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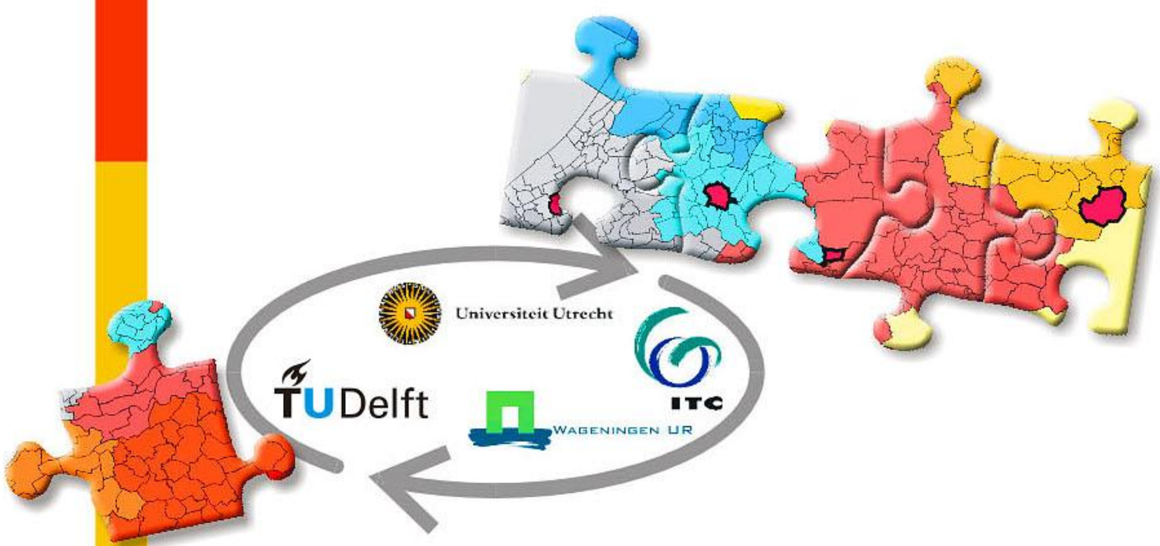
The suitability of GIS methods for analyzing urban sprawl, and the influence of scale.

Dennis Weijers



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MSc Thesis

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Summary

There is a lot of confusion about the concept of urban sprawl. Many different definitions, and ambiguity of how to analyze, measure and monitor urban sprawl do exist. Most of the research that measures and analyzes urban sprawl with a Geographical Information System (GIS), has measured the urban sprawl only at one spatial scale. But does the scale not always affect measurements? Therefore this study researches the suitability of the most widely used GIS methodologies that are used within the literature to analyze urban sprawl, and the effect, influence, of scale on these methodologies. The central research question is:

What is the suitability of the GIS methods which are used for analyzing urban sprawl, and what is the influence of scale on these methods?

The application of a case study enables the testing of the suitability of the found GIS methods and the influence of scale on these methods. In this case the Green Heart, the Netherlands, has been examined as the case study area.

To fully understand the concept of urban sprawl, first several questions are answered. What does urban sprawl entails? How does urban sprawl expresses itself physically and spatially? What are the catalysts of urban sprawl? What are the benefits of using a GIS to measure urban sprawl? Which methods are commonly or normally used to measure urban sprawl with a GIS? What is the influence of scale on the methods? And which variables influence the methodology of measuring urban sprawl with a GIS.

Urban sprawl has many definitions which share facts but differ in details. The definition of Galster et al., (2001) is the most widespread. In their study urban sprawl is defined as an urbanized area with low levels of density, continuity, concentration, clustering, centrality, nuclearity, mixed use, and proximity, (different combinations are possible). Distinctive characteristics of urban sprawl are: expansion of the urban area into the suburbs, the development of single purpose settlements, car dependent developments, low density, uneven patterns, spontaneous and unplanned (incremental and uncoordinated), and a loss of open rural area. However there is a growing need to reach consensus and determine a widely and broadly accepted definition of what urban sprawl exactly entails.

Different forms of urban sprawl are classified in terms of compactness and dispersion degrees. Five different physical forms of urban sprawl currently exist. First is compact development, which expresses itself physically by the contiguous development of built-up areas adjacent to the existing urban area, without the creation of patches, and mainly in high density. The second form (type) of urban sprawl is the linear strip development, in which urban (built-up) developments occur along infrastructural works or rivers. The third form is polynucleated development, where several smaller built-up areas agglomerate, and create a distinct urban area separated from the existing urban area, thus the creation of multiple nuclei, which are physically and spatially separated from each other. The fourth urban sprawl form is scattered development, where built-up develops in a discontinuous and uncoordinated way away from the urban area, which leads to the creation of open and vacant land between built-up areas. The fifth and last form of urban sprawl is leapfrogging development, where the development of new built-up areas leapfrogs over existing barriers.

The drivers or catalysts of urban sprawl can be classified into four separate categories: economy, society, transport, and policy. Economy can be further divided into macroeconomic (globalization

and the European Union) and microeconomic drivers (market failure, competition between municipalities, and purchasing power between countries). Population growth and housing preferences are drivers of urban sprawl which can be classified as societal drivers. For the transportation category the rise of automobiles is the most important driver of urban sprawl. Finally in the policy category, coordination problems on the physical planning and policy failure are the most important divers of urban sprawl.

Governments need to make spatial plans by using updated and accurate information, and the expansion of the urban area is a challenge. Conventional and traditional survey and mapping techniques have become too expensive and time consuming. As a response, GIS techniques emerged to monitor urban sprawl. GIS is capable of visualizing remotely sensed images (classified into land use maps), and monitoring them. Ultimately, by using them, GIS is even capable of forecasting land use changes. Urban sprawl can be analyzed as a GIS, where spatial statistics parameters and indices can be calculated for characterizing the landscape properties, spatial distribution, land use change, and the extent of urban sprawl.

Urban sprawl can be analyzed with a GIS once the land use change is analyzed, when the pattern of the developed built-up (urban) areas area is analyzed, and when landscape metrics are configured. Landscape metrics describe and quantify the structure of landscapes (the composition and the arrangement) and the spatial relationships. Land use changes occur when urban sprawl exhibits itself in an area. The process of change detection provides insight into the underlying land use changes. Analyzing the pattern of the built-up area gives insight into the form of the expanding built-up areas. Landscape metrics partly support the analysis of the urban sprawl pattern. The pattern of a landscape is typified by its size, shape, arrangement and distribution of individual landscape elements.

Before analyzing urban sprawl with a GIS, it is important to consider some of the variables which influence the measurements. First there is the definition problem of urban sprawl, because of a lacking of a commonly agreed definition of what urban sprawl exactly entails. Secondly, there are two classification problems influencing the measurement of urban sprawl: the amount of classes and classification methods. For example landscape metrics all respond differently when more land use classes are used. And a difference in classification methodology, leads to a different composition of the land use class, which has its reflection on the landscape metrics value. The third problem which influences the measurement of urban sprawl are data problems. Data quality and data availability has its reflections on the landscape metrics. The last variable which influences the measurement of urban sprawl is the modifiable areal unit problem (MAUP). MAUP is a problem which occurs while analyzing spatially aggregated data. MAUP consist out of two aspects, the scale and the zoning problem. The scale problem is also called the grain problem, which indicates the size of the cell. The zoning problem results from the spatial configuration of the areal units. In this study the influence of scale is systematically examined by increasing the grain size from 5 by 5 to 50 by 50 to 500 by 500 meters.

Overall there are eleven most commonly used GIS methods identified for analyzing urban sprawl. It is impossible to include all GIS methods which are used to measure urban sprawl. Therefore only a selection of the most widely used methods has been described. The selection of most widely used GIS methodologies is arbitrary and disputable. In this research the literature on urban sprawl has been reviewed. The most cited authors and their methodologies are taken as a starting point, and these methodologies are classified as most widely used if their methodologies are also widespread used by less cited authors (which is arbitrary and disputable). The eleven most commonly used GIS methods for analyzing urban sprawl are:

Landscape metric	**Comments**
Class area (CA)	Measures absolute growth of the urban class.
Number of patches (PA)	Measures the extent of the urban class
Edge density (ED)	Measures the total edge of the urban class.
Area weighted mean patch fractal dimension (AWMPFD)	Measures shape complexity of the urban patches.
Built-up density	Measures the dispersion of the urban patch (spatial distribution).
Contagion	Measures the extent to which landscapes are aggregated or clumped.
Shannon's entropy	Measures the degree of spatial concentration and dispersion of the urban class.
Pattern identification	**Comments**
Urban growth	Indication of the direction of the urban sprawl.
Classification new developments	Configuration and classification of the urban developments
Land use change	**Comments**
Land use change detection	Change of land use classes in time, and the probability of change
Markov Cellular Automata Chain	Indication of the future direction of the urban sprawl.

The application of a case study enables the testing of the suitability of the found GIS methods and the influence of scale on these methods. In this case the Green Heart has been chosen as study area. The western part of the Netherlands locates an urban area in the shape of a horseshoe. This area is called the Randstad, containing the cities Amsterdam (capital of the Netherlands), Den Haag, Rotterdam, and Utrecht. The Green Heart is a green, open and agricultural area enclosed by the horseshoe (the Randstad). The name the Green Heart is a metaphor for the enclosed green, open, and agricultural (green) area which is situated in the center (heart) of the Randstad. The Green Heart is a nationally protected landscape with some unique characteristics: peat- meadow areas, landscape diversity, openness, and peace and quietness. There are signals that the characteristics of the Green Heart are threatened by the urban sprawl of the Randstad. Researchers state that the Green Heart is under pressure, as more and more open and green space is being replaced by built-up. The goal of the case study is to test the suitability of the methodology on how to analyze urban sprawl with a GIS, and the influence of the scale.

In the end the Markov Cellular Automata Chain model was not conducted because of the lacking software. The suitability of the landscape metrics number of patches (NP) and edge density (ED) does not add much information to the analysis of urban sprawl. These two metrics are vague indicators, which only support the findings of contagion and Shannon's entropy. The calculation of these two landscape metrics are easy and not time consuming, however their effectiveness is limited. These landscape metrics should only be used in combination with the landscape metrics contagion and Shannon's entropy. They cannot be used solely, as no real conclusion can be drawn from these indicators.

To conclude, it can be said that the other GIS methods add valuable information to the analyzes of urban sprawl. Scale however has a significant influence on the measurement of urban sprawl with

GIS methods. Many methods react predictably to the change of scale, with the exception of the landscape metric contagion. Scale influences the results significantly. This especially applies to the methods depending on the shapes of the built-up areas, like the class area, AWMPDF, Shannon's entropy, built-up density and urban growth. Finally, in contrast to the 5 meter analysis, distinctive development patterns cannot be observed when applying a 500 meter resolution analysis.

There is a persistent need to reach consensus on what urban sprawl entails, and how to operationalize urban sprawl. The incorporation of the multi scale analysis is of vital importance to a sound analysis of urban sprawl. Without the multi scale analysis the structure, function and dynamics of urban sprawl of the Green Heart would have been remained unnoticed. Also insight is gained on the sensitivity of the methodologies. However what is not discussed and analyzed more thoroughly is the influence of the amount of classes on the landscape metrics. Therefore it is strongly recommended to measure the sensitivity of the amount of classes on the landscape metrics when analyzing urban sprawl with a GIS.

1. Introduction

Studies indicate that half of the world population is living in urban areas. Studies also expect this percentage will continue to grow in the coming years. The increasing urbanization is caused by a growing population and the tendency of people to move to the cities. The clustering of people in urban areas affects the landscape, the ecology of an area, travel patterns, resource consumption and water discharge (Tewolde et al., 2011, p. 2149; UNEP, 2012; UNFPA, 2012). For (local) governments it is interesting to have exact information about the extent of the urban area (how is the land currently used) and the urban growth (the direction). This kind of information is needed for the urban planning of fast changing regions, to make sustainable and smart decisions (Herold et al., 2002, p. 1443; Jat et al., 2008, p. 26).

1.1 Problem definition

Urban sprawl has many different definitions, and confusion exists about what urban sprawl entails. For now let say that urban sprawl includes the fast extension of the urban areas into the suburbs (Galster et al., 2001, pp. 681 – 684). The urban area and its population are growing, more and more people live in cities. Because of the rapid growth of the urban area governments face a challenge, as they need to keep their information about the urban area up to date to make well-informed planning decisions. The conventional and traditional survey and mapping techniques to monitor the increasing urban areas are expensive and time consuming. As a response there has been a growing interest in research on how to map and monitor urban sprawl with the use of Geographical Information Systems (GIS). Remotely sensed images are cost effective and are more and more used as input to analyze urban sprawl, where GIS techniques are used to extract impervious (built-up) area (the urban area) from satellite (remotely sensed) images (Jat et al., 2008, p. 27). GIS techniques in combination with statistical techniques are now used in many urban sprawl studies. To be able to characterize urban sprawl there is the need to detect the pattern of expansion, to quantify the sprawl with appropriate scales, and to use the right statistical techniques within a GIS (Jat et al., 2008, p. 27).

As said urban sprawl has many different definitions and no consensus, about what urban sprawl exactly is, has been reached (Batty et al., 2003, p.1; Christiansen et al., 2001, p. 2; Eryilmaz et al, 2008, p.1; Poelmans et al., 2009, p. 10; Tewolde et al., 2011, p. 2149). Galster et al. (2001) state that "the literature on urban sprawl confuses causes, consequences and conditions. A first step toward developing policies to deal with the causes or consequences of sprawl, is if agreement could be reached on what urban sprawl is and how to measure it empirically and compare its occurrence across a large number of urban areas" (Galster et al., 2001, pp. 881 – 882). Alongside different authors make use of different statistical techniques to monitor and describe urban sprawl within an area. Davis et al. (2005), remark the following: "the breadth of methods and inconsistency of findings testifies to the variety of perspectives on the nature of sprawl and how best to quantify it" (Davis et al., 2005, p. 269). Also many researchers conduct their research on urban sprawl only at one spatial scale, mostly caused by a lack of data, however some researcher do measure and analyze the urban sprawl of an area at different scales (and from different sources). This often leads to confusion when discussing about what urban sprawl is, and how to measure, analyze and or monitor urban sprawl.

1.2 Goal of the study

As stated in the problem definition there is a lack of consensus concerning what urban sprawl entails and how to measure it. Also most of the research that measure and analyze urban sprawl with a GIS, measure the urban sprawl only at one spatial scale. But does the scale not always influence measurements? As the modifiable areal unit problem (MAUP) is a well known concept within geography, one would expect that scale will have an influence on the measurement of urban sprawl.

Indistinctness about the concept urban sprawl, and how to analyze, measure, and monitor urban sprawl consists. Therefore this study researches the suitability of the most widely used GIS methodologies that are used within the literature to analyze urban sprawl, and the effect, influence of scale on these methodologies. What the most widely used GIS methodologies are is arbitrary and disputable, because who and how is it decided which methodologies are most widely used? In this research the literature on urban sprawl is reviewed. The most cited authors and their methodologies are taken as a starting point, and these methodologies are classified as most widely used if their methodologies are also widely used by less cited authors (which is arbitrary and disputable). The goal of this study is to take a first step towards the consensus building on how to analyze urban sprawl with a GIS. The expectation is not to create, as a result, a complete concept on how to analyze urban sprawl with a GIS. No the expectation is to contribute to the discussion on how to reach consensus on how to analyze urban sprawl with a GIS. As well as to explore which methodologies are most widely used for measuring urban sprawl with a GIS. And to test these methodologies on their suitability and test if scale changes influence the results.

To fully understand the concept of urban sprawl, questions as; what are the definitions of sprawl, does urban sprawl expresses itself always in the same physical form, why does urban sprawl happen, should be answered. Also the question might raise why use a GIS to understand and analyze urban sprawl? And if a GIS is used to analyze urban sprawl, which methods should be used, and which methods are mostly used? What is the influence of scale on these methods? And are there other variables which influence the methodology of measuring sprawl with a GIS?

The main research question of the study is:

What is the suitability of the GIS methods which are used for analyzing urban sprawl, and what is the influence of scale on these methods?

The following research questions are explored in order to realize the main goal of this study.

- *What is urban sprawl?*
- *What types of urban sprawl exist?*
- *What are the drivers of urban sprawl?*
- *Why should urban sprawl be measured/analyzed with a GIS?*
- *What is the influence of scale on the measurement of urban sprawl with a GIS?*
- *Which variables influence the methodology on the measurement of urban sprawl with a GIS?*

With the help of a case study there is the possibility to test the suitability of the found GIS methods and the influence of scale on these methods. In this case the Green Heart is chosen as the case study area.

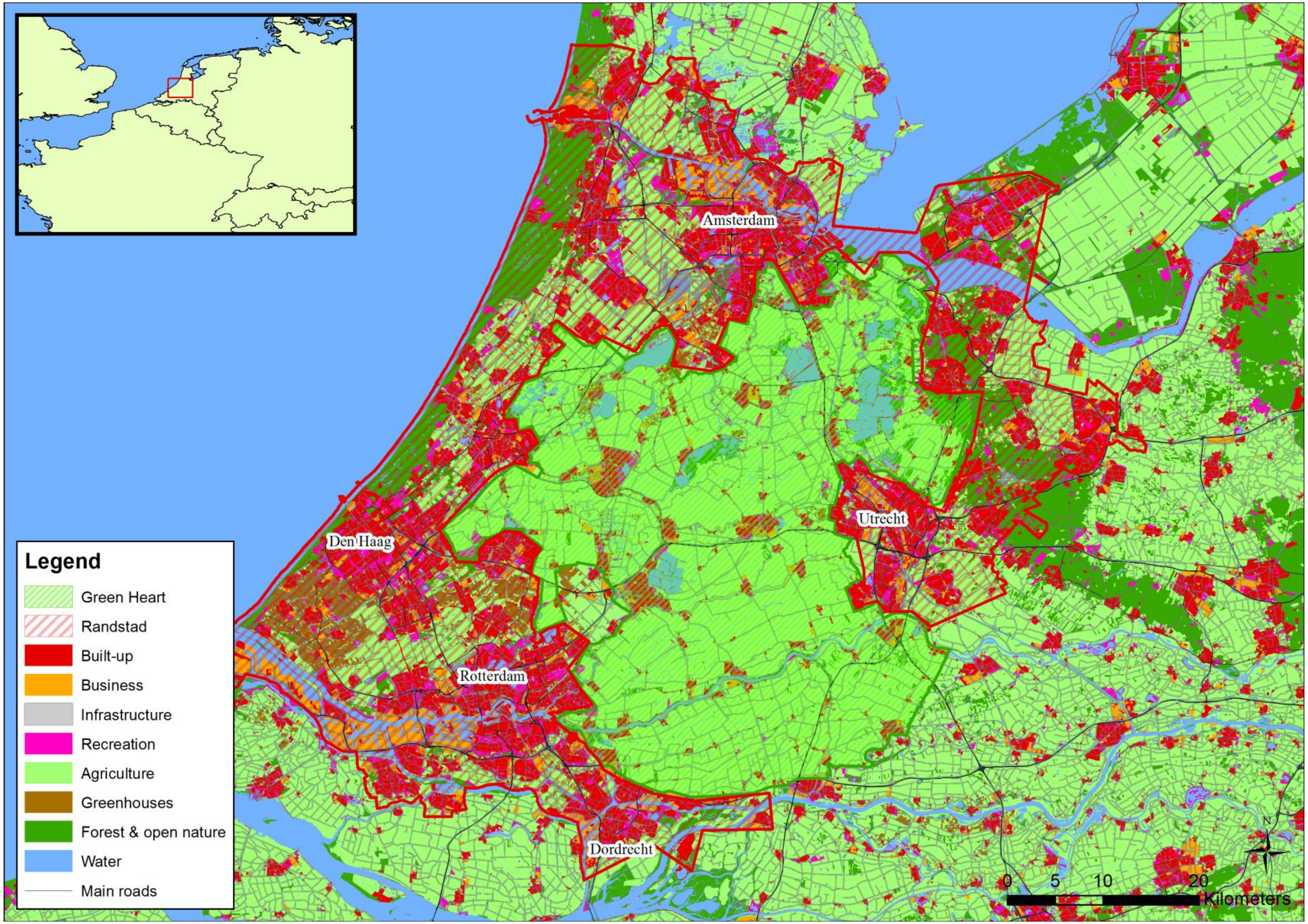
1.3 Case study Green Heart

The western part of the Netherlands locates an urban area in the shape of a horseshoe. This area is called the Randstad, containing the cities Amsterdam (capital of the Netherlands), The Hague, Rotterdam, and Utrecht. The Green Heart is a green, open and agricultural area enclosed by the horseshoe (the Randstad). “Green Heart” is a metaphor for the enclosed green, open, and agricultural (green) area which is situated in the center (heart) of the Randstad (figure 1). The Green Heart is a Dutch concept which was introduced in 1958.

The Green Heart is a cultivated area. Before cultivated, it existed as a river delta with peat swamps. Nowadays the Green Heart is known as a green, open, agricultural, and cultural-historical landscape. Since 1958 the Dutch policy of physical planning protects the Green Heart to ensure that the area can act as the green counterpart of the Randstad. The policy aims to maintain the Green Heart as an open, green, and agricultural area. However, since 1958 there are signals that the characteristics of the Green Heart are threatened by the urban sprawl of the Randstad. The fourth report on physical planning (1988) of the Netherlands stated that the objective of the Green Heart was to maintain and enhance the spatial characteristics which are so typical for the area. Despite policy which intended the opposite, the Green Heart was urbanizing, more and more buildings, infrastructure and greenhouses emerged (Stuurgroep Groene Hart, 1992, p. 3). Since 1958 the Green Heart has shrunk in size. In the period between 1960 and 1980 the growth of various space consuming sectors exceeded the national average (for instance, growth of housing was in 1974 three times as high). The spatial developments within the Green Heart are not only driven by policy. Different actors like project developers, environmental organizations and companies want to realize their land claims within the Green Heart (Ruimtelijk Planbureau, 2005, pp. 8 – 11, 59 – 77). In recent years numerous studies have been conducted on the Green Heart. A huge amount of studies measure the effectiveness of the policy, which tries to protect the Green Heart against the urban pressure. However, the Green Heart is still losing its distinctive characteristics due to the urban pressure, hence the motivation for the numerous studies about the effectiveness of the policy. Researchers state that the Green Heart is under pressure, that more and more open and green space is being replaced by built-up. They also stated that the policy of protecting the Green Heart is not that effective. They recognize that between 1960 and 1980 the growth in housing exceeded the national average. They recognize that the Green Heart is an attractive living area. Furthermore, businesses like to escape from the congested and jammed Randstad to the outskirts of the Green Heart (Planbureaurapporten, 2004; Randstedelijk Rekenkamer, 2009; Ruimtelijk Planbureau, 2005; Ruimtelijk Planbureau, 2006; Valk et al., 1997).

The goal of the case study is to test the suitability of the methodology on how to analyze urban sprawl with a GIS, and the influence of the scale. In order achieve the goal of the case study, there is the need to know more about the concepts Green Heart and urban sprawl. It is important to know exactly what the Green Heart means as a concept. This can be done by understanding its history, core qualities and the policy of the Green Heart.

Figure 1: Position Green Heart, the Netherlands, 2008 [1]



1.4 Delimitation of the case study

To avoid misunderstandings, the definitions of the Green Heart and Randstad for this study are given. The Green Heart is an open and green landscape which is surrounded by urban space. It is an area where agriculture occupies most of the land, an area which is cultivated (former peat swamps) and finally it is area with open and green space (Kwaliteitsatlas, 2012; Ruimtelijk Planbureau, 2005, p 7). The Dutch government precisely defined in the 'Nota Ruimte' (Dutch report on physical planning) the boundaries of the Green Heart in 2004 (Randstedelijke Rekenkamer, 2009 p. 17). The precise boundaries of the Randstad are disputable. However, there is a general consensus that it at least contains the urban area of the cities Utrecht, Amsterdam, Den Haag, Rotterdam, and Dordrecht. Several parties define the Randstad as the urban area around the Green Heart and the Green Heart itself (Ministerie VROM, 1996, p. 9; Ostendorf et al., 1996, p.93; Verburg et al. 2012, p. 1). Others express the view that the Randstad only consists of the area around the Green Heart (CBS, 2012a). In this thesis if the term Randstad is used it refers to the urban area around the Green Heart (figure 1).

This study is limited to the years 1989 till 2008. The reason is the availability of data. Since 1989 the university of Utrecht collects the land use GIS files of the Netherlands. For this study the land cover GIS files (Bestand Bodemgebruik, BBG) of 1989, 1993, 1996, 2000, 2003, 2006 and 2008 are available.

1.5 Contents report

This report has its focus on urban sprawl and the measurement of urban sprawl with GIS. The first chapter introduces the problems and the goals of the study (and case study). The next chapter (two) contains the literature research on urban sprawl, giving answer to the following questions; what comprises urban sprawl, why does urban sprawl happen, how does urban sprawl express itself in a spatial and physical way, what are the effects of urban sprawl, what is the importance of GIS to urban sprawl, how can urban sprawl be measured with a GIS, does scale influence the measurement of urban sprawl, and are there other variables which influence the measurement of urban sprawl? The third chapter describes the background information about the area of the case study, the Green Heart. It covers the history, policy, and core qualities of the area, which allows a better understanding of the area. Also the urban pressure, which the Green Heart experience, is described. The fourth chapter is about the methodology on how to measure urban sprawl with a GIS. Which methods can be used to analyze the urban sprawl of an area? However not all methods can be discussed in this chapter as there are too many different methods, analyzes which provide information about the urban sprawl of an area. Therefore only the 'most' used methodologies within scientific literature are chosen. The fifth chapter concentrates on the results, obtained by making use of the chosen methodologies on how to measure urban sprawl with a GIS. The urban sprawl of the Green Heart is also analyzed in this chapter. The sixth chapter deals with the discussion, the case study makes it possible to apply and test the chosen methodologies. Feedback, problems, and or recommendations are given in this chapter. The seventh chapter is the concluding part of the study. Here the research question of the study is answered.

2. Theoretical framework urban sprawl

In this chapter the concept of urban sprawl is further elaborated. First the definition of urban sprawl is given to get a good grasp on what urban sprawl entails. Subchapter two explains the different types of sprawl and their spatial physical characteristics. To understand why urban sprawl happens the driving forces are explained in subchapter three. Not only is it important to understand what sprawl is and how it can be measured. It is also vital to understand the entire concept, which means understanding the forces (drivers) that make urban sprawl happen. In the fourth subchapter the effects of urban sprawl are described. The fifth subchapter deals with the question: why should GIS be used to understand and measure urban sprawl. The sixth subchapter tells which components of urban sprawl are to be measured, to be able to define and typify the urban sprawl of an area. The scale influence is discussed in subchapter seven. Finally, the last subchapter of this chapter clarifies which variables should be taken into account when measuring urban sprawl.

