Baatz and Schape (2000). In this method two neighbouring nodes can only merge if they are each other's most similar neighbour. The edges to be contracted are found as local minima in the dissimilarity matrix.

The maximum independent edge set (MIES) is the edge oriented counterpart of the MIS and is selected according to 3 rules (Kropatsch et al., 2005):

(1) Contraction edges are selected according to minimum dissimilarity.
(2) The selection is maximal and each node is contained in exactly 1 contraction kernel.
(3) No contraction kernel contains edges with adjacent edges on both ends.

The MIES has been developed to guarantee a reduction in nodes of at least two between the subsequent layers of the graph pyramid making the segmentation process more efficient and creating regular and smaller pyramids. For details about the MIES decimation scheme see Kropatsch et al. (2005).

6.2.3 Stop criteria

The stop criterion determines whether two nodes selected by a decimation scheme will actually merge. Thus, the stop criterion influences sizes and shapes of the regions and finally terminate the region growing process. A stop criterion can be defined as a threshold function (Navon et al., 2005), a goodness of fit indicator (Zhang, 1996) or as a statistical test (Lallich et al., 2003). In this paper a global threshold value is used as a stop criterion: if the dissimilarity between two mergers is larger than the threshold value they cannot be merged. When in an iteration no merges can be made the segmentation process will end.

6.2.4 Segmentation of spatial data

To enable a pyramid segmentation process in a GIS, a spatial dataset needs to be converted into a RAG. In a GIS typically two data formats are used: the vector format and the raster format. The vector format consists of a set of non overlapping geo-referenced objects, represented by polygons, lines or points. The raster format consists of a regular grid of geo-referenced cells. A spatial dataset can be described by a RAG by representing each data element (pixel, raster cell, point or polygon) by a node and the relationships between neighbouring data elements by edges. In a raster dataset the adjacency can be determined using a neighbourhood of 4 or 8 cells, in a point dataset adjacency can be determined by Delaunay triangulation and in a polygon dataset adjacency can be determined by determining the bordering elements for each polygon. To calculate the dissimilarity between two data elements the attribute table is used. In a GIS the attribute table may consist of different data types, including nominal, ordinal, interval and ratio data. To be able to include each of these data types in the segmentation process the dissimilarity criteria presented in Table 1 are calculated using Equation 1.

$$ss_k = n_k * \mathrm{var}_k = n_k * std_k^2 = \frac{\sum_{i \in k} \sum_{j \in k | j > i} (d_{ij})^2}{n_k} \quad (1)$$

where d_{ij} the data difference between data element i and data element j, n_k is the number of data elements in the region k, ss_k is the sum of squares of region k, var_k is the variance of region k and std_k is the standard deviation of region k. The derivation of the relation can be found in the Appendix.

For interval and ratio data d_{ij} can be expressed as the Euclidian distance between two data values. For nominal or ordinal data values an alternative measure for data difference is needed. Such an alternative measure for data difference will not yield a statistically valid measure of sum of squares, variance or standard error, but can still provide a useful measure of heterogeneity. In this paper the data difference for nominal data types is defined as a function of the relative frequency of occurrence of an attribute class in the neighborhood of a data element (Equation 2). The relative frequency is taken to correct for differences in neighborhood sizes, which may occur in point or polygon data or at the borders of a raster dataset.

$$d_{ij} = \sum_{c \in C} \frac{1}{2} * abs(rf_{ic} - rf_{jc}) \text{, where } rf_{ic} = \frac{\sum_{l \in nb_i} z_l^c}{|nb_i|} \text{, and } z_l^c = \begin{cases} 1 & if \quad att_l = c \\ 0 & otherwise \end{cases} \quad (2)$$

d_{ij} is the data difference between two nodes i and j and c is a class from the set C containing all possible classes of the nominal attribute, rf_{ic} is the relative frequency of occurrence of class c in the set nb_i containing all neighbouring nodes l of node i, $z_l^c \in \{0,1\}$ is a decision variable indicating whether attribute table entry att_l contains class c for neighbourhood node $l \in nb_i$ and |.| denotes the cardinality or number of elements in a set.

6.3 Materials and methods

6.3.1 Evaluation of segmentation algorithms

The quality of a segmentation algorithm depends on the application. A good segmentation algorithm for one application may be a bad choice for another application. The quality of a segmentation is often tested against human interpretation or is based some quantitative indicator. Evaluation against human interpretation usually involves the qualitative comparison of the segmentation results with the original picture (Jolion, 2003; Meinel and Neubert, 2004; Neubert et al., 2006). A more objective approach is to test the segmentation against a set of independent human interpretations of the same image (Martin et al., 2001). In this way a reference dataset is created which is not influenced by the segmentation result and the deviation of the segmentation result from the human segmentations can be compared to the variation between the different human interpretations. Different from image analysis, for the application of regionalization in spatial data we are not necessarily interested in matching the human interpretation as close as possible. For the general application of regionalization, we are interested in the relation between the differences in data pattern and the final segmentation result.

A metrical indicator is a measure of a specific quality of the algorithm, for example the heterogeneity of the regions in relation to the number of delineated regions and the size of the dataset (Zhang, 1996; Zhang et al., 2005). In general the delineation of the dataset in a few homogeneous regions is desirable, but the exact meaning of these indicators and the relation to the desired segmentation is unknown.

In this paper we will use a different approach using a framework which consists of an artificial data generator and metrical indicators. Using a predefined reality allows to systematically test the performance of an algorithm in relation to the predefined characteristics of the data. In our analysis we aim to answer the following questions for different data patterns:

(1) Which of the algorithms provides the most accurate segmentations?

(2) What is the sensitivity of the algorithm to user defined parameters?

(3) What is the efficiency of the algorithm?

The accuracy of the segmentation is defined as the match between the regions delineated by the algorithm and the predefined regions in the dataset and is a measure of the degree to which the algorithm is able to detect the differences between data patterns. The sensitivity of an algorithm influences the applicability of the algorithm. If an algorithm only provides accurate segmentations at very specific input settings or the response of the algorithm to user defined parameters is highly unpredictable, creating a good segmentation of the pattern will be difficult even if the algorithm is capable of providing very accurate segmentation results. The efficiency of an algorithm influences the applicability in a similar way. If an algorithm is inefficient and requires extensive computational resources to segment the data, creating an accurate segmentation may become an unfeasible job.

Geo-data patterns can vary in different meaningful ways. For practical reasons we limited the evaluation of the segmentation algorithms to continuous and nominal data patterns, focussing on the effect of heterogeneity in the dataset. Heterogeneity in the dataset may be interpreted as measurement uncertainty, distortion or variation in the measured phenomenon. The following questions are addressed:

(Q1) Which algorithms are most appropriate to delineate regions contrasting in mean value in a continuous dataset with evenly distributed heterogeneity? This question is relevant for example, when objects need to be detected differing from each other in absolute data value, which is distorted by systematic measurement uncertainties throughout the dataset and when the size of the uncertainty independent from its location.

(Q2) Which algorithm can best be used to delineate regions contrasting in mean value and heterogeneity in a continuous dataset? This question is relevant for example, when objects need to be detected differing from each other in absolute data value and in heterogeneity.

(Q3) Which algorithm can best be used to delineate regions only contrasting in heterogeneity in a continuous dataset? This question is relevant for example, when objects need to be detected which are only differing in heterogeneity.

(Q4) Which algorithm can best be used to delineate regions contrasting in heterogeneity in a nominal dataset? This question is relevant for example, when objects differ only in the frequency of occurrence of classes, but not in the observed class types.

Different data formats, such as point, polygon or raster data, may result in different adjacency relations. Therefore, an additional question was formulated:

(Q5) What is the effect of the different neighbourhood configurations on the performance of the algorithms?

In the next sections, the pattern generator, the evaluation procedure and the metrical indicators are explained.

6.3.2 The pattern generator

Data patterns were generated by randomly assigning data values to a configuration of data elements. A configuration consists of a number of data elements in predefined

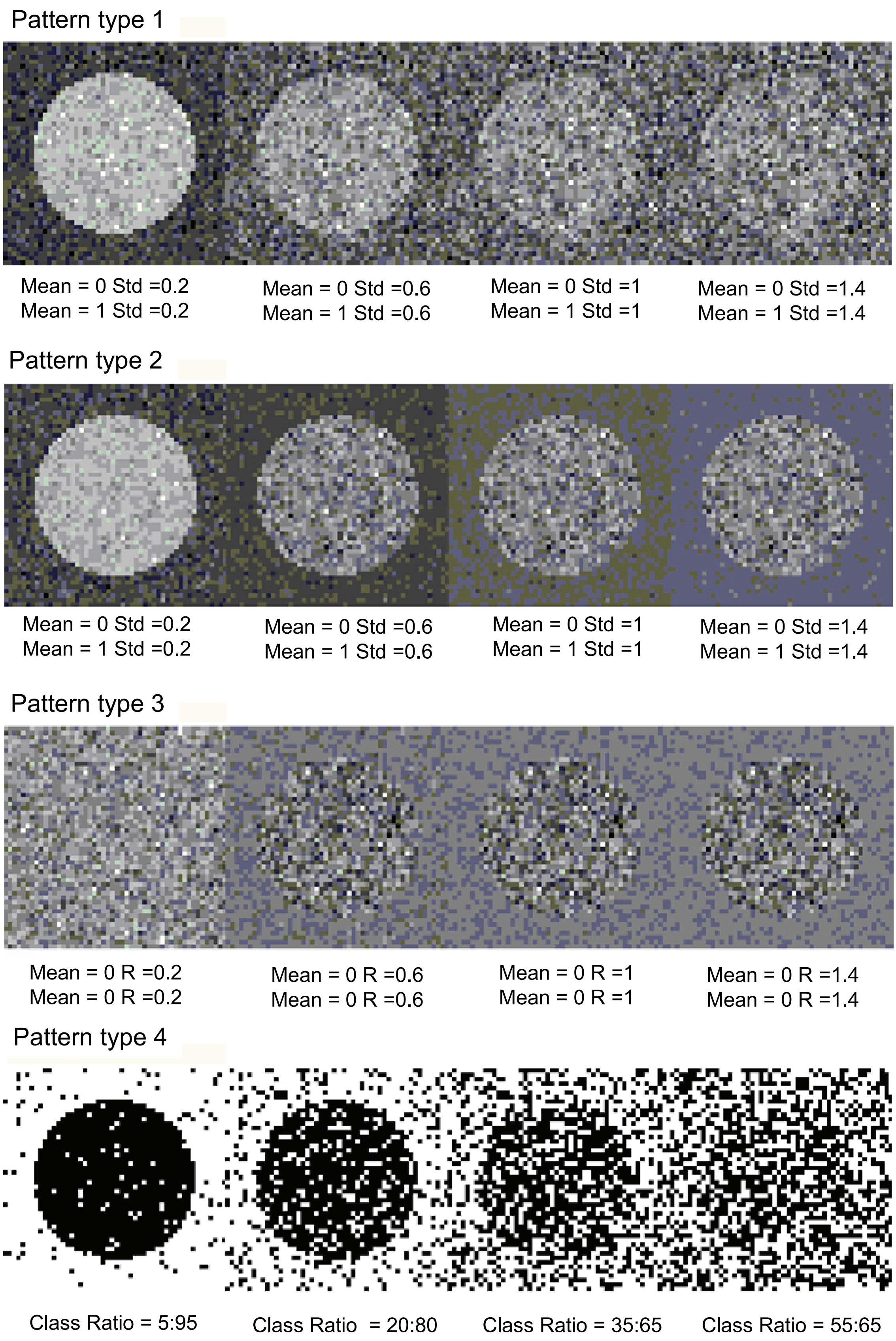

Figure 2. Visualization of the 3 continuous and 1 nominal series of data pattern tested. For details see text and Table 1.

regions and adjacency relations. To answer the questions listed above, a series of data patterns has been generated with different characteristics for each question, details of the followed procedure to generate data patterns are explained below. All datasets generated are based on a configuration of 2500 data elements in 2 regions. Five types of data patterns were used, their characteristics are presented in Table 2 and examples of the different data patterns are shown in Figure 2.

(1) To measure the performance of the algorithms in separating regions contrasting in mean data value (question Q1), a series of data patterns was generated in a raster configuration with a 4 neighbourhood, drawing values from a normal distribution. For region 1 the mean value was 0 and for region 2 the mean value was 1, for both regions the standard deviation was kept equal and varied between 0.2 and 1.4 in steps of 0.2 for different data patterns. Each data pattern was generated 9 times (Pattern type 1, Figure 2A).

(2) To measure the performance of the algorithms in separating regions contrasting in mean data value (question Q2), a series of data patterns was generated in a raster configuration with a 4 neighbourhood, drawing values from a normal distribution. For region 1 the mean value was 0 and the standard deviation 0.2. For region 2 the mean value was 1 and the standard deviation was varied from 0.2 and 1.4 in steps of 0.2. Each data pattern was generated 9 times (Pattern type 2, Figure 2B).

(3) To measure the performance of the algorithms in separating regions contrasting in mean data value (question Q3), a series of data patterns was generated in a raster configuration with a 4 neighbourhood, drawing values from a uniform distribution. The uniform distribution was chosen to obtain a more evenly distributed heterogeneity within a region to facilitate the segmentation task. For region 1 and 3 the mean value was 0, the range of the variation was 1 for region 1 and varied between 1.3 and 3.1 in steps of 0.3 for region 2. Each data pattern was generated 9 times (Pattern type 3, Figure 2C).

(4) To measure the performance of the algorithms in separating regions contrasting in nominal heterogeneity (question Q4), a series of data patterns was generated in a raster configuration with a 4 neighbourhood. The two regions differed in frequency of occurrence of the two classes. The patterns were randomly assigned to the data elements by drawing random values from a uniform distribution varying between 0 and 100. If a number was drawn below a certain threshold the data element was assigned to class 1, otherwise to class 2. The threshold values for the regions differed, the following pairs of threshold value were evaluated for the two regions: 5-95, 10-90, 15-85, 20-80, 25-75, 30-70, 35-65, 40-60, 45-55. Each data pattern was generated 9 times (Pattern type 4, Figure 2D).

Table 2. Overview of the characteristics for the 5 series of the test data patterns: [a] = standard deviation, [b] = range, [c] = threshold value. All pattern types comprise 2500 data elements in 2 regions and were analyzed in 9 repetitions. Patterns types 1, 2, 3 and 4 are visualized in Figure 2 and the different data configurations of pattern type 5 are visualized in Figure 3. For further information see text.