2.1 Urban sprawl

In the existing literature different definitions of urban sprawl are given (Christiansen et al., 2001, p. 2; Eryilmaz et al, 2008, p.1). Most of the definitions share facts and only differ in details. Therefore, first several definitions of several authors are cited. Urban areas are many times situated next to agricultural areas and or natural areas (and their biodiversity). Urban areas are nowadays still growing, the growth of the urban areas causes sprawl. This instigates the extension of the urban perimeter, i.e. land cover changes of agricultural and natural land into built-up, from productive available natural land with biodiversity to built-up land. Urban sprawl is the fast expansion of the urban area into suburbs, these suburbs have a discontinuous low-density and uneven pattern (Tewolde et al., 2011, p.2149). Poelmans et al. (2009) agree with the definition of Tewolde et al. (2011), adding however that it involves a specific form of urban development which is characterized by auto-dependency (Poelmans et al., 2009, p. 10). The understanding of the patterns of urban sprawl is helpful for the city planners to plan future developments like the natural resources, natural resource utilization and infrastructural facilities (Sudhira et al., 2004, p. 29). Eryilmaz et al. (2008) describes the characteristics of urban sprawl also as: low density dwelling development outside the city borders, low dense development, an area depending on the transportation of cars, and a loss of open rural area. However, they also speak of a transitional area (from urban to rural), and the development of single function settlement areas. Where Tewolde et al. (2011) talks about an uneven pattern as characteristic, Eryilmaz et al. (2008) typify this characteristic as spontaneous and unplanned (Eryilmaz et al., 2008, p. 1). Batty et al. (2003) share this thought of uncoordinated growth, i.e. the expansion of the urban area without thinking about the consequences, thus unplanned and incremental (Batty et al., 2003, p.1). Cities can also grow around the periphery. In that case the growth is typified as coordinated, resulting in a compact city (see policy of Green Heart, compact city). Compactness implies coordination of the amount and direction of the growth of a city. In that respect the growth of a compact city is the opposite of urban sprawl. Within a compact city people easily travel by public transport and there is not much space for cars (see policy of Green Heart, compact city). However this type of urban form is rare, and one is unlikely to actually witness it in the real world (Batty et al., 2003, p. 2). It is quite easy to blame policy failures in this respect and forgetting about the numerous powerful actors that are endlessly claiming grounds. Most of the European cities are more compact than Northern American ones, although the lacking coordination is still leading to sprawl-like growth (Batty et al., 2003, p.4). The urban sprawl patterns in Europe differ because of historical and societal context from North America. Until the 1960s the historical compact structure of the European city was maintained. The historical European city was typified by a dense core and the urban fringe was relatively small and surrounded by rural areas (Poelmans et al., 2009, p. 10). Sometimes there are contradictions concerning sprawl. For example large areas of organized and homogeneous residential areas. It does not look like an uncoordinated development, because uncoordinated development can only be determined when the entire context is examined. Often these residential areas in the suburbs have led to a loss of agricultural land and the rise of single function settlement areas. These areas depend on the automobile as most important mean of transportation, as social services and related facilities are still situated in the cities (Batty et al., 2003, p. 3). The European Environment Agency (2006) state that "sprawl is commonly used to describe physically expanding urban areas". The characteristics of these physically expanding urban areas are; low-density expansion of the urban fringe mainly into agricultural land, a patchy development, scattered, a tendency for discontinuity, leap-frogs over areas, leaving agricultural enclaves (EEA, 2006, p.6). Sprawl, thus, describes the conditions and patterns of the development characteristics of the expanding urban area over a period of time. This only covers urban sprawl in general terms, its exact connotations are still debated (Besussi et al., 2010, p. 17). The definition of sprawl also depends on the place. Differences can be found between geography, politics, history and current land use planning, per place and per country, for example the differences in sprawl between Europe and the United States. Researchers and or authors in the US might define the suburban sprawl areas in Europe as urban, as they witness lower densities in their suburban sprawl areas (Besussi et al., 2010, p. 18). The differences in definitions of the aforementioned authors, along with many others, suggest that that there are different forms, types and levels of sprawl (Almeida, 2005, p. 26).

However the definition of Galster et al. (2001) is probably the most cited and used definition of urban sprawl. In this study urban sprawl is defined as:

"Sprawl is a pattern of land use in a urbanized area that exhibits low levels of some combination of eight distinct dimensions: density, continuity, concentration, clustering, centrality, nuclearity, mixed uses, and proximity" (Galster et al., 2001, p. 685).

As stated, there are different forms, types and levels of sprawl. The characteristics or dimensions can change. The definition above also suggest that sprawl can be defined as a process of development, where you look at the changes in patterns of the land and over time. The eight distinct dimensions of urban sprawl are now explained.

- Density: the ratio of the total population of the sprawl area to its total land area. This indicator is the most widely used, very high population density numbers, which can be found in the center of Rotterdam for example, will significantly differ from the sprawl areas.
- Continuity: the degree of unbroken built-up area of the sprawl area to the urban borders. Cities can expand unbrokenly with a high density, urban growth. It is also possible that cities expand unbrokenly with a low density, urban sprawl. Although, there are several authors defining discontinuity as a typical characteristics of urban sprawl, leaving a patchwork of open land between built-up areas. It is also possible that there is a sprawl along infrastructure in an unbroken way with low density, linear strip development. Natural obstacles (water, forest, slopes) are not considered as an interruption of the continuous development pattern.

- Concentration: “the degree to which development is located disproportionately in relatively few square miles of the total urbanized area rather than spread evenly throughout” (Galster et al., 2001, 690). A high concentration means that the urban sprawl happens concentrated, in as few places as possible with a high population density per square kilometer. A low concentration means a disperse sprawl and a low population density per square kilometer.
- Clustering: differs from concentration and density in the way that the focus is not on the development patterns in the area (or the development across grids but within grids). It is the degree to which the sprawl minimizes the amount of land per square kilometer. So it is possible to have four compact sprawl areas, which have a high density (less occupied land means more houses per square kilometer) but they can be scattered. In that case it would still be classified as clustered (as they occupy not that much land), while a sprawl around the city with a low density is perhaps continuous, but not clustered as they occupy a lot of land.
- Centrality: the degree to which the urban sprawl is located with respect to the central business district (CBD, or the city center). Urban sprawl areas that are further away will have a lower centrality (disperse sprawl, as it happens ‘far’ away from the CBD).
- Nuclearity: extent to which the sprawl area has a mononuclear development pattern, as opposed to a poly-nuclear development pattern. A mononuclear structure is an urban area with one CBD which is the only locus of intense development. If the edge cities grow, they can take over specialized tasks/functions of the CBD. In that case, known as poly-nuclearity, the CBD no longer forms the locus of intense development. Nuclearity is closely related to concentration. An urbanized area can have more nuclei, but concentrations are low when the population density of the nuclei does not differ significantly from the average population density of the urban area.
- Mixed use: the degree to which two different land uses exist within the sprawl area. Single purpose built sprawl areas, like residential areas, have a low mixed use, and are an indication of sprawl. For example the city center of Rotterdam is a mixture of business, infrastructure, residential and recreation.
- Proximity: “the degree to which different land uses are close to each other across an urbanized area” (Galster et al., 2001, 697). Proximity shows the distances between the different land uses. For example the average distance people have to travel to their work, shops, recreation. The urbanized areas where people have to travel great distances to their works and facilities have a low proximity and exhibit more sprawl (Galster et al., 2001, pp. 687 – 704).

The question remains what entails urban sprawl within this study as there is no worldwide accepted definition of urban sprawl? In this study the concept of sprawl is described in very broad terms. All built-up area is classified as urban, which is arbitrary and disputable. However many studies on urban sprawl follow this thought of making a distinction between built-up and non built-up areas. The urban sprawl in these studies are defined by the spatial extension of the built-up areas (Jat et al., 2008; Mayas, 2003; Sudhira et al., 2004; Torrens et al., 2000). Many researchers do not classify all urban growth as urban sprawl. Problem of this classification, including all built-up, is that farms, small isolated housing blocks, and other small sized built-up (developed) areas are recognized and classified as urban sprawl. However, these ‘miss’ classifications are small in size, and do not influence the description of the pattern of urban sprawl significantly. Built-up developments in time are or will be considered by one as urban sprawl and not to others (Wilson et al., 2003, p. 276). However, defining all urban growth as urban sprawl has the advantage that it allows the users to decide whether or not a development in time meets their criteria of urban sprawl.

2.2 Types of urban sprawl

There are different definitions of sprawl, however, they all share the same common thought that urban sprawl is the expansion of the urban area outside its borders into the suburbs. In most cases the development is single purpose and car dependent, agricultural and natural lands get lost and patches, enclaves, are created. Therefore researchers have created classifications of the different types of sprawl. As stated, the type of sprawl found in North America and Europe differs. In North America development is not contiguous but spread out, whereas in Europe the density is higher but the form is more evenly equally scattered across the region, thus leaving more open spaces (Batty et al, 2003, p. 4). Galster et al. (2001) have classified sprawl into the following five types, which are classified in terms of degree of compactness, dispersion or 'scatteration' (figure 2 and 3).

(1) Compact contiguous development: sprawl forms gradually around the urban area, not creating patches, and mainly has a high density.

(2) Strip or linear development: the urban expansion along infrastructural works or rivers, the expansion is continuous but scattered, leaving agricultural and natural land open.

(3) Poly-nucleated nodal development: several smaller towns are agglomerated, the sprawl is discontinuous, much lower density than the traditional settlement, physically separated from the urban city of which it sprawled. Creating new 'larger' agglomeration of towns separately from each other (Batty et al., 2003, p. 4).

(4)The scattered sprawl development: uncoordinated discontinuous development away from the historical central core, creating open and vacant land between new built-up areas.

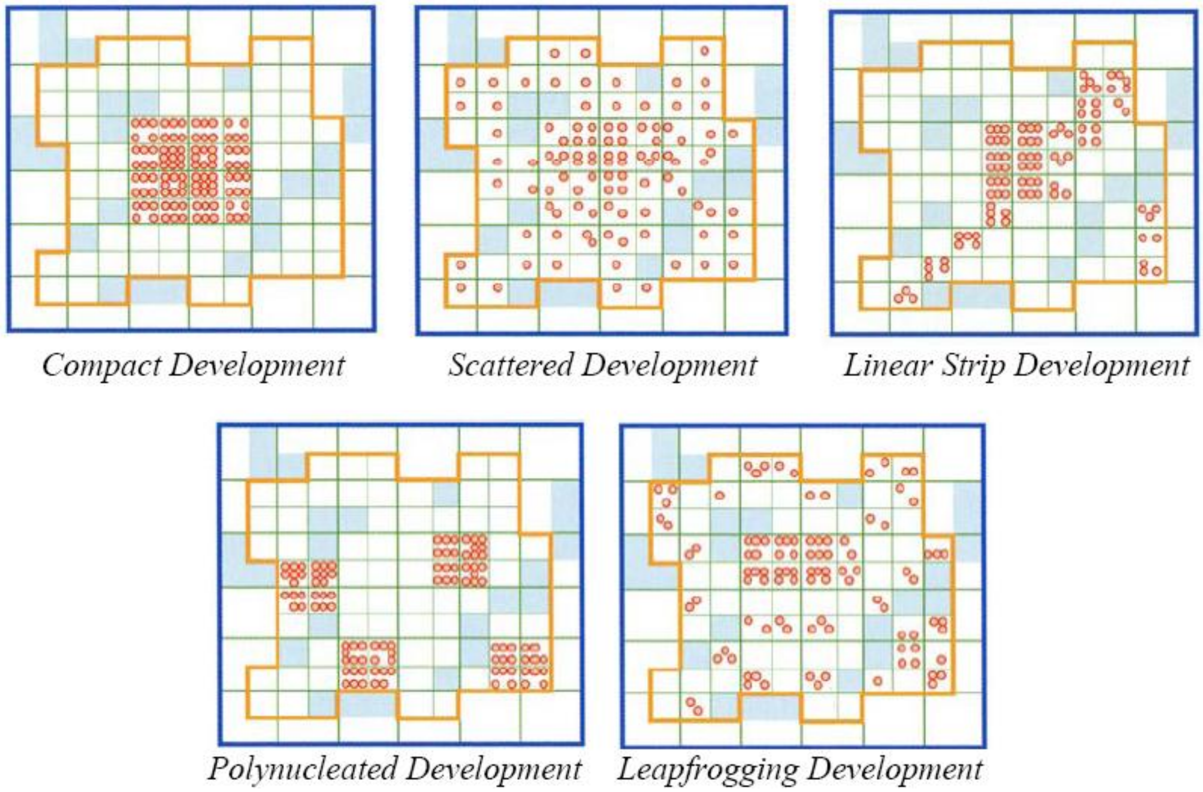
(5) Leapfrogging development: is the development that leapfrogs over existing barriers (Batty et al., 2003, pp. 4 – 6; Besussi et al., 2010, pp. 18 – 20).

Figure 2: Types of urban sprawl

	High Density	Low Density
Compact Contiguous	*Circular or radial using mass transit*	***Possible but rare ?***
Linear Strip Corridor	*Corridor development around mass transit*	*Ribbon development along radial routes*
Polynucleated Nodal	*Urban nodes divided by green belts*	*Metro regions with new towns*
Scattered Discontiguous	***Possible but rare ?***	*Metro regions with edge cities*

Batty et al., 2003, p.5

Figure 3: Physical forms of sprawl



Batty et al., 2003, p.6

2.3 Drivers of urban sprawl

Cities in the western World are still growing, although populations in the western world are not reproducing themselves sufficiently (declining fertility rates) and the urbanization has diminished with respect to the 1950s. The question raises why cities are still getting larger? And why are urban areas occupying more and more land? There are several key forces acting as centrifugal forces which make cities expand outside their borders (deeper into the suburbs and rural areas). People demand more and more living space, whereas they still want to enjoy the amenities of a city. Because of the improvement of transportation (increased action radius), further dispersion from the existing city is possible. The opportunity and the demand for living in new single family homes, away from the crowded and 'noisy' cities, is accommodated by the automobile. The improved transportation is not the only factor to accelerate sprawl. A mix of forces, including micro and macro socio-economic trends, such as land prices, housing preferences, demographic trends, cultural traditions and constraints, attractiveness of the urban and rural area, transportation and planning policies, accelerate and contribute to urban sprawl (Batty et al., 2003, pp. 1 – 5; EEA, 2006, p. 6). Historical trends show that since mid-1950s the average European city grew with 33%, however the built-up area expanded with 78%. The sprawl is greater than expected in regard to the population growth. The compact enclosed cities are being replaced by free standing apartment blocks, and (semi) detached houses. The moderate increase of population, and the large expansion of the urban area are observed in for example Ireland, the Netherlands, Portugal, and Spain. (EEA, 2006, p. 11). "General analysis shows that residential sprawl and the development of economics activities, in turn linked to the development of transport networks, are intrinsic causes of expanding cities" (EEA, 2006, p. 17). This is a consequence of increasing passenger and freight transport, and also the increased price of urbanized land. Living in the crowded and expensive city center is not that attractive anymore. While at the same time living in the rural areas is now associated with an increase of quality of life and being closer to nature. The acquisition of agricultural land is relatively cheap, compared to the urban land, which makes it very attractive for developers and investors. Municipalities sometimes are also a catalysts of urban sprawl. They want to generate new income and thus compete which each other to attract investors for residential, commercial and industrial land development (EEA, 2006, p. 17).

Areas where the impacts of urban sprawl are most visible are areas with high population density and economic activity, countries like Belgium and the Netherlands, southern (München) and western (Ruhrgebiet) Germany, northern Italy, Paris. Or regions with rapid economic growth such as Ireland, Portugal, eastern Germany, Madrid. Also, urban sprawl is most occurring along transport corridors and along coast lines and river valleys (EEA, 2006, p. 9).

Christiansen et al. (2011) conducted a literature review to identify the driving forces behind urban sprawl in Europe. In the end they classified the drivers of urban sprawl into four categories: economy, society, transport, and policy. Below the four categories are explained.

2.3.1 Economy

At first the macroeconomic drivers of urban sprawl are explained, in the second part the microeconomic drivers are described.

Globalization is one of the drivers behind urban sprawl. Europe is, like every continent, affected by the international economy. The last 20 years China and India, recently also Brazil, shown a tremendous economic growth, which did affect Europe in several ways. In China and India labor and products are cheaper, explaining the tremendous investments in these countries the past decades. Europe is affected by these developments and the need to restructure their economy occurs. The European Union now aims to become the most competitive and dynamic knowledge-based economy in the world (Lisbon strategy). This may draw people to the cities and concentrate activities. Logically this will go along with increased pressure on the land, which can be a driving force of urban sprawl.

Another factor on macro level is the European Union. An objective of the EU is to reduce social and economic regional differences within the EU. In order to fulfill this objective the EU is promoting economic and social development, to which a good transportation network is crucial. Without a effective and efficient transportation network a region may not be able to profit from the economic opportunities in the same way as other regions. Also without a good transportation network the region, as possible location for business and employees, is less attractive. Because of the better transportation networks of several regions/countries (support of the European Regional Development Funds, for example Spain did almost spend their entire budget on transportation), the accessibility of the area increased. The increased accessibility makes urban sprawl in the new accessible areas possible (Christiansen et al., 2011, pp. 9 -11.)

On microeconomic level market failure can be defined as a driver of urban sprawl. There are three types of market failures. Firstly there is the land price, which may be developed for residential or industrial purpose, may not reflect the real value. This is caused by the social value people attach to that area. For example, a green and open agricultural area surrounding a small village may be worth, if you look only at the type of ground, less than when the recreational value is taken into account which inhabitants experience. The second market failure is one of reduced accessibility. Individuals have a false sense of commuting cost, because the possibility of congestion (and its costs) is not taken into account and may reduce the speed, and increase the travel time. The last market failure is cause by municipalities that do not take extra costs into account (physical and social infrastructure). New site development also includes investments such as roads, water, sewer, schools and facilities. However these costs are, usually paid by the entire municipality, thus all the inhabitants. If the costs of these investments would be included in the price of the new homes, the development would be more pricier, which would have its subsequent effects on urban sprawl.

Competition between municipalities is also a driver of urban sprawl at the microeconomic level. The goals and interest of municipalities can differ. Cities can pull people to the region because of its (specialized) economy. The surrounding municipalities may want to attract new inhabitants. New inhabitants lead to higher tax revenues (which are often much needed). However, people demand rural large single family homes, which results in the development of low-density areas.

Another microeconomic driver of sprawl is the increase of purchasing power and the land prices. For example the average income in the Netherlands have doubled since 1960. Since the Second World War, Western Europe witnessed an enormous economic growth, which resulted in higher demand for housing and also more opportunities that enabled urban sprawl. The land prices within the city center are high, while at the other side the price of houses in the peripheral areas are lower. The development of houses in these peripheral areas are more profitable. At first cities and more specific their economies pulled people to the region. But due to the high prices, the lack of larger houses (suitable for families), lack of capacity, noise and the experience of being unsafe, people are pushed out of the cities (Christiansen et al., 2011, pp. 11-12).

2.3.2 Society

Population growth is most of the time defined as the primary cause of urban sprawl. However this only applies to the years 1960 – 1980. Another driver for sprawl is the housing preference of people and the characteristics of residential areas. According to research, low crime rates and a quiet neighborhood are the most important reasons for people to move to peripheral areas. The city characteristics such as, lots of traffic, noise, and pollution, can lead to the feeling of insecurity. Also being close to the rural areas and nature are factors which pull people to the peripheral areas. In cities there is usually a lack of green spaces (in general), facilities to sport, and playgrounds. Expensive smaller homes are also pushing people away from the city. Also the individual income is a factor that relates with housing preference. People with high incomes have more housing possibilities, this however, can lead to social segregation. Another force of urban sprawl are the second homes, especially in countries like Austria, Greece, Slovenia, and Sweden. They convert their second rural homes into their first homes. Another factor which makes sprawl possible is the flexibility of work. Technology, internet for example, made it possible to work outside the office (Christiansen et al., 2011, pp. 16 – 19).

2.3.3 Transportation

Until the rise of the automobile, people where limited in their movement. For a long time people could only depend on walking (later on in time ferries and trains emerged), which limited long distance travel from home to work. With the advent of the automobile, the action radius of people increased significantly. Companies do no longer have to establish their businesses along transportation nodes of railway stations and ports, and people do no longer have to live ‘close’ to work. The automobile made urban sprawl possible. Because of the urbanization and the increasing population in cities, more roads were needed. Roads are a driver of urban sprawl, in making new areas accessible. Research also shows that there is a strong correlation between car dependency and density. Denser cities show less car use than urban sprawl areas with a low density. (Christiansen et al., 2011, pp. 19 – 20).

2.3.4 Policy

Policy failure or regulation failure can be a driver of urban sprawl. Public authorities decide how the land development should be managed. If there is little or no regulation and/or policy concerning the land development, sprawl can develop virtually unlimited. Per European country the policy of land management differs. Countries such as Britain, Denmark, and the Netherlands have strong regional state guidelines for land-use planning. In Europe these three countries are ranked as the countries which have the largest potential to control urban sprawl. However sometimes there are problems of local interest. Municipalities may not perceive urban sprawl and low density built-up areas as undesirable, which happens when municipalities associate densification with negative effects. Coordination problems on physical planning is also a driver of urban sprawl. It is very difficult to coordinate physical planning. Another driver behind urban sprawl is the land use and the building types. High density and high utilization of housing will reduce development pressure. However if a great part of the city is occupied with parking lots, costly ground is occupied which could be used for housing or industry, leading to pressure which may result in urban sprawl (Christiansen et al., 2011, pp. 20 – 23).

2.4 Effects of urban sprawl

Urban sprawl is generally by governments perceived as a negative, unwanted, and undesirable development. Governments, such as the Dutch government, tries to stimulate the realization of compact cities, which have the opposite characteristics of urban sprawl. Compact cities are characterized by a higher density i.e. less space consuming and less resource (land) consuming. Problems or effects that are related to urban sprawl are congestion, time wasting (travel time), lack of a sufficient social infrastructure and the erosion of agricultural land. Batty et al. (2003) define three perspectives on the impacts of sprawl.

The first is the despoiling of the countryside, eroding and ruining the rural economy and characteristics. Once agricultural land is transformed to built-up areas it is almost impossible to reverse this transformation, only at very high costs. Not only is it almost irreversible, it also means the loss of open spaces, and the creation of patches. Also agricultural and green areas functions as ecosystems, such as the production of food, habitat for flora and fauna, recreation, water retention and storage, are all irreversible changed/damaged. The properties of soil change, such as water permeability and loss of biodiversity, are changed. The covering of the soil with built-up land, such as housing, business, and concrete, is known as soil sealing. Soil sealing leads to impermeability, it will influence the change in water flow patterns and or the fragmentation of habitats. When rainwater for example falls on these concrete sealed areas they are polluted by the tire abrasion, dust and the concentration of metals, which in the end will wash into the rivers (Batty et al., 2003, pp. 1- 6; EEA, 2006, pp. 28 - 31; European Soil Data Center, 2012; Jat et al., 2008, p. 26; Nechyba et al., 2004, p. 186; Poelmans et al., 2009, p. 10; Yu et al., 2007, p. 96).

Secondly, sprawl is less efficient than a compact city, as there is more infrastructure, utilities and other related services needed. Urban sprawl is more time consuming for commuters, it causes congestion, increases money spent on transport, loss of agricultural land, and loss of ecologies, to summarize greater costs because of the spread out. People are able nowadays to demand more in terms of housing characteristics, which makes the separation of residential and work locations possible. Also more and more people are living in individual households (growth of 11% between 1990 – 2000 in Europe). These developments are less efficient in terms of occupying space. On average two individual households use more water than a two person household, a two person household also uses also 20% less energy. Thus on average the consumption of resource per capita did increase (Batty et al., 2003, pp. 1- 6; EEA, 2006, pp. 28 – 31; Nechyba et al., 2004, p. 186).

Third, social structure (equity), those who earn more money have more possibilities for housing. Sprawl can thus generate segregation of the population (Batty et al., 2003, pp. 1- 6; EEA, 2006, pp. 28 - 35).

So far only 'negative/unwanted' effects of urban sprawl are mentioned. However, oft-forgotten, urban sprawl has also several benefits. For example the radius of residential and work sites has increased, giving the individual more 'freedom', and more important a much wider set of job opportunities (Batty et al., 2003, p. 9). Another benefit of sprawl is the decreasing housing prices in the cities. Pressure on housing in the cities declined because people were able to live further away from work and thus increased the accessible housing stock. The prices of houses in the rural areas are lower, which means living conditions increased. Also for business, urban sprawl can be beneficial. Normally developers do not want to be located on the outskirts of the city, because of a lack of market. When leapfrogged development of urban sprawl occurs, empty patches of land emerge, which are more attractive for developers (Holcombe, 1999, pp. 3 – 4).

2.5 GIS & urban sprawl

Governments develop physical plans for the future. To be able to make plans, updated and precise information is needed. The rapid expansion of the urban area challenges governments. They need to know how, where and in what direction the urban area is expanding, in order to make sustainable future plans (resource allocation and infrastructural works for example (Herold et al., 2002, p. 1443; Jat et al., 2008, p. 26)). However, the conventional and traditional survey and mapping techniques are too expensive and also time consuming. As a response to this problem, research interest on how to monitor urban sprawl with Geographic Information Systems (GIS) techniques emerged. GIS (and remote sensing) can provide useful information for the monitoring of the urban land. GIS gives the opportunity to observe land use changes, visualize them, monitor them, and even forecast them. Remote sensing gives the ability to exquisite data via the space or air borne sensors (in a cost effective way and with temporal frequency), resulting in multispectral, multi-resolution, and multi-temporal data, which is used for the creation of land use maps (Araya, 2009, pp. 7 – 10; Herold et al., 2002, p. Jat et al., 2008, p. 27). Digital change detection techniques, with the help of multi spectral remotely sensed images, which is a great source for extracting and analyzing land use maps, show many potential in observing landscape dynamics regardless the causal factors. Increasing improvements in the quality and availability of remotely sensed images makes the land use maps of a higher spatial resolution (more detail is visible, and thus the data becomes more precise), and with the help of a GIS these digital change detection techniques are becoming more accessible and easier (Araya et al., 2010, p. 1550; Harika et al., 2012, p. 383; Tewolde et al., 2011, p. 2149). With GIS, spatial statistics parameters and indices can be calculated from land use maps, which characterizes the landscape properties, spatial distribution, change of land use, pattern, and the extent of urban sprawl (Jat et al., 2008, p. 27; Sudhira at el., 2004, p. 29).

2.6 Measuring urban sprawl

According to Sudhira et al. (2004) (one of the most cited authors on urban sprawl in combination with GIS), it is only possible to understand a dynamic concept as urban sprawl when; the land use change is analyzed, there is an identification of the pattern, and when landscape metrics are configured (Sudhira et al., 2004, p. 30). The land use change analysis gives information on the dynamics of the changing composition of the land. The identification of the pattern gives information about the direction and type of urban sprawl. The landscape metrics gives information about the configuration of the land cover classes and the landscape. However, the analysis of the sprawl pattern and the configuration of landscape metrics correlate with each other, and cannot be seen apart. With the identification of the pattern a first impression of the pattern is obtained, the landscape metrics provide statistical insight of the configuration of the urban sprawl. Landscape metrics give information about the configuration of the land. Meaning information about the fragmentation and spatial concentration of the land use classes is gained.

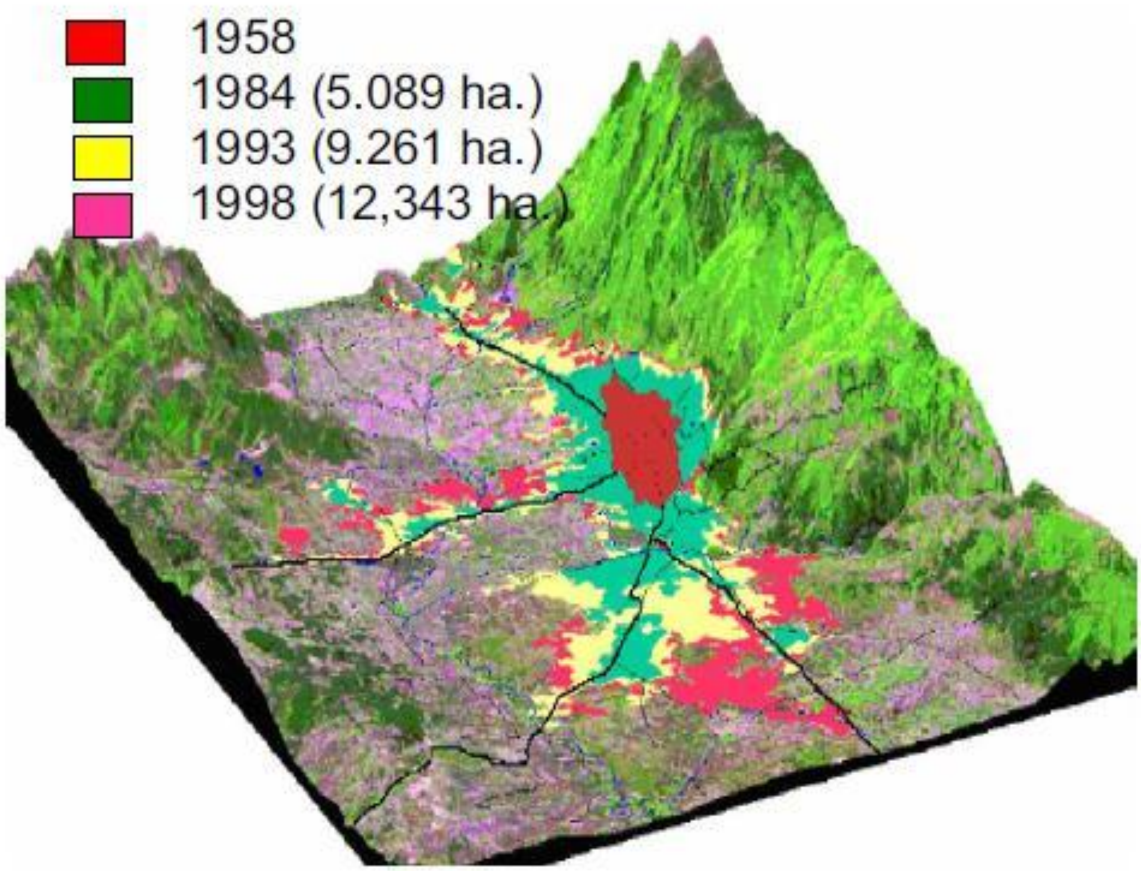
2.6.1 Land use change analysis

Change detection refers to the study of identifying changes of the state of an object (phenomenon) in time. Different time steps are used to identify changes, by making use of different multi temporal data sets of an area, which can be done with remotely sensed data (which is the most of the time the source for the creation of land use maps). Change detection is (successfully) applied in the following applications; land use change analysis, monitoring shifting cultivation, assessment of deforestation, study of changes in vegetation phenology, seasonal changes in pasture production, damage assessment, and other environmental changes (Singh, 1989, p. 989). The process of change detection also provides more insight into the underlying land use changes. The most common method for land use change detection is post classification comparison (Araya, 2009, p. 22 – 24, Singh, 1989, p. 996). There are also other change detection methods like; image differencing, image rationing, image regression, and vegetation index differencing, which are categorized into two main change detection methods; pre-classification and post classification methods (Mubea et al., 2010, p. 127). However, the most commonly used method is post classification comparison, more information on the other methods is provided by Araya (2009) and Singh (1989). Post classification comparison refers to the comparison of independently classified images (of course of the same source, otherwise classification definition problems might arise). Of course the accurateness of the change map is dependent on the precision of the classification of the land use map, the resolution of the land use map and other error propagations (Mubea et al., 2010, p. 127).

2.6.2 Urban sprawl pattern identification

This subchapter is complementary to the next subchapter. The urban sprawl pattern identification is a visual interpretation of where the occurring growth of the urban area is located. It is helpful to identify the shape of the pattern, its future directions, and which environments are threatened by the urban sprawl. The spatial pattern becomes visible by systematically mapping the growth in time (figure 4). The pattern and the configuration of the urban sprawl can be further described by making use of landscape metrics. Visualizing urban growth is not the only way to foster pattern identification. It is also very helpful to classify the growth in time. What kind of growth is occurring, is the new created urban area a result from the expansion of the existing urban area, or is it leapfroggingly creating new urban areas, or are areas within the urban area 'filled' in.

Figure 4: Urban sprawl Bursa area



Source: Eryilmaz et al., 2008.

2.6.3 Landscape metrics

The effects, drivers, characteristics, types and definition of urban sprawl have been explored and described. However how can the urban sprawl of an area be described? Landscape metrics are used to describe and quantify the structure of landscapes (the composition and the arrangement) and the spatial relationships (Walz, 2011, p. 5). Landscape structure is a synonym for the pattern of a landscape. The pattern of a landscape is typified by the "size, shape, arrangement and distribution of individual landscape elements. The reason for using metrics in spatial analysis may be to record the structure of a landscape quantitatively on the basis of area, shape, edge lines, diversity and topology-descriptive mathematical ratios" (Walz, 2011, p. 5).

Landscape metrics are quantitative measures of spatial structures and patterns which can be used to describe urban sprawl. The landscape metrics can be subdivided into three levels of measurement (table 1). (1) Patch level, describes the individual patches as area, provides metric information (characterize the spatial character and context) for individual patches in the landscape. Mostly patch metrics will serve as input for the calculation of landscape metrics. (2) Class level, which uses data of the patches that belong to the same type (same land use type). "Class indices separately quantify the amount and spatial configuration of each patch type and thus provide a means to quantify the extent and fragmentation of each patch type in the landscape" (Fragstats, 2012a). (3) Landscape level, describes the entire landscape, the full extent of the data. Of primary interest is the pattern of the landscape mosaic, the spatial character and distribution of patches (Fragstats, 2012a; Szabó, 2008, p. 7).

Table 1: Landscape metrics

		Level of heterogeneity		
		Patch	*Class*	*Landscape*
Aspect of pattern	*Area & edge*			
	Shape			
	Core area			
	Contrast			
	Aggregation			
	Diversity			

The landscape metrics are grouped into the levels of heterogeneity however they can be further grouped to the aspect of landscape pattern.

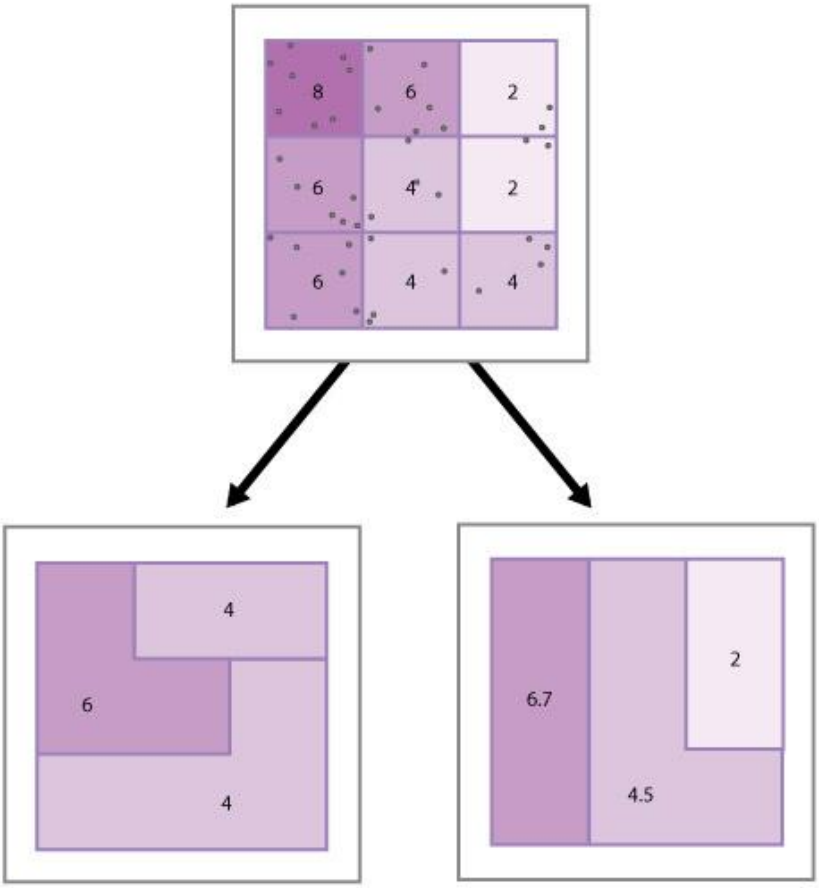
- Area & edge: deals with the size of patches and amount of edge created (describes the spatial 'grain' of the landscape.
- Shape: deals with geometric complexity.
- Core area: deals with areas inside (heart) polygons specified by buffer function or edge distance, description of the patch interior.
- Contrast: deals with the magnitude of difference between adjacent patch types.
- Aggregation: "aggregation refers to the tendency of patch types to be spatially aggregated. This property is also often referred to as landscape *texture*. The term 'aggregation' is used as an umbrella term to describe several closely related concepts: 1) dispersion (spatial distribution of a patch type), 2) interspersion (spatial intermixing of different patch types), 3) subdivision (degree of subdivision of a class or landscape), and 4) isolation (degree of spatial isolation of a patch type) " (Fragstats, 2012b, p. 110).
- Diversity: unsurprisingly this measures the diversity of a variable, i.e. the quantification of the landscape composition. The diversity measurements are influenced by two components. (1) Richness, the number of different classes of a variable, also called the compositional component of diversity. (2) Evenness, the distribution of the different classes of a variable, also described as the structural component of diversity. One of the landscape metrics which is used in this study to measure diversity is Shannon's entropy, which is more sensitive to the changes in richness than evenness (Fragstats, 2012b, pp. 73 – 158).

It should be taken into account that the landscape metrics are developed for ecological processes. Therefore many landscape metrics are not suitable for describing and analyzing urban sprawl. The landscape metrics which were widely used in the reviewed literature are used to analyze urban sprawl in this study. Sometimes several landscape metrics highly (to perfectly) correlate, which makes the metrics redundant, meaning measuring only one is sufficient (as is the case with patch density and mean patch size for example (Fragstats, 2012b, p. 22).

2.7 Scale influence

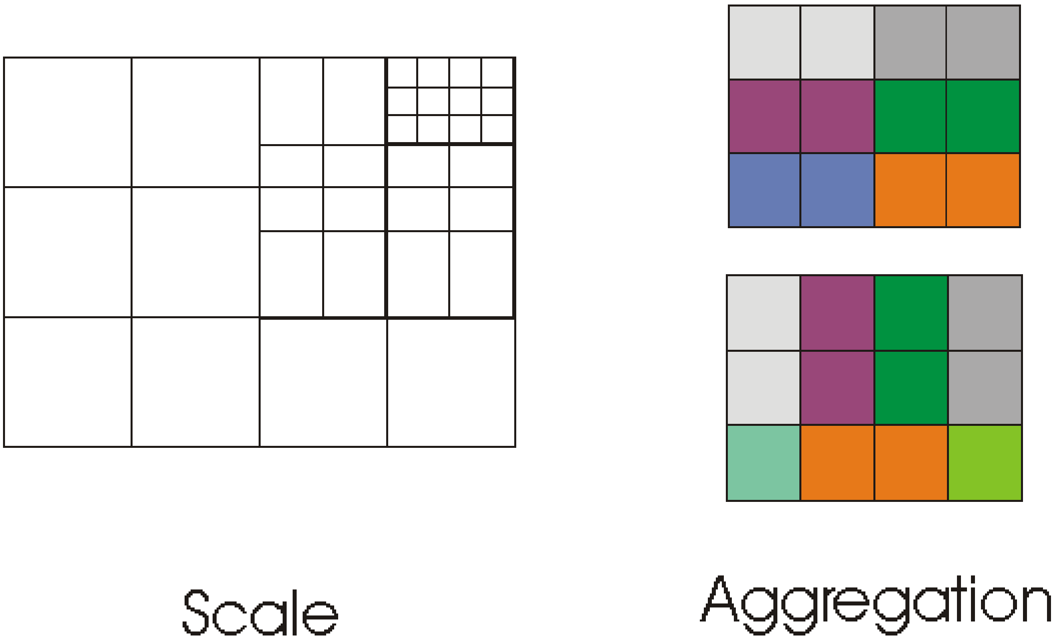
As stated in the introduction, there is assumed that scale will influence the results of the measurement of urban sprawl. Scale problems, scale influence are part of the modifiable areal unit problem. The modifiable areal unit problem (MAUP) is a problem which occurs while analyzing spatial aggregated data, where the results differ when the same analysis is applied but a different aggregation scheme is used (ESRI, 2012). “Areal data, where the spatial objects only exist after data collected for one set of entities, are subjected to an arbitrary aggregation to produce a set of spatial units” (Openshaw, 1984, p. 3). There are so many ways to modify and define spatial objects, and few, if any, sets of non-modifiable units. Areal units are arbitrary and modifiable because they can be aggregated to form units of different size or spatial arrangements (Jelinski et al., 1996, p. 130). For example, census data are collected per household, which is a non-modifiable unit. However, because of privacy the data are aggregated in arbitrary and modifiable areal units like wards or zip codes, which have no intrinsic geographical meaning. If the results of a research are depending on modifiable and arbitrary units, the value of the work should always be questioned to some extent (Openshaw, 1984, p. 4). Different aggregations methods will give different results. A lot of geographers do know about the MAUP, but they do not expect it to have a significant effect on their research, that their numbers are fixed. But the simple figure below already shows that MAUP does influence results (figure 5). MAUP consist out of two aspects, the scale and the zoning problem (figure 6). The scale problem is also known as the grain problem, which indicates the size of the cell. The zoning problem results from the spatial configuration of the areal units (Benson et al., 1995, p. 114; Butkiewicz et al., 2010, p. 2; Kwan et al., 2008, p. 11; Wu, 2004, p. 125; Wu et al., 2000, p. 7). The scale problem includes “the variation in results that may be obtained when the same areal data are combined into sets of increasingly larger areal units of analysis. The zoning problem, by contrast, refers to any result variation due to alternative units of analysis where *n*, the number of units, is constant” (Jelinski, 1996, p. 139). Why are most of the areal units called modifiable and arbitrary? The process of defining and creating areal units do not have a fixed set of rules, there are no standards, no international conventions to guide the spatial aggregation process (Openshaw, 1984, p. 3).

Figure 5: Example of data aggregation influencing the value of spatial units



Azavea, 2012

Figure 6: Scale and aggregation (MAUP)



Geob 370 -- Advanced Issues in GIScience, 2012. Scale shows the differences in the cell size. Aggregation shows the differences in the spatial configuration of the areal units.

2.8 Influencing variables

In previous (sub)chapters has been explained how urban sprawl can be measured by using a GIS. However there are some important concerns which should be considered as they may influence the measurement of urban sprawl with a GIS (Irwin et al., 2006, p.6). Three variables are identified which influence the measurement of urban sprawl with a GIS; definition problems, classification problems, and data availability.

2.8.1 Definition problems

The literature study on what the precise definition of sprawl is, did not result in one precise and commonly accepted definition. Within the literature many different definitions of urban sprawl are used (Christiansen et al., 2001, p. 2; Eryilmaz et al., 2008, p.1). The majority of the definitions share the same facts, but differ in details. It can be concluded that there is not a commonly accepted definition of what urban sprawl entails (Batty et al., 2003, p. 1; Christiansen et al., 2001, p. 2; Davis et al., 2005, pp. 268 – 269; Eryilmaz et al., 2008, p. 1; Poelmans et al., 2009, p. 10; Tewolde et al., 2011, p. 2149). The literature also acknowledges that a commonly agreed definition is needed (Davis et al., 2005, p. 268 - 269; Galster et al., 2001, pp. 681 – 682; Torrens et al., 2000, p. 6). As a result of the non-existence of an commonly agreed definition two events take place. First, the definition of urban sprawl is place-dependent. There are differences in geography, politics, history, and current land use planning per place and per country. Geographers and urban planners within the United States have different perceptions of what urban sprawl is, compared to European planners and geographers (Besussi et al., 2010, p. 18). Second, there is disagreement on which built-up developments are considered as urban sprawl and which as urban growth (Wilson et al., 2003, p. 276).

2.8.2 Classification problems

There are two types of classification problems which influence the measurement of urban sprawl; the amount of classes, and classification methods. Several landscape metrics are sensitive to the amount of land use classes, for example the landscape metrics; number of patches, edge density, Shannon's entropy, area weighted mean patch fractal dimension. In general it can be said that the landscape metrics are the most sensitive to the increasing classification details (amount of land use classes) at very low class numbers (less than 10 land use classes). The response of adding more detail, adding more classes to a land use map, is per landscape metric different. For example the number of patches will show a linear response. While the edge density and Shannon's diversity will show an increasing logarithmic function, and the area weighted mean patch fractal dimension will show a declining logarithmic function. Also, the landscape metric contagion will show a declining erratic trend (Huang et al., 2006, p. 2943). More information on the influence of the amount of classes on landscape metrics can be found in Huang et al. (2006).

Classification methods also influence the measurement of urban sprawl. Studies have shown landscape metrics to be sensitive to the definition of land use classes, because different meanings are given to classes (different class definitions). Different landscape pattern metrics can be obtained when different class definitions are used, that is why the source should always be taken into account (the landscape maps which were used, different sources use different classification definitions), and the methodology (Brown et al., 2004, p. 12).

Another problem related to classification are the classification techniques, methods, and problems which arise when classifying remotely sensed images. This problem is not discussed in this study, because of its extensiveness. Describing the different methods (like supervised, unsupervised, and knowledge-based expert systems) for generating a land use class map from a remotely sensed image is a particular study on itself. Many studies on classifying remotely sensed images have been conducted, for further readings see: Araya, (2009); Harika et al. (2012); Jat et al. (2008); Mubea et al. (2010); Tewolde et al. (2011); Yu et al. (2007).

2.8.3 Data problems

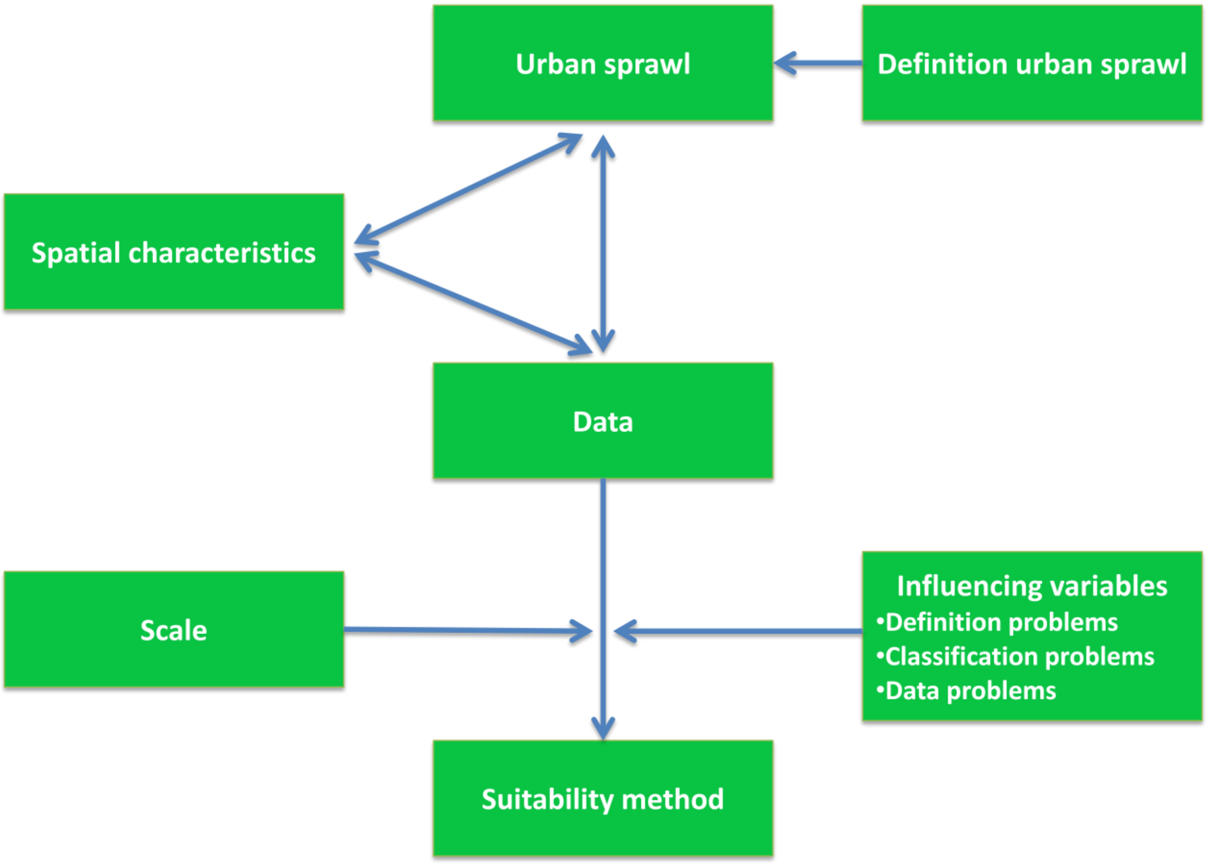
The quality of data, the availability, and the cost of data all influence the results of the measurement of urban sprawl. First of all, the availability of data is important. With the Landsat Thematic Mapper and IKONOS satellite high spatial resolution became available (Herold et al., 2002, p. 1444). But still data limitations are the primary lack of a high resolution (correlation with the MAUP, see next subchapter) analysis of urban sprawl (Irwin et al., 2006, p. 2). Without a high resolution, it is difficult (impossible) to quantify detailed differences in urban sprawl patterns. Thus still data availability remains a problem when analyzing urban sprawl with a GIS. It is also of importance to consider which source of data will be used. A land use classification is not the best source when calculating landscape metrics of habitat quality for a specie. The source which is chosen should be developed for the same intended purpose, i.e. the source of the data should match the study (Brown et al., 2004, p. 17).

2.9 Conceptual model

The research question of the study is: *What is the suitability of the GIS methods which are used for analyzing urban sprawl, and what is the influence of scale on these methods?* Thanks to the reviewed literature, this question can be translated into the following conceptual model (figure 7).

Someone’s experience of urban sprawl, depends on their interpretation of the definition of urban sprawl. Urban sprawl has its spatial characteristics, which are indirectly dependent on the definition of urban sprawl. This problem transferred to the data. The spatial characteristics as well as the perception of urban sprawl can differ, which has its reflection in the data. If the data have been developed for the same purpose, there is a match between the data and the study. The data functions as input for the methodology for the measurement of urban sprawl. However, suitability of a method for the analysis of urban sprawl depends on the scale and other influencing variables (data availability, the amount of classes, and the classification methodology).

Figure 7: Conceptual model



3 Theoretical framework case study Green Heart

A case study provides an excellent opportunity to test the suitability of the found GIS methods and the influence of scale on these methods. In this case the Green Heart is chosen as study area. Urban sprawl of an area cannot be completely understood when the context is unknown. Therefore the history, policy, core qualities, and the experienced urban pressure of the Green Heart is described in this chapter.

3.1 History Green Heart

The Green Heart is part of the Rhine-Meuse delta. Originally the area consisted of peat swamp, requiring efforts to actually make the area livable. The first inhabitants settled on the sandy parts of the banks and embankments. In the tenth century, because of the growing population, a need for new land arose. The reclamation of peat land of areas around the rivers started. During the reclamation, a typical landscape with elongated villages and small stretches of land surrounded with canals arose (figure 8). Around 1300 the entire land of the Green Hart had been cultivated.

Figure 8: Typical peat landscape of the Green Heart

Source: Landschap lezen, 2012

After the reclamation the inhabitants (mostly farmers) found themselves in a vicious circle. The water was still a threat for the cultivated land, resulting in a need for windmills, which pumped the water out of the area (figure 9). The dewatering lead to the settling of the soil, i.e. meaning the surface of the peat land was getting closer to the water level, which means the process of dewatering was needed again. (This process, in time, can make the peat land no longer suitable for agriculture, but only suitable for cattle breeding). In the fourteenth and fifteenth century peat winning became more profitable. After winning peat, large peat lakes arose. During the seventeenth and eighteenth century these lakes were drained to protect the villages (from water hazards) but also to increase the area of farming lands(Groene Hart, 2012; Ibelings, 1996; Ruimtelijk Planbureau, 2005, pp. 54 – 57; VPRO, 2012). After the Second World War the Green Heart rapidly developed (due to social, technological , transportation, and economical developments). Concrete made it easier to built houses on the wet building sites. The increasing welfare increased the mobility of the population, i.e. the travel radius increased, making it possible to live further away from work (possibility to work in the Randstad (conurbation of urban cities) but to live in the Green Hart (rural open area)).

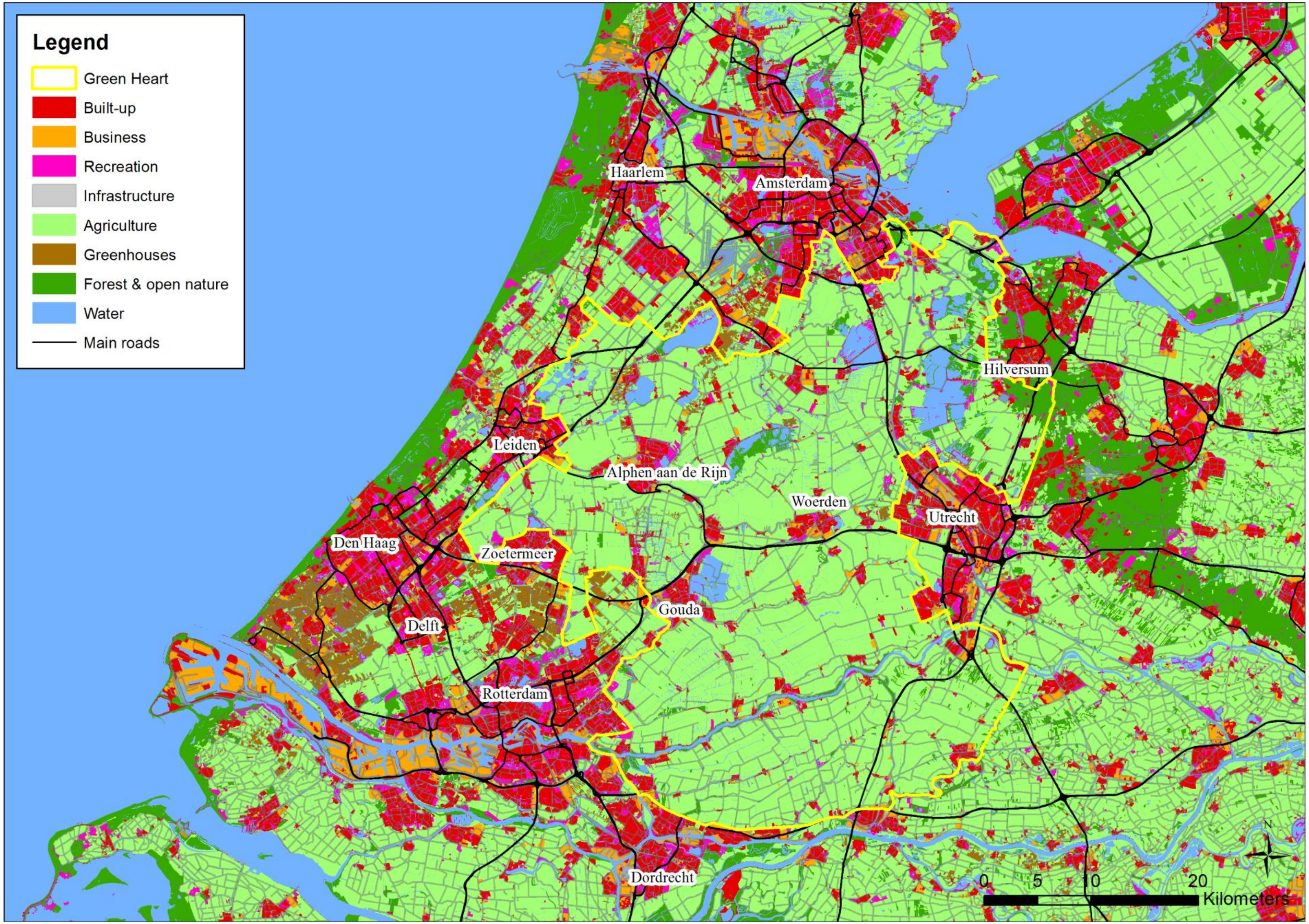
Figure 9: Windmills of Kinderdijk

Source: Rijkswaterstaat, 2012 (the windmills are listed on the World Heritage list of UNESCO)

In 1958 the concept Green Hart was introduced for the first time in an official document of the government, although the name was not Green Heart but Land of the West (free translation of 'Westen Des Lands'). The Dutch metropolis (the Randstad) was described as a circle of smaller and larger (cities) agglomerations lying around the green areas (Green Heart) of Holland and Utrecht (provinces). The policy was aimed at keeping the Green Heart open and free from urbanization. Further agglomeration of the Randstad to one urban area was stated as undesirable. Therefore the Green Heart was intended to be an area for agriculture and cattle breeding (and recreation), and should act as a counterpart for the urban Randstad (IKC RO, 2012; Kuiper et al, 2005, Randstedelijke

Rekenkamer, 2009). At first the Green Heart mainly functioned as food supplier, preventing another Hunger Winter (food was scarce during the winter of 1945 during the Second World War). In the years after 1958 the Green Heart also functioned as a settlement area for people from the cities. From approximately 1960 till 1990 the Green Heart functioned unintentionally as an overflow area of the Randstad. The process of urbanization and fragmentation (for example, a road cuts a green area into two parts) increased significantly, degrading the qualities of the Green Heart (Stuurgroep Groene Hart, 1992, p.16). The national government tried to stop the overflow of people from the Randstad to the Green Heart by giving the Green Heart the status of agricultural landscape, where farmers protected the quality of the unique landscape (Randstedelijke Rekenkamer, 2009, p. 13; Ruimtelijk Planbureau, 2005, p. 15). Nowadays the Green Heart mainly functions as counterpart of the Randstad, as an unique open, green and agricultural area. Over 80% of the Green Heart is agricultural land, but the area itself is not uniform. The borders of the South, West and North of the Green Heart have a high density of built-up area. Whereas the (south) east mainly consists of pastures and open land (figure 10).