Pattern type	Data type	Mean difference between regions	Variations in heterogeneity per region	Neighborhood
1	Continuous	1	0.2,0.4,0.6,0.8,1.0,1.2,1.4 [a]	4
			0.2,0.4,0.6,0.8,1.0,1.2,1.4 [a]	
2	Continuous	1	0.2,0.4,0.6,0.8,1.0,1.2,1.4 [a]	4
			0.2 [a]	
3	Continuous	0	1.3, 1.6, 1.9, 2.2, 2.5, 2.8, 3.1 [b]	4
			1 [b]	
4	Nominal		5, 10, 15, 20, 25, 30, 35, 40, 45 [c]	4
			95, 90, 85, 80, 75, 70, 65, 60, 55 [c]	
5	Continuous	1	0.2,0.4,0.6,0.8,1.0,1.2,1.4 [a]	4,6,8,irregular
			0.2,0.4,0.6,0.8,1.0,1.2,1.4 [a]	

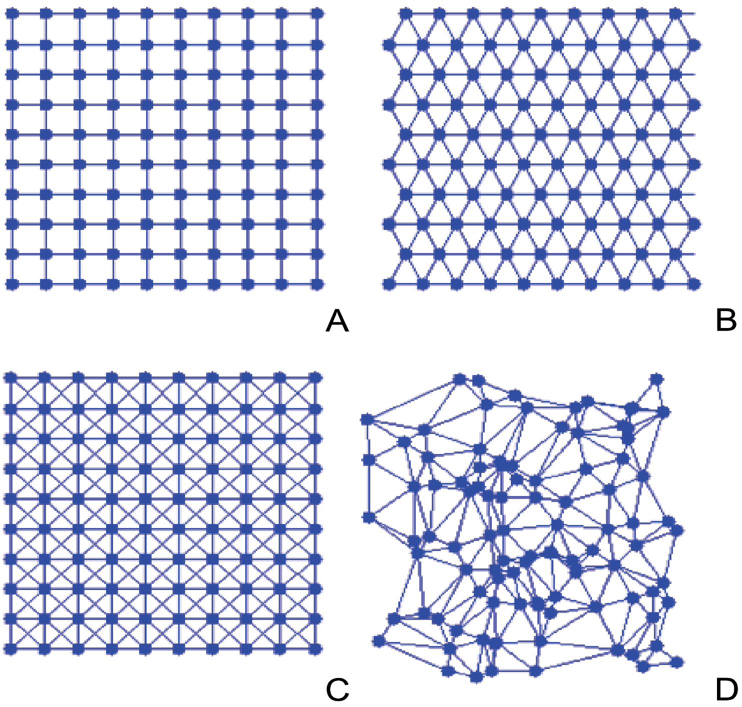

Figure 3. Visualization of the region adjacency graph different neighbourhood configurations: the 4 neighbourhood (A), the 6 neighbourhood (B), the 8 neighbourhood (C) and an irregular neighbourhood (D). Each dataset consists of 100 data elements.

To measure the performance of the different algorithms in different neighbourhood configurations (question Q5), a series of data patterns similar to pattern type 1 was generated in a 4, 6, 8 and irregular neighbourhood configuration. The irregular configuration was generated by locating points randomly in space using a uniform distribution to generate coordinates of the points followed by Delaunay triangulation to determine adjacency relations. The different neighbourhoods are illustrated in Figure 3.

6.3.3 Evaluation procedure

The evaluation procedure of the segmentation algorithms consisted of two steps for each of the questions. In the first step the whole series of data patterns was evaluated using the performance indicators which will be explained below. For each combination of data pattern from a series and segmentation algorithm, a standardized set of 100 segmentations was generated. This standardized dataset contains a sample of segmentations across the whole range of all possible segmentations to allow comparison between algorithms and is created by systematically varying the threshold value τ over its valid range $[0,\tau_m\rangle$ in equidistant steps. A threshold value is considered valid if it results in a segmentation consisting of more than one region. The threshold value τ_m representing the upper bound of the range of valid threshold values is equal to the smallest threshold value that merges all data elements into a single region. The performance indicators for accuracy, sensitivity and efficiency were calculated based on this standardized set.

In the second step the results were analysed using analysis of variance (ANOVA) for each of the performance indicators separately. Due to the design of the experiment, the decimation scheme, dissimilarity criterion, heterogeneity, neighbourhood size and their interactions could be used as explanatory factors of the variation observed in each of the performance indicators. The Tukey honesty test was used to distinguish groups of algorithms which perform statistically the same for a certain indicator using MATLAB®.

Accuracy

The accuracy of a segmentation is expressed as a function of the mismatch between the regions delineated by the algorithm and the predefined regions in the dataset. Following the work of Martin et al. (2001), we define the local refinement error E_i for data element i as the mismatch between region R_a containing i in segmentation A and R_b containing i in segmentation B as (Equation 3):

$$E_i = \frac{|R_a| \setminus |R_b|}{|R_a|} \tag{3}$$

where |.| denotes the cardinality, i.e. the number of elements in a set, and \ the relative complement, i.e. the number of elements in region R_a which are not in region R_b.

The local refinement error is defined as an asymmetric measure and describes the mismatch in one direction only. When A is the delineated segmentation and B contains the predefined regions E_i expresses the degree to which the delineated region is too coarse (TC_i^τ). When A contains the predefined regions and B is the delineated segmentation E_i expresses the coarseness of the predefined region, or stated the other way around the degree to which the delineated region is too fine (TF_i^τ) (Figure 4). Accuracy of a segmentation at threshold τ $A_S(\tau)$ is expressed as a function of two accumulated error measures (Equation 4):

$$A_S(\tau) = 1 - \frac{\max(\sum_{i \in V} TF_i^\tau, \sum_{i \in V} TC_i^\tau)}{n} \quad (4)$$

where V is the set of all nodes in the RAG^0. The accuracy of the algorithm ($A_{S,\ max}$) is expressed by the largest value of $A_S(\tau)$ obtained for any τ and we define T_{opt} as the set of threshold values resulting in a segmentation with an accuracy of $A_{S,max}$. To allow comparison between datasets of different sizes the accuracy is normalized using the accuracy value at threshold τ_m. $A_S(\tau_m)$ defines the minimum maximum accuracy in the set of 100 segmentation regardless the quality of the algorithm and is determined by the number and the size of the predefined regions (Equation 5).

$$A_S = \frac{A_{S,max} - A_S(\tau_m)}{1 - A_S(\tau_m)} \quad (5)$$

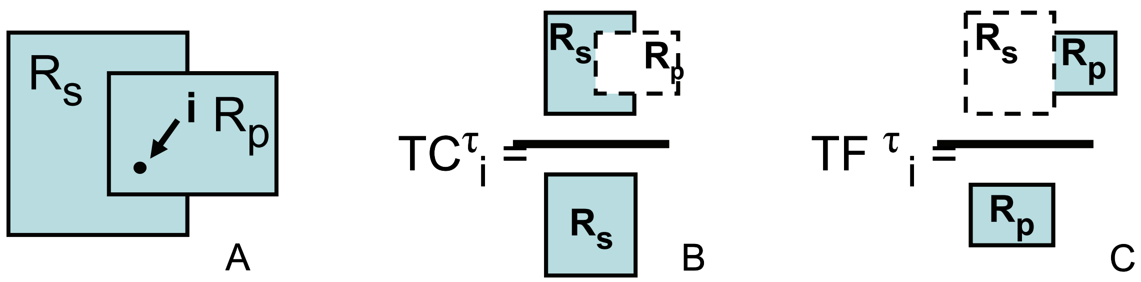

Figure 4. Illustration of the calculation of local refinement errors between segmentation S and predefined region P. A: location of data element i in regions R_s and R_p. B: the coarseness is calculated by dividing the number of data elements of R_s not in R_p by the total number of data elements in R_s. C: fineness is calculated by dividing the data elements of R_p not in R_s by the total number of data elements in R_p.

Sensitivity

To measure the sensitivity of the algorithms to user defined parameters two indicators were developed: the range of optimal threshold values (R_{opt}) and the number of direction changes (C_A), increases and decreases in accuracy at consecutive threshold values τ. The range of optimal threshold values expresses the ratio of the number of optimal threshold values T_{opt} and the total number of threshold values evaluated (T_{tot}). (Figure 5, Equation 6).

$$R_{opt} = \frac{|T_{opt}|}{|T_{tot}|} \tag{6}$$

Algorithms that provide accurate segmentations for a wide range of threshold values (high R_{opt}) are easier to apply than algorithms which provide accurate classifications only at very specific threshold values.

The number of directional changes C_A expresses the predictability of the response of the algorithm to changes in threshold value and is measured by counting the number of times the sign of the slope in the accuracy curve changes (Figure 5). In

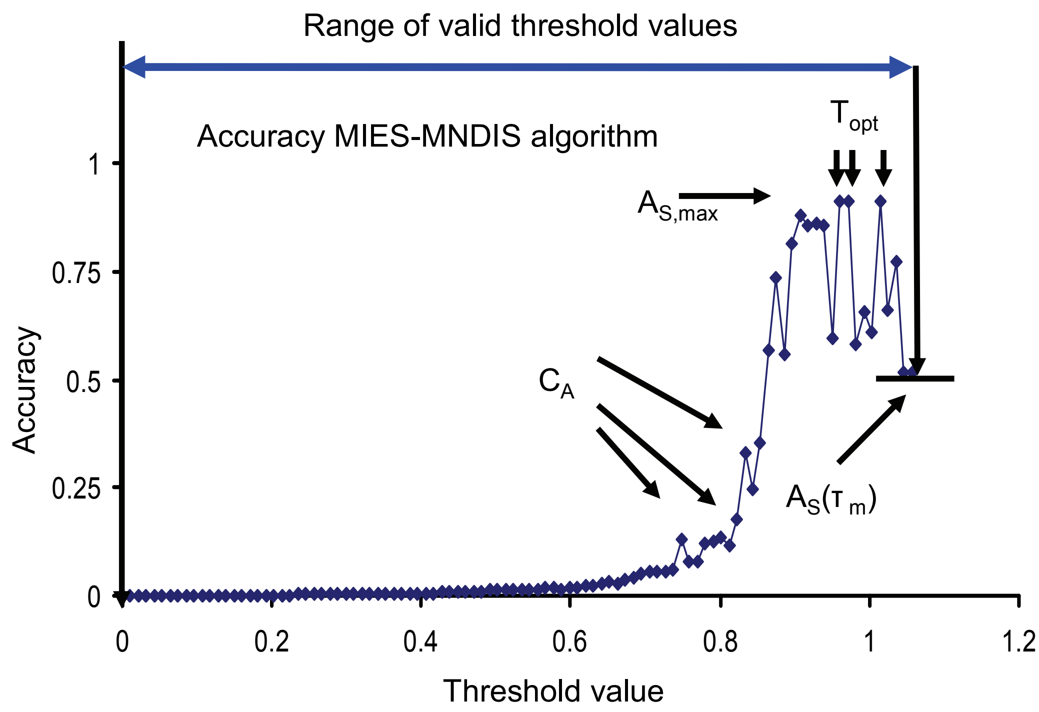

Figure 5. Illustration of the performance indicators for detailed explanation see text. The accuracy = of the algorithm (A_S) = (0.94-0.53)/(1-0.53)=0.85; The range of optimal thresholdvalues is R_{OPT} = 3/100 = 0.03 and the number of direction changes C_A = 17 based on a set of 100 segmentations within the valid threshold range [0,1.07> for algorithm MIES-MNDIS on pattern type 1 with a standard deviation of 0.8.

(5)

applications the search for an optimal segmentation will be facilitated when the accuracy consistently increases or decreases with an increase in threshold value and thus low values of C_A.

Efficiency

The height of the pyramid is a measure of the number of iterations (N_I) needed and can be used as an indicator of the required computation effort (Kropatsch et al., 2005).

6.4 Results

The results of the ANOVAs are summarized in Table 3. All effects and their interactions contribute significantly to the variation in the dataset, with $p < 0.0001$ for most effects. Therefore the contribution of the effects and their interactions to total variance explained is presented and used for interpretation (Bliese and Halverson, 1998). Interactions between decimation schemes and dissimilarity criteria are presented per performance indicator in Tables 4 to 7. The algorithms will be referred to by the abbreviated decimation scheme and dissimilarity criterion names or by their group names. The abbreviations used can be found in Table 1.

For each of the pattern types a different combination of dissimilarity criterion and decimation scheme performed with the highest accuracy (Table 4). For pattern types 1 and 2 the MBF decimation scheme reached the highest average accuracy of the segmentation (A_S), in combination with the IVAR and ITD dissimilarity criterions, (79% and 73%, respectively). For pattern type 3 the combination of MIS-AIH resulted in the highest A_S (57%, respectively) and for pattern type 4 the MIES performed best in combination with both STD and VAR dissimilarity criterions (65% and 65%, respectively).

A_S was sensitive to differences in the heterogeneity of the dataset (Table 3 and Figure 6), although the effects of the differences in heterogeneity were dependent on the combination of decimation schemes and dissimilarity criteria used and on the pattern type. Larger heterogeneity resulted in lower A_S for pattern types 1 and 4 (Figures 6A and 6B), due to obscuring of the differences between the contrasting mean values of the regions. In contrast, higher heterogeneity resulted in higher A_S for pattern type 3 (Figure 6C), since in this pattern type the difference between the regions with the same mean value of 0 originated from the variation in data values. In pattern 2 the regions differed in mean value as well as heterogeneity, for some combinations of decimation scheme and dissimilarity criterion the increase of heterogeneity is

Table 3. Importance of the main effects decimation scheme (S), dissimilarity criterion (C) and heterogeneity in the data set (H) and their interactions expressed as the percentage of the total variation of the data set (% of the total sum of squares). All effects were significant effects at the α<0.05 level. Effects explaining more the 10% of the variation are formatted bold.

Indicator	Terms	Pattern 1	Pattern 2	Pattern 3	Pattern 4
A_S	*S*	3	8	2	2
	C	**21**	**14**	**64**	**14**
	H	**44**	**37**	4	**57**
	S-C	7	**15**	7	4
	S-H	1	2	2	2
	C-H	4	6	4	5
	S-C-H	7	7	3	4
	Error	**13**	**10**	**14**	**11**
R_{OPT}	*S*	7	6	1	5
	C	**39**	**45**	**47**	**43**
	H	4	5	0	6
	S-C	**13**	**10**	4	7
	S-H	5	3	0	3
	C-H	3	3	5	5
	S-C-H	5	8	4	5
	Error	**23**	**20**	**39**	**25**
C_A	*S*	**14**	**11**	**27**	**11**
	C	**38**	**53**	**48**	**48**
	H	1	2	1	0
	S-C	**17**	**16**	**15**	**13**
	S-H	2	1	0	0
	C-H	**14**	8	2	**14**
	S-C-H	8	5	1	6
	Error	6	5	5	7
N_I	*S*	**10**	8	**15**	**10**
	C	**34**	**24**	**50**	**33**
	H	2	2	0	5
	S-C	**29**	**29**	**26**	**15**
	S-H	1	2	0	3
	C-H	7	7	1	**17**
	S-C-H	8	**13**	1	**11**
	Error	8	**14**	6	7

Table 4. The accuracy of the segmentation (A_S) for combinations of dissimilarity criterion and decimation scheme The lowest group of mean A_S values which are statistically not different are indicated by a box, the combinations deviating less than 25% from the best result are indicated by the grey shading.