Figure 10: Overview Green Heart 2008 [1]



3.2 Policy Green Heart

In 1960 the first report on physical planning of the Netherlands was introduced. After the Second world war the Netherlands witnessed an enormous growth of the population (known as the 'baby boom') and a shortage of homes. Throughout history the Western part of the Netherlands, the Randstad, (the economic hub of the Netherlands) always had been highly populated. However the population was growing even faster because of the movement of people towards the Randstad (urbanization). The plan was aimed to spread the increasing population over the entire country and to prevent the urbanization to the Randstad by stimulating the economy in the other parts of the Netherlands. The government feared for an overpopulation of the Randstad. They were convinced it would be preferable if the cities of the Randstad would remain separated from each other, rather than forming one large agglomeration. Therefore they stated that the Green Heart should be protected for further urbanization.

The second report on physical planning of the Netherlands was introduced in 1966. And the third report was introduced in steps between 1973 and 1983. Both reports shared the same thoughts on how to organize and plan the space in the Randstad and the Green Heart. The government was shocked by the high population prognosis. Their persistent fear remained that the Randstad would grow to one uncontrollable large city with ghettos. 'Concentrated deconcentration' (free translation of 'gebundelde deconcentratie') was believed to be the answer. Several kilometers from the urban ring (the Randstad) municipalities were designated as 'growth nucleus' (free translation of 'groeikernen', which meant that a lot of new houses were built in these nucleus for the growing population). The growth nucleus were designated for absorbing the growing population in the Western part of the Netherlands. The aim was to create new economical independent cities. This way it would be possible to preserve the Green Heart as an open and agricultural landscape. Strict building policies were introduced for new building/housing sites in the Randstad. The government hoped that the growth nucleus would attract a huge amount of people and that the businesses would follow these people. The growth nucleus were mainly situated at the outskirts of the Randstad, several growth nucleus were Alkmaar, Hellevoetsluis, Hoorn, Lelystad, Purmerend. The growth nucleus were designated to stop the growing cities of the Randstad, to prevent the spread of suburbanization (especially the suburbanization into the Green Heart). In the beginning of the 1970's the suburbanization reached its top. In 1980 the construction of new homes actually started, partly because of an additional financial impulse of the government.

From 1980 the cities started to suffer from the suburbanization process. The cities were losing mainly wealthy people resulting in a high pressure on facilities, lose of purchasing power and a decreasing average income. The growth nucleus policy was successful with respect to the amount of people living in the new cities. However it failed to attract businesses, and thus the growth nucleus increased the commuter flow. The goal of creating new independent cities failed, alongside the 'old' cities lost quality and the environment was damaged by an increasing commuter flow.

In 1988 the fourth report on physical planning was introduced. It was mainly targeted at giving the Randstad the opportunity to compete with other European regions. The government recognized the special position of the Randstad. Geographically the Randstad has a great position for logistics and it literally has a green heart. The government realized that the Netherlands should utilize the advantages of the Randstad, and increase the spatial quality for international businesses. The government also aimed to increase the economic core area of the Netherlands from the Randstad to the cities of Northern Brabant and Central Gelderland.

In 1992 the fourth report was altered because of a changing composition of the government. The concentrated deconcentration idea was left. Instead, a new spatial policy of the government was introduced 'the compact city'. This new policy, the compact city, meant a shift away from the old policy of growth nucleus. It was also a reaction to the increasing international competition. The government targeted at creating cities where the different functions (housing, working and facilities) were close to each other. By making Randstad cities strong and compact they could act as the engine of the Dutch economy. The increasing traffic, congestion and pollution were the reasons for leaving the idea of growth nucleus. The government now aimed to reduce mobility. New business and housing locations were supposed to be realized in the already built-up areas of the cities. Housing and offices in suburbanized locations or along the highways, particularly within the Green Heart, without access to public transport should be prevented by this policy. In short, the plans involved: building compact cities, reducing mobility (forensics), protecting the environment and a revival of the cities along with economic growth (Bruijne et al, 2001, pp. 113 – 122; IKCRO, 2012; Ostendorf et al, 1996, pp. 91 - 101; Randstedelijke Rekenkamer, 2009, pp. 13, 98; Ruimtelijk Planbureau, 2006, pp. 26 – 29; Stuurgroep Groene Hart, 1992, pp. 3 – 10; Valk et al, 1997, pp. 57 – 73; Zonneveld, 1991, pp. 96 - 98).

The fifth report on physical planning is not described. Although the report on physical planning was introduced in 2004, it is not necessary to take the report into account. The path of two tracks (facet and sector) is a long way, meaning that normally the plans are implemented after 10 years or more (Stuurgroep Groene Hart, 1992, p. 72). For example the policy for growth nucleus were not operationalized in the seventies, after twelve years the policy plans were implemented and performed (Ostendorf et al., 1996, p. 94).

3.3 Core qualities Green Heart

The Green Heart is a national landscape (free translation of Nationaal Landschap). Within the Netherlands twenty areas are classified as national landscapes. An area can become a national landscape if it consists out of a unique combination of cultural heritage and natural elements. Such as stream valleys, water management systems, agriculture, and mounds. The twenty areas provide an example of the typical Dutch country side. However these typical country sides are threatened by urbanization and the exodus of farmers (Nationaal Landschap Noordoost-Twente, 2012). The areas which are classified by the national government as national landscape are formed to protect the landscape diversity of the Netherlands. The report on physical planning (Nota Ruimte) of 2004 outlines the landscape features that need protection. To protect these areas from urbanization it is determined that new housing is only allowed to take care of the local natural population growth. Large-scale spatial developments are not allowed. For other spatial developments there is a 'yes, but' policy, which means that spatial developments are only possibly if they maintain or enhance the core qualities of the landscape (Ministerie van I&M, 2010, p. 4). Governmental documents from the 1958 till now aim to preserve and develop the core qualities of the Green Heart. For example the ministry of environmental defense and the Green Heart foundation want to preserve the cultural heritage and natural elements of the Green Heart. They define the Green Heart as a typical traditional Dutch landscape with reclamations and peat areas. The ministry of agriculture, nature and food quality has the objective the preservation and strengthening of the characteristics of the Green Heart

(Randstedelijke Rekenkamer, 2009, p. 102). The objective of the steering committee Green Heart is to enforce the contrast of the metropolitan environment of the Randstad and the open and green space of the Green Heart. Another objective is to maintain the diversity of landscape, in particular the characteristics of the open landscape of the peat land areas, which function as the core of the Green Heart. And preventing the compartmentalization of the visual and actual reduction of the Green Heart as a result of the densification and construction of infrastructure, urbanization and green houses (Stuurgroep Groene Hart, 1992, p. 8, 79 - 80).

The Green Heart has the following landscape characteristics, core qualities, which makes it a national landscape; diversity of landscape, peat-meadow character, openness, and peace and quiet (Randstedelijke Rekenkamer, 2009, p. 44).

3.4 Urban pressure

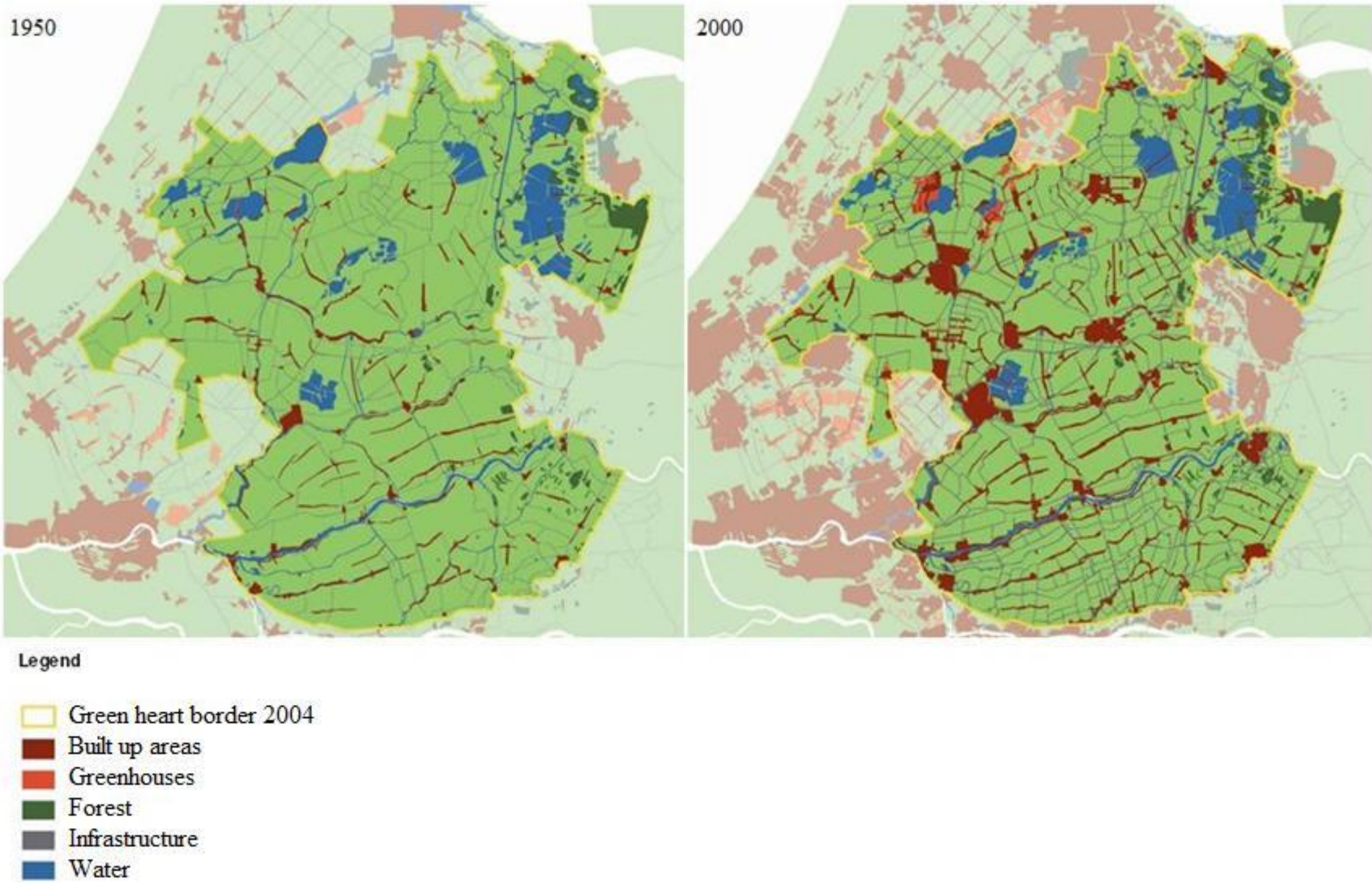
The welfare of the Netherlands is, indirectly, determined by the Randstad. The Randstad itself has an unique position of being one of the most important gateways to Europe (because of its geographic position). The Randstad earns almost 50% of the gross national product of the Netherlands. The Randstad has internationally the most potential to compete with Europe (and the world). (Competition is nowadays more and more between economic regions). Therefore developments in the Randstad should ensure a good international competitive position of the Netherlands (CBS, 2012a; Ministerie VROM, 1996, pp.9-31; TNO, 2012; Zonneveld, 1991a, pp. 184-185; Zonneveld, 1991b. p. 186 - 189). Also the fourth report on physical planning (vierde nota ruimtelijke ordening) chose to strengthen the economic position of the Randstad, to be able to compete with the increasing competition between European cities (Stuurgroep Groene Hart, 1992, p.7).

Since 1958 is has been recognized that social-economical, transportational, and political developments (population growth, increasing mobility and economical development) put pressure on the Green Heart (Randstedelijke Rekenkamer, 2009, p. 13; Ruimtelijke Planbureau, 2005, p. 7). The Green Hart has shrunk with 25% when you take into account its borders of 1958 (figure 11). The 25% once open area is now transformed to built-up areas and is placed outside the borders of the Green Heart outwards. The latest adjustments to the borders of the Green Heart originate from 2004. In the 'Nota Ruimte' the government changed the borders in two areas, the Zuidplaspolder and Rijenburg, both changes made urbanization possible. Not only did the borders change. Also, from 1958 until 2000 the built-up area within the Green Heart was multiplied by four ((Randstedelijke Rekenkamer, 2009, p. 13) figure 12).

Figure 11: Changing borders Green Heart

Source: After Randstedelijke Rekenkamer, 2009

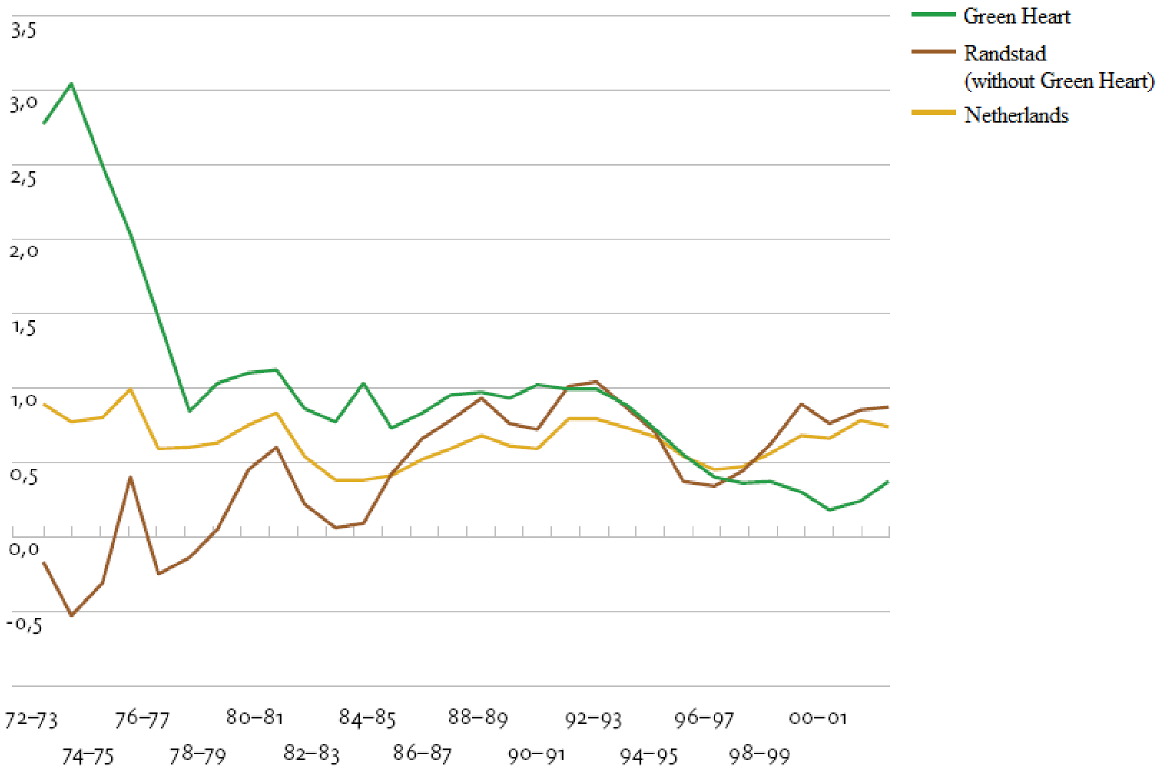
Figure 12: Changes in built-up areas Green Heart 1950-2000



Source: Randstedelijke Rekenkamer, 2009.

The Green Heart is a desirable area to live. It combines the benefits of living in a rural area with the amenities of the proximity of an urban and economic centre (good geographic position). The population development shows that until 1991 the Green Heart grew faster than the Netherlands and the Randstad (figure 13).

Figure 13: Population development



Source: After Ruimtelijk Planbureau, 2005

In the beginning (1973-1978) the population growth is twice to three times higher than the Netherlands and the Randstad on average. This can be explained by the perfect geographic position and the policy at the time. The cities Alphen aan den Rijn, Gouda and Woerden were given the status of growth nucleus and regional centers, which is odd as they lay within the Green Heart, this confirms the idea that the government policy has not always been consistent. They want to keep the Green Heart open, green, and free form urbanization, however they do select growth nucleus (Alphen aan den Rijn, Gouda and Woerden) that lay within the Green Heart (Ruimtelijk Planbureau, 2005, p. 94; Stuurgroep Groene Hart, 1992, p. 24). From 1991 the growth in the Green Heart is equal to or less than the average growth of population in the Netherlands and the Randstad. The development of the housing market shows the same pattern. In the beginning (1970's) the growth of the housing market in the Green Heart is twice to three times higher on average than in the Randstad and the Netherlands. And from 1990/1991 the growth is equal or less. In 2000, 4,9% of the area is occupied for living against 5,3% of the Netherlands and 15,9% of the Randstad (Ruimtelijk Planbureau, 2005, pp. 59-77; Randstedelijke Rekenkamer, 2009, p. 20).

The Friends of the Earth Netherlands, the Green Heart foundation and the fifth report on physical planning (Nota Ruimte) state that built-up (mainly businesses and infrastructure) is the main threat for the peat-meadow landscape of the Green Heart (Randstedelijke Rekenkamer, 2009, p. 102). However, the peat-meadow characteristics are an unique landscape (cultural heritage), and agriculture is often unable to compete against urbanization. In the past decades it has been shown that this process is difficult to control. The accumulation of individual often acceptable new homes, greenhouses, and infrastructure are eroding the characteristics and core qualities of the rural area. The rural land is eroded, meaning it is even more difficult to withstand the pressure, a negative spiral movement. This can already be seen in the growth nucleus Alphen aan de Rijn, Gouda, and Woerden (Stuurgroep Groene hart, 1992, p. 24). Other urbanization threats occur along the main infrastructure. In the wake of growing amounts of car movements, infrastructure expanded as well, leading to the compartmentalization of the Green Heart, and the loss of openness. Research confirms that residents, visitors, and commuters who make use of the infrastructure of the Green Heart do not experience that they are in a green and open area, because of the blocked view. The tremendous growth of visible location along infrastructure , which is appealing to companies, is a serious threat for the core qualities of the Green Heart. Research also confirms that besides housing, industrial sites and business sites, also green houses are experienced as urbanization (Stuurgroep Groene Hart, 1992, p. 32). Although the described policy intended the opposite, the Green Heart did urbanize to a high extent. The process of urbanization (including green houses) has therefore adopted a considerable amount of land, and in certain areas did lead to a serious loss of spatial quality (Stuurgroep Groene Hart, 1992, p. 3 – 16).

So far background information of the Green Heart is given, which allows a better understanding of the case study area. The next chapter continues with the methodology of measuring urban sprawl with a GIS.

4. Methodology

Measuring the growth of urban sprawl is often done by satellite images (or existing land cover maps), GIS techniques and simple math. The satellite images can be classified into land cover maps (by making uses of the spectral values of the pixel and classification techniques). Once classified, the two land cover maps of a time series of the same area can be compared and the growth of the built-up area can be calculated. However this does not tell anything about the pattern of the urban area, and the pattern of the expansion of the urban area/urban sprawl, and if there is a correlation between the former land cover type and the new urban land. For urban planners it is essential to understand the change of land use, the pattern of urban sprawl, and the configuration of the built-up environment. Insight in urban sprawl provides the understanding of the relationship between urban form and its processes (Yeh et al., 2001, p. 83). These insights give municipalities the ability, and also the support to make sustainable development plans in changing regions (Herold et al., 2002, p. 1443; Jat et al., 2008, p. 27). In order to characterize, describe, quantify and detect patterns of urban sprawl, appropriate scales are needed (Sudhira et al., 2004, pp. 33 – 34). Utilizing "landscape metrics as quantitative measures of spatial structures and patterns gives the ability to describe urban land use features, structures and patterns of a landscape" (Herold et al., 2002, pp. 1445 – 1446). Most of the landscape metrics correlate with each other.

For this study the most widely applied methods* (in literature) such as landscape metrics (landscape metrics are used to describe and quantify the structure of landscapes), land use change analysis, and urban sprawl pattern recognition, are used to analyze urban sprawl. Sudhira et al. (2004) use the following landscape metrics to analyze the urban sprawl in their study: Shannon's entropy and map density, these two landscape metrics are probably two of the widely used landscape metrics for analyzing urban sprawl. And Shannon's entropy is probably the most used landscape metrics to describe urban sprawl (Araya et al., 2010, pp. 1553 – 1556; Jat et al., 2008, p. 29; Sudhira et al., 2004, pp. 33 – 34; Yu et al., 2007, p. 100). Shannon's entropy measures the degree of spatial concentration and dispersion of a variable in an area. Jat et al. (2004) use map density as a landscape metric to describe urban sprawl. It can be used to describe, or examine, the homogeneity or dispersion of any spatial phenomenon. Widely used is the built-up density, which indicates the urbanization density (Jat et al., 2004, p. 29; Sudhira, 2004, pp. 33 – 34). The contagion index describes the heterogeneity of a landscape. Indicates whether the land use classes of a landscape are clumped or more aggregated, and what the probability is that a pixel of land use class *a* is adjacent to that of land use class *b* (Araya et al., 2010, pp. 1553 – 1556; Herold et al., 2002, p. 1445; Yu et al., 2007, p. 100;). Angel et al. (2007) and Camagni et al. (2002) classify the types of urban sprawl. In this way different types of sprawl are examined, described and classified (Angel et

* This study researches the suitability of the most widely used GIS methodologies within the literature to analyze urban sprawl, and the influence of scale on these methodologies. It is however impossible to include all GIS methods which are used to measure urban sprawl. Therefore only a selection of the most widely used methods has been described. It's disputable and arbitrary to identify the most widely used GIS methodologies. In this research the literature on urban sprawl is reviewed. The most cited authors and their methodologies are used as a starting point, and these methodologies are classified as most widely used if their methodologies are also widely used by less cited authors (which is arbitrary and disputable).

al., 2007, p. 2: Camagni et al., 2002, p. 204). The land use map allows for the calculation and classification of the map density, Shannon's entropy, contagion, new developments, and the land use change detection (transition probability matrix). The map density, Shannon's entropy, contagion, and the transition probability matrix calculations, along with classification of the developments gives insight into the processes of urban sprawl in the Green Heart. Thus landscape metrics, alongside with land use change analysis, and urban sprawl pattern recognition are used to describe (the) urban sprawl (within the Green Heart).

However there is a need to study how these metrics which describe urban sprawl respond to the scale aspect of the modifiable areal unit problem. The modifiable areal unit problem is a problem which occurs when analyzing spatial data that are aggregated, the results of the analyses will differ when a different scale or extent is used. There is a need to know how sensitive the landscape metrics are for the MAUP. Otherwise the urban sprawl in the Green Heart cannot be analyzed and described properly. In this study the MAUP is limited to the scale aspect.

This chapter describes the methodology on how to measure urban sprawl with a GIS. The chosen methods are arbitrary in the way that they do not represent all the available methods. These methods are chosen because they are most (commonly) used in the literature regarding measuring urban sprawl. More metrics can always be used, especially if the research is aimed at a specific part of urban sprawl, however these methods result in a clear overview of the urban sprawl of an area. The methods used for this study are described in table 2, and in table 3 the level of heterogeneity (see p.25) for the landscape metrics are given.

Table 2: Methods for measuring urban sprawl with a GIS

Landscape metric	**Comments**
Class area (CA)	Shows the absolute growth of the urban class.
Number of patches (PA)	Measures the extent of fragmentation of the patch type.
Edge density (ED)	Measures the total edge of the urban class. Increases with new nuclei, may decline when urban areas agglomerate.
Area weighted mean patch fractal dimension (AWMPFD)	Measures shape complexity of the urban patches. Simple forms like a triangle, round, and or a square are close to the value of 1, complex forms are close to the value of 2.
Built-up density	Shows the dispersion of the urban patch (spatial distribution).
Contagion	Measures the extent to which landscapes are aggregated or clumped.
Shannon's entropy	Measures the degree of spatial concentration and dispersion of the urban class.
Pattern identification	**Comments**
Urban growth	Indication of the direction of the urban sprawl.
Classification new developments	Indication of the configuration of the urban growth.
Land use change	**Comments**
Land use change detection	Indicates which land use classes are threatened by urban sprawl.
Markov Cellular Automata Chain	Indication of the future direction of the urban sprawl.

Table 3: Level of measurement landscape metrics

Landscape metric	**Level of heterogeneity**	**Comments**
Class area (CA)	Class level	Required is information about how the urban area alters in time. Therefore the entire class urban (built-up) is measured. Also the class level is the only available level of heterogeneity for this metric.
Number of patches (PA)	Class level	The extent of fragmentation of the urban area is needed, therefore this metrics needs to be measured on the class level. It is also possible to measure this metric on the landscape level, however in that case the total amount of patches in the landscape will be calculated.
Edge density (ED)	Class level	Again, the urban class itself is of particular interest for this metric, because it provides information on the configuration of the urban class. It is also possible to measure this metric on landscape level to calculate the ED for the entire landscape.
Area weighted mean patch fractal dimension (AWMPFD)	Class level	Again like the metrics PA and ED this metric can be measured on the class and landscape level. AWMPFD measures shape complexity of the urban patches. One might expect that the level of heterogeneity (or the measurement level) would be patch level, but this is not possible. In this case one only needs to know the AWMPFD of the urban land use class, and not for other land use classes and their patches.
Built-up density	Class level	This metric measures the density of urban pixels.
Contagion	Landscape level	This metric can only be measured on the landscape level (see table 2).
Shannon's entropy	Landscape level	This metric can only be measured on the landscape level (Mcgarigal et al., 1995, pp. 14 – 15).

4.1 Class area

Class area (CA) measures the total overall urban growth of an area. It is a straightforward metric, which basically measures the amount of urban pixels per time step. It is also possible to measure the percentage of the total area covered by the urban class, by dividing the class area by the total area (Alexakis et al., 2011, p. 7; Araya, 2009, p. 26; Herold et al., 2002, p. 1446; Xi et al., 2009, p. 4).

4.2 Number of patches

The number of patches (PA) is a simple quantification of the amount of individual urban patches. It does not contain any information about the area, or the disparity of patches, or the density. However it does provide information on the amount of new created patches in time (Alexakis et al., 2011, p. 7; Araya, 2009, p. 27; Herold et al., 2002, p. 1446; Xi et al., 2009, p. 4; Yu et al., 2007, p. 100). Perhaps it is not the most useful landscape metrics, as it does not contain that much information about sprawl. However it gives an indication of the fragmentation of the patches within the area. If the landscape area is kept the same the number of patches provides the same information as patch density or mean patch size, therefore these metrics are not calculated. Also the number of patches is used for other methods, like the relative Shannon entropy (Fragstats, 2012c).

4.3 Edge density

An edge is the border between two different land cover classes. Edge density (ED) does in contrast to number of patches and patch density take into account the shapes of patches, the complexity of the shape of a patch. When new urban areas emerge the edge density of the urban land use class should increase, a decrease is possible when areas agglomerate. The formula to calculate the edge density is:

$$ED = \frac{E}{A}$$

Where:
E = Total edge in meters
A = Total area (ha)
(Araya, 2009, p. 27; Alexakis et al., 2011, p. 7; Eiden et al., 2012; Herold et al., 2002, p. 1446).

4.4 Area weighted mean patch fractal dimension

The area weighted mean patch fractal dimension (AWMPFD) measures the shape of the urban patches. It measures the complexity of the patches, values close to one represent compact and rectangular/round (simple) shapes, values close to two represent complex and irregular shapes. AWMPFD measures the average patch fractal dimension of a land use type weighted by the patch area (which means larger patches weigh more than smaller ones). The formula to calculate the AWMPFD is:

Vector

$$AWMPFD = \sum_{i=1}^{m} \sum_{j=1}^{n} \left[\left(\frac{2 \ln p_{ij}}{\ln a_{ij}} \right) \left(\frac{a_{ij}}{A} \right) \right]$$

Raster

$$AWMPFD = \sum_{i=1}^{m} \sum_{j=1}^{n} \left[\left(\frac{2 \ln (0.25 p_{ij})}{\ln a_{ij}} \right) \left(\frac{a_{ij}}{A} \right) \right]$$

Source: Mcgarigal et al., 1995, p. 111

Where:
p = patch perimeter (m),
a = patch area (m^2).
(Alexakis et al., 2011, p. 7; Mcgarigal et al., 1995, p. 95; Yu et al., 2007, p. 100; Xi et al., 2009, p. 4).

4.5 Built-up density

The built-up density is calculated by dividing the number of built-up pixels by the total number of pixels in a kernel, region, administrative level, or a municipality. The built-up density identifies urban growth centers, and in combination with Shannon's entropy, the dispersion per region. High density of built-up refers to a compact city, medium density refers to less compact built city, and low density refers to sparsely spread built-up areas (Sudhira et al., 2004, p. 34).

This method is operationalized with the help of the GIS program Erdas Imagine. Erdas includes the function focal density. The focal density calculates the mean value of the center pixel by using the pixel values that are within the focal window (Erdas, 2012). The size of the focal window (the kernel) is set on 3 by 3 pixels. Jat et al. (2008) choose the size of the kernel based on the maximum number of land use categories available. In their study there are 10 land use classes, which means a 3 by 3 kernel is insufficient, therefore they make use of a 5 by 5 kernel. In this study the amount of land use categories is limited to two, therefore a 3 by 3 kernel is used. Of course other methods exist for creating a density map, however the kernel function creates a smooth map. But most important the kernel function weights nearby points more than points that lie further away from each other (Hillier, 2011, p. 71).

4.6 Contagion index

The contagion index is an aggregation metric which measures the dispersion and interspersion, it measures the landscape configuration (Fragstats, 2012b, p. 113). Dispersion refers to the spatial distribution of a patch type (the spread of the patch type, how disperse is it, the spatial distribution of a patch type), and interspersion refers to "the spatial intermixing of different patch types without explicit reference to the dispersion of any patch type" (Fragstats, 2012b, p. 19). Herold et al., (2002) state that "the contagion index describes the fragmentation of a landscape by the random and conditional probabilities that a pixel of patch class *I* is adjacent to another patch class *k*" (Herold et al., 2002, pp. 1445 – 1446).

$$\text{CONTAG} = \left\{1 + \frac{1}{2\ln m}\left[\left(\sum_{i=1}^{m}\sum_{k=1}^{m} p_i \frac{g_i}{\sum_{k=1}^{m} g_{ik}}\right) - \ln p_i \frac{g_{ik}}{\sum_{k=1}^{m} g_{ik}}\right]\right\} 100,$$

where
m is the number of patch types (classes),
p_i is the proportion of the landscape occupied by patch type (class) i,
g_{ik} is the number of adjacencies (joins) between pixels of classes i and k.
Source: Herold et al., 2002, p. 1445

Contagion measures the extent to which a landscape element (patch types) is aggregated or clumped (dispersion). When the patch types of a landscapes are well interspersed a lower contagion index value is obtained than when they are poorly interspersed. High contagion index values are obtained when the landscape has a few large, and contiguous patches (contagion is high because many cells are adjacent to each other in large and contiguous patches (many internal cells)). Lower values are obtained thus when a landscape is marked with many small and dispersed patches (Fragstats, 2012b, p. 113; Herold et al., 2002, pp. 1445 – 1446; Mcgarigal et al., 1995, p. 52).

The contagion index is based on raster cell adjacencies and not patches. The contagion index consist of the sum over the patch types of the products of two probabilities:

1. The probability that a cell belongs to patch type *i.*
2. The probability that cell which belongs to patch type *I* is adjacent to a cell which belongs to patch class *k* (Mcgarigal et al., 1995, p. 52; Herold et al., 2002, pp. 1445 – 1446).

4.7 Shannon's entropy

Entropy has its origins in the information theory. Information theory consists of the measurement and transmission of information. Entropy measures the quantities of transmitted information, however not the meaning of the information (the value or meaning a person gives to information). It quantifies the abstract concept of information, describing the information by using mathematics (Pászto et al., 2009, pp. 2-4).

In this context Shannon's entropy measures the degree of spatial concentration and dispersion of a variable in an area. It measures whether the geographical phenomenon (here urban land) is more dispersed in the area or shows a compact pattern.

Shannon's spatial entropy: $H_n = \sum_i^n p_i \; log(\frac{1}{p_i})$

Where p_i is the probability or proportion f a phenomenon (variable) occurring in the *i*th one.

The entropy is a robust spatial statistic, and where other spatial sprawl statistics (for example the Gini coefficient or the Lorenz curve) are dependent on size, shape, and amount of regions (Thomas, 1981, p.3), "and the results can change substantially with different levels of areal aggregation"(Yeh et al., 2001, p. 88), entropy is less affected by these variables. The relative entropy is Shannon's entropy normalized by *log(n)* which means that the amount of the variable is taking into account, which is a better method to calculate the entropy, "because its value is invariant with the value of *n*, the number of regions" (Yeh et al., 2001. P. 88).

Relative entropy: $H_n = \sum_i^n p_i \; log(\frac{1}{p_i}) \,/\, log(n)$

If the value is close to 1 then the built-up areas are unevenly dispersed around the area, if the value is close to 0 the built-up areas are concentrated. But still relative entropy is to some extent sensitive to different shapes and sizes of the regions. If two different scales are used to measure the sprawl, the outcome will be different. This problem can be solved, as it is possible to exactly measure the differences of the scales, scale problems do influence in many ways spatial analysis (Thomas, 1989, p. 13). If the largest region of two is subdivided into smaller regions (almost same size of the other scale), it is then possible to measure the entropy with the following equation:

$$H_n = \sum_{i=1}^{m} p_i \; log(\frac{1}{p_i}) + \sum_{i=1}^{m} [p_i \sum_{i=1}^{ni} * (p_i * \frac{i}{p_i}) \; log\left(\frac{p_i \, 1}{p_{i(i)}}\right)]$$

Entropy measures the distribution of a geographical phenomenon, however it is also possible to measure the difference of entropy in time. The following formula calculate the magnitude of change of urban sprawl in time:

$$\Delta H_n = H_n\,(t+1) - H_n(t)$$

(Jat et al., 2008, p. 28; Tewolde et al., 2011, pp. 2153 – 2154; Yeh at al., 2001, pp. 84 - 89).

4.8 Urban growth

This methodology is straightforward and simple. Per available time step the urban growth is captured. This way the urban growth is assessed. It might lead to the recognition of different patterns per time step, because in time, the location variables for people and companies can change (Eryilmaz et al., 2008, pp. 4 – 8). Of course this methodology is closely related to the land use change detection methodology, where more land use classes are used. However this methodology zooms in on the specific urban growth/sprawl per different time step.

4.9 Classification new developments

New developments are added to built-up areas between time series *t*1 and *t*2, *t*2 and *t*3, and so on. The new emerged areas can be classified into three different types of built-up areas.

- Infill: meaning that open space which is surrounded by urban/built-up land is changed to built-up.
- Extension: new urban areas which intersect with the existing urban areas.
- Leapfrog: new urban areas which do not intersect with the existing urban areas. This development has the greatest effect on the growth of the urban footprint as well as the fragmentation of land (Angel et al., 2012a, pp. 26 – 29).

Infill: newly developed built-up areas must be surrounded by existing built-up areas. This means automatically that a newly developed built-up area which has as neighbors only built-up area can be classified as *infill.* However it is possible that there is an open space within an urban area which in time is developed partly as built-up. This means that the area will not have direct neighbors of built-up everywhere, but still should be classified as infill. Therefore for time step *t*1 the core areas of built-up areas are defined as polygon, and if new developments will take place in these polygons they will be classified as *infill.*

Extension: newly developed built-up areas must intersect with the existing built-up areas of time step *t*1. Of course it is also possible, as there are four time steps for the case study, that an urban development in time step *t*3 can be classified as extension as this area intersects with an extension area of time step *t*2. However it is possible that some pixels will not be directly adjacent (or have an intersection) with the built-up areas of time step *t*1 (or *t*2 or *t*3), therefore a threshold value must be defined. The threshold value defines which newly built-up developments are classified as extension in terms of distance away from the original built-up areas. Angel et al. (2007) argue that all urban developments which do not intersect should be classified as leapfrog. Which is in my opinion not entirely true, working with a high resolution automatically involves that new developments which occur within a distance of 50 meters of existing built-up areas are defined as a leapfrog development, which is arbitrary. The suggestion is to set a threshold distance of 250 meters for the classification for the extension class. Choosing 250 meters is highly arbitrary, and is not substantiated with scientific literature, however it removes potentially arbitrary classified leapfrog development. The threshold distance of 250 meters is selected by a sensitivity analysis. Each time 50 more meters was added to the threshold distance until no new developments area where found which had any possible connection with the existing built-up area (for example via a natural barrier such as water, or a highway).

Leapfrog: built-up that do not intersect with built-up areas (while using the 250 meters threshold value). Finding the leapfrog areas is easy, because, if correct, all other newly developed built-up areas who do not belong to this class are already classified.

For this methodology it is wise to use vector data instead of raster data. Vector data allows for working with simple queries (select by location), which makes the classification of the newly developed built-up areas less time consuming. However it is impossible to measure the influence of scale when working with the original vector data.

4.10 Landscape change detection

Landscape change detection, or land use change (LUC), provides information on the amount of land use change in the study area for a period of time. Land use change is the alteration of land, the change is based on the need of mankind (exceptions are natural hazards). Land use change has its impact on the management of land, as they alter the biodiversity and the impact on human life (Islam et al., 2011, p. 81). With satellite images, classified land use maps in the format of a raster, it is possible to calculate the area in which land use change occurs in different time steps. This type of analysis will give information about the correlations between land use classes (Harika, 2012, p. 387).

There are several ways to calculate and detect the change of land use. The easiest way is to make use of a raster calculation. With the raster calculation both cell values are added. The cell value of cell *k* from 1989 is added to the cell value of cell *k* from 2008. The cell values of every land use class for both maps (1989 and 2008) should have different values. This way it is easy to create a transition value table, and to create a land use change map (table 4).

Table 4: Example transition land use change value table

Value 1989	Value 2008	Transition value 1989 + 2008
1 = Built-up	10 = Built-up	11 = Built-up (no changes)
2= Water	20 = Water	12 = From water to built-up
		21 = From built-op to water
		22 = Water (no changes)

4.11 Markov Cellular Automata Chain Model

The dynamics of urban sprawl can be analyzed with the Cellular Automata Markov Chain model. This model predicts the future of urban sprawl, which is of importance to municipalities to make sustainable development plans in the changing regions. The Cellular Automata Markov Chain model predicts the future by using the past. Land use change is detected and analyzed (land use change analysis (LUC)), which results in a transition probability matrix. And regression analyses are conducted to add the spatial weighting factor to the model (Araya et al., 2010, pp. 1553 – 1556; Harika et al., 2012, p. 386; Herold et al., 2002, p., 1445; Islam et al., 2011, pp. 83 – 87; Yu et al., 2007, p. 100; Sudhira et al, 2004, pp. 33 – 34; Tewolde et al., 2011, pp. 2153 - 2154).

The Markov Chain model is commonly used by geographers when they are concerned with the movements of variables from one ‘state’ to another. State can be the size of a city, but also land cover type. The Markov Chain model describes and analyzes the nature of the changes that occur. The model can be used to forecast future changes. The Markov Chain model is based on the concept of probability. The Markov Chain model makes use of the information related to the observed probabilities of the past trends in a chosen time span (Cole, 2012, p. 9; Collins, 1975, pp. 3 – 6).

It is a stochastic model, the state of the system in time ($t2$) is derived from the state at an earlier time ($t1$), and does not depend on the history of the system before time $t1$. The Markov model becomes a Markov Chain model if the process is a process of multiple time series of transitions of the values. The Markov Chain model can be expressed as:

$$vt_2 = M * vt_1$$

where:
vt_1 = input land cover type at time 1
vt_2 = output land cover type at time 2
M = the transition matrix for the time interval between time 1 and 2.

If the time period is the only dependant variable for the probabilities, and no other process is of relevance, the model is stationary or homogeneous in time. If there are multiple time steps available, calibration and validation of the Markov Chain model is possible, by comparing the predicted land use map, created by the model, with the actual land use map. But the Markov model has disadvantages, theoretically it is possible to have a stationary model, however it results in analytical and computational difficulties. It also ignores the drivers which produce the changes of land use. The model is not spatial, it does not provide any sense of geography. Also the model depends on time, however for a long period of time the results of the model may become unattainable (Cole, 2012, pp. 9 – 10; Mubea et al., 2010, pp. 131 - 132).

The Markov Chain model describes the land cover change in a period of time. Insight is gained, for example that agricultural land has a 12% probability that it will change into urban land, however no knowledge is gained about the spatial distribution of the land use classes. It is possible to gain information on the spatial distribution by integrating Cellular Automata (CA) into the Markov Chain model. “The CA component of the CA-Markov model allows the transition probabilities of one pixel to be a function of the neighboring pixels” (Araya et al., 2010, pp. 1554). The CA adds spatial contiguity as well as the expected spatial distribution of the land cover classes. The CA process creates a spatial weighting factor, for example a higher weight is given to areas that are nearby to already existing urban land, or infrastructure. Regression analyses can be conducted to examine the relationship between land use changes and spatial variables. This relationship can reflect location behaviors and preferences. However it is difficult to assess which relationships are vital to the land use change. Li et al. (2004) suggest the following: “probabilities of land use changes are a function of three spatial variables: distances to built-up, distance to roads, and distance to a city” (Li et al., 2004, p. 340). Selecting the appropriate spatial variables is very important as it influences directly the performance of the model.

4.12 Scale aspect

Detailed spatial analysis of urban land use patterns is often impossible, data limitations are primary reasons for not conducting detailed spatial analyses (high resolution analysis). Detailed (high resolution) data are difficult to get, but allow for the analysis and spotting of detailed differences in urban patterns. However most of the available land use data are derived from aerial photographs or remotely sensed imagery, which are often coarse (low resolution) scaled (Irwin et al., 2006, pp. 1 – 3; Hasse et al., 2003, p. 160). Sprawl as concept is widely known, however researchers study the sprawl mostly at one spatial scale (see for examples Eryilmaz et al., 2008; Harika et al., 2012; Herold et al., 2002; Islam et al., 2011; Li et al., 2004; Sudhira et al., 2004; Tewolde et al., 2011; Yeh et al., 2001). These studies however forget that when scales, unit size and or shape, and or extent are changed this will alter the results. Many spatial analyses and patterns are scale dependent, for instance it is possible that on an aggregate scale urban sprawl exhibit a compact development pattern, but a scattered pattern is exhibited on a detailed (high resolution) level (Irwin et al., 2006, p. 7). Jelinski et al. (1996) opts that the MAUP should not be ignored, but there should be a better sense of its scope and magnitude. By sensitivity analysis, insights are gained on which variables are sensitive to variations of scale and how sensitive they are (Jelinski et al., 1996, pp. 136 – 137). In this study the commonly used GIS methods are analyzed systematically for their scale sensitivity by increasing the grain size from 5 by 5 to 50 by 50 to 500 by 500 meters. The land use map with the grain size 5 by 5 is used as a base map for the up scaling to 50 by 50 and to 500 by 500 meters. By the creation of the raster maps the maximum area cell assignment technique is used, which means that the cell gets the attribute value of the single feature which has the largest area within the cell. Performing analysis at several spatial scales is a widely used way to examine scale dependencies, however, so far it is widely ignored in the urban sprawl literature (Irwin et al., 2006; Wu et al., 2004). Analyses which are limited to one scale fail to discover scale dependent effects (Irwin et al., 2006, pp. 1 – 7). It is also recommended to only compare values of landscape metrics if they are measured at the same scale (Saura, 2004, p. 198). The scale aspect should not be seen as a problem, the different scale analysis can be used to understand the multiple-scale characteristics of urban sprawl (Wu et al., 2004, p. 125).

The findings of several authors regarding the scale dependency of the landscape metrics are tested during the study case. These findings are:

- Diversity (Shannon's diversity or Shannon's entropy) will decrease linearly with increasing grain size. Land cover types that are clumped will disappear slowly, where dispersed ones will be lost rapidly (Benson et al., 1995, p. 114; Turner et al., 1989, p. 153).
- "The rate at which land cover types will decrease with decreasing resolution depends on their spatial arrangement. If a rare land cover type is highly aggregated, it tends not to disappear or to diminish slowly; if it is well dispersed in small patches, it disappears rapidly" (Turner et al., 1989, p. 153).
- In general if grain size increase, contagion decreases, however it will not show a linear relationship, but a monotonically (Turner et al., 1989, pp. 160 – 161; Wu et al., 2000, p. 6, 11).
- Number of patches and the edge density, both show consistent and predictable changes when grain size increases, and can be predicted, accurately, with regression functions (Wu et al., 2000, p. 1, 15).

The scale sensitivity is analyzed for all methods except the method the classification of new developments (which is analyzed with the original vector data set).

4.13 Land use map case study Green Heart

In this study the land use maps of CBS, called 'Bestand Bodemgebruik (BBG)' are used. The land use maps of the Netherlands are recorded since 1989 (however in time the methodology of recording changed) and contain the digital geometry of the land in the Netherlands. The basic of the geometry of this file is largely derived from the analogue topographic map, the TOP10NL with a scale of 1:10.000 (Kadaster, 2012). The geometrical precision of the TOP10NL is 5 meters (0,5 millimeters of drawing precision (Mücher et al., 2003, p. 22)).

For this study the BBG files of 1989, (1996 and 2003 for some methods) and 2008 are used. For the calculation of the landscape metrics the maps are reclassified into raster files with a cell size of 5 meters (the geometrical precision) containing two land use classes; built-up and non built-up. The built-up class consists out of the following subclasses:

- Railway
- Motorway (including semi paved areas)
- Airports
- Housing
- Retail, catering and public facilities
- Dump
- Cemetery
- Extraction sites
- Building sites
- Parks
- Sport fields
- Allotment (vegetables garden)
- Green houses
- Day recreational area, residence recreational area, <u>no recreational water</u>

The non built-up class consists out of the following subclasses:

- Forest
- Agriculture (except green houses)
- Open, dry, and wet natural areas
- All thinkable type of waters (including recreational water)

The chosen classification is arbitrary and disputable. For analyzing urban sprawl one only needs to identify built-up areas. There are some remarkable subclasses which are classified as built-up: green houses and recreational areas. Green houses are most of the times classified as agricultural. However, research states that besides housing, industrial sites and business sites, also green houses are seen as urbanization (Stuurgroep Groene Hart, 1992, 79 – 80). The class residence recreational area is classified as built-up as it consists out of campsites, holiday homes, and hostels. The class day recreational area, which in some rare occasions is really green and open area without any built-up forms, is classified as built-up because these areas consist out of day campsites, zoos, theme parks, yacht clubs (water is not included), children's farms, playgrounds, picnic areas and playing fields. Both recreational areas really consist out of built-up forms such as houses, which is the case with holiday homes, hostels, campsites, camping's (sanitary building), or concrete (theme parks, zoo, playgrounds). But why not classify recreational water as built-up? Recreational water consists out of swimming water, recreational lakes for swimming, and water in marinas. However the banks of these areas must at least consist for three quarters out of sports field or day – and or residential recreation areas.

To classify the new developments of built-up areas the original vector BBG file is used.

For the land use change detection the raster land use map is reclassified into five classes, because analyzing a land use change detection map with only two classes is less meaningfull. The five classes are:

- Built-up/urban, containing out of the same subclasses aforementioned (except for the recreation classes)
- Recreation (which include the subclasses: parks, sport fields, allotments (vegetables garden), day recreational area, residence recreational area, and no recreational water)
- Water
- Forest and nature, containing the subclasses forest, dry and wet natural terrain.
- Agriculture (without greenhouses).

This study analyzes and describes the urban sprawl within the Green Heart. As boundary the defined official boundary which is stated in the physical report on planning of 2004 is used. Although in subchapter 3.4 it is stated that the boundary did change in the years 1990 and 1993. The boundaries that were used in 1990 and 1993 were based on reports of the Ministry of Housing, Physical Planning and the Environment. The 'Planbureau voor de leefomgeving' which provided the figure for the 'Randstedelijke Rekenkamer' answered that indeed the boundaries of 1990 and 1993 were not officially. The boundaries were created with official government documents which described the boundary of the Green Heart in words (thus no real official line was drawn). However especially the south-eastern border is arbitrarily placed (see appendix). This means that there was an official documented border for the Green Heart in the years 1990 and 1993, however the exact location of the border was never specified.

4.14 The selected methods for the study case

In total eleven most commonly used GIS methods for analyzing urban sprawl have been identified. However there was no possibility to conduct the method Markov Cellular Automata Chain. Although there was the opportunity to make use of the software of four Dutch universities (Delft, Enschede, Utrecht and Wageningen), none had a software license which enables the usage of the Markov Cellular Automata Chain model. Of course there is the possibility to built a cellular automata model, however this requires a significant amount of time and given the time available for this thesis not feasible. The other methodologies can all be analyzed with open source software, maps with open source GIS programs, landscape metrics can be computed with Fragstats.

In the end ten commonly most used GIS methods for analyzing urban sprawl will be tested on their suitability, and the influence of scale on these methods (table 5). As aforementioned the scale sensitivity is analyzed for all methods with the exception of the method for classification of new developments (which is analyzed with the original vector data set (table 5)).

Table 5: Most commonly used GIS methods for analyzing urban sprawl

Landscape metric	**Selected for case study?**	**Scale sensitivity analyzed?**	**Comments**
Class area (CA)	Yes	Yes	Absolute growth of the urban class.
Number of patches (PA)	Yes	Yes	Measures the extent of the urban class
Edge density (ED)	Yes	Yes	Measures the total edge of the urban class.
Area weighted mean patch fractal dimension (AWMPFD)	Yes	Yes	Measures shape complexity of the urban patches.
Built-up density	Yes	Yes	Shows the dispersion of the urban patch (spatial distribution).
Contagion	Yes	Yes	Measures the extent to which landscapes are aggregated or clumped.
Shannon's entropy	Yes	Yes	Measures the degree of spatial concentration and dispersion of the urban class.
Pattern identification			**Comments**
Urban growth	Yes	Yes	Direction of the urban sprawl.
Classification new developments	Yes	No	Configuration of the urban developments
Land use change			**Comments**
Land use change detection	Yes	Yes	Change of land use classes in time.
Markov Cellular Automata Chain	No	Inapplicable	Indication of the future direction of the urban sprawl.

5. Results case study Green Heart

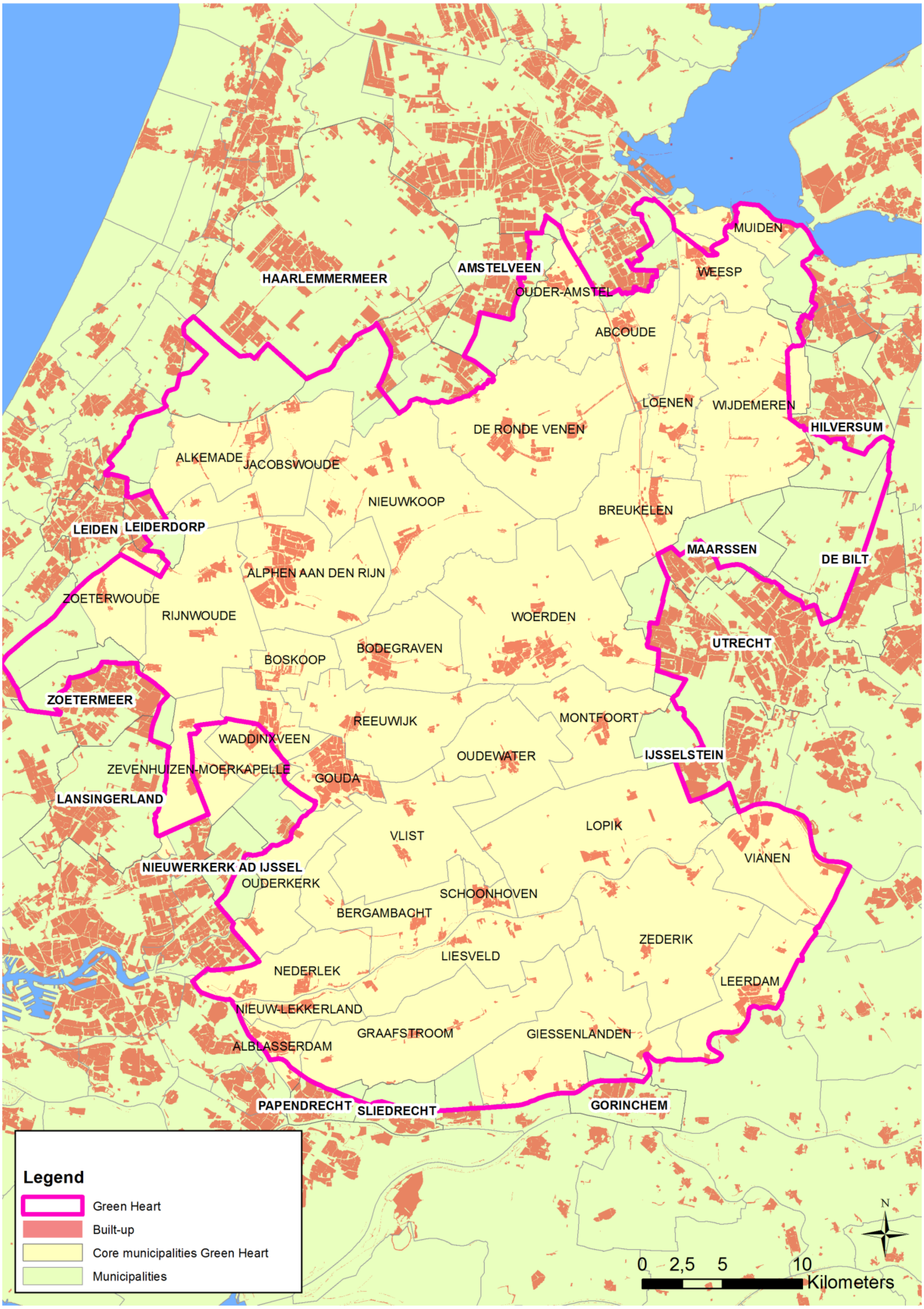
Before testing the selected GIS methods which measure the urban sprawl of the Green Heart some back ground information about the growth of the area is provided. The Green Heart locates three ‘large’ municipalities; Alphen aan den Rijn (71.658 inhabitants in 2008), Gouda (70.857 inhabitants in 2008), and Woerden (48.383 inhabitants in 2008). Several municipalities are partly situated within the Green Heart; Amstelveen, de Bilt, Haarlemmermeer, Leiden, Maarssen, Utrecht, and Zoetermeer for example (figure 14). However their built-up areas are situated outside the borders of the Green Heart. The population growth of the core municipalities of the Green Heart between 1989 and 2008 is about 51.500. The municipalities of Alphen aan den Rijn, Gouda, Woerden (the three ‘large’ municipalities of the Green Heart), and Nieuwkoop show a significant difference in relative growth (figure 15). Therefore the expectation is that the urban sprawl will physically express itself the most in this region.

The land use maps which are used in this case study are the BBG (Bestand Bodemgebruik) layers of 1989, 1996, 2003, and 2008. The classification of the classes can be found in subchapter 4.13. The BBG layers are converted to raster files using the maximum area cell assignment technique. With this technique the cell gets the attribute value of the single feature which has the largest area within the cell. Another possibility is to make use of the cell center cell assignment technique. With this technique the cell gets the attribute value of the feature which is in the center of the cell. The cell center technique is considered less suitable, with this technique a feature can represent an entire cell even if the feature only covers 1% of the surface. The 5 by 5 meter raster map is used for the up scaling process to 50 by 50 and 500 by 500 meter raster cell size maps.

Within this study the emphasis of the MAUP (modifiable areal unit problem) is on the scale aspect, therefore the zoning problem is not taken into account.