Dissimilarity criterion		Pattern 1				Pattern 2				Pattern 3				Pattern 4			
		Decimation scheme				Decimation scheme				Decimation scheme				Decimation scheme			
		BF	*MBF*	*MIS*	*MIES*	*BF*	*MBF*	*MIS*	*MIES*	*BF*	*MBF*	*MIS*	*MIES*	*BF*	*MBF*	*MIS*	*MIES*
D	*SL*	2	2	18	21	50	30	52	60	5	5	3	0	19	13	12	24
	CL	41	58	20	45	40	92	17	43	0	33	1	0	27	49	12	44
	AL	58	47	46	59	72	68	61	65	35	34	29	33	60	55	54	48
MH	*DIS*	68	62	63	74	51	53	56	58	25	31	35	30	59	58	62	64
	STD	64	59	68	73	51	55	60	61	27	31	34	32	60	57	62	65
	VAR	65	59	71	75	52	55	61	61	29	31	35	34	61	58	64	65
AH	*TD*	21	48	7	31	25	91	13	39	4	25	4	6	22	50	14	41
	SSQ	34	61	15	44	30	72	25	39	4	8	3	5	34	53	20	48
RIH	*IDIS*	38	70	20	60	48	91	23	67	0	6	0	17	47	61	19	59
	ISTD	39	64	18	49	48	83	29	60	0	0	0	1	38	52	16	41
	IVAR	72	79	37	70	71	77	48	64	2	3	1	0	61	64	50	64
AIH	*ITD*	62	57	68	64	87	93	77	85	41	52	57	53	57	56	58	59
	ISSQ	60	60	71	65	76	81	77	81	26	30	32	24	56	58	58	59

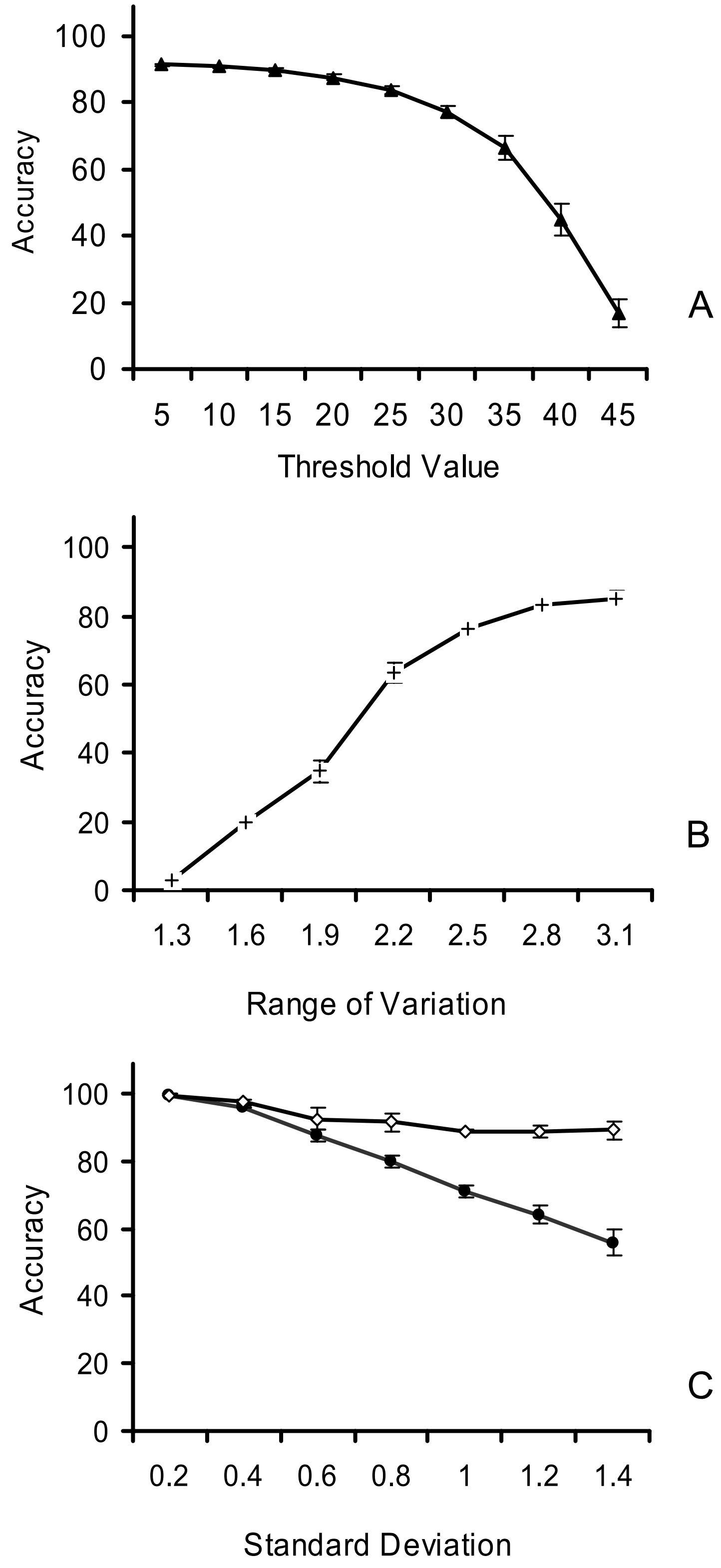

Figure 6. Mean accuracy and standard deviation of for the best performing algorithms as functions of the heterogeneity in the pattern: (A) —●— MBF-IVAR in pattern type 1 and —◇— MBF-ITD in pattern type 2, (B) −+− MBF-ITD in pattern type 3, and (C) —▲— MIES-VAR in pattern type 4.

Table 5. The range of optimal threshold values (R_{OPT}) for combinations of dissimilarity criterion and decimation scheme. The lowest group of mean R_{OPT} values which are statistically not different are indicated by a box, the combinations deviating less than 25% from the best result are indicated by the grey shading.

Dissimilarity criterion		Pattern 1				Pattern 2				Pattern 3				Pattern 4			
		Decimation scheme				Decimation scheme				Decimation scheme				Decimation scheme			
		BF	*MBF*	*MIS*	*MIES*	*BF*	*MBF*	*MIS*	*MIES*	*BF*	*MBF*	*MIS*	*MIES*	*BF*	*MBF*	*MIS*	*MIES*
D	*SL*	4	4	10	2	4	2	1	2	1	1	3	4	14	16	13	11
	CL	13	12	5	5	61	86	43	60	1	1	1	1	48	66	42	67
	AL	6	5	2	2	7	5	2	3	1	1	1	1	6	7	2	3
MH	*DIS*	5	15	1	2	6	13	1	3	1	1	1	1	5	12	1	2
	STD	6	18	1	2	8	15	1	3	1	1	1	1	8	23	1	2
	VAR	10	27	1	3	11	23	2	4	1	1	1	1	13	35	1	2
AH	*TD*	40	47	31	41	30	59	28	45	29	33	24	35	34	51	30	52
	SSQ	49	59	21	46	50	54	22	44	27	31	26	29	41	60	24	53
RIH	*IDIS*	4	2	1	1	5	3	3	1	2	2	2	1	2	3	2	1
	ISTD	3	2	4	2	4	5	4	1	1	1	4	1	2	2	1	1
	IVAR	5	6	4	3	13	6	3	4	3	4	6	6	3	3	2	2
AIH	*ITD*	72	67	10	27	87	92	20	30	35	58	20	42	67	65	17	39
	ISSQ	75	75	9	18	81	61	11	34	3	16	2	5	66	69	16	43

Table 6. The number of changes in direction of accuracy (C_A) for combinations of dissimilarity criterion and decimation scheme. The lowest group of mean C_A values which are statistically not different are indicated by a box, the combinations deviating less than 25% from the best result are indicated by the grey shading.

Dissimilarity criterion		Pattern 1				Pattern 2				Pattern 3				Pattern 4			
		Decimation scheme				Decimation scheme				Decimation scheme				Decimation scheme			
		BF	*MBF*	*MIS*	*MIES*	*BF*	*MBF*	*MIS*	*MIES*	*BF*	*MBF*	*MIS*	*MIES*	*BF*	*MBF*	*MIS*	*MIES*
D	*SL*	1	1	19	40	40	19	46	47	1	1	25	39	3	2	3	3
	CL	6	1	21	25	1	1	2	3	20	1	31	39	1	1	1	1
MH	*AL*	14	5	35	36	13	5	35	40	21	12	44	45	12	7	27	25
	DIS	26	8	37	32	39	12	46	44	36	13	40	39	28	7	32	38
	STD	23	4	32	30	38	8	43	44	34	8	36	39	25	5	28	32
	VAR	26	4	41	40	40	7	45	46	42	10	45	50	23	4	30	32
AH	*TD*	1	1	2	2	1	1	3	5	1	1	1	4	1	1	2	2
	SSQ	1	1	2	2	3	1	6	7	2	1	4	7	1	1	3	3
RIH	*IDIS*	14	27	11	29	17	35	13	44	1	2	4	11	14	10	11	25
	ISTD	13	22	13	26	15	29	16	43	1	1	9	8	10	9	4	14
	IVAR	29	27	31	44	26	22	47	43	7	6	34	39	15	11	22	26
AIH	*ITD*	2	1	6	4	2	1	4	2	7	2	11	10	3	2	8	5
	ISSQ	2	1	5	4	2	1	4	4	11	2	31	22	3	1	7	5

Table 7. The number iterations (N_I) for combinations of dissimilarity criterion and decimation scheme. The lowest group of mean N_I values which are statistically not different are indicated by a box, the combinations deviating less than 25% from the best result are indicated by the grey shading.

Dissimilarity criterion		Pattern 1				Pattern 2				Pattern 3				Pattern 4			
		Decimation scheme				Decimation scheme				Decimation scheme				Decimation scheme			
		BF	*MBF*	*MIS*	*MIES*	*BF*	*MBF*	*MIS*	*MIES*	*BF*	*MBF*	*MIS*	*MIES*	*BF*	*MBF*	*MIS*	*MIES*
D	*SL*	57	1939	643	112	9	138	14	11	57	1691	614	399	8	178	13	11
	CL	6	77	9	10	6	32	8	10	6	95	8	10	6	34	8	10
	AL	7	182	20	12	7	303	18	12	8	168	25	14	8	223	22	13
MH	*DIS*	6	104	21	13	6	220	48	29	7	155	52	33	6	150	20	13
	STD	7	99	17	12	7	188	29	21	6	144	40	28	6	128	14	12
	VAR	7	98	17	12	6	187	25	22	7	144	40	28	6	128	14	12
AH	*TD*	6	34	8	10	6	35	8	10	6	35	8	10	6	36	8	10
	SSQ	6	34	8	10	6	39	8	10	6	37	8	10	6	39	8	10
RIH	*IDIS*	42	830	1068	420	36	194	1005	196	74	2090	1292	806	17	566	611	229
	ISTD	37	858	1023	396	38	355	799	244	64	2187	1201	997	19	634	671	419
	IVAR	13	247	466	73	18	193	213	86	55	1434	630	435	14	419	305	113
AIH	*ITD*	7	50	10	10	7	58	10	10	7	44	9	11	7	53	9	11
	ISSQ	7	55	10	10	7	71	10	10	7	66	10	11	7	71	9	11

disturbing proper delineation of regions, whereas other algorithms are relatively indifferent to the increase in heterogeneity (Figure 6A).

Besides heterogeneity, most of the variation in A_S between decimation schemes and dissimilarity criteria combinations could be attributed to an effect of dissimilarity criterion (Table 3). When comparing the segmentation results of the 4 pattern types, the largest consistency in high accuracy was reached with the ITD dissimilarity criterion, irrespective of the decimation scheme used (Table 4). Both AIH dissimilarity criterions (ITD and ISSQ) performed in general well for the other quality criteria, demonstrating a low sensitivity to parameter settings and high efficiency, although the ranges of optimal thresholds (R_{opt}, Table 5) were smaller when AIH criterions were combined with MIS and MIES (on average 25%) than with BF and MBF decimation schemes (on average 62%).

The MH dissimilarity criterions performed well for pattern types 1 and 4 (A_S between 57 and 75%), but for pattern type 2 these criterions resulted in A_S between 51% and 61% and were out-performed by various other dissimilarity criterions in combination with the MBF decimation scheme (92% for CL, 91% for TD and IDIS, and 83% for ISTD). Moreover, for the MH dissimilarity criterions R_{opt} was small (on average 6 over all pattern types, with a maximum value of 35) and the C_A was high (on average 29) when compared to other dissimilarity criterions.

The RIH and some of the D and AH dissimilarity criteria resulted also in accurate segmentations, but only in combination with the MBF decimation scheme. However these combinations were either sensitive to parameter settings as reflected in small R_{opt} and high C_A values, or were not efficient since they required a high number of iterations (Table 6 and 7). The RIH dissimilarity criteria performed insufficient for all three additional performance indicators (R_{opt}, C_A and N_I).

The contrasts in the neighbourhood configurations as shown in Figure 3 had very little effect on the segmentations, resulting in values of variance explained for each of the 4 performance indicators of 1% and below (data not presented).

6.5 Conclusions and discussion

In this paper we evaluated the application of graph pyramid segmentation techniques in GIS data. To assess these segmentation algorithms we developed an evaluation framework, consisting of a pattern generator and metrical indicators. We evaluated each of the algorithms for their performance on 5 different pattern types, using indicators for accuracy, sensitivity and efficiency. The pattern types varied in data type heterogeneity and neighborhood relations.

Based on the results presented above, it can be concluded that with respect to the research questions Q1 to Q5 (section 3.1) can be answered as follows.

(A1) Regions in continuous datasets differing in mean value and evenly distributed heterogeneity are most accurately regionalized using the algorithm MBF-IVAR. However, a number of combinations of decimation schemes and dissimilarity criteria work well, especially the MH-measures dissimilarity criteria combined with the MIES decimation scheme.

(A2) Regions contrasting in both mean value and heterogeneity in a continuous dataset can most accurately be segmented with the algorithm MBF-ITD. The MBF decimation scheme can also be combined with a number of other dissimilarity criteria. The AIH dissimilarity criteria perform well with all decimation schemes.

(A3) Regions in a continuous dataset which differ only in heterogeneity, can not be accurately delineated with the types of algorithms tested in this paper. In datasets with major differences in heterogeneity compared to mean values preprocessing of the data is needed, for example by using a filter to characterize the heterogeneity around the data element (Lee, 1980).

(A4) Regions which differ only in heterogeneity but not in class type in a nominal dataset can best be delineated using the MH-measures STD and VAR combined with the MIES decimation scheme.

(A5) The neighborhood configurations have little effect on the performance of the algorithms.

No algorithm with an best overall performance for each of the performance indicators could be identified. The AIH dissimilarity criterion provided the highest accuracy across pattern types and decimation schemes. Therefore this type of dissimilarity criterion seemed to be robust under different conditions. For pattern type 1 and type 4 the MH-measures VAR, DIS, STD outperformed the AIH dissimilarity criterion, but the performance of these dissimilarity criteria was not consistent across patterns varying in heterogeneity. As a result, the MH-measures appeared to be less reliable for application to real data where the variation in heterogeneity is not known.

The MBF decimation scheme provided the most accurate segmentations for all pattern types and could be combined with many different dissimilarity criteria. This decimation scheme appeared to contribute to the reliability of the segmentation algorithm to obtain accurate segmentation results. A major disadvantage of the MBF dissimilarity criterion is the large number of iterations needed to obtain a segmentation, increasing the calculation time. The most efficient algorithms (least demanding for computational resources) were obtained with the BF and MIES decimation schemes, where the BF was more efficient, but the MIES more accurate. So in general we recommend the combination of the AIH dissimilarity criterion and the MBF decimation scheme in applications when the distribution of the heterogeneity in the dataset is unknown, but the combination with the BF or MIES decimation schemes when computation time is relevant. If the difference in heterogeneity is relevant as a criterion to delineate objects, pre-processing of data is required, for example by filtering.

In the literature the BF and MIES decimation schemes are generally combined with the SL dissimilarity criterion. Although in our evaluation this combination did not perform particularly well, good results have been reported (Felzenszwalb and Huttenlocher, 1998; Kropatsch and Haxhimusa, 2004; Ma et al., 2007). These good results can partly be explained from the fact that the algorithms were applied to images contrasting in mean value with limited heterogeneity in the data. Moreover, these results were obtained by using a different, more complex, locally adaptive stop criterion involving size dependency and a measure of internal heterogeneity based on the largest dissimilarity in the region. It can be concluded that the stop criterion may also contribute to a large extent to the segmentation result. To obtain better understanding of this interaction additional research is needed.

The MBF decimation scheme is often combined with the ITD dissimilarity criterion (Baatz and Schape, 2000). According to our evaluation this is a very robust combination capable of delineating regions even when the heterogeneity in the dataset is unevenly distributed, which is in line with observations of Baatz and Schape (2000). On the other hand, the algorithm needs relatively long calculation times and does not provide the most accurate results when heterogeneity is evenly distributed across the image.

The MIS decimation scheme is often used in combination with the AL dissimilarity criterion (Jolion and Montanvert, 1992; Laemmer et al., 2002; Lallich et al., 2003; Ma et al., 2007). According to our evaluation this is not one of the best combinations, more accurate results would be obtained with for example the ITD dissimilarity criterion. This is in line with the finding of Ma et al. (2007), who also conclude that a better performance may be obtained for algorithms based on the MIS decimation scheme, when combined with other dissimilarity criteria.

In this paper a new evaluation framework has been introduced consisting of a pattern generator and a set of performance indicators. This idea is not new, in the early 1980's a similar framework (Milligan, 1985) was used to evaluate the performance of hierarchical clustering algorithms (Milligan, 1980; Milligan et al., 1983). The methodology presented has proven to be able to evaluate the response of algorithms to predefined differences in data pattern in a systematic way. For the further development of graph pyramid segmentation in geo-data more questions need to be answered. For example: How can we regionalize datasets on the basis of multiple attributes and different data types (Jellema et al., accepted)? How can these attributes be standardized (Milligan and Cooper, 1988) and weighted in the segmentation process (Milligan, 1989; Jellema et al., accepted)? And what is the best way to evaluate the quality of a segmentation when a reference dataset is not available (Milligan, 1981)? We think that the evaluation framework as presented provides a sound basis for systematic evaluation of these questions and can thus help in strengthening the scientific basis of using segmentation algorithms in geodata.

Acknowledgements
We like to thank Dr. Paul Goedhart, for his valuable statistics advice.

Chapter 7

Designing a hedgerow network in a multifunctional agricultural landscape - balancing trade-offs among ecological quality, landscape character and implementation costs

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Submitted to: *European Journal of Agronomy.*

Abstract

Development of multifunctional agriculture is often complicated, due to the complexity of the agro-ecological relations acting at multiple spatial scales and the involvement of many different stakeholders. We present an explorative approach named Landscape IMAGES, which offers insight in the full range of possible futures without prioritizing by forehand. Using a heuristic optimization technique, called Differential Evolution, and the concepts of Pareto optimality and Pareto efficiency, trade-offs between land use functions are revealed. For each quantitative solution a spatial explicit picture of the future landscape can be visualized. These insights offers room for discussion, perspective sharing and elaborate decision making to increase understanding among stakeholders.

The methodology of Landscape IMAGES is illustrated with an example of the redesign of an agri-ecological zone in the Netherlands, where ecological, landscape character and implementation costs were considered. The case study was performed to support an NGO with the evaluation of a sketch design of an improved hedgerow structure. Interactions between the ecological quality, landscape quality and implementation costs were explored using a heuristic optimization technique and quantitative indicators. By identifying the original landscape and the restructured landscape in the solution space, it became clear that the decision rules employed by the NGO impacted positively on connectivity, values of indicators for landscape character were slightly reduced. The methodology was considered useful by the NGO to reflect on their own rules for landscape design and the confrontation of the sketch design and the Pareto optimal solution set, allowed them to value their design within the whole range of possible solutions.

Keywords: multifunctional agriculture, landscape planning, hedgerow network, landscape character, spatial optimization, Pareto efficiency, Pareto optimality

7.1 Introduction

With the diversification of farming systems as an answer to the sustainability problems in agriculture and the increasing urbanization of Europe, new activities like nature conservation, agro-tourism and landscape character are gaining importance (Vos and Meekes, 1999; O' Conner et al., 2006). Different from the traditional agricultural activities of food and fibre production these activities can not be managed at a farm or field scale, but need to be managed at a regional scale (Gottfried et al., 1996; Cumming et al., 2006). To realize these landscape functions farmers need to co-operate and interact with other stakeholders in the region (Holloway et al., 2006; Franks and McGloin, 2007).

Spatial planning of land use and management activities aiming at sustainable natural resource management is in many occasions much debated, due to the high number of involved stakeholders with often contrasting perspectives and expectations about future development of a region (Kangas et al., 2005). To complicate matters, scientific understanding about biological processes governing environmental functions in complex agro-ecosystems and the possibilities for site-specific model application and prediction are generally limited (Carpenter et al., 2006).

In such situations, as a first step, scientists and planners should attempt to make interactions between the demanded environmental functions explicit and assist the decision making process by feeding the discussions with sketches of possible futures for a given case study region. The second step would be the selection of acceptable designs for implementation, preferably without assigning often arbitrary weights to the importance of ecosystem services to stimulate acceptance by the involved stakeholders. Therefore, the selection process should be able to identify the designs that satisfy the requirements as good as possible, while eliminating inferior solutions (Das, 1999).

A widely applied planning method is the construction of sketch designs based on narrative development scenarios (Münier et al., 2004) or optimization studies (Annetts and Audsley, 2002). However, these studies only explore a very limited part of the solution space of possible future defined by different ecosystem functions (Figure 1A). Sketch designs provide single solutions without any reference to the boundaries of the system, whereas optimization studies focus on the maximization of extremes rather than finding acceptable compromises. Moreover, existing multi-criteria approaches for spatial planning perform no systematic exploration of the solution space. As a consequence, the currently used methods fail to clarify the interactions between environmental functions and present a narrow view of the future possibilities, addressing only a limited number of perspectives (Carpenter et al., 2006). We developed the Landscape IMAGES methodology (Groot et al., 2007) that entails

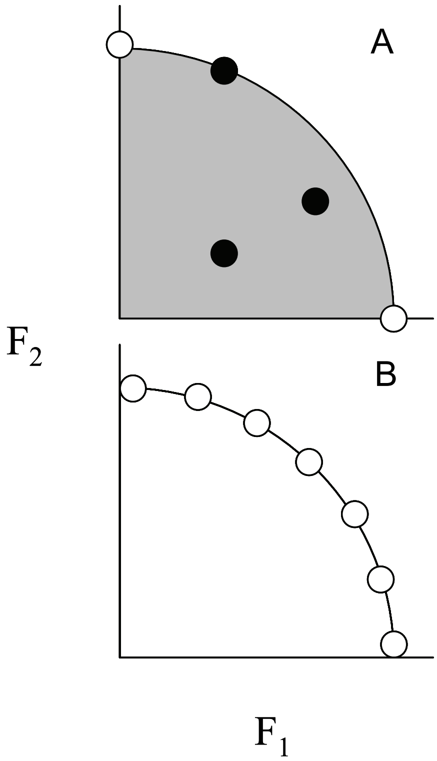

Figure 1. The proportion explored (in white) of the total feasible solution space (in grey) defined by the trade-off between two functions F1and F2 by (A) narrative scenario development (●), optimization (○) and by (B) the Landscape IMAGES framework yielding a set of discrete Pareto optimal solutions (○).

the exploration of the whole solution space (Figure 1B) to find the trade-offs or the optimal pattern of interactions between the land use functions (Chee, 2004) and enables the identification of a limited number of Pareto optimal designs. In this paper we present the methodology and an application to redesign a hedgerow structure in an agri-ecological zone in the Netherlands. The paper is build up as follows: in section 7.2 we present the Landscape IMAGES framework and an introduction into the case study (section 7.3), followed by the results (section 7.4) and the discussion (section 7.5).

7.2 Methodology

7.2.1 Conceptual model

The exploration of the trade-offs between performance criteria or objectives can be formulated as a multi-objective design problem, which can be generally stated as follows:

$$\text{Max } F(x) = (F_1(x),...,F_y(x))^T \quad (1)$$

$$x = (x_1,...,x_z)^T \quad (2)$$

Subject to i constraints:
$g_i(x) \leq h_i$ (3)

where, $F_1(x),...,F_y(x)$ are the y objective functions that are simultaneously maximized or minimized, and $(x_1,...,x_z)$ are the decision variables that represent the activities allocated to the z spatial units. The decision variables can assume values from a predefined array $x \in S$, where S is the solution or parameter space. Constraints (Equation 3) may arise from the problem formulation, for instance by limitations on the inputs or outputs related to farming or management activities.

7.2.2 Pareto-based differential evolution

The trade-offs between the objectives were explored with a multi-objective implementation of the evolutionary strategy of Differential Evolution (DE) developed by (Storn and Price, 1997). Currently, DE is widely used in the research community due to its simplicity efficiency and robustness (Bergey and Ragsdale, 2005; Mayer et al., 2005). DE involves the iterative improvement of a set of solutions or genotypes, consisting of alleles. In our application the genotypes represent alternative landscapes and the alleles are decision variables in which the occupation of the field borders were encoded as a real number. A genotype is a multi-dimensional vector $p=(p_1,...,p_z)^T$ of z alleles. Each allele p_i is initialized as $p_{i,0}$ by assigning a random number within the allowed range:

$$p_{i,0} = L(p_i) + r_i\,(U(p_i) - L(p_i)) \quad (4)$$

where r_i denotes a uniformly distributed random value within the range [0,1] and L and U are the lower and upper values of the allowed range. A new generation t+1 is created by applying mutation and selection operators on the individuals in the population of genotype P of the current population t. The first step of the reproduction process is generation of a trial population P’ that contains a counterpart for each individual in P, produced by parameterized uniform crossover of a target vector and a mutation vector. The mutation vector is derived from three mutually different competitors c_1, c_2 and c_3 that are randomly selected from the population P in the current generation t. The allele values are taken from the mutation vector with probability C_R:

$$p'_{i,t+1} = \begin{cases} c_3 + F \times (c_1 - c_2) & \text{if } r_i < C_R \\ p_{i,t} & \textit{otherwise} \end{cases} \quad (5)$$

where r_i is a uniformly distributed random variable. The parameter $F \in [0,2]$ is a parameter that controls the amplification of differential variations. After a mutation, the value of $p'_{i,t+1}$ can extend outside of the allowed range of the search space. For allele values that violate the boundary constraints the repair rule presented in Equation 6 is applied. This rule implements a mechanism that can be denoted as 'back folding': the adjustment for the allele is calculated by interpolation into the allowed range from the boundary by a value that is proportional to the difference between the boundary and violation values:

$$p'_{i,t+1} = \begin{cases} L(p_i) - \dfrac{p'_{i,t+1} - L(p_i)}{F} & \text{if } p'_{i,t+1} < L(p_i) \\ U(p_i) - \dfrac{p'_{i,t+1} - U(p_i)}{F} & \text{if } p'_{i,t+1} > U(p_i) \\ p'_{i,t+1} & \textit{otherwise} \end{cases} \quad (6)$$

A trial genotype $p'_{i,t+1}$ replaces $p_{i,t}$ if it has a better ranking, a higher efficiency or is in a less crowded area of the search space (see below) than the parent genotype. Population size N is determined by the number of alleles in the genotype z and a multiplication factor M. The last parameter in the DE algorithm is the number of generations G, which serves as the stopping criterion.

The first criterion for replacement of individuals by a trial solution is Pareto-based ranking as proposed by (Goldberg, 1989). Individuals in the population are

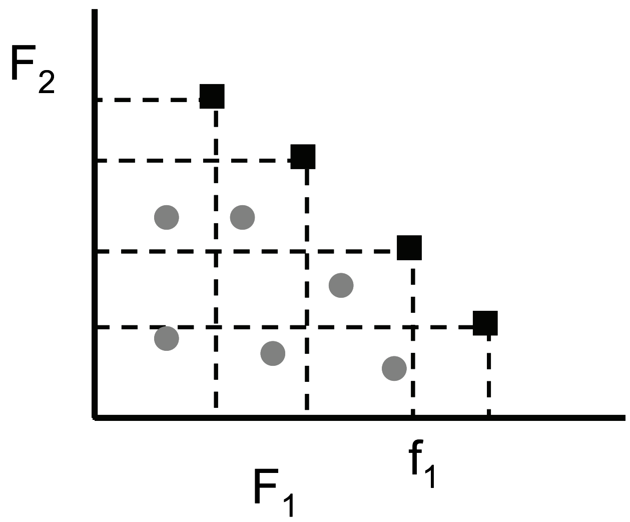

Figure 2. Pareto Optimality: symbol ■ indicates solutions which are not dominated by any other solutions: If f_1 is set as a minimum level for objective function F_1, there will be no alternative solution in the dataset providing a larger value for objective F_2.

Pareto optimal when they are not dominated by any other individual and ranked 1 non-dominated individuals is ranked 2. This process is continued until all individuals (Figure 2). The rank 1 individuals are removed from population and a new set of in the population are assigned a Pareto rank.

If two solutions have the same Pareto rank a second criterion, Pareto efficiency, is taken into account. A solution is Pareto efficient of order k, if it is not dominated by any other solution in all k-dimensional subsets of the y dimensional solution space (Das, 1999), where $1 \leq k \leq y$ and y is the number of objectives. Solutions with a low Pareto efficiency order are considered better solutions and the concept of Pareto efficiency can be seen as an extension of concept Pareto optimality

If two solutions have the same rank and efficiency, a third selection criterion, the crowing distance, is taken into account. The metric Θ represents the within-rank solution density and is calculated from the normalized distance for each objective between adjacent solutions in the search space, as follows (Deb et al., 2002):

$$\theta = \sum_{j=1}^{k} \frac{\left| d_i - \bar{d} \right|}{\left| B_j \right|} \tag{7}$$

where B_j is the boundary for objective j, which can be estimated from the difference between the minimum and maximum objective values. Parameter d_i denotes the Euclidian distance between two consecutive solutions within the Pareto front of a given rank and the parameter $\bar{d}$ is the average of these distances. An individual is replaced by a trial solution of the same rank and efficiency if the latter is located in a less densely populated part of the solution space. This criterion promotes the spread of solutions within the objective space.

7.3 Hedgerows in the Frisian Woodlands

The Frisian Woodlands are a unique agricultural area in the north of Netherlands consisting of a mosaic of fields bordered by hedgerows. The landscape of the Frisian Woodlands is comparable to the Bocage landscapes in Brittany and Normandy (Baudry et al., 2001) and contains the densest hedgerow networks of the Netherlands (Dijkstra et al., 2003). The hedgerows were originally planted as cattle fence and property boundary, but are nowadays highly valued for their ecological and cultural-historical qualities (De Boer, 2003). The prevailing land use activity between the hedgerows is dairy farming. On some farms a limited proportion of up to 5% of the area is used for forage maize production, while the rest of the area is occupied by permanent grassland. In this setting the Landscape IMAGES framework has been applied to support the development of an agro-ecological zone of 873 ha by evaluating and generating alternatives for a sketch design produced by a regional, non-governmental landscape management organization 'Landschapsbeheer Friesland' (LBF) responsible for planning and implementation of the adjustments to the zone. The landscape configurations generated in this case study represent the placement of hedgerows in the case study area. The results of the explorations were compared with the performance of the original hedgerow configuration and the implemented sketch design developed by the landscape management organization.

7.3.1 Objectives and indicators

Objectives and indicators for the Landscape IMAGES application were developed in an iterative process of design, demonstration and redesign between the researchers and LBF, in which the representatives of LBF played an active role in the formulation of objectives and indicators. In the course of three meetings a set of objectives and indicators initially proposed by the researchers was adjusted to match the interests of LBF. The final set included indicators for: ecological quality, landscape character, and implementation and maintenance costs.

7.3.2 Ecological quality

Spatial coherence of the hedgerow network was used as a measure for ecological quality. Depending on their mobility different species will experience a different degree of clustering of habitat in the network. This relation can be described as a function between dispersal capacity (D_{cap}) of the species and the size of the largest interconnected cluster of habitat in the network (Urban and Keitt, 2001). In the case study the integral of this function was used as measure of spatial coherence and was maximized. The relation between dispersal capacity and maximum cluster size can be calculated efficiently by determining critical distances in the network structure using graph theory (Bondy and Murty, 1977). A critical distance is the minimum non-habitat distance between two parts of the network that needs to be crossed in order to be able to connect these two parts. For species which are capable of crossing such a critical distance a larger part of the network is accessible than for species which are not able to cross this distance. The hedgerow network can be described as a graph by representing each of the hedgerows as a point or node, and the possible connections between the hedgerows as lines or edges. Each connection between two hedgerows is weighted by the minimum distance between them. The critical distances in the network can now be determined by calculating a minimum spanning tree (Nešetřil et al., 2001) or the minimum set of edges that connects all parts of the networks.