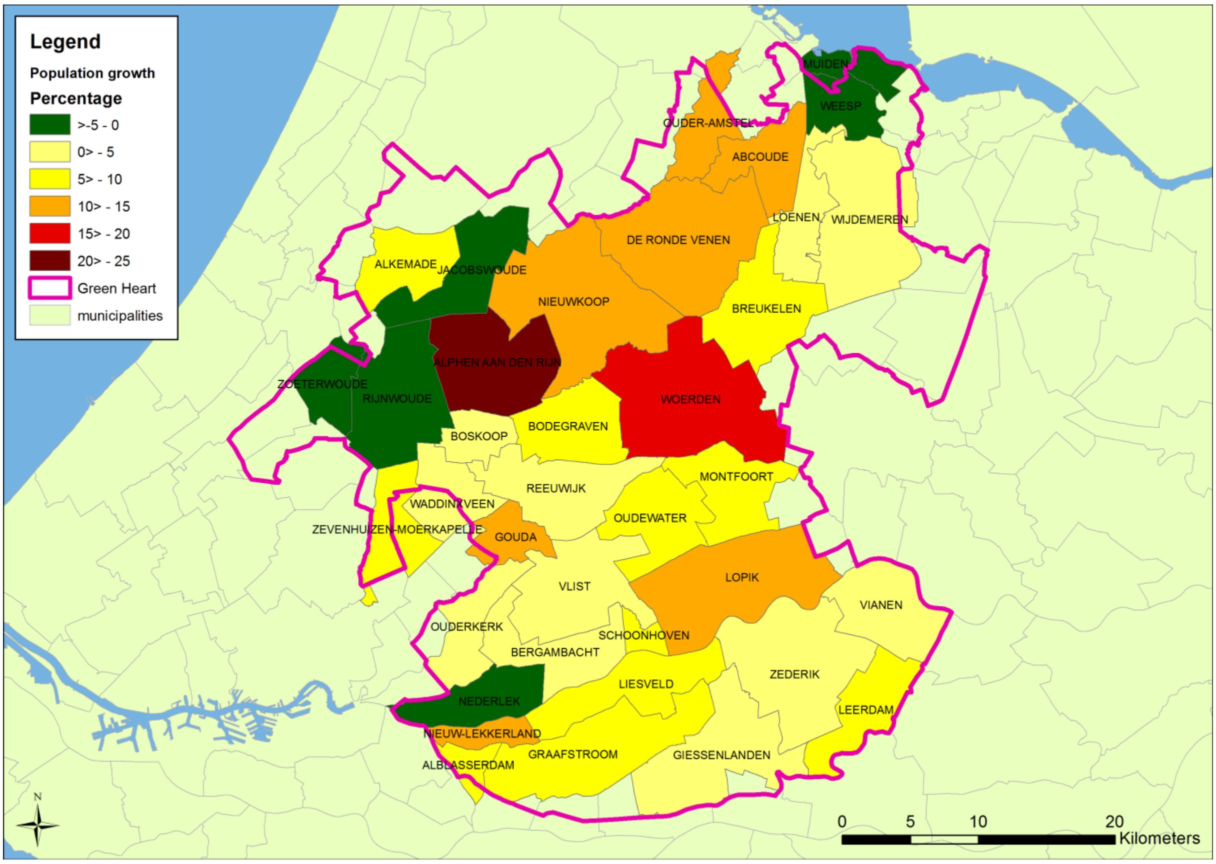
The application of a case study provides the opportunity to test the suitability of the found GIS methods and the influence of scale on these methods. In this case the Green Heart is chosen as case study area. Ten out of the eleven found GIS methods are used: class area (CA), number of patches (NP), edge density (ED), area weighted mean patch fractal dimension (AWMPFD), built-up density, contagion, Shannon’s entropy, urban growth, classification new developments, and the land use change detection. The influence of scale is not tested for the method land use change detection.

Figure 14: Overview municipalities Green Heart 2008 [1]



Built-up class in this figure consists out of the land use classes residential and commercial, the built-up class do not include the land use classes infrastructure, recreation and greenhouses. This way it easy to see the living and work areas of the area.

Figure 15: Population growth Green Heart 1989 – 2008 [1,2]



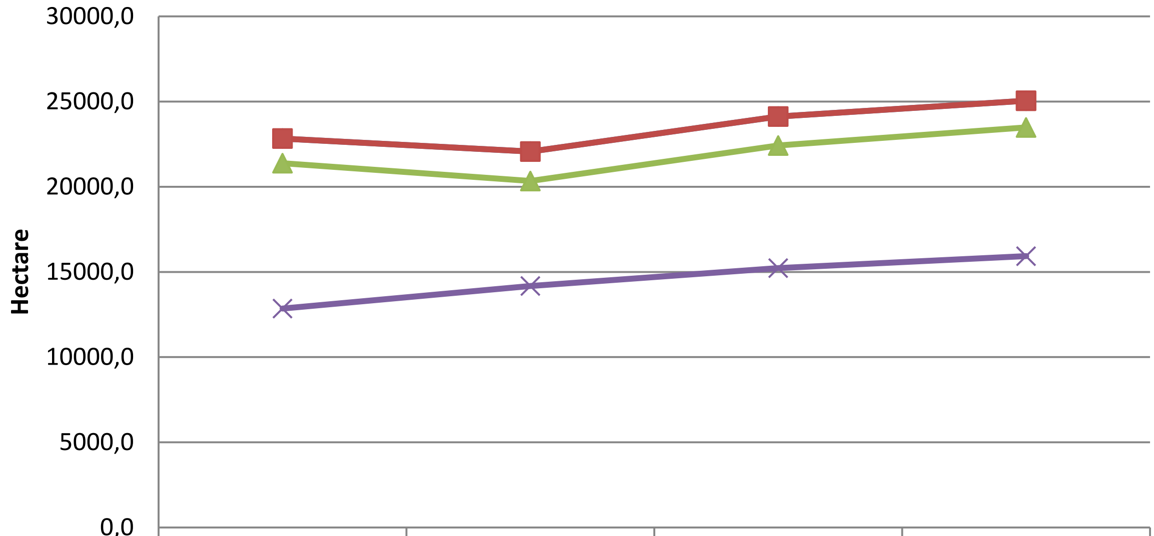
Source: CBS Statline, 2012. The merger of municipalities between 1989 and 2008 are considered.

5.1 Landscape metrics

Class area

The landscape metric class area provides an excellent start to analyze urban sprawl. Insight is obtained on the absolute growth of the urban class. The growth of the urban class is set on 9,7% with a cell size of 5 meters, 9,8% with a cell size of 50 meters, and 23,9% with a cell size of 500 meters for the period 1989 – 2008. Indicating that the growth is equal for the cell sizes 5 and 50 meters, but differs significantly for the cell size of 500 meters (figure 16). If the analysis would have only consisted of a 500 meter cell size, the conclusion would have been that the urban area would have grew by almost 25%. However when the analysis of the other cell sizes are also taken into account the growth is much limited. Also the absolute area covered in hectare differs significantly between the two smallest cell sizes and the largest cell size (table 6). A difference of approximately 10.000 hectares of urban area for the 500 meter cell size can be explained. Much of the infrastructure is not recognized as urban with this coarse resolution. Especially roads who do not intersect with any other form of built-up class. Many roads are surrounded by agricultural lands, and when using the maximum area cell assignment technique, these roads often show a smaller total area with respect to the area of agriculture and thus these cells are classified as agricultural. The same applies to very small settlements. Which means that the conclusion stated by Turner et al (1989) also applies for this study: *"The rate at which land cover types will decrease with decreasing resolution depends on their spatial arrangement. If a rare land cover type is highly aggregated, it tends not to disappear or to diminish slowly; if it is well dispersed in small patches, it disappears rapidly" (Turner et al., 1989, p. 153).*

Figure 16: Class area (urban class) measurements Green Heart



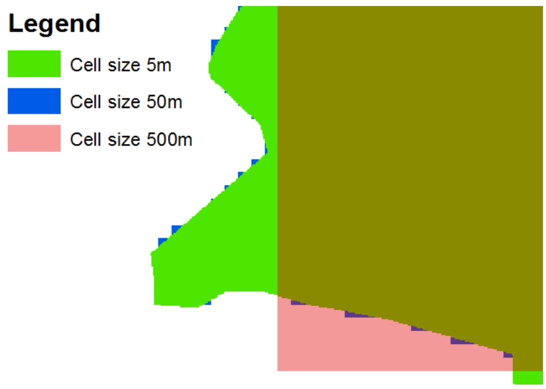
	1989	1996	2003	2008
Vector	22831,0	22066,3	24121,1	25047,8
5m	22831,1	22067,0	24121,9	25047,5
50m	21382,5	20335,8	22420,3	23480,0
500m	12850,0	14175,0	15225,0	15925,0

Remarkable is that the conversion of the original vector dataset to the 5 meter raster resolution dataset have no significant influence on the amount of urban class (figure 16). Although it is not that remarkable when considered that the geometrical precision of the TOP10NL (original vector dataset) is 5 meters.

Table 6: Urban area covered in Green Heart

Cell size	Green Heart area in HA	Urban area 1989 in HA	Urban area 1989 in % of total area	Urban area 2008 in HA	Urban area 2008 in % of total area
5m	180.565,4*	22.831,1	12,6%	25.047,5	13,9%
50m	180.757,8*	21.382,5	11,8%	23.480,0	13,0%
500m	179.775,0*	12.850,0	7,1%	15.225,0	8,5%

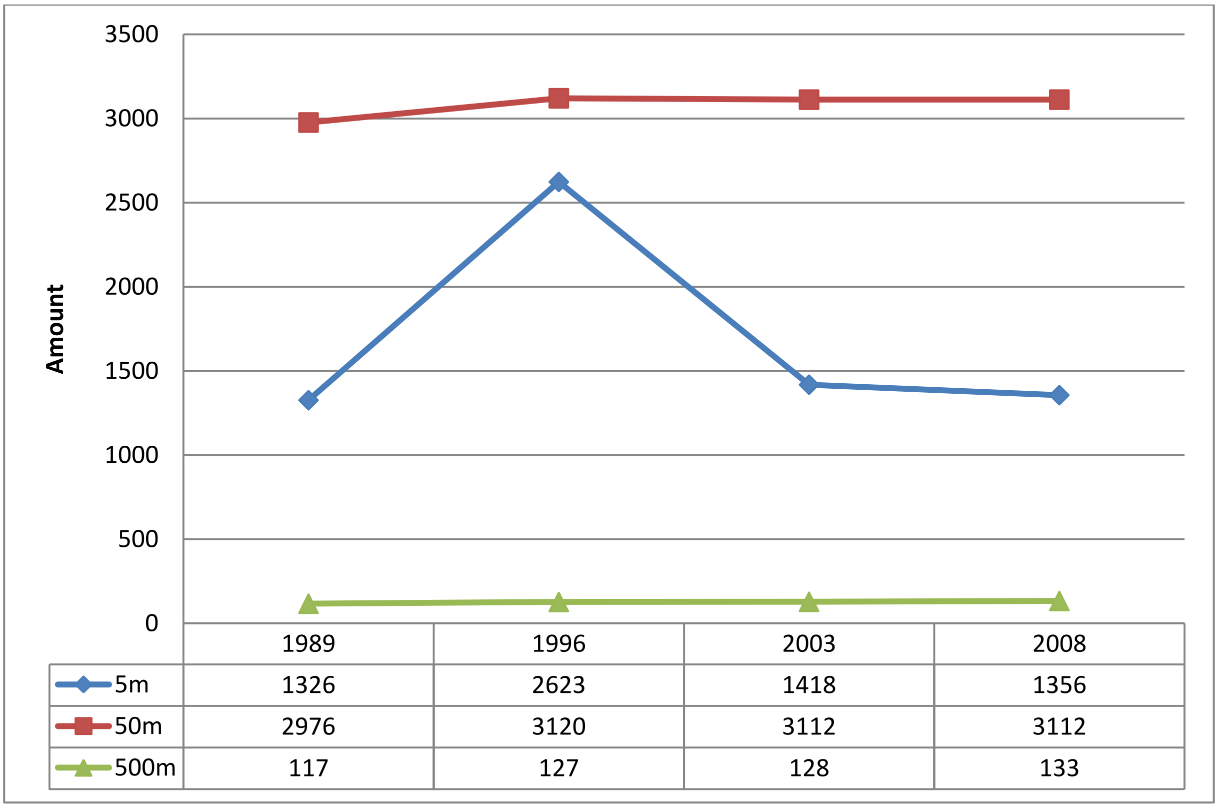
* Slight differences in the total area are caused by the differences in cell sizes of the raster format.



Number of patches

The number of patches counts the amount of individual urban patches, and gives an indication of the fragmentation of the patches within the area. In general there is a slight increase of the amount of urban patches, which indicates that urban growth did occur gradually in the surrounding of the existing urban areas. However for the 5 meter cell size analysis, there is a strange outlier in the number of patches for 1996 (figure 17). The explanation, probably, can be found in the data, and classification of the data itself (CBS, 2012b). In 2000 the research method for the land use map was changed. For the first time the basic geometry of the digital topographic map 1:10 000 (the Top10Vector, the Topographical Service Netherlands) was used. Afterwards the BBG map of 1996 was created according to the new and old methodology (old methodology: the maps of the land use of the Netherlands were digitized by the CBS itself). The BBG file of 1996 that was available for this study did make use of this new methodology. The new methodology contains some minor adjustments to the classification (especially by the alteration of the dirt and semi paved roads), which influenced the infrastructure class, and led to an increase of small patches of infrastructure. These infrastructural changes can only be detected with a high resolution (5 meter cell size) and are not detectable at a lower resolution (50 and 500 meter cell size). The conclusion of Wu et al. (2000) regarding the consistent and predictable patterns of the number of patches and scale: *number of patches and the edge density, both show consistent and predictable patterns when grain size increases, and can be predicted, accurately, with regression functions (Wu et al., 2000, p. 1, 15):* does only apply for the 50 and 500 meter resolution. The number of patches are expected to decrease when aggregating more data (increasing cell size), and could be predicted with a regression function. However the 50 meter resolution analysis shows an increase of the number of patches with respect to the 5 meter resolution analysis, however a reason for this cannot be given.

Figure 17: Number of urban patches Green Heart

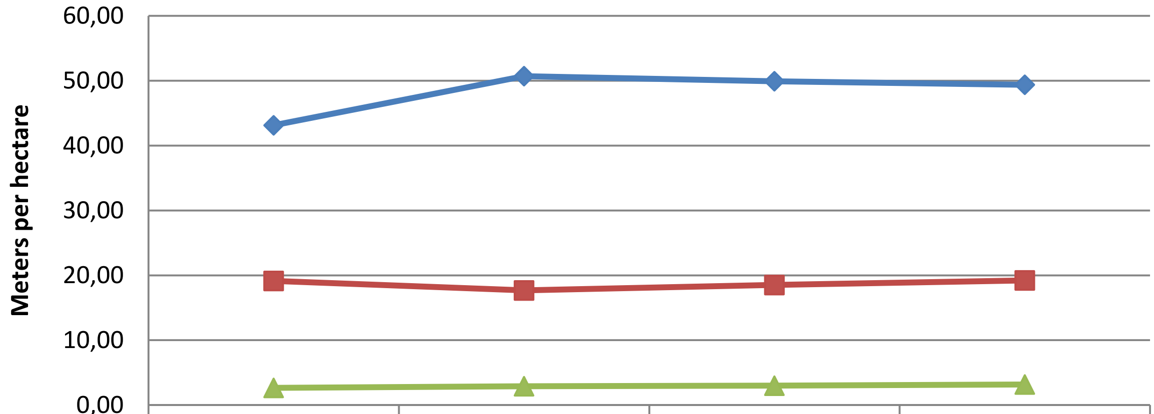


	1989	1996	2003	2008
5m	1326	2623	1418	1356
50m	2976	3120	3112	3112
500m	117	127	128	133

Edge density

The edge density measures the border between two different land cover classes, and takes the shapes (the complexity) of the patches into account. When new urban areas emerge the edge density of the urban class should increase and a decrease is possible when urban areas agglomerate. Overall the edge density shows a small increase, which could indicate to growth of the urban area, either directly surrounding the existing urban area, or a small growth of new emerged urban areas (figure 18). The conclusion of Wu et al. (200): *number of patches and the edge density, both show consistent and predictable patterns when grain size increases, and can be predicted, accurately, with regression functions (Wu et al., 2000, p. 1, 15):* applies to this study. The edge density shows a consistent and predictable pattern when the grain size is increased.

Figure 18: Urban edge density Green Heart

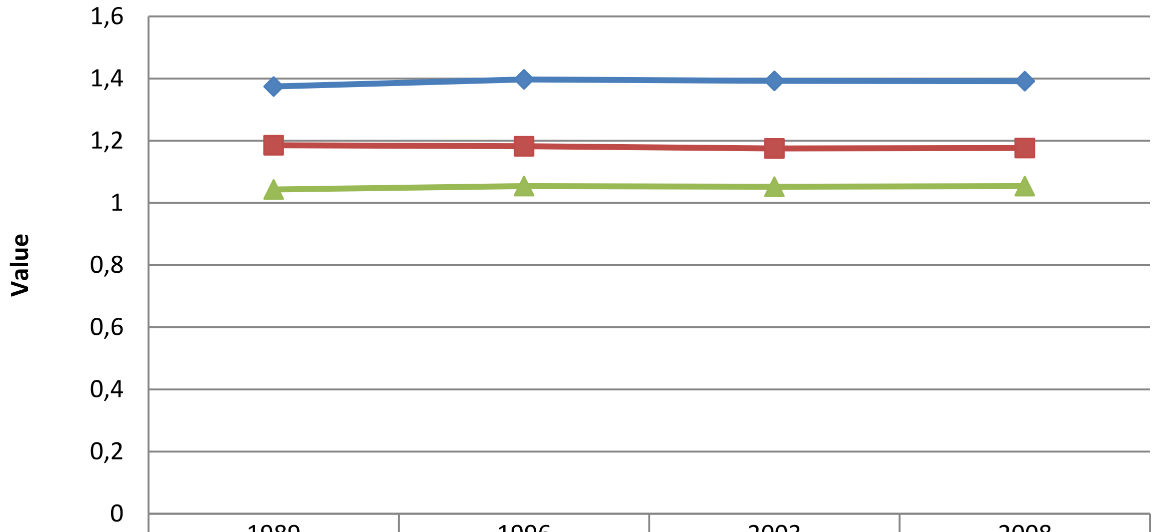


	1989	1996	2003	2008
5m	43,13	50,71	49,92	49,38
50m	19,14	17,68	18,51	19,22
500m	2,66	2,91	3,00	3,18

Area weighted mean patch fractal dimension

The area weighted mean patch fractal dimension (AWMPFD) measures the shape of urban patches. Where the edge density takes the complexity of the shapes of the patches into account, the AWMPFD measures the complexity of the shapes of the urban patches. The value of AWMPFD range between 1 and 2. Thereby 1 represents compact and rectangular/round (simple) shapes, and 2 represents complex and irregular shapes. The scale problem (MAUP) is perfectly displayed by this landscape metric. With a 5 meter resolution the AWMPFD lies between 1,37 and 1,40. When a lower resolution is applied, for example 500 meters) the AWMPFD value lies between 1,04 and 1,06 (figure 19). Looking at the 5 meter resolution it could be concluded that the shape is a bit complex, and certainly not simple and rectangular. In contrast, a 500 meter resolution points out that the shapes of the urban area within the Green Heart are regular and very simple.

Figure 19: Area weighted mean (urban) patch fractal dimension

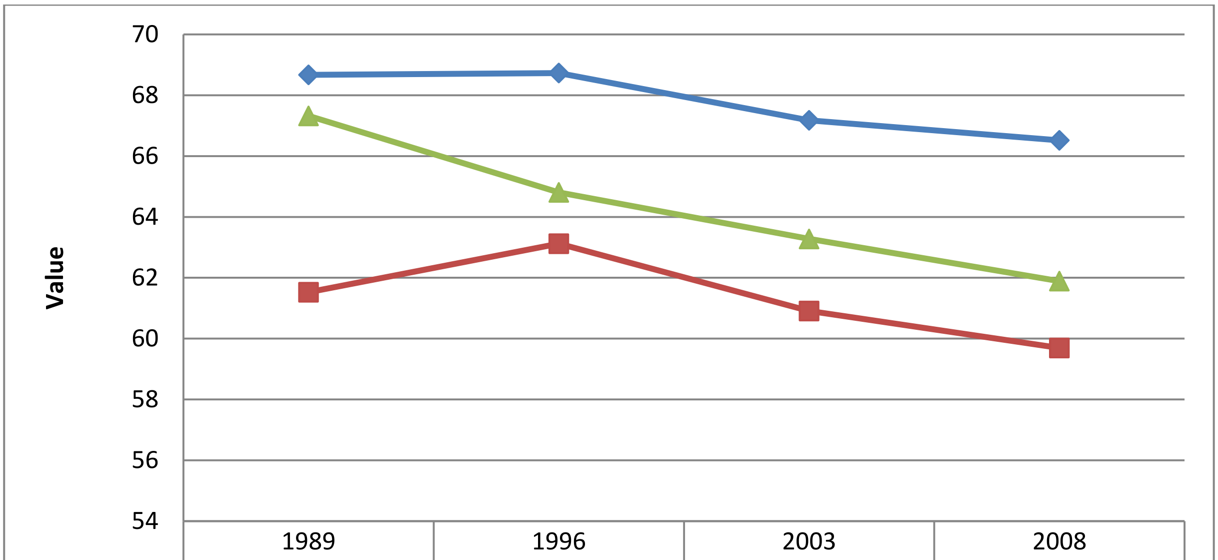


	1989	1996	2003	2008
5m	1,3743	1,3974	1,3926	1,3917
50m	1,1855	1,1822	1,1752	1,1766
500m	1,0433	1,0542	1,0522	1,0541

Contagion

he contagion index measures the extent to which a landscape is aggregated or clumped (dispersed or interspersed). The value of the contagion index range between 0 and 100. A value of 0 is obtained when patch types are well interspersed, scattered and not aggregated, referring to many small and dispersed patches. A value of 100 is obtained when maximal aggregation of patch types is witnessed, i.e. only a few large contiguous patch types do exist. In general, for the Green Heart, it can be concluded that the contagion value does decline in time. However the contagion index varies for all resolutions, between the 60 and 70. Meaning there are some larger continuous patches (more aggregated), and the land use classes are not well interspersed. But still there is some fragmentation and interspersion of patch types, definitely an increase in time of more small fragmented patch types because of the declined contagion index. The conclusion of Turner et al. (1989) and Wu et al. (2000): *in general if grain size increase, contagion decreases, however it will not show a linear relationship, but a monotonically (Turner et al., 1989, pp. 160 – 161; Wu et al., 2000, p. 6, 11)*, is in line with the obtained results (figure 20).

Figure 20: Contagion index Green Heart

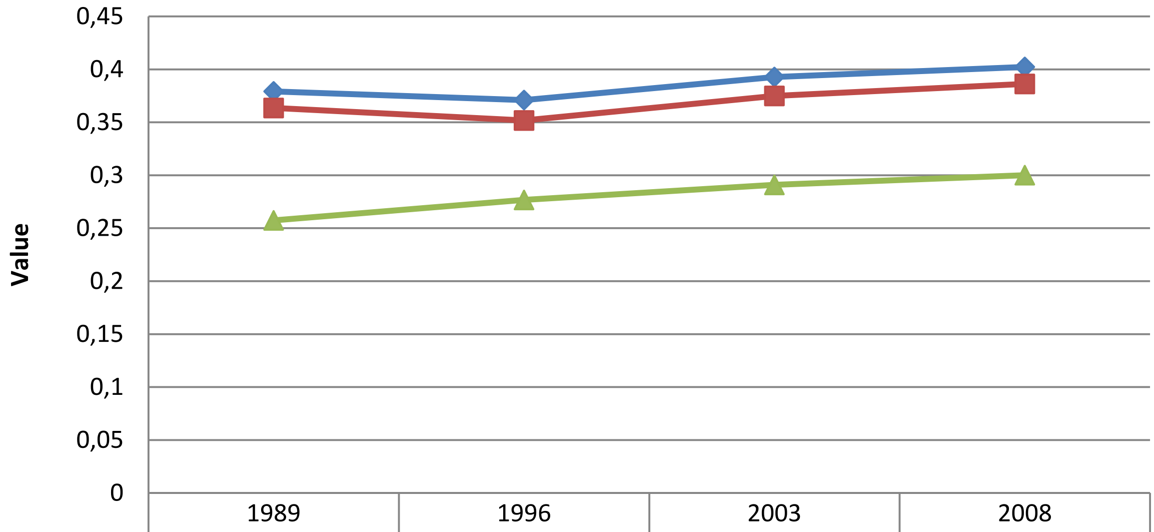


	1989	1996	2003	2008
5m	68,6705	68,7312	67,1763	66,5179
50m	61,5243	63,1195	60,9073	59,6921
500m	67,321	64,8069	63,277	61,8906

Shannon's entropy (Shannon's diversity)

Shannon's entropy (Shannon's diversity index) is a diversity landscape metrics which quantifies landscape composition. It measures the degree of spatial concentration and dispersion of a variable. The entropy value ranges from 0 to 1. When a value of 0 is obtained the distribution of the variable (in this case the urban class) is maximally concentrated in one region, a compact city. To continue when a value of 1 is obtained the variable is evenly distributed in the landscape, dispersed and not spatially concentrated in one region. The results show that the entropy value decreases linearly with the increasing cell size (figure 21). Which means that the conclusion of Benson et al. (1995) and Turner et al. (1989): *Shannon's entropy will decrease linearly with increasing grain size. Land cover types that are clumped will disappear slowly, where dispersed will be lost rapidly (Benson et al., 1995, p. 114; Turner et al., 1989, p. 153)* is in line with the results. However, only when 1996 is not taken into account. A linear decrease cannot be obtained when 1996 is taken into account. Probably because of the new methodology used for the creation of land use map (see number of patches (p.61)). The obtained results also allow for the measurement of difference of entropy in time. In this case the entropy increases, but only slightly, which indicates that the developments are going more toward a more dispersed pattern (instead of a more compact pattern), which confirmed by the obtained results of the landscape metric contagion.

Figure 21: Shannon's diversity index Green Heart



	1989	1996	2003	2008
5m	0,3792	0,371	0,3928	0,4023
50m	0,3635	0,3517	0,3749	0,3862
500m	0,2574	0,2767	0,2909	0,3001

For a quick overview of all the landscape metrics per year and resolution see table 7.

Table 7: Overview landscape metrics Green Heart

		Class level				Landscape level	
Year	**Cell size**	**CA**	**NP**	**ED**	**FRAC_AM**	**CONTAG**	**SHDI**
1989	*5 Meter*	22.831,1	1.326	43,1273	1,3743	68,6705	0,3792
1996	*5 Meter*	22.067,0	2.623	50,7100	1,3974	68,7312	0,3710
2003	*5 Meter*	24.121,9	1.418	49,9237	1,3926	67,1763	0,3928
2008	*5 Meter*	25.047,5	1.356	49,3819	1,3917	66,5179	0,4023
1989	*50 Meter*	21.382,5	2.976	19,1394	1,1855	61,5243	0,3635
1996	*50 Meter*	20.335,8	3.120	17,6755	1,1822	63,1195	0,3517
2003	*50 Meter*	22.420,3	3.112	18,5119	1,1752	60,9073	0,3749
2008	*50 Meter*	23.480,0	3.112	19,2207	1,1766	59,6921	0,3862
1989	*500 Meter*	12.850,0	117	2,6561	1,0433	67,3210	0,2574
1996	*500 Meter*	14.175,0	127	2,9146	1,0542	64,8069	0,2767
2003	*500 Meter*	15.225,0	128	2,9972	1,0522	63,2770	0,2909
2008	*500 Meter*	15.925,0	133	3,1844	1,0541	61,8906	0,3001

The built-up density identifies the dispersion of the urban class per region. High density of the built-up class refers to a compact city and low density refers to sparsely spread built-up areas. Only the three 'large' municipalities show a real increase in high density built-up area for all the resolutions (figure 22 and 23). Remarkably, the infrastructure is perfectly visible on the high resolution density map (5 meter cell size), on the 50 meter resolution map only the highways are visible. However for the 500 meter density map no infrastructure is visible at all and the pattern of settlements are now more random and difficult to explain as the context (highways) of the landscape is lost.