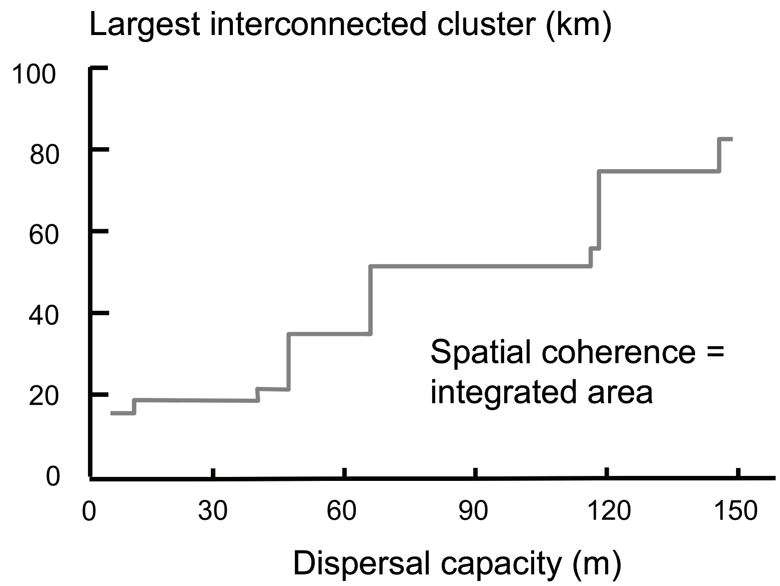

Figure 3. Spatial coherence of the hedgerow network, defined as the integral of the relation between the dispersal capacity (m) and the largest interconnected cluster of habitat (km) in the network.

7.3.3 Landscape character

Landscape character is defined as the presence, variety and arrangement of different landscape features, which gives a landscape a specific identity and makes it stand out from other landscapes (Swanwick and Consultants, 2002). The patterns of fields and hedgerows determine the appearance of the Frisian Woodlands and give a sense of place to the people inhabiting the landscape (Renting and Van Der Ploeg, 2001; Stedman, 2003). Together with LBF the following indicators for variation, continuity and historical characteristics of the hedgerow patterns were developed.

(1) The hedgerows divide the landscape into elongated visual chambers (Figure 4). Variation in length of these chambers contributes to the visual quality of the landscape (De la Fuente de Val et al., 2006). This indicator was maximized.

(2) In the hedgerow landscape of the Frisian Woodlands, a sightline from road to road (Figure 4) is undesirable and perceived as disturbing the pattern of the landscape. To optimize the continuity of the landscape the indicator porosity, expressed as number of continuous sightlines from road to road, was defined and minimized.

(3) Historically, the landscape has a high ratio of longitudinal hedgerows (L) over transversal hedgerows (T) relative to the parcelling direction, resulting in elongated visual chambers (Anonymous, 2006). This characteristic was maintained by maximizing the L/T-ratio.

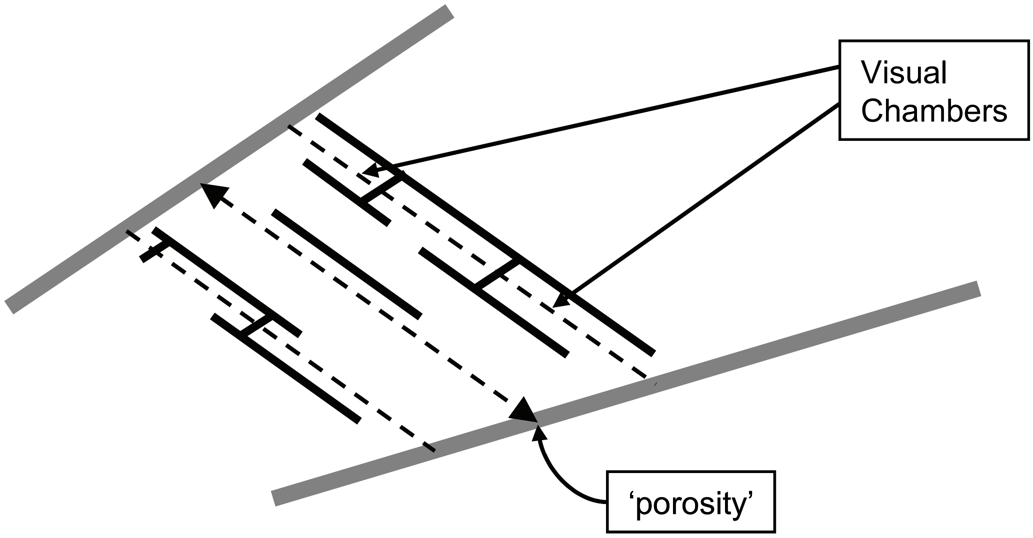

Figure 4. Landscape pattern of the Frisian Woodlands. The hedgerows divide the landscape into elongated visual chambers. Sightlines from road to road (porosity) are undesirable. Legend: road hedgerow, sightline.

7.3.4 Implementation costs

To evaluate the consequences of different implementation options removal, planting and maintenance of hedgerows were considered as separate objectives.

(1) Removal of existing hedgerows can disrupt the historical characteristics of the landscape and is costly. Therefore, removal of hedgerows was minimized.

(2) Addition of new hedgerows is also costly and was minimized.

(3) From the perspective of some farmers aiming to develop large-scale industrial farming systems, the presence of hedgerows forms a barrier to manoeuvre with machines and for the enlargement of fields. Moreover, these farmers consider hedgerows as unwanted sinks of labour for maintenance and related costs. To represent this perspective, the total hedgerow length in the landscape was minimized.

7.4 Results

The final solution set provided by the algorithm offers a large range of possible landscape configurations. The 7 dimensional objective space was visualized by projecting the solutions on a two dimensional surface. This is illustrated in Figure 5 for the trade-offs between spatial cohesion, total hedgerow length and L/T ratio. Spatial cohesion was found to be strongly correlated with total hedgerow length (Figure 5A). Identifying in the solution space the original landscape and the sketch design developed by the LBF demonstrates that the decision rules employed by the LBF

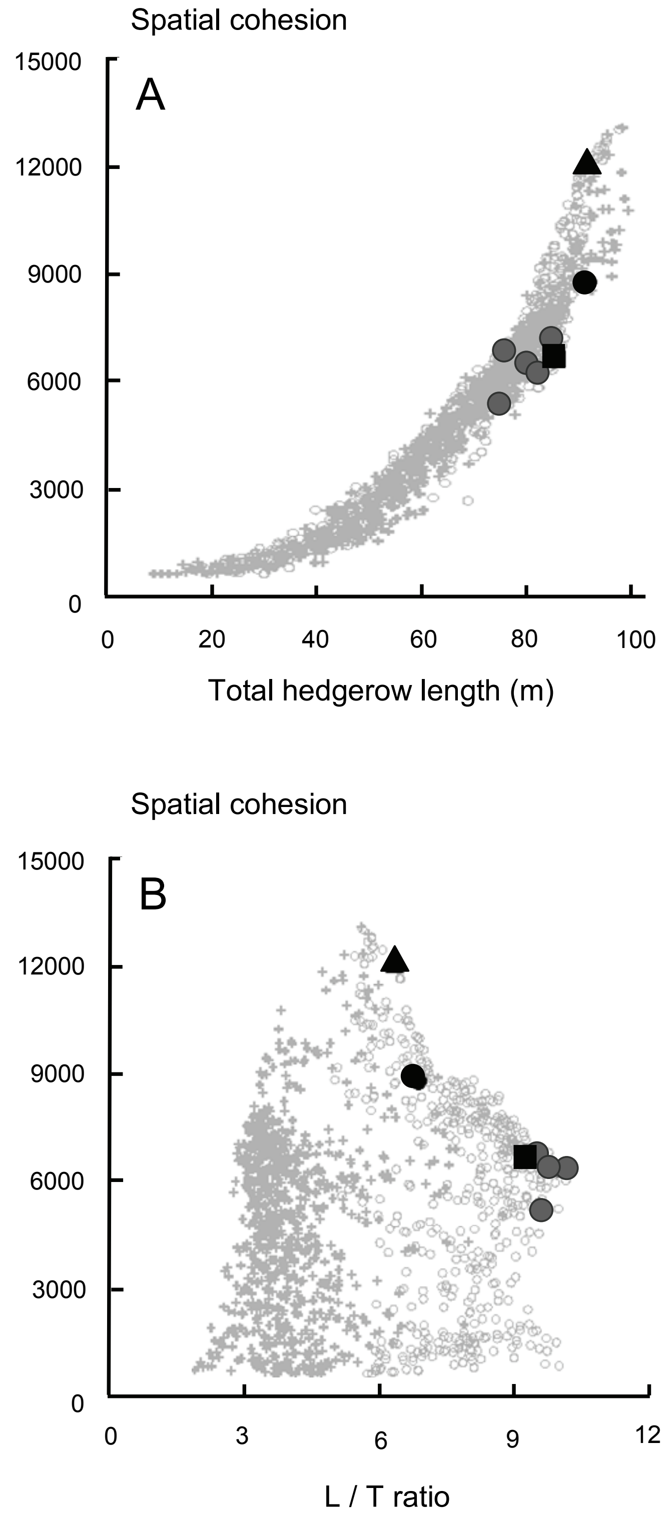

Figure 5. Spatial cohesion of the hedgerow network in the case study area in relation to total hedgerow length (A) and the ratio of hedgerows longitudinal and transversal to the parcelling direction (L/T-ratio, B). Each point represents a landscape configuration. Symbols indicate Pareto efficiency of k=7 (+), k=6 (o) or k=5 (●). The original landscape (■), the sketch design (●) and a design in which the spatial cohesion of the networks is maximal, using the same length of hedgerow as the sketch design (▲).

impacted positively on spatial cohesion. Further improvements in spatial cohesion are possible without increasing the total length (and therefore maintenance costs) of hedgerows in the landscape. Figure 5B shows that improvements in spatial cohesion are generally made at the cost of the L/T ratio of the landscape. This implies that trade-offs occur and priorities need to be set to make further planning decisions. In the sketch design of LBF, which involved the planting of hedgerows transversal to the parcelling direction, the L/T ratio apparently was seen as less important than improvements in spatial cohesion and declined from 9 to 6.5.

Solutions with a low Pareto efficiency order can be typified as the 'best compromises' and are interesting from a planner's point of view. Less extreme points are more likely to be efficient in lower dimensions. In the solution space the best compromised solutions are near the original situation, indicating only minimal changes in the spatial cohesion, hedgerow length and L/T ratio (Figure 5).

In Figure 6 two alternative landscapes designs are presented. Although these landscapes have similar economic and ecological performance their appearance is very different. The presence of different alternative solutions for similar parameter settings demonstrates different ways in which certain objectives can be matched and may stimulate discussions about the detailed implementation of a landscape plan.

7.5 Discussion

The solution space generated by the Landscape IMAGES framework reveals the 'manoeuvring space' for decision makers on multifunctional land use issues. Based on scientific knowledge it provides information about the minimum and maximum values for the desired objectives, it demonstrates the interactions between land use functions including trade-offs and possible synergies and provides a number of alternative solutions to combine different of land use objectives. These outputs providing multiple options and a sound basis for decision making may contribute to the understanding of the system and to balanced decision making that does justice to interests of broad groups of stakeholders, which is considered instrumental for scientific support of active management of ecosystem services (Robertson and Swinton, 2005).

The results presented here can be considered as an output of a successful interactive modelling development process, originating from a joint effort of researchers and landscape planners and managers. The NGO 'Landschapsbeheer Friesland' considered the application of the Landscape IMAGES framework to be supportive in their landscape re-design process. By defining objectives and indicators, their implicit design rules have been made explicit. In the project meetings, where presentation of preliminary results from various intermediate versions of the model played an important role, additional constraints for the formulation of the sketch design became apparent. In this iterative process, input for tuning of the model was obtained, which was subsequently incorporated as additional indicators and constraints on data and calculations. The confrontation between the sketch design and the Pareto optimal set allowed LBF representatives to value their own design within the whole range of possible solutions.

The case study area used in this paper has been designated a ‘National Landscape’ of the Netherlands to harness habitat quantity and structure for biodiversity conservation. In an earlier prototype application the Landscape IMAGES methodology has been used to assess the interactions between farming activities on fields and linear landscape elements, and the impacts on economic results, nature value, landscape quality and environmental health at field, farm and landscape scales (Groot et al., 2007). Exploratory approaches can contribute to design issues on these various scales ranging from field to region and from landscape to continent (cf., Berger and Bolte, 2004; Holzkämper et al., 2006; Polasky et al., 2005). The underlying data will change in resolution and the relations to calculate indicators will be scale-dependent, but the main building blocks of the exploratory methodologies will prove to be robust and can be implemented in a generic manner: a GIS, a multi-objective optimizer, a visualization tool and a formulation of the optimization problem for calculation of the diverse indicators. Hölzkamper and Seppelt have proposed a similar generic optimization approach for design of multifunctional landscapes (2007).

In previous applications we have used linear programming based approaches to design and exploration land use systems (Rossing et al., 1997). We found generating nearly-optimal solutions (Makowski et al., 2001) more cumbersome than using Pareto-based differential evolution. An additional benefit of the latter method is its tolerance to different specifications of the optimization problem, which can be easily integrated in a GIS and can be coupled to complex computational algorithms such as mechanistic simulation models and spatial metric calculations, for instance to determine the minimum spanning tree. Mathematical programming methods fall short when faced with large combinatorial problems, as is the case in the applications in this section. Evolutionary computation is a useful compromise for the type of complex decision problems presented here where interest is more in trends and variation in the solutions than in precise optimality.

Thus, the flexibility of multi-objective evolutionary computation offers opportunities for connecting different spatial scales as well as different scientific disciplines to create new perspectives for sustainable land use. Future applications will rely on increased algorithmic efficiency, particularly in view of sparse solutions spaces at high numbers of objectives, and techniques to select and present relevant solutions in the discussion and negotiation process.