Figure 22: Built-up density map Green Heart 1989 [1]

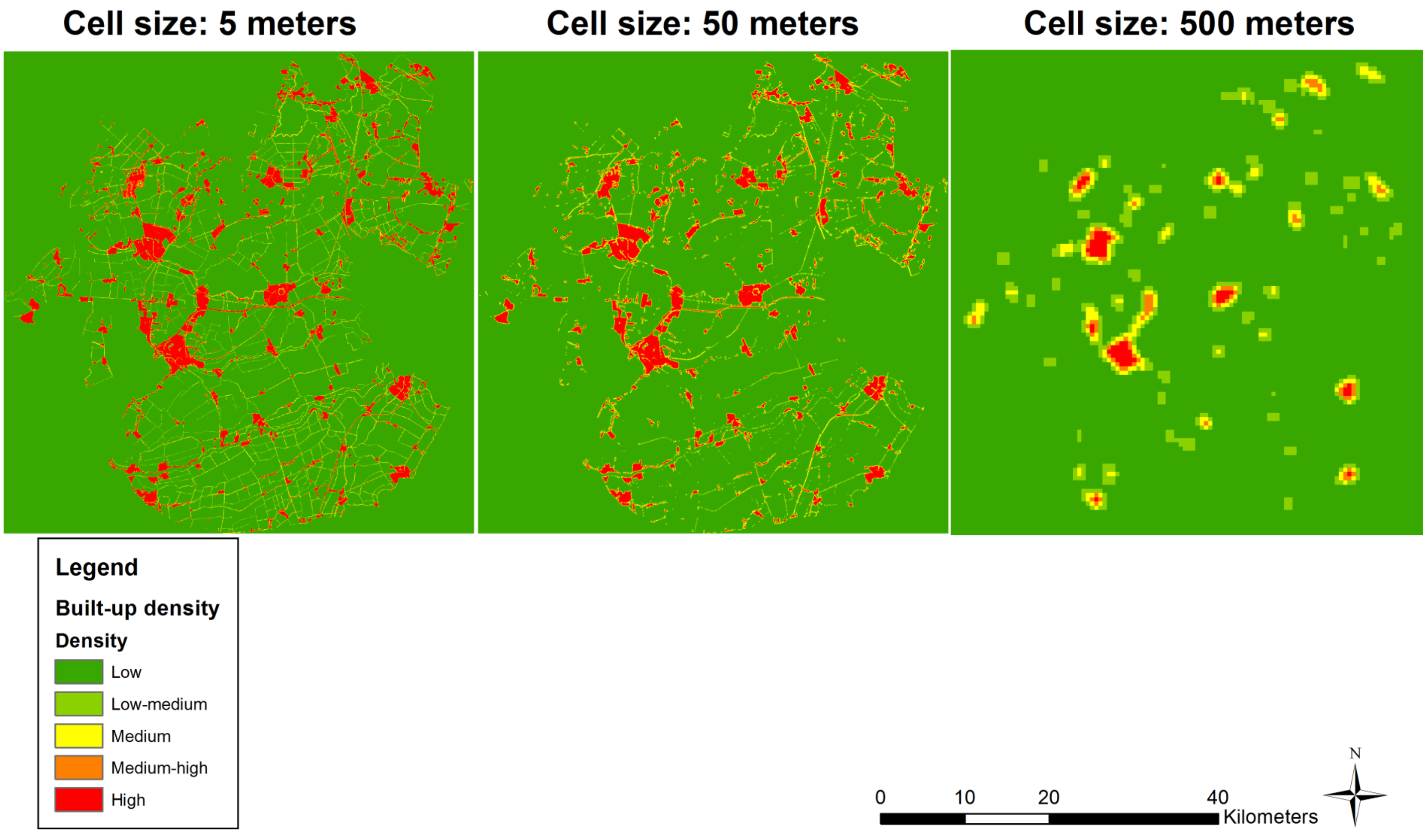
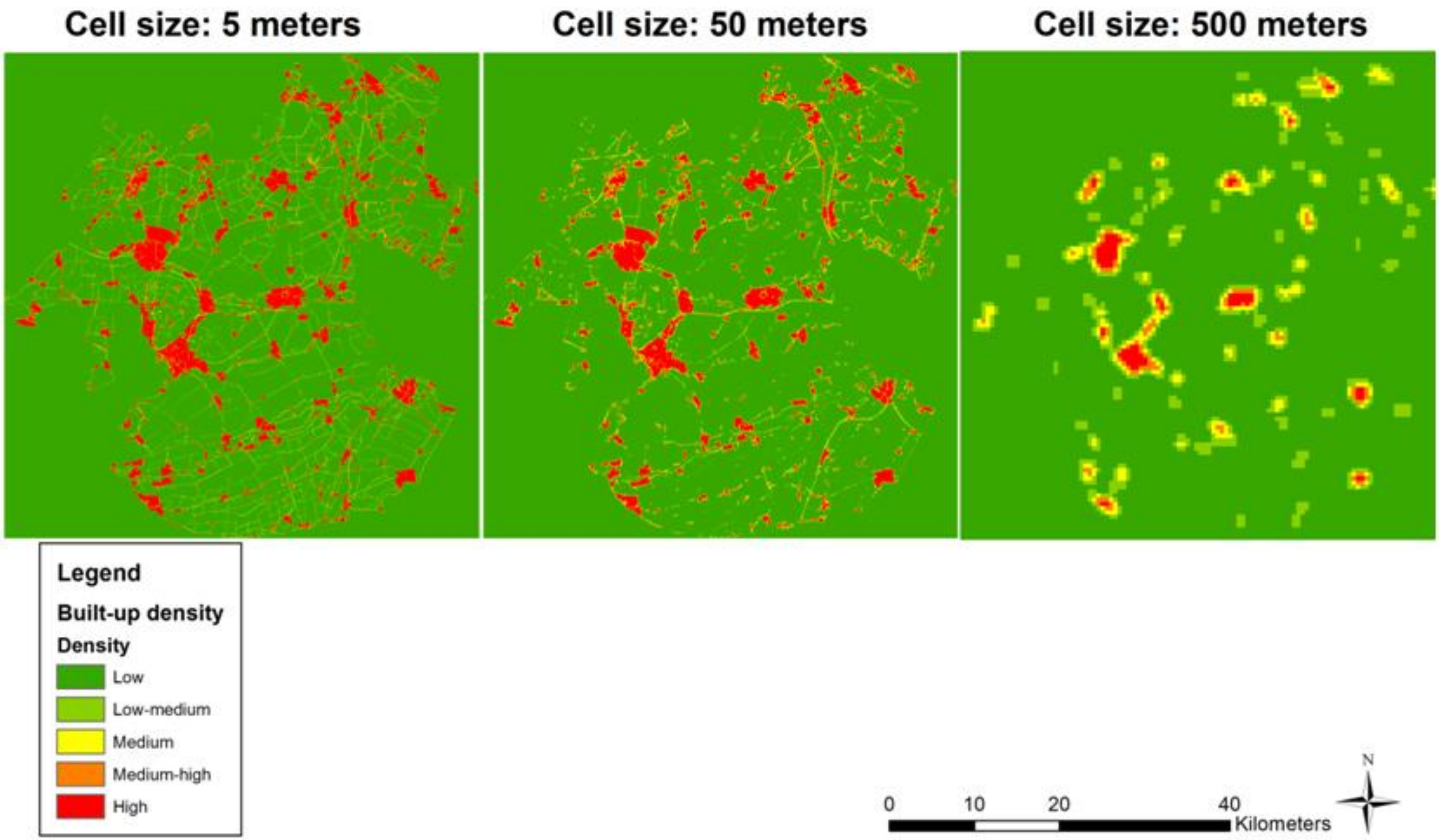


Figure 23: Built-up density map Green Heart 2008 [1]



5.2 Urban growth

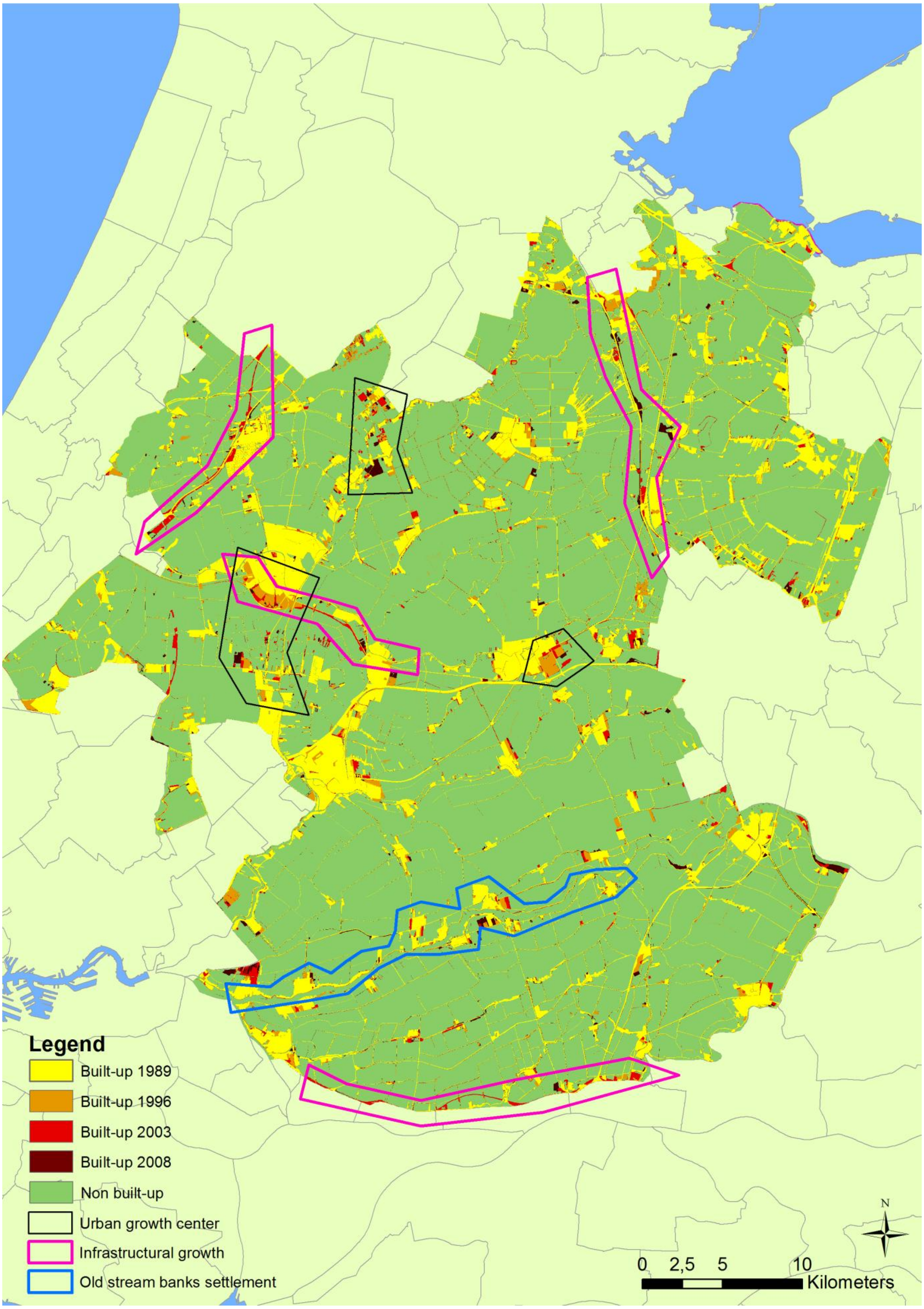
The urban growth analysis is straightforward, per time step the urban growth is captured and visualized. This way urban growth patterns can be recognized, and perhaps different growth patterns per time step can be spotted. Whether the found patterns are similar on all three resolution levels is interesting.

Firstly, the 5 meter cell size resolution urban growth map is discussed (figure 24). In the southern part (blue polygon) the typical historical settlements along the sandy parts of the banks and embankments of rivers can be found. Northward three new highways or intensification of the built-up area alongside the highways have emerged (pink polygons), which is also the case for the south however the highway itself is precisely on the border of the Green Heart and thus not visible in the map (figure 24). Also the three 'large' municipalities (Alphen aan den Rijn, Gouda and Woerden) and the municipality Nieuwkoop show a huge increase in the urban area, which corresponds with the findings of the analysis of the population growth.

The 50 meter cell size resolution urban growth map does not significantly differ from the 5 meter cell size map (figure 25). Just not all local roads can be detected anymore.

The 500 meter cell size resolution differs completely from the other two maps. Identifying the urban growth centers requires some considerable effort. However if the map is analyzed without any background knowledge, the conclusion would be that there are some settlements which reflect an expansion of the urban area, beside a lot of leapfrog development (figure 26).

Figure 24: Urban growth map Green Heart 1989 – 2008, spatial resolution of 5 meters [1]



The classification of the built-up and non built-up class can be found in subchapter 4.13

Figure 25: Urban growth map Green Heart 1989 – 2008, spatial resolution of 50 meters [1]

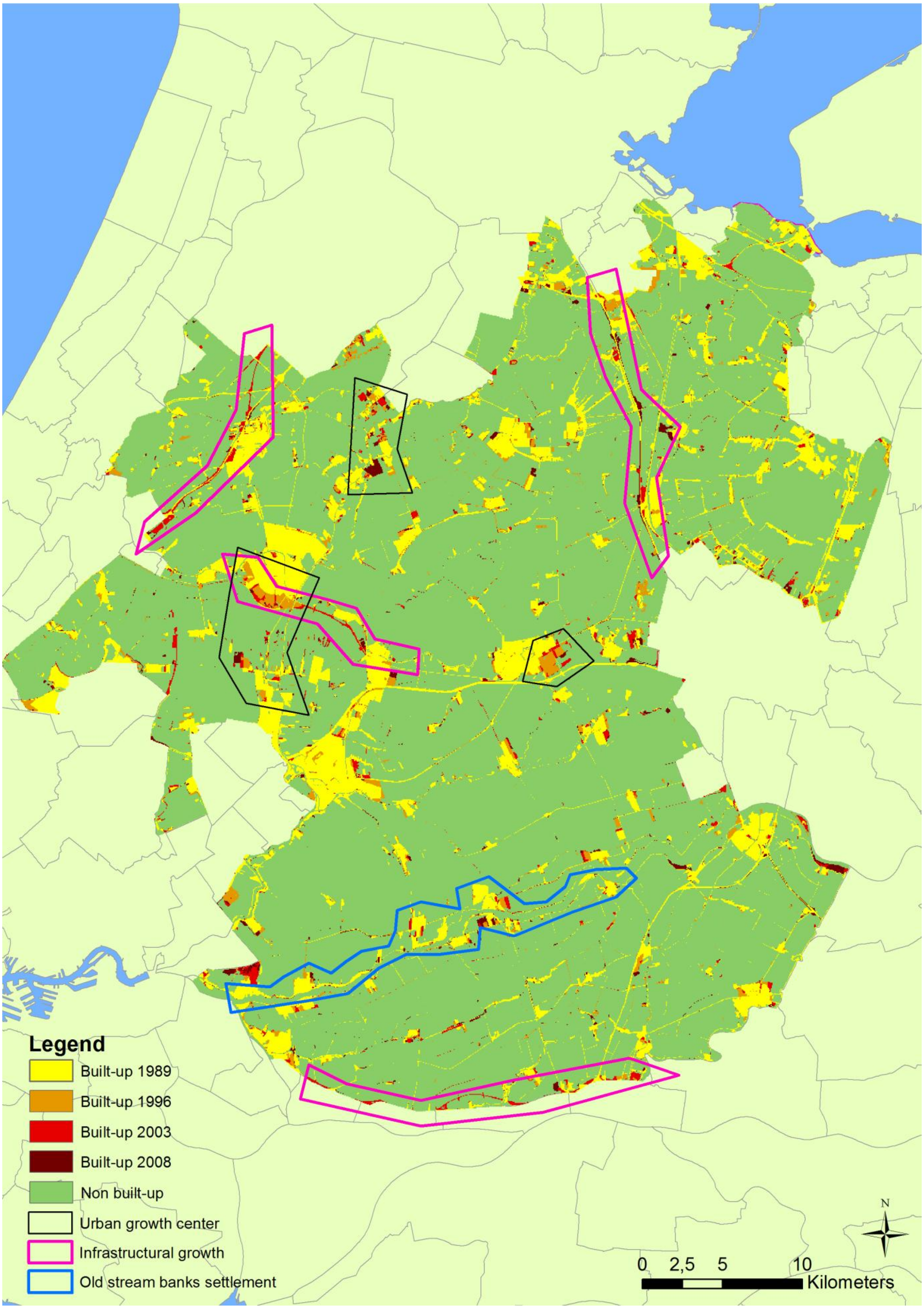
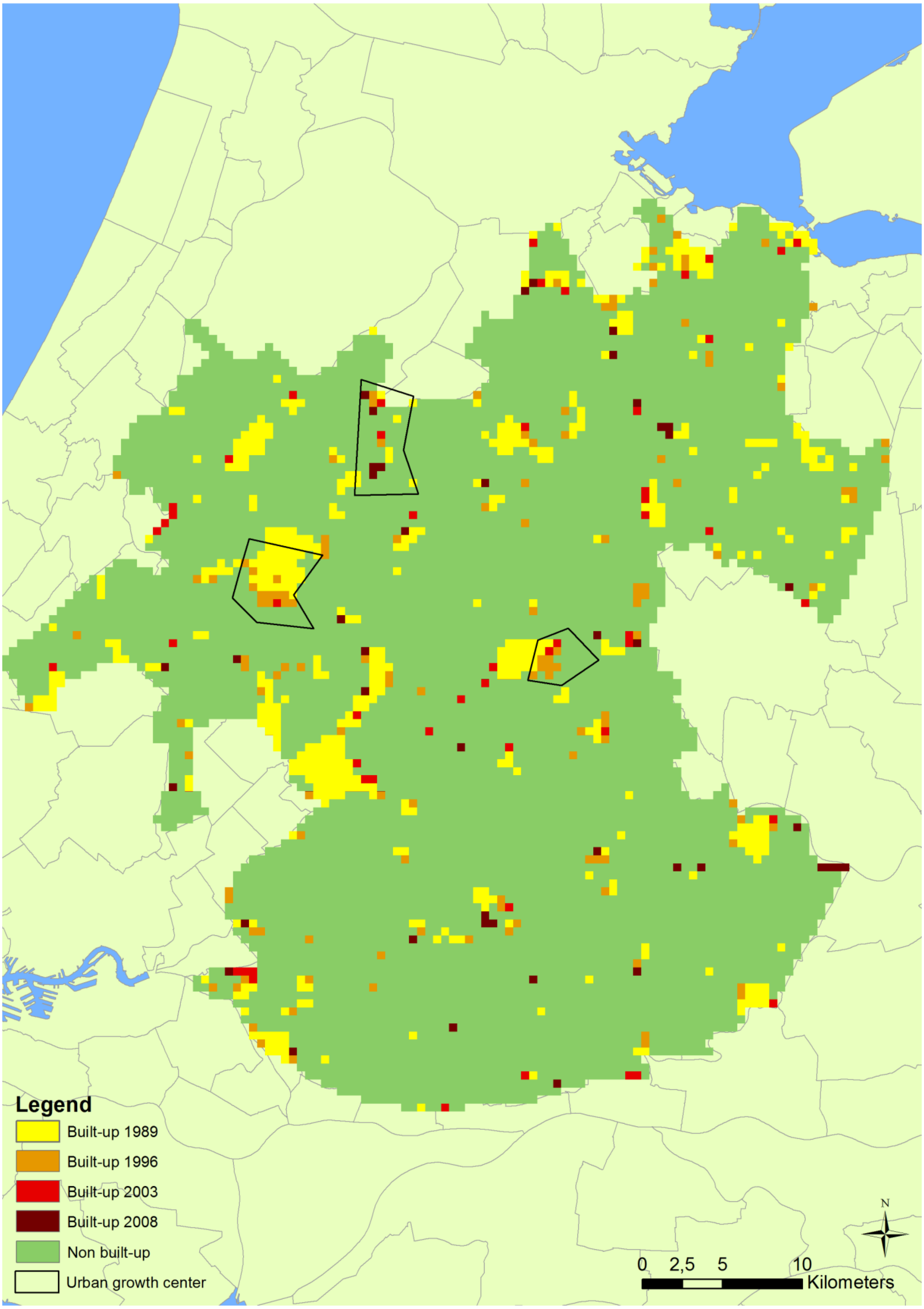


Figure 26: Urban growth map Green Heart 1989 – 2008, spatial resolution of 500 meters [1]



If you are trying hard the same urban growth centers as the growth centers of the 5 meter resolution map can be identified.

5.3 Classification new developments

The classification of new built-up developments supports the identification of the direction of urban sprawl. New urban developments are classified in three classes:

- Infill: built-up development in existing built-up area.
- Extension: built-up development intersected with existing built-up areas.
- Leapfrog: built-up development not intersected, meaning located 250 meter from existing built-up areas.

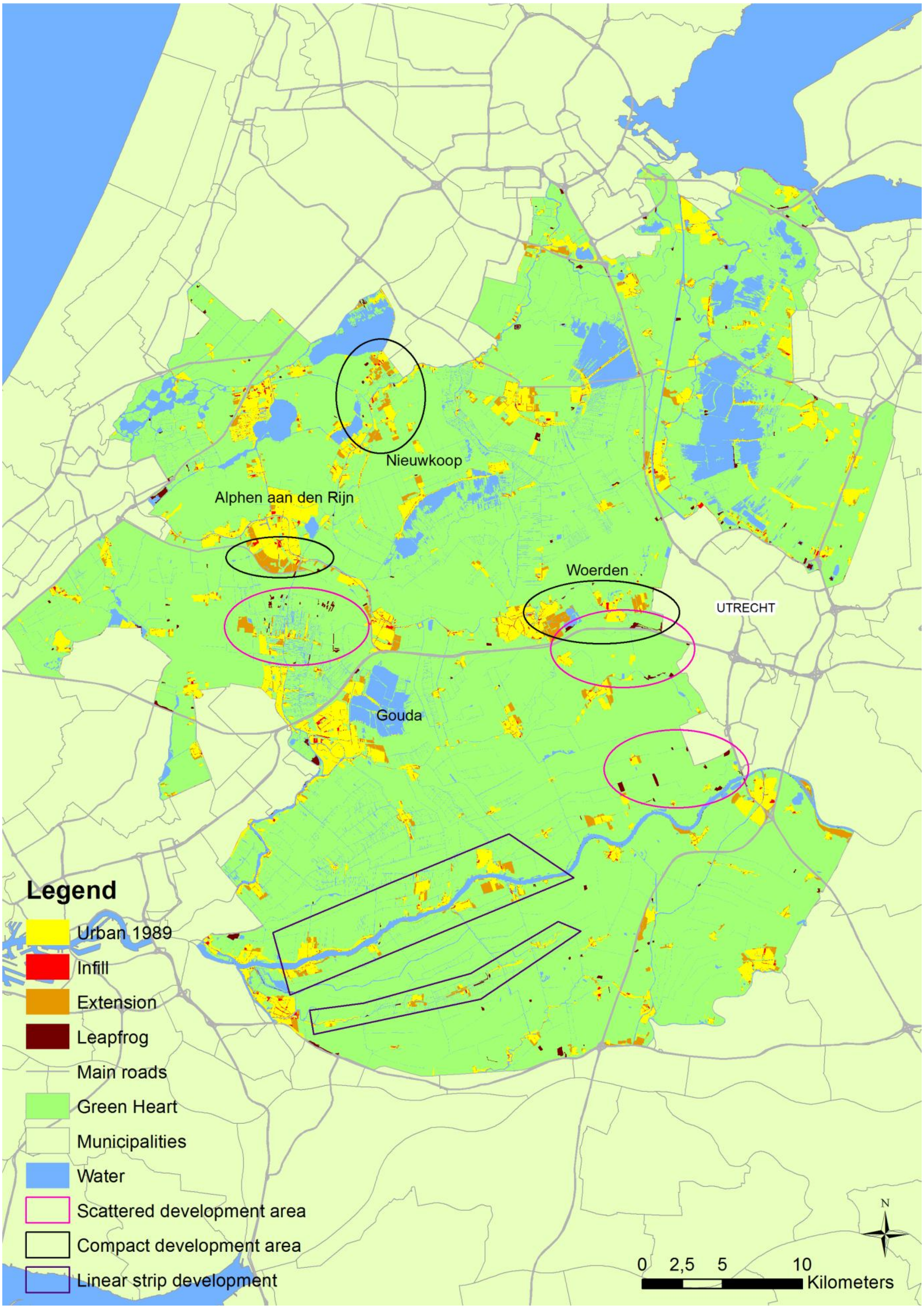
The Green Heart shows some infill developments in the municipalities Alphen aan den Rijn, Gouda, and Woerden. Most new built-up development are classified as extension.

Three core areas have witnessed significant increase in built-up development. The municipality of Nieuwkoop (municipality in the northern area of the Green Heart, consisting out of the villages Ter Aar, Liemeer and Nieuwkoop, these municipalities merged in 2007) has shown a lot of new built-up developments, where the former municipalities Ter Aar and Liemeer grew in a converging direction by the development of greenhouses. The second core area is formed by the municipality Alphen aan den Rijn, which has expanded its built-up area in southern direction. The third core is the municipality Woerden. The municipality has been expanding its built-up border to the East in the direction of Harmelen (municipality which merged with Woerden) and Utrecht, which has its built-up borders directly at the Green Heart border. These three areas can be classified as compact development areas.

In some areas there are some small leapfrog developments. Three areas show several leapfrog developments. The most significant one is the area between Alphen aan den Rijn and Gouda. Where as in the municipality of Boskoop new greenhouses have emerged. The second area is the area East of Woerden, where new built-up area is created along the highway, which probably leads to one continues built-up area between Woerden and Utrecht in the future. The last leapfrog development area is in the south eastern part of the Green Heart. Described areas can be classified as scattered development areas.

Two areas in the south of the Green Heart show a clear and distinct linear strip development. These old settlements along the river banks are expanding towards each other (figure 27).

Figure 27: Classification of new built-up developments Green Heart 1989 – 2008 [1]



The land use class infrastructure was not included in the urban classification. Infrastructure works as a connection through which all urban development's would be classified as expansion.

5.3 Landscape change detection

On all resolutions levels agriculture forms the largest, absolute, supplier of new urban land (figure 28, 29, and 30). However recreation has lost relatively most of it land to urban developments. The transition probability on all the resolution levels shows more or less the same percentages (table 8). However the resolution influences the probabilities. The lower the resolution (thus the larger the cell size) the probability that a land use class does not change increases. This can be explained by the fact that small isolated patches disappear as grain size increases.

Table 8: Transition probability matrices

Cell size 5m		**To**				
		Urban	*Recreation*	*Agriculture*	*Nature*	*Water*
From	*Urban*	77,41%	3,56%	15,54%	1,55%	1,94%
	Recreation	7,71%	70,19%	9,27%	3,53%	9,30%
	Agriculture	3,32%	0,75%	93,82%	1,20%	0,91%
	Nature	3,24%	3,66%	14,03%	72,10%	6,96%
	Water	3,66%	0,70%	13,40%	1,18%	81,06%

Cell size 50m		**To**				
		Urban	*Recreation*	*Agriculture*	*Nature*	*Water*
From	*Urban*	76,84%	3,88%	15,87%	1,76%	1,64%
	Recreation	7,37%	71,22%	9,72%	3,60%	8,08%
	Agriculture	3,14%	0,77%	94,33%	1,18%	0,57%
	Nature	2,38%	3,73%	14,14%	74,15%	5,61%
	Water	2,77%	0,63%	9,63%	1,18%	85,79%

Cell size 500m		**To**				
		Urban	*Recreation*	*Agriculture*	*Nature*	*Water*
From	*Urban*	83,56%	4,05%	9,46%	0,45%	2,48%
	Recreation	4,41%	69,12%	13,24%	4,41%	8,82%
	Agriculture	2,52%	0,57%	95,31%	0,84%	0,76%
	Nature	0,47%	3,29%	21,60%	62,91%	11,74%
	Water	0,61%	0,61%	8,35%	0,20%	90,22%

Remarkable land use changes can be found near the municipality of Nieuwkoop. Here a lake has been converted to agricultural land. To the east of Woerden the opposite happened, as agricultural lands were changed into a lake (figures 28, 29, and 30).