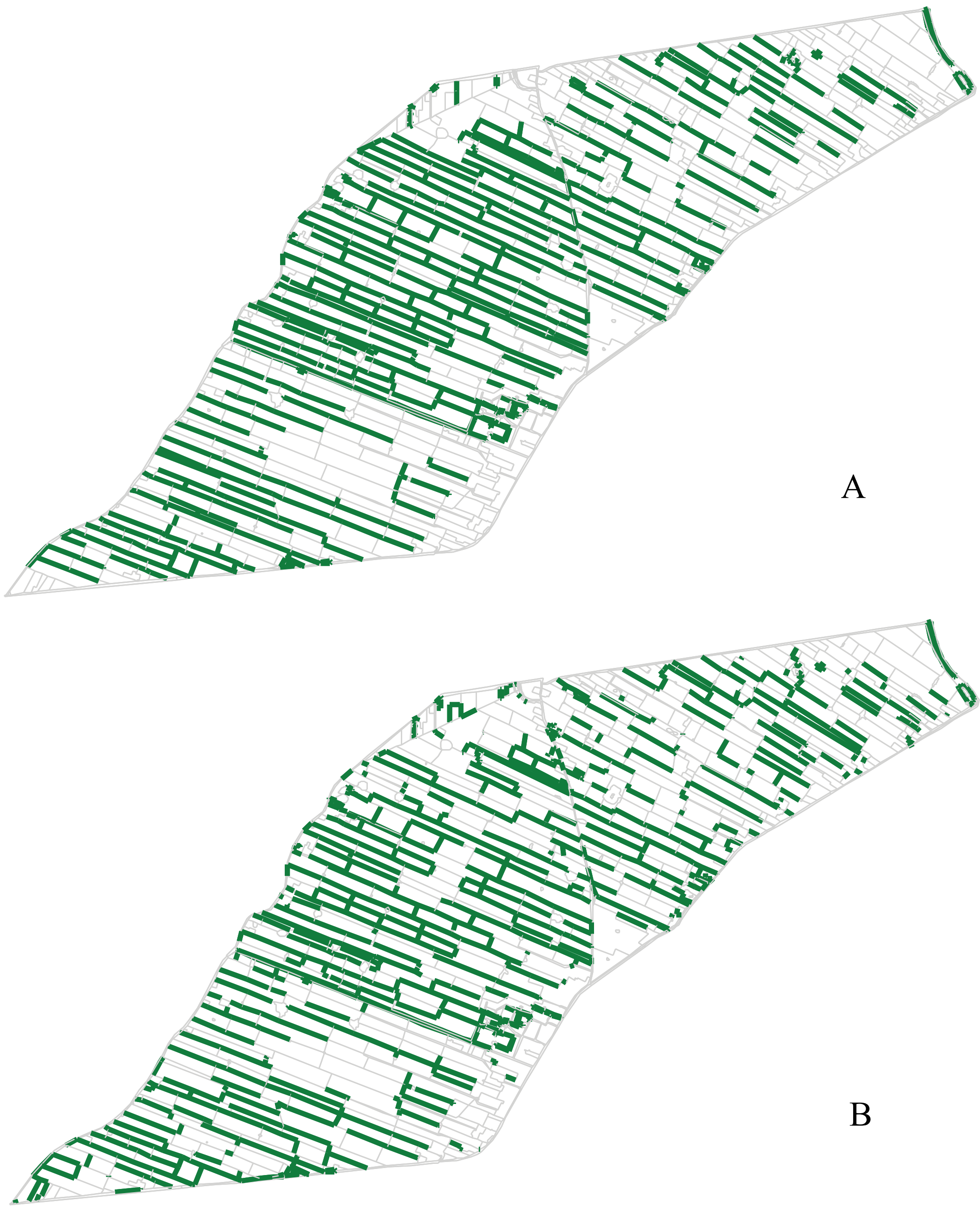

Figure 6. Original hedgerow configuration in the 873 ha case study region in the Northern Frisian Woodlands (A) and a generated landscape (B) with similar hedgerow length (85.6 km in A and 85.7 km in B) and connectivity (6.7 and 6.9, resp.), but strongly contrasting ratio between longitudinal and transversal hedges (8.79 in A and 5.75 in B) and porosity (45 and 15, resp.).

Acknowledgements

We would like to thank Foppe van der Meer and Els van Loon of Landschapsbeheer Friesland (LBF) for their cooperation in the project and their contribution to the elaboration of the methodology.

Chapter 8

General discussion

8.1 Introduction

In response to the problems with the sustainability of agriculture and increasing urbanization of Europe, multifunctional farming systems are being developed that serve various ecological, environmental and social functions besides the traditional function of food and fiber production. Landscape functions such as nature conservation or landscape character can not be managed at a farm or field scale but need to be managed at a regional scale. Spatial planning of land use activities aiming at sustainable natural resource management at a regional scale typically involves a high number stakeholders with often strongly contrasting perspectives and expectations about future developments. To facilitate balanced decision making insight is needed in the trade-offs and synergies between different land use functions at multiple spatial scales. In this thesis I have contributed to this need by:

(1) developing a generic analytical framework to analyze the interaction between land use functions at field, farm and landscape scale;

(2) developing a methodology for the evaluation of spatial coherence in (linear) ecological networks;

(3) developing an analytical method for landscape character assessment based on spatial patterns on a map;

(4) exploring possibilities to apply graph theory in land use studies.

In this chapter strong points and limitations of my research are presented, as well as recommendations for further research using the methodologies developed in this thesis. Potential application of the results will be discussed at the end of the chapter.

8.2 Balancing land use objectives at multiple spatial scales

In Chapters 2, 3 and 7 of this thesis a generic analytical framework, called Landscape IMAGES, has been developed to analyze the interaction between land use functions at multiple spatial scales. The Landscape IMAGES framework is based on the optimization of a set of mathematical functions using the concept of Pareto optimality and differential evolution. Each mathematical function describes a different land use function and can be defined at field, farm and landscape scale. The output of the framework consists of a cloud of optimal solutions, defining the trade-off surface or optimal pattern of interactions between functions (Chee, 2004). The solutions can be visualized and their performance quantified to further stimulate discussions about the consequences of the different designs. The cloud of Pareto optimal solutions provides insight in minimum and maximum levels for each of the land use functions and their interactions. Stakeholders and planners may use these trade-offs to discuss different levels of ambition for the realization of the objectives (Opdam et al., 2006) or to find synergies between land use functions (Knickel and Renting, 2000). Trade-offs show the opportunity cost of what must be given in one dimension to obtain more in the other dimension (Stoorvogel and Antle, 2001). For each solution alternative 'near-optimal' solutions (Makowski et al., 2001) are available in the solution space offering a set of feasible options, rather than a single blue print design (Prendergast et al., 1999). The Landscape IMAGES framework is generic because new functions can easily be adopted.

8.2.1 Strong points

In future-oriented land use studies different modeling approaches are being used. Examples are predictive modeling, single or multi-objective optimization and multiple criteria analysis. Predictive models (Caplat et al., 2006; Matthews, 2006; Verburg et al., 2002) project or simulate future trends from the current situation. These models provide only single solutions without reference to the boundaries to the solution space. There is no information available whether better solutions may exist. In optimization approaches, such as single objective optimization (Cabeza, 2003; Strange et al., 2006; Early and Thomas, 2007) or multi-objective optimization (Annetts and Audsley, 2002; Seppelt and Voinov, 2002; Hajkowicz et al., 2005; Marshall and Homans, 2006), a single land use function or a combination of land use functions is maximized. In contrast to predictive models the solutions are located at the boundaries of the solution space, but do not describe the boundary as such. The strength of the Pareto optimization methodology is that not the objective functions themselves are being maximized, but the trade-offs between the objectives are being optimized. In this way the whole boundary of the solution space is revealed, providing multiple optimal solutions and describing the interactions between objectives.

Another strong point of Pareto optimization is that objective functions do not need to be weighted in advance and brought to a common denominator, but are optimized within their own range. Typically, different land use functions will be expressed in different units of measurement. Within the Landscape IMAGES there is no need to express the value of one unit of a land use function in terms of units of another land use function. This allows land use functions from different disciplines to be implemented as such. As long as a function is quantifiable in the model, it can be combined with other functions. This is different, for example, in multiple criteria analysis where decisions are being made by weighting the relative value of options in advance (Balasubramaniam and Voulvoulis, 2005; Hajkowicz and Collins, 2007). In this thesis, economic, agronomic, nature and landscape functions have been combined.

8.2.2 Limitations

In literature concerns have been raised about the application of heuristic algorithms for optimization problems, because in contrast to exact methodologies, such as linear programming, heuristic optimization algorithms have no guarantee of optimality (Pressey et al., 1997; Fischer and Church, 2005; Vanderkam et al., 2007). Considering the objective of landscape IMAGES I do not see this as a major problem. The objective of the framework is not to develop a single optimal blue print design, but to stimulate thinking about consequences of alternative land use decisions in terms of multiple land use functions. For this objective near-optimal solutions will be acceptable. In scientific literature Differential Evolution is widely appreciated as a reliable optimization methodology providing close to optimal solutions (Bergey and Ragsdale, 2005; Mayer et al., 2005), which was confirmed at the beginning of this research in a number of small experiments not described in this thesis. In addition, the problem of sub-optimality should be considered in the perspective of many other uncertainties, such as uncertainties in data and indicators and the heterogeneity of values attributed to landscape characteristics and land use solutions by humans.

Another limitation in the Landscape IMAGES framework is the large number of iterations required to optimize the trade-off surface as the number of functions increases. As a result, the application of computer-intensive models cannot be included in the landscape IMAGES framework to evaluate the different land use functions. Currently, this limits the possibilities to include complex spatial or temporal interactions in the model and as a result landscape IMAGES provides only static images of future landscapes. This problem can be solved in three different ways. In Chapter 3 an optimization strategy is proposed using a two step approach. Instead of evaluating the performance of landscape functions during the optimization process, a set of prefab landscape configurations can be generated and evaluated in advance. In the optimization process one of the ‘prefab’ landscape configurations is selected and optimized for other land use functions within the defined constraints. In (Dogliotti et al., 2003) a similar approach is used for the optimization of crop rotations. Another two-step approach to solve this problem is found in (Seppelt and Voinov, 2002; Groeneveld, 2004). These researchers optimize simplified models before optimizing the complex model. The set of improved solutions are used as input for the complex model. The last option is simple increase computing power by using a distributed computing system (Rajkumar and Sulistio, 2008). The computational load will then be distributed across multiple computers.

The final limitation that addressed is the relation between the future images and current situation. The solutions provided by the framework are based on the evaluation of a spatial configuration of states. Different from predictive models (Bakker et al., 2005; Bogale et al., 2006; Verburg et al., 2006; Garcia-Frapolli et al., 2007) there is no link between the current situation and the solution provided. Therefore the framework is not suitable for trend extrapolation or to evaluate the time needed for a specific set of policy measures to achieve a desired future.

8.3 Spatial coherence in linear habitat networks

Two different approaches have been proposed in Chapters 4 and 7 to analyze spatial coherence of linear habitat networks. In Chapter 4 a spatially continuous conceptual model of connectivity was approximated by discretization of space using graph theory to describe and analyze between as well as within habitat connectivity relations. The new theoretical model for connectivity is a generic model: it bridges the patch oriented and the linear element oriented views on the landscape; it allows a consistent interpretation of connectivity at different spatial levels, including the concepts of link, patch and landscape connectivity; and it provides an analysis framework for the many different indicators of connectivity developed in ecology, including structural as well as functional measures. Graph theoretical measures derived from social sciences were applied to diagnose the functioning of the network and to determine the importance of different parts of the network.

In Chapter 7 graph theory has been applied to analyze the relation between the amount of interconnected habitat in the network and the dispersal capacity of a species. The methodology is related to other graph theoretical approaches in ecology (Urban and Keitt, 2001; Fall et al., 2007), but has an improved efficiency with which this relation is calculated. The amount of interconnected habitat influences the number of individuals in the network and can be seen as an indicator of survival probability (Verboom et al., 2001), especially when scaled against the ecological characteristics of a target species (Vos et al., 2001b).

The graph-based methodology in Chapter 7 can be used as a general indicator of spatial coherence in the network for a range of species, whereas the methodology in Chapter 4 can be used to direct spatial planning measures to reinforce the functioning of the network for specific target species or species profiles (Vos et al., 2001b). These characteristics make the methodology in Chapter 7 more suitable for the Landscape IMAGES framework, which is based on random changes in the landscape by the evolutionary optimization processes in the absence of detailed species information, while the methodology in Chapter 4 more suitable for a participative planning workshop (Opdam et al., 2006).

8.3.1 Strong points

In ecology a plethora of connectivity indicators have been developed to measure the strength of connections in the landscape. A distinction can be made between structural indicators (Moilanen and Nieminen, 2002; Winfree et al., 2005), based on the geometrical characteristics of the landscape and functional indicators based on process measurements (Vos et al., 2001a; Kindlmann et al., 2004) or simulation (Van Apeldoorn et al., 1998; Vuilleumier and Metzger, 2006) of the interaction between species and landscape (Goodwin, 2003). The graph theoretical model functions as an integrating framework for all of these measures and any of these measures can be implemented in terms of graphs. The ecological realism of the graph model depends on the connectivity measure being used. When a simple structural indicator such as a maximum dispersal distance is used (Chapter 4), the degree of ecological realism is relatively low, similar to the application of pattern indices (Gustafson, 1998; Cardille et al., 2005; McGarigal and Marks, 1995). However, as demonstrated in this thesis, even with a simple measure of connectivity, a quick scan analysis of the functioning of the network can be performed. This may be usefull in planning processes where detailed species information is often lacking. A higher degree of realism can be obtained when a functional connectivity measure, such as the number of immigrants, calculated with a simulation model is used (Van Apeldoorn et al., 1998; Vuilleumier and Metzger, 2006). The graph theoretical analysis than can be used aggregate model results at a higher integration level, for example to evaluate the importance of connections for the functioning of the network as a whole.

8.3.2 Limitations

In Chapter 4 and 7 a number of graph theoretical measures have been presented to evaluate spatial coherence of the network. These measures quantify certain properties of the network, for example the amount of habitat or the betweenness of a node, which are related to the functioning of the network. So far these relations have only been hypothetical. The graph theoretical indicators should be validated to substantiate the assumed ecological relevance. For practical application of the measures thresholds will need to be defined in relation to conservation objectives. Therefore, I propose to further investigate these graph theoretical measures using field observations or simulation models (Wiegand et al., 1999; Opdam et al., 2002).

Another limitation is the static character of the graphs and the graph measures proposed. As a result of human activities, habitats and connectivity relations in the agricultural landscape are constantly changing. Research has shown that these activities can have important effects on the connectivity in the landscape (Clergeau and Burel, 1997; Baudry et al., 2003; Purtauf et al., 2004). Even the relatively static structures such as hedgerows are in fact dynamic when viewed a long enough time scale (Schmucki et al., 2002); in the Frisian Woodlands hedgerows are cut in a 20 year cycle to maintain dense hedgerows of relatively small trees (De Boer, 2003). A conceptual solution may be found in the application of dynamic graphs. A dynamic graph is not fixed in time but may evolve through local changes, for example by the insertion or deletion of a node or edge (Amato et al., 1997; Urban and Keitt, 2001).

8.4 Characteristic regional landscape patterns

The answers to the questions: "What are characteristic landscape patterns for a region?" and "Where are they located?" are subjective and depend on the person being asked. In Chapter 5 a computerized approach has been developed using a graph-based spatially constrained clustering algorithm to delineate homogeneous landscapes based on the spatial data patterns in a GIS. The clustering algorithm merges similar data elements into larger regions, until the difference in pattern between all adjacent regions is above a certain threshold. Once the different landscape regions are defined, the landscape character can be described quantitatively and analyzed using non spatial clustering techniques or a landscape ideotype.

8.4.1 Strong points

Landscape character is commonly assessed by determining the number and distribution of different landscape features in predefined analysis units (Peccol et al., 1996; Palmer and Roos-Klein Lankhorst, 1998; Farjon et al., 2002; Scott, 2002; Geertsema, 2003; Ayad, 2005; De la Fuente de Val et al., 2006). The selection of the observation scale, the size and shape of analysis units, is a critical step in these methods and may severely bias the outcome of the pattern analysis (Openshaw and Tayler, 1981; Jelinski and Wu, 1996; Dark and Bram, 2007). In literature this effect is called the modifiable area unit problem or MAUP. In the methodology described in this thesis the region growing algorithm adapts size and shape of the analysis units to the landscape pattern itself, defining homogeneous regions of similar pattern.

Another interesting characteristic of the algorithm is that it may be used to explore the different perceptions on landscapes of people. By iteratively producing different landscape character maps and discussing the delineation and characterization of the landscape, local knowledge and personal views about the study area can be revealed. The advantage of this approach over for example using a drawing board is that borders around regions will not be drawn intuitively, but are the result of explicit formulation and implementation of ideas in the region growing algorithm. It will be interesting to actually test this approach, for example to characterize and delineate the different 'National Landscapes' of the Netherlands, using local perceptions of the regions (Anonymous, 2006).

8.4.2 Limitations

The result of the region growing algorithm is depends on many explicit and implicit decisions. Decisions are needed on: which algorithm to use; its parameter settings; which characteristics are included in the database; how to measure landscape characteristics and how these different characteristics will be weighted. To maintain transparency each of these decisions should be well documented and the final analysis result should be validated against an independent dataset. Further research is needed to study the consequences of such decisions. In this thesis I have made a start in Chapter 6 by evaluating 52 different segmentation algorithms to delineate different data patterns. It shows that the 'mutual best fit' decimation scheme, in combination with the 'increase in total deviation' dissimilarity criterion achieves accurate delineation results for a variety of patterns and is relatively insensitive to user defined parameters.

8.5 Application to spatial planning processes

Currently the usefulness of computer modeling tools for decision making processes in land use planning is under much debate (Prendergast et al., 1999; David, 2001; McCown, 2002; Walker, 2002; Sterk, 2007; Van Paassen et al., 2007). Traditionally decision support systems are seen as decision making tools, nowadays it has become clear that land use models should be seen as part of a social learning process (Loevinsohn et al., 2002; Walker, 2002; Sterk, 2007). Computer models may help stakeholders to express and share their own mental models, to generate communal knowledge about the system, to obtain insights in system complexity (Pahl-Wostl and Hare, 2004), to set the agenda and to create social communities (Sterk, 2007). In the literature a number of conceptual and technical characteristics are described for model to be usefully applied in social learning processes: flexibility of the model to adapt to a new social and bio-physical context, flexibility to allow shifts in ambition levels providing alternative options (Prendergast et al., 1999; Opdam et al., 2006) and the presentation of transparent and easy interpretable results (Luz, 2000; Buchecker et al., 2003).

During my study I found indications that Landscape IMAGES as presented in this thesis possesses such characteristics. The version of Landscape IMAGES as described in Chapter 3 was presented to an NGO in the Frisian Woodlands, Landschapsbeheer Friesland. The organization expressed its interest to see the approach applied in an ex-post evaluation of one of their landscape plans. This required a change from agro-economic land use functions to the development on indicators for landscape character and ecological quality. The Landscape IMAGES approach proved to be able to include these new functions relatively easy. Most time was spent elaborating the scientific foundation of the calculation processes. During the evaluation of the landscape plan for the agro-ecological zone, indicators and functions have been adjusted during an iterative process of implementation, discussion and improvement with the LBF. In a different research setting the landscape images framework has been applied to a different region of the Netherlands to explore the potential of ecological networks for pest suppression in agriculture (Groot et al., 2006).

By generating a cloud of Pareto optimal solutions the trade-off surface between land use functions is revealed. These trade-offs can be visualized in 2 dimensional figures, as presented in Chapters 2, 3 and 7 and be used by the stake-holders to discuss best compromises between objectives (Opdam et al., 2006) or to find synergies between land use functions (Knickel and Renting, 2000). Experiences with the NGO 'Landschapsbeheer Friesland' and representatives of farmers' organization N-LTO support the importance of interpretability results by graphical means of communication. For each solution alternative 'near-optimal' solutions (Makowski et al., 2001) are available in the solution space offering a set of feasible options to choose from. Each solution represents a spatially explicit landscape configuration evaluated quantitatively by indicators at different spatial scales and can be spatially visualized to deepen the understanding of the interactions between land use function (Chapters 2, 3 and 7).

There is still a lot to be learned about how to best deploy knowledge captured in models for planning purposes. The contribution in this thesis demonstrates new methodological and modeling options, and because of their development with a societal actor hold promise for achieving relevance in land use planning. To actually prove the applicability and to evaluate the framework, Landscape IMAGES framework needs to be tested and further developed in participative planning processes. Further developments of the regional plan for the Frisian Woodlands may provide such an opportunity.

Appendix

In Chapters 5 and 6 an alternative way to calculate the sum of squares, the variance and the standard deviation is introduced. Here the relation is derived:

$$
\begin{aligned}
d2_{kk} &= \sum_{z\in Z}\sum_{i\in k}\sum_{j\in k}\alpha^{z}(d_{ij}^{z})^{2} \\
&= \sum_{i\in k}\sum_{j\in k}(d_{ij}^{z})^{2} \\
&= \sum_{i\in k}\sum_{j\in k}(x_i - x_j)^{2} \\
&= \sum_{i\in k}\sum_{j\in k}\left[\left(x_i - \bar{x}\right) - \left(x_j - \bar{x}\right)\right]^{2} \\
&= \sum_{i\in k}\sum_{j\in k}(x_i - \bar{x})^{2} + \sum_{i\in k}\sum_{j\in k}(x_j - \bar{x})^{2} - 2\sum_{i\in k}\sum_{j\in k}\left(x_i - \bar{x}\right)\left(x_j - \bar{x}\right) \\
&= 2n_k\sum_{i\in k}(x_i - \bar{x})^{2} - 2\sum_{i\in k}\sum_{j\in k}\left(x_i x_j - x_i\bar{x} - x_j\bar{x} + \bar{x}^{2}\right) \\
&= 2n_k\sum_{i}(x_i - \bar{x})^{2} - 2*0 \\
&= 2n_k ss_k \\
&= 2n_k^{2}\,\mathrm{var}_k \\
&= 2n_k^{2} std_k^{2}
\end{aligned}
$$

where x = {x_1, x_2, … x_n} is the set of continuous attribute values for attribute z, |Z| = 1 and $\alpha^z = 1$.

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Summary

In response to the problems with the sustainability of agriculture and increasing urbanization of Europe, multifunctional farming systems are being developed that serve various ecological, environmental and social functions besides the traditional function of food and fiber production. Landscape functions, such as nature conservation or landscape character, can not be managed at a farm or field scale but need to be managed at a regional scale. Spatial planning of land use activities aiming at sustainable natural resource management at a regional scale typically involves a high number stakeholders with often strongly contrasting perspectives and expectations about future developments. To facilitate balanced decision making insight is needed in the trade-offs and synergies between different land use functions at multiple spatial scales.

This thesis addresses this need by developing a generic analytical framework to analyze the interactions between land use functions at field, farm and landscape scale. In addition new methodologies have been developed using graph theory to assess the functioning of agricultural landscapes, focussing on the spatial coherence of ecological networks and landscape character. Graph theory is a mathematical theory, which uses a data format of pair-wise relations between objects or graphs, to solve mathematical problems. This is an interesting approach for landscape studies, because different from other data formats, spatial relations between the objects in the landscape can be modeled and analyzed directly. All methodologies developed in this thesis have been illustrated with case studies from the Northern Frisian Woodlands, a unique dairy farming area in the north of the Netherlands characterized by a landscape of pastures intersected by hedgerows. Farmers in the Northern Frisian Woodlands are pioneers in the development of landscape management, multifunctional agriculture and regional collaboration.

The interaction between land use functions at multiple spatial scales is examined by determining trade-off surfaces between land use functions with a spatially explicit optimization approach. The conceptual model for this approach is presented in Chapter 2. A trade-off surface can be seen as the boundary of the feasible set of function combinations and represents the 'window of land use options' for the decision maker given the state of knowledge and the implemented models. The trade-off between different land use functions is determined using multiple goal optimization. To this effect, a heuristic search method consisting of the concepts of Differential Evolution and Pareto optimality is used. Rather than optimizing a specific objective, the concept of Pareto optimality allows the direct optimization of the trade-off surface. In Chapter 3 this idea is implemented in the Landscape IMAGES framework and as proof of

concept a near-real case study in the Frisian Woodlands has been elaborated demonstrating its applicability. By adjusting land use intensities and hedgerow configurations different landscape plans are generated to balance four objectives: 1. maximize economic returns for farms, 2. maximize diversification of the botanical composition of fields and hedgerows, 3. maximize variation in and half-openness of the landscape, and 4. minimize nutrient losses to the environment. The trade-offs are presented as 2-dimensional projections of the 4-dimensional cloud of Pareto optimal solutions and for each of the solutions a spatially explicit image of the future landscape can be presented, based on a quantitative scientific model.
When the number of objectives in the optimization problem increases the efficacy of simple Pareto optimality decreases due to the large number of Pareto optimal solutions in the solution set. In Chapter 7 the concept of Pareto optimality is extended by introducing the concept of Pareto efficiency to distinguish among solutions within the same Pareto rank. The extended version of the Landscape IMAGES framework is applied to evaluate alternatives of a landscape plan for an agri-ecological zone in the Northern Frisian Woodlands, made by the NGO Landschapsbeheer Friesland (LBF). Objectives and indicators for Landscape IMAGES were developed in an iterative process of design, demonstration and redesign between the researchers and LBF, in which the LBF had an active role. By positioning the current situation and LBF's landscape plan within the whole set of Pareto optimal solutions, options for improvement of the landscape plan and the consequences of the design rules applied by the NGO could be evaluated. In the General discussion (Chapter 8) the Landscape IMAGES framework is discussed in relation to a number of requirements for the successful application of decision support models in landscape planning, based on literature. To further develop the Landscape IMAGES framework, it needs to be implemented in a participative planning processes.

Graph theory has been applied for the analysis of landscape functions in two different ways. In Chapters 4 and 7 graph theory has been used for evaluation of spatial coherence of linear habitat networks and in Chapters 5 and 6 graph theory has been used for identification of landscape patterns.
As there was no conceptual model available to accurately describe and analyze linear ecological networks due to the predominance of patch-based models, a new graph theoretical model for connectivity has been developed in Chapter 4. This model bridges the patch oriented and the linear element oriented view on landscapes in ecology; it allows a consistent interpretation of connectivity at different spatial levels, including the concepts of link, patch and landscape connectivity; and it provides an analysis framework for the many different indicators of connectivity developed in

ecology, including structural as well as functional measures. The applicability of the graph theoretical model is demonstrated using the graph theoretical indicators of degree, closeness, core value and betweenness to diagnose the functioning of the network and to predict the effect of connectivity on local species distribution, species spread, vulnerability of the network for fragmentation and importance of specific habitats for the total network coherence. The proposed methodology could be used in planning processes to direct conservation measures. In Chapter 7 graph theory is applied to describe the relation between the amount of interconnected habitat in a network and the dispersal capacity of a species. The amount of interconnected habitat influences the number of individuals in the network and the survival probability of species. The integral of this relation is used as a general measure of spatial coherence of a network for a range of species.

In Chapter 5 graph theory is applied for landscape character assessment. A computerized approach has been developed, which uses a regionalization algorithm derived from image analysis, to delineate and characterize homogeneous landscapes based on spatial data patterns in a GIS. The regionalization algorithm merges similar data elements into larger regions, until the difference in patterns between all adjacent regions exceeds a threshold. The resulting division of the landscape is then classified and validated against an independent data source. In Chapter 5 the results of the computerized methodology were compared with assessments by experts. The methodology could be used to analyze and map different human landscape perceptions. The regionalization algorithm itself can be applied as a general analysis tool in geosciences, where the delineation of spatial data patterns is needed.

Results of the landscape characterization are partly depending on the algorithm used. Therefore, in Chapter 6, 52 different algorithms have been evaluated for their skill to delineate different data patterns. An analysis framework consisting of a pattern generator and indicators has been developed and used to assess the accuracy, sensitivity and efficiency of the algorithms. The advantage of such a benchmark approach is that the response of algorithms to variations in data patterns can be measured directly and objectively. The analysis shows a wide variety in performance among algorithms. It was concluded that the algorithm applied in Chapter 5 provides accurate delineation results for a variety of patterns and is relatively insensitive to user defined parameters. Strengths and weaknesses of the new graph theoretical approaches are discussed in Chapter 8.

Samenvatting

Als antwoord op de duurzaamheidproblematiek in de agrarische sector en de toenemende verstedelijking in Europa worden er multifunctionele landbouw bedrijfssystemen ontwikkeld die naast de productie van voedsel en vezels ook ecologische, milieu en sociale functies bezitten. Landschapsfuncties zoals natuurbeheer of het behoud van landschappelijk karakter, kunnen niet worden gerealiseerd op de schaal van een enkel veld of bedrijf. Voor de planning van deze landgebruikactiviteiten op een regionale schaal is de betrokkenheid van diverse belanghebbenden noodzakelijk, wier visie en verwachting over de toekomstige ontwikkelingen in een gebied vaak tegenover elkaar staan. Om afgewogen beslissingen mogelijk te maken is inzicht nodig in de uitruil en win-win relaties tussen de landgebruikfuncties op verschillende schaalniveaus.

Dit proefschrift speelt in op deze behoefte door het ontwikkelen van een generiek analytisch model dat de interacties tussen landgebruikfuncties op veld-, bedrijfs- en landschapsschaal inzichtelijk maakt. Daarnaast worden er methoden aangereikt om landschapsfuncties in het agrarische gebied te kunnen evalueren, waarbij de focus ligt op de ruimtelijke samenhang van ecologische netwerken en op het karakter van landschappen. Bij de ontwikkeling van deze methoden speelt de graaf theorie een belangrijke rol. Grafentheorie is een wiskundige theorie, die gebruik maakt van een beschrijving van paarsgewijze relaties tussen objecten om problemen op te lossen. Deze eigenschap maakt het mogelijk om, in tegenstelling tot andere vormen van probleembeschrijving, ruimtelijke relaties in het landschap op een directe manier te beschrijven en analyseren. Alle in dit proefschrift gepresenteerde methoden zijn geïllustreerd met behulp van voorbeelden uit de Noordelijke Friese Wouden. Dit unieke melkveehouderij gebied in het noorden van Nederland wordt gekenmerkt door een landschap van graslanden doorsneden met houtwallen. De boeren in de Noordelijke Friese Wouden zijn pioniers op het gebied van landschapsbeheer, multifunctionele landbouw en regionale samenwerking.

Interacties tussen landgebruikfuncties op meerdere schaalniveaus zijn inzichtelijk gemaakt door de uitruilrelaties tussen deze landgebruikfuncties te benaderen met een ruimtelijk expliciet optimaliseringmodel. Het conceptuele idee achter deze benadering wordt uiteengezet in Hoofdstuk 2. De uitruilrelaties tussen functies kunnen worden gezien als de grenzen aan de ontwikkelingsmogelijkheden van een gebied of de set aan kansen voor de ruimtelijke planner, gegeven het huidige kennisniveau en de geïmplementeerde modellen. Voor de berekening van de uitruilrelaties wordt het probleem gedefinieerd als een meervoudig optimalisatieprobleem. Dit wordt opgelost door middel van een heuristiek

zoekalgoritme gebaseerd op het simuleren van evolutionaire processen, de zgn. Differentiële Evolutie, gecombineerd met Pareto rangordenen. Deze combinatie van technieken maakt het mogelijk om direct de uitruilrelatie tussen landgebruikfuncties te benaderen, in plaats een specifieke doelstelling te optimaliseren en is geïmplementeerd in het model 'Landscape IMAGES' (Hoofdstuk 3). Als een functioneel bewijs is een demonstratie casus uitgewerkt voor de Noordelijke Friese Wouden. Door het schuiven met houtwallen en landgebruik worden er verschillende inrichtingsplannen gegenereerd, waarbij aan vier verschillende doelstellingen moest worden voldaan: 1. maximalisatie van de economische inkomsten van de bedrijven, 2. maximalisatie van de plantendiversiteit op velden en in houtwallen, 3. maximalisatie van afwisseling en openheid van het landschap, en 4. minimalisatie van stikstofuitspoeling. De uitruilrelaties zijn gevisualiseerd als 2-dimensionale projecties van een 4-dimensionale puntenwolk met Pareto-optimale oplossingen. Bij elk punt van de wolk hoort een kaart met een toekomstig landschapsbeeld op basis van een kwantitatief wetenschappelijk model.
Naarmate het aantal doelstellingen in het optimalisatieprobleem toeneemt, verliest de techniek van Pareto rangordenen zijn kracht, omdat er relatief veel oplossingen met een hoge Pareto rang ontstaan. Daarom wordt in Hoofdstuk 7 de methode uitgebreid met het concept van Pareto efficiëntie. Dit concept maakt het mogelijk om onderscheidt te maken tussen oplossingen met dezelfde Pareto rang. Deze uitgebreidere versie van Landscape IMAGES is gebruikt om alternatieven voor een landschapsplan van een agro-ecologische zone in de Noordelijke Friesche Wouden te evalueren, gemaakt door Landschapsbeheer Friesland (LBF). Tijdens deze samenwerking zijn, in een aantal ontwerpsessies met LBF, de doelstellingen en indicatoren voor het model ontwikkelt, waarbij ideeën werden gedemonstreerd aan en becommentarieerd door de LBF, om vervolgens te worden aangepast. Door het huidige landschap en het ontwerp van LBF in de wolk van Pareto optimale landschapsplannen te plaatsen, konden mogelijkheden tot verbetering van het bestaande plan en de landschapsontwerpregels van de LBF worden geëvalueerd. In de algemene discussie (Hoofdstuk 8) wordt het Landscape IMAGES model besproken aan de hand van een aantal aandachtspunten voor de succesvolle toepassing van beslissingsondersteunende modellen beschreven in de wetenschappelijke literatuur. Voor de verdere ontwikkeling en toetsing van het model is de toepassing in een interactief planningsproces met meerdere belanghebbenden noodzakelijk.

In dit proefschrift is grafentheorie is op twee verschillende manieren toegepast voor evaluatie van landschapsfuncties. In de Hoofdstukken 4 en 7 wordt grafentheorie gebruikt voor de evaluatie van de ruimtelijke samenhang in lijnvormige habitatnetwerken en in de Hoofdstukken 5 en 6 wordt grafentheorie gebruikt voor identificatie van landschapspatronen.

In Hoofdstuk 4 wordt een nieuw graaftheoretisch model gepresenteerd voor het beschrijven en analyseren van ruimtelijke samenhang in lijnvormige habitatnetwerken. Het model is bedoeld als een alternatief voor locatiespecifieke modellen. Het nieuwe model slaat een brug tussen de lijn- en locatiespecifieke perceptie van landschap in de ecologie; het interpreteert veelgebruikte begrippen als de connectiviteit van een verbinding, de connectiviteit van een plek en landschapsconnectiviteit, op een consistente manier; en het biedt een generiek analytisch kader voor de verschillende structurele en functionele connectiviteitsmaten in de ecologie. De toepasbaarheid van het graaftheoretisch model wordt gedemonstreerd aan de hand van het gebruik een aantal graaftheoretische indicatoren voor netwerkanalyse. De graafindicatoren verbondenheid, nabijheid, kernwaarde en tussenheid, kunnen worden gebruikt om de verspreiding van soorten en de bereikbaarheid, de kwetsbaarheid voor fragmentatie en de brugfunctie van specifieke stukken van het netwerk te evalueren. De gepresenteerde methodologie zou kunnen worden gebruikt in planningsprocessen om de implementatie van natuurbeschermingsmaatregelen te sturen. In Hoofdstuk 7 wordt grafentheorie toegepast om de relatie tussen de hoeveelheid verbonden habitat in een netwerk en het verspreidingsvermogen van een soort te beschrijven. De hoeveelheid verbonden habitat is bepalend voor de grootte van populaties en dus voor de overleving van een soort. De integraal van deze functie kan worden gebruikt als een algemene indicator voor de ruimtelijke samenhang van een netwerk voor een groep soorten met verschillend verspreidingsvermogen.

In Hoofstuk 5 is grafentheorie toegepast voor de bepaling van het karakter van landschappen. Op basis van een regionaliserend algoritme is er een gecomputeriseerde aanpak ontwikkeld, die homogene landschappen afbakent en karakteriseert op basis van ruimtelijke datapatronen in een Geografisch Informatie Systeem (GIS). Het regionaliserend algoritme voegt gelijkende naburige data-elementen samen tot grotere regio's totdat het verschil tussen de regionen boven een vooraf ingestelde drempelwaarde ligt. De resulterende verdeling in landschappen wordt vervolgens geclassificeerd in landschapstypen en dient gevalideerd te worden met behulp van een externe gegevensbron. In Hoofdstuk 5 worden de resultaten van de computergebaseerde methodologie vergeleken met landschapskarteringen gemaakt door experts. De gepresenteerde methode zou toegepast kunnen worden om de verschillende landschapsbelevingen van mensen te analyseren en in kaart brengen. Het regionaliserend algoritme zou ook gebruikt kunnen worden als een algemene methode voor afbakenen van ruimtelijke datapatronen in de geo-informatiekunde.

De resultaten van de landschapsclassificatie zijn voor een deel afhankelijk van het gebruikte algoritme. Daarom worden er in Hoofdstuk 6 52 verschillende regionalisatie algoritmen vergeleken op hun toepasbaarheid voor het analyseren van datapatronen. Hiervoor is een evaluatiemethode ontwikkeld die bestaat uit een generator van datapatronen en uit indicatoren die de accuratesse, de gevoeligheid en de efficiëntie van de algoritmen kunnen meten. Een belangrijk voordeel bij deze benadering is dat het effect van de van te voren gedefinieerde variaties in een datapatroon op de werking van de algoritmen direct en objectief kan worden gemeten. De evaluatie laat een grote variatie in prestaties van de algoritmen zien. Eén van de conclusies is dat het algoritme gebruikt in Hoofdstuk 5 accurate resultaten oplevert bij het onderscheiden van een verscheidenheid aan patronen en relatief ongevoelig is voor door gebruikers gedefinieerde parameters. In Hoofdstuk 8 worden de sterke en zwakke punten van de verschillende graaftheoretische benaderingen bediscussieerd.

Acknowledgements

Although this thesis carries only one name, a PhD research cannot be carried out alone. Here, I would like to express my appreciation for all contributions, large and small, to my thesis.

First I would like to thank my team of supervisors: my co-promotor Walter Rossing and my promotors Ariena van Bruggen and Paul Opdam, for their dedication and support throughout my research. ´Walter, I have learned a lot from you and enjoyed having you as my daily supervisor. Your open and positive attitude, your willingness to lend your brains for different kinds of problem solving, but also you capability to step back and led me find my own way, are only three of the many positive qualities I discovered over the past few years.´ ´Paul, you are always searching for constructive solutions, helped in finding the core and ways to display the key messages of my research'. 'Ariena, I appreciate your enthusiasm and dedication to science and students, your questions have sharpened my mind and my research, I would like to thank you for guarding my PhD process'.

Beside these three pillars, my research has benefitted a lot from the collaboration with two colleagues. 'Derk-Jan, quantitative meets qualitative. It took a while before I was ready, but then our project took off. That was fun!'. 'Jeroen, Big Friendly Giant, without your magic there would still be computers in the building calculating for me. But your scientific contribution to my thesis is much larger, as is reflected in the number chapters with you as co-author.

One of my important questions before I started this project was whether collaboration with other researchers would be possible. It was. My project became part of the WUR-INRA project, a collaboration between Wageningen University and the Institut National de la Recherche Agronomique in France. First, I would like to thank the Dutch members of the project for their input in my research: Martin van Ittersum, Gerry van de Ven, Henk Renting, Kees Booij, Niels Dignum, Paul Swagemakers and Bart Venhorst. Every half a year there was a meeting with our French partners in Paris or Wageningen. Also, I would like to thank the French team for our discussions on multifunctional agriculture, especially Catherine Laurent for organizing these sessions and Muriel Tichit for our conversations on ecology and modeling. I would like to thank Jacques Baudry, Françoise Burel and Claudine Thenail for their explanations about hedgerow ecology and their hospitality during my visit in Rennes, France.

Doing a PhD with a large theoretical component, the research involved a lot of hard work on mathematics. Fortunately, Wageningen has a number of good mathematicians to support. I would like to thank: Paul Goedhart, Michiel Jansen, Frits Claassen, Lia Hemerink and Cajo ter Braak for their contributions to this project.

I would like thank the Geodesk: Frans Rip, Marc Hoogerwerf and Theo van der Heijden, for providing me with the data of the Frisian Woodlands and Kymo Slagers for checking each of the 99,286 polygons.

For the applied component of my thesis, I would like to thank Foppe van der Meer and Els van Loon (Landschapsbeheer Friesland) for their collaboration on the Landscape IMAGES model and Jaap Dijkstra (LTO Noord), Fokke Benedictus and Teake Hoeksma (Environmental Cooperative Noardlike Fryske Wâlden) for their landscape character maps.

My desk has been situated at two different locations. For the first two years I have been a guest of the team ‘Ecological Networks’ at the research institute Alterra, later I moved to the Biological Farming Systems group at Wageningen University. I would like to thank the members of these groups and of the neighbouring groups ‘Ecological Models and Monitoring’ and ‘Horticultural Production Chains Group’ for being my social working environment over the past few years. I especially would like to thank: Carla Grashof-Bokdam, René Jochem, Rogier Pouwels, Claire Vos, Jana Verboom, Hans Baveco and Willemien Geertsema for your scientific input, Wampie Schouwenburg for your invaluable help with the layout the thesis, Eelco Franz and Sacha Semenov for your attempt to teach me table tennis, Peter Carberry for your invitation to CSIRO - Sustainable Ecosystems and your hospitality at Surfers Paradise, and my Alterra roommates: Henk Meeuwsen for the laughs, Anna Zaborowska for your hospitality in Mikolajki, Laura Bosschieter for your friendship and Fabrice Ottburg, for trying to show me the ‘common spadefoot’, which I still haven’t seen.

In the end, doing a PhD is impossible without a supportive home ground. I would like thank my family, family-in-law and friends for distracting me from my work, making hikes, playing board games, volleyball, going scuba diving or having good conversations. I would like to thank my paranymphs Floor Boerwinkel and Frans van Bommel for their support during my defense, Mark van Passel for reading through some chapters (6 orval), my parents and my sister for supporting me over the past 33 years, but I especially want to thank Emmy Hagenaars. ‘In times of stress you look for different ways to help, but the biggest help of all is that I know that you are there for me. Thanks for all.’

Curriculum Vitae

André Jellema was born on August 9th 1974 in Den Helder, the Netherlands. From 1993 to 1999 he studied Biology at Wageningen University, specializing in ecology, computer modeling and GIS. His MSc projects included studies on the population dynamics of roe deer in the Netherlands and on the spatial distribution of land cover types in Tigray, Ethiopia. In 1997 he attended a course in tropical field ecology organized by the Tropical Biology Association at Elsamere Conservation Center, Kenya. After his graduation in 1999 he worked at the Centre for Geo-information, Wageningen University, developing and teaching internet supported courses, in particular a course on spatial modeling in landscape ecology (SMILE). In 2001 and 2002 he worked in Botswana as a remote sensing specialist on a vegetation map of the Okavango delta at the Harry Oppenheimer Okavango Research Center, University of Botswana. In 2003 he started his PhD research at the Biological Farming Systems group, Wageningen University, of which this thesis is the end result. During this period he has been an active member of the PE&RC PhD Student Platform and the Wageningen PhD Council. In his spare time he enjoys scuba diving.

List of publications

Peer-reviewed journals

Jellema A., Groot J.C.J., Rossing W.A.H. (submitted): Designing a hedgerow network in a multifunctional agricultural landscape - balancing trade-offs between ecological quality, landscape character and implementation costs. *European Journal of Agronomy.*

Jellema A. and Rossing W.A.H. (submitted): Evaluation of graph pyramid segmentation algorithms for regionalization of spatial data in a GIS. *International Journal of Geographical Information Science.*

Jellema A., Rossing W.A.H. and Opdam P.F.M. (submitted): On connectivity in linear habitat networks using a graph theoretical model. *Ecology*

Jellema A., Stobbelaar, D.J., Groot J.C.J., Rossing W.A.H (accepted): Landscape character assessment using region growing techniques in geographical information systems. *Landscape and Urban Planning.*

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Ringrose, S., Chipanshi, A. C., Matheson, W., Chanda, R., Motoma, L., Magole, I. & Jellema, A. (2002): Climate- and human-induced woody vegetation changes in Botswana and their implications for human adaption. *Environmental Management* **30**, 98-109.

Congresses and conferences

Jellema, A., Groot, J.C.J., Rossing, W.A.H., (2007): Region growing in GIS, an application for landscape character assessment. In: *MODSIM07, International congress on modelling and simulation land, water & environment management: integrated* system*s of sustainability*, Christchurch, New Zealand, 10 - 13 December 2007, Christchurch, New Zealand, p. 207.

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Jellema, A., Rossing, W.A.H., Opdam, P.F.M. (2004): Landscape prototyping: towards an integrative approach for the design and analysis of multifunctional agricultural landscapes. In: *European farming and society in search of a new social contract - learning to manage change. Proceedings of the 6th European IFSA Symposium*, Vila Real, Portugal 4-7 April 2004, 293-302

Jellema, A., Heitkönig, I.M.A., Van Lammeren, R.J.A. (2000): Teaching expert modelling for biodiversity management via the internet. In: *Book of abstracts : 2000 World Conference on Natural Resource Modelling,* Wageningen, the Netherlands, 2000, p. 24.

Other documents

Jellema, A. (2003): Landschaps-prototypering : een integrale benadering voor het ontwerpen en analyseren van multifunctionele agrarische landschappen. Landschap **20**, 14-18.

Jellema, A, de Vries, S. (2003): Towards an indicator for recreational use of nature: modelling car-born visits to forests and nature areas (FORVISITS). Wageningen : Natuurplanbureau, (Werkdocument 2003/17), p. 59.

PE&RC PhD education certificate

With the educational activities listed below the PhD candidate has complied with the educational requirements set by the C.T. de Wit Graduate School for Production Ecology and Resource Conservation (PE&RC) which comprises of a minimum total of 32 ECTS (= 22 weeks of activities)

Review of Literature (5 ECTS)

- Conceptual integration and optimization of landscape functions

Writing of Project Proposal (3 ECTS)

- Landscape prototypes for multi-functional agriculture

Laboratory Training and Working Visits (1 ECTS)

- Hedgerow ecology; INRA RENNES (2005)

Post-Graduate Courses (3 ECTS)

- PhD Masterclass: integrative research for the planning and management; Sense (2004)

Deficiency, Refresh, Brush-up Courses (3.5 ECTS)

- QUASIL; WUR (2003)
- Biologische landbouw; PHLO (2003)

Competence Strengthening / Skills Courses (3.9 ECTS)

- Project management planning; STOAS (2003)
- Multivariate analysis; PE&RC (2005)
- PhD Competence assessment; WGS (2006)
- Procesbegeleider – academic consultancy training; DO (2008)

Discussion Groups / Local Seminars and Other Scientific Meetings (5 ECTS)

- Agricultural production systems (2003/2004)
- Statistics, maths and modelling in production ecology and resource conservation (2005/2006)

PE&RC Annual Meetings, Seminars and the PE&RC Weekend (1.5 ECTS)

- PE&RC Weekend (2003)
- Annual meeting (2004)
- Annual meeting (2005)

International Symposia, Workshops and Conferences (11 ECTS)

- The young landscape ecologist (2003)
- WUR-INRA Multifunctional agriculture workshops (2003-2006)
- 6^{th} European symposium on farming and rural systems research and extension (2004)
- IALE World congress (2007)
- MODSIM Conference (2007)

Courses in which the PhD Candidate has Worked as a Teacher

- Analysis of farming systems FMA 10804 (6 days); BFS (2003)
- System analysis, simulation and systems management PPS 20304 (30 days); PPS (2004, 2007, 2008)
- Analysis and design of organic farming systems BFS 3006 (14 days); BFS (2005)
- Capita Selecta: graphs, networks and applications (4 days); CGI (2007)