Figure 31 is also a perfect example of how scale influences land use development. Where for the 5 and 50 meter resolution the infrastructural growth can be detected, it is not reflected on the 500 meter resolution map.

Figure 28: Land use change Green Heart 1989 – 2008, cell size 5 meters [1]

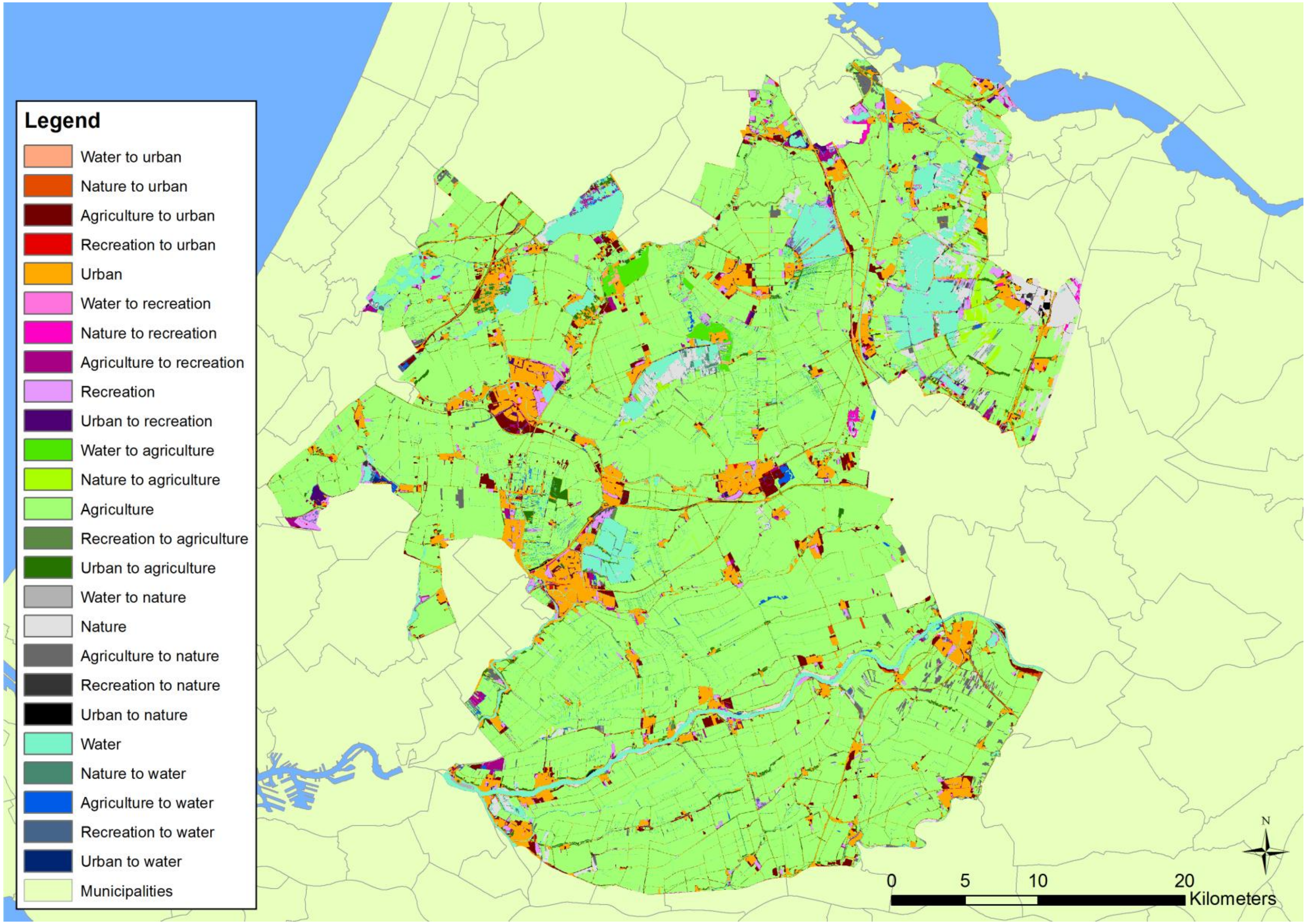


Figure 29: Land use change Green Heart 1989 – 2008, cell size 50 meters [1]

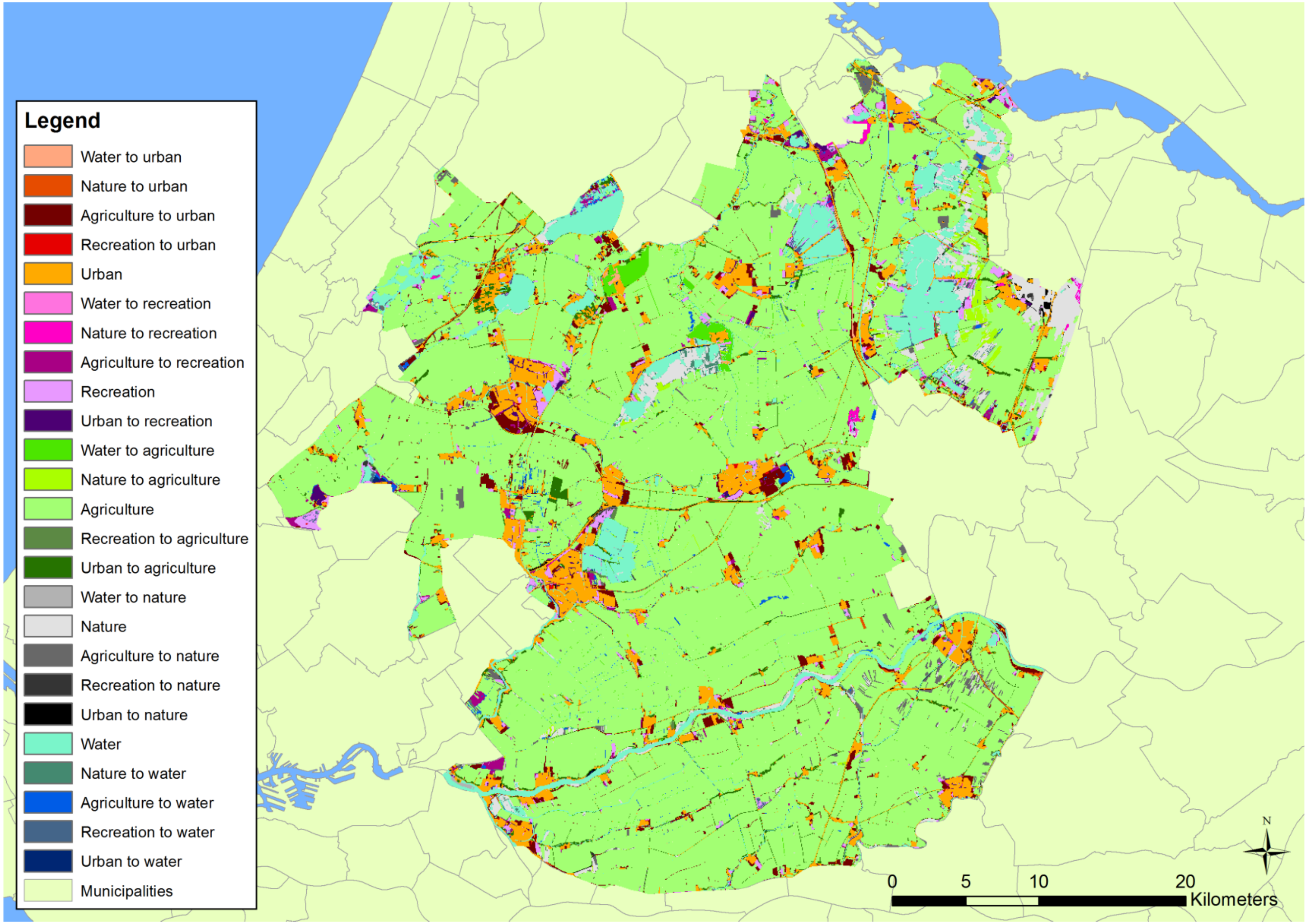


Figure 30: Land use change Green Heart 1989 – 2008, cell size 500 meters [1]

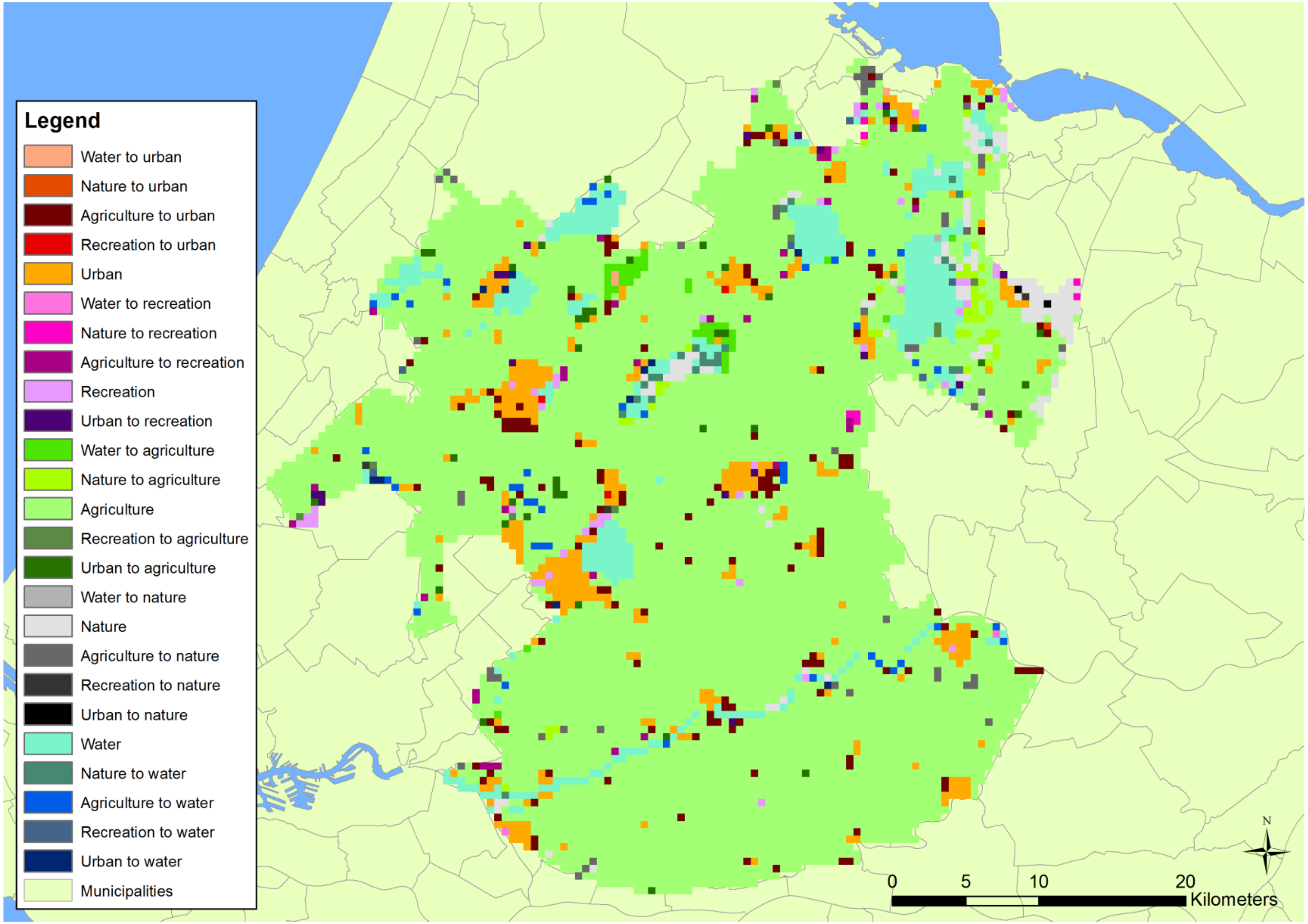
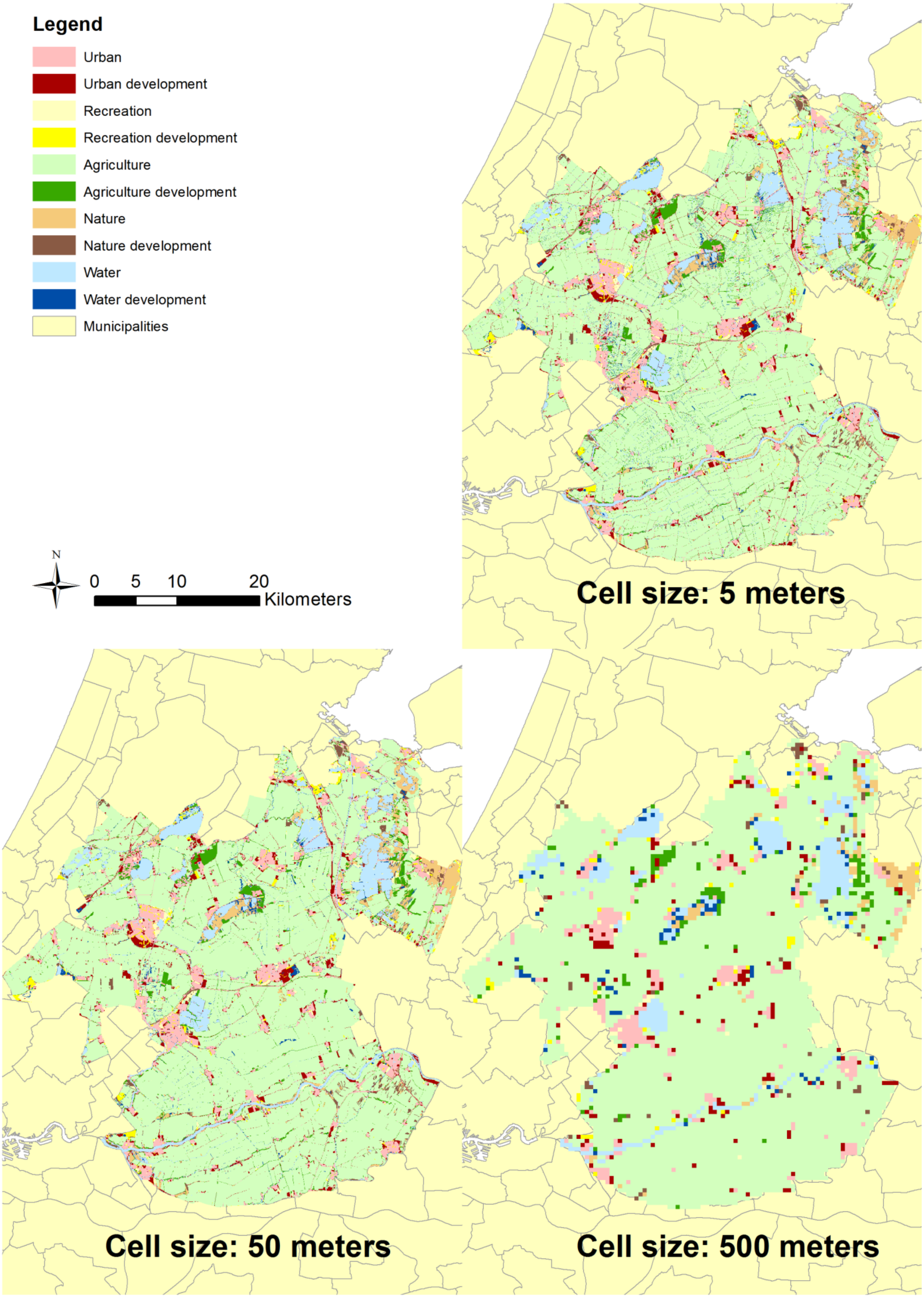


Figure 31: Land use development Green Heart 1989 – 2008 [1]



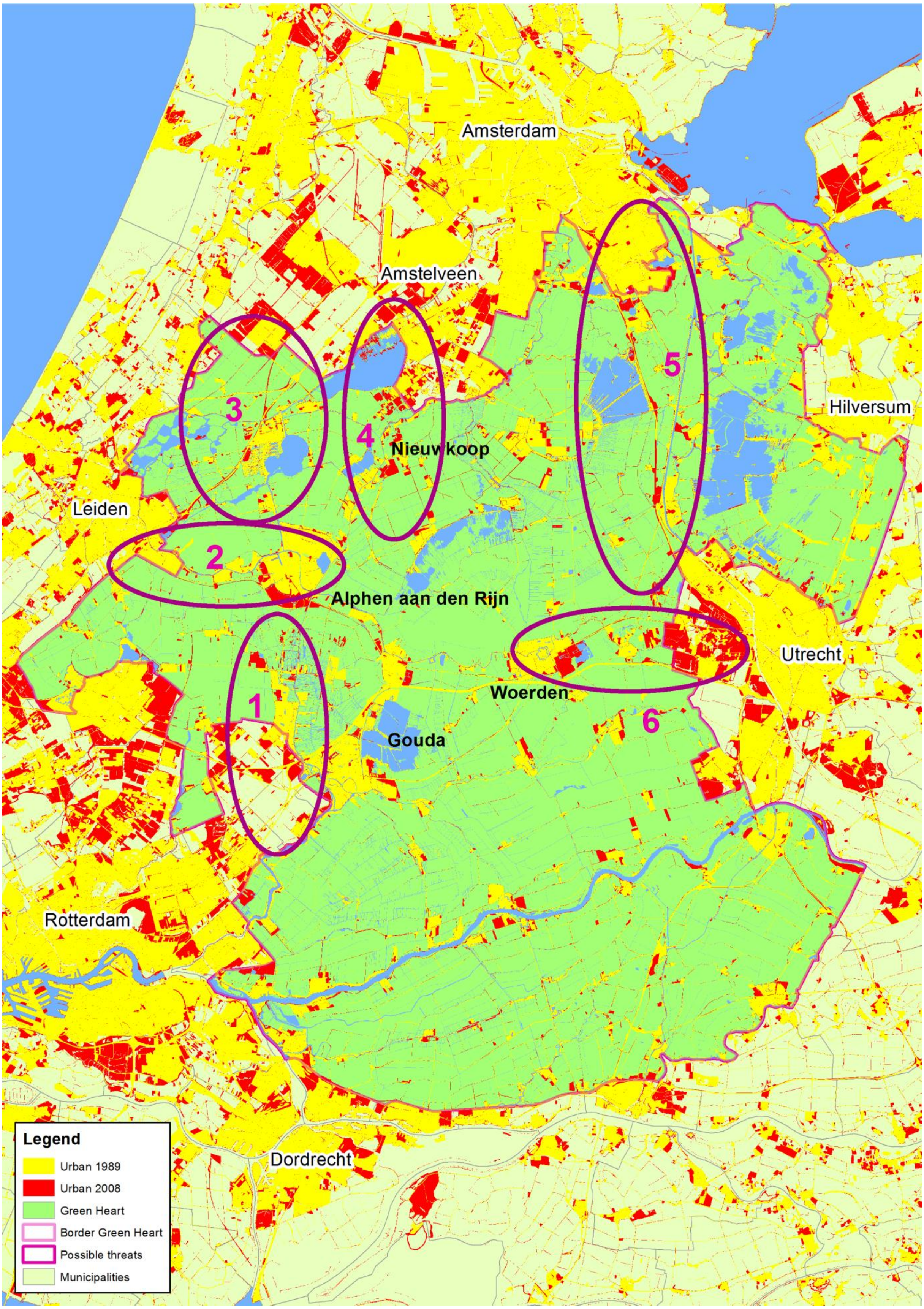
5.4 Conclusion urban sprawl Green Heart

The size of the urban class grew by 9,7% with a cell size of 5 meters, 9,8% with a cell size of 50 meters, and 23,9% (!) with a cell size of 500 meters for the period 1989 – 2008. Remarkable is that there is no difference between the growth of the urban class for the 5 meter resolution and the original vector dataset, meaning the conversion from the vector file to a 5 meter resolution raster file had no significant influence. In general there is a slight increase in the amount of urban patches, which indicates a gradual urban growth in the surrounding of the existing urban areas, apart from some leapfrog developments. On every resolution the edge density shows a small increase, indicating to a growth of the urban area, either directly surrounding the existing urban area, or a small growth of new emerged urban areas. There is also a difference between the AWMPFD values per resolution. Looking at the 5 meter resolution it could be stated that the shape is a bit complex, and certainly not simple and rectangular, whereas the description for the 500 meter resolution would be that the shape of the urban areas within the Green Heart are regular and very simple. The contagion index ranges on all resolutions between 60 and 70. Referring to a situation consisting of some larger continuous patches (more aggregated) on the one hand, and not well interspersed land use classes on the other hand. But still some fragmentation and interspersion of patch types can be found, a small increase of more small fragmented patch types because of the declining contagion index in time. The entropy increases, however just slightly, indicating a rise of a more dispersed pattern of development (instead of a more compact pattern). This is confirmed by the obtained results of the landscape metric contagion. Only the three 'large' municipalities show a real increase of the high density built-up area for all resolutions. In the north of the Green Heart three (new) highways or intensification of the built-up area alongside the highways have emerged. The same applies to the southern part however the highway itself is right on the border of the Green Heart. Also the three 'large' municipalities (Alphen aan den Rijn, Gouda and Woerden) and the municipality Nieuwkoop demonstrate a large growth of urban area, which corresponds with the findings the population growth analysis. However in the 500 meter resolution analysis these developments have been unnoticed, the right conclusion would be that for some settlements the urban area has expended, whereas the other parts are covered by a lot of leapfrog development. In some areas there are some small leapfrog developments. Three areas definitely show several leapfrog developments. The most significant one is the area between Alphen aan den Rijn and Gouda. Here, in the municipality Boskoop new greenhouses have emerged. The second area is the area East of Woerden. Here new built-up area has been created along the highway, which will probably lead to a connection of Woerden and Utrecht in the future. The last area with several leapfrog developments is in the south eastern area of the Green Heart. These three areas can be classified as scattered development areas. To sum up, it can be concluded that the description of the urban sprawl of the Green Heart differs significantly between the high resolution analysis, the 5 and 50 meter cell size, and the low resolution analysis (500 meter cell size).

For the future six areas can be identified that pose a potential threat to the core qualities of the Green Heart. In these six areas, additional built-up development are highly expected (if the observed trends will continue to develop). For some areas, this would lead to the agglomeration of the Randstad cities with the 'larger' (Alphen aan den Rijn, Gouda, Nieuwkoop, and Woerden) municipalities of the Green Heart (figure 32). In four of the six areas highways act as catalysts (areas 2, 3, 5, and 6). As a result of the expected north west built-up developments of the Green Heart, the border of the Green Heart might be adjusted in time. The urban areas in the north west area of the

Green Heart have agglomerated, the residual area will be compartmentalized into five small rural areas, which are entirely surrounded by built-up areas.

Figure 32: Expected future developments Green Heart [1]



6. Discussion

There is a persistent need to reach consensus on what urban sprawl exactly entails. During the literature study, methodology and case study many questions arose while reading about urban sprawl. Especially questions about: when is the expansion of a city called urban growth and when urban sprawl, how do you define and classify spatial characteristics of urban sprawl, and which threshold distance should be used when classifying the built-up developments as extension?

Urban growth versus urban sprawl

For instance, when should urban (built-up) development be classified as urban growth and when as urban sprawl? Within the existing literature there is no agreement on when urban (or built-up) development is qualified as urban sprawl. Therefore in this thesis urban sprawl is qualified as all built-up development, though this is arbitrary. Farms, small isolated housing blocks and other small sized built-up developments are all classified as urban sprawl. Furthermore, in this way the 'normal' growth of a city is also classified as urban sprawl.

Spatial characteristics of urban sprawl

Urban sprawl is characterized by the expansion of the urban area outside its borders into suburbs, the development of single purpose settlements and car dependency settlements, settlements with low density, unevenly patterned settlements, settlements which are spontaneous and unplanned (or uncoordinated and incremental), and settlements which reduce the amount of open rural area. However within existing literature no decisive answer is provided, neither rules or guidelines which state exactly when something is classified as low density, or what the urban area exactly consists of, or when a pattern is uneven, or how to test whether a development is unplanned and incremental?

Threshold distance built-up developments

The borders of the urban area are of great importance, especially when classifying new built-up developments (infill, extension and leapfrog development). When a new built-up development does not intersect the urban area, does this automatically means it should be classified as a leapfrog development and a form of urban sprawl? Also when the development occurs within an euclidian distance of 100 meters of the existing built-up, should it then not be classified as the extension of the urban area? Which threshold distance should be used for built-up developments occurring within the vicinity of the urban area? In this study it is suggested that within a vicinity of 250 meters the new developments should be classified as the extension of the urban area. However does this also apply for other areas?

The concept of urban sprawl has been with us for quite a while, however the aforementioned examples and questions underline the need for further research. Especially studies which contribute to a consensus on what urban sprawl entails. Not to forget, studies which state rules, guidelines, and operationalize, what can be considered as urban sprawl. It should be determined what low density is, what the threshold distance for developments (which will be classified as extension) in the vicinity of the existing built-up environment is, which development patterns can be typified as uneven and which development patterns can be classified as 'normal' urban growth. Establish when urban sprawl of an area can be characterized as compact, scattered, linear, polynucleated or leapfrogging. At the moment, a lot of knowledge on urban sprawl has been compiled, but there is still a lack of clear rules and consensus on these rules. Of course it is impossible and also undesirable to come to one dimension regarding the rules and guidelines, because of the enormous differences between countries (for example the differences of urban sprawl between Europe and North America).

Once consensus is reached on what urban sprawls entails and consensus is reached on the rules and the operationalization of the concept of sprawl, the analysis of urban sprawl areas would be more significant. Urban sprawl studies for different areas cannot be compared when the methodology differs, when the applied concept of urban sprawl differs, when the analysis is only done at one spatial resolution, when the classification of land use classes are different, etcetera. The goal of this study is to take a first step towards the consensus building on how to analyze urban sprawl with a GIS. The expectation has not been to create, as a result, a complete concept on how to analyze urban sprawl with a GIS. Instead, this study is aiming to contribute to the discussion on reaching consensus on how to analyze urban sprawl with a GIS. This study summarizes the most frequently used techniques on how to measure urban sprawl with a GIS. This study helps to see the wood for the trees. Especially the incorporation of the multi scale analysis is of vital importance to a sound analysis of urban sprawl. Without the multi scale analysis the structure, function and dynamics of urban sprawl would have been remained unnoticed. In that case no insight would have been gained on the sensitivity of the methodologies as well. For example when the urban sprawl of the Green Heart would be analyzed only at the 500 meter cell size resolution the linear strip developments would have been unnoticed. Also the expansion of Woerden in the direction of Utrecht, and the agglomeration of the municipality of Nieuwkoop would not have been revealed. Furthermore the growth of the built-up area would be about 24% with this spatial resolution in contrast to a 10% growth of the built-up area in the 5 and 50 meter resolution analysis. Also the shape, i.e. the complexity of the shape is strongly influenced by the resolution, which is no surprise. The 500 meter resolution analysis creates expectation that all the built-up forms are compact and rectangular, to a lesser extent this applies as well for the 50 meter resolution. However the 5 meter resolution analysis shows that the shape of the built-up areas is a bit complex, and certainly not simple and rectangular at all.

However what is not discussed and analyzed more thoroughly is the influence of the amount of classes on the landscape metrics. Although for several metrics the expected change, due to the increase of land use classes, for the metric value can be well estimated. For several metrics like contagion it is difficult to estimate the influence of the amount of classes. And yet a lot of studies which analyze the urban sprawl of a region do not take into account this influencing variable. Which is also the case for this study, which is mainly focused on the scale aspect. Just like the MAUP, the amount of classes used for the analysis can and will influence the obtained results. Therefore it is strongly recommended to add the research Huang et al. (2006) conducted when analyzing urban sprawl with a GIS. Like the scale problem, the landscape metrics should also be computed for the same landscape using a different amount of land use classes. It is however quite remarkable that many (respected) researchers do not take the MAUP and the amount of classes into account when analyzing the urban sprawl of a region, where all landscape metrics react differently to these two variables.

7. Conclusion

The main research question of the study is:

What is the suitability of the GIS methods which are used for analyzing urban sprawl, and what is the influence of scale on these methods?

Eleven commonly used GIS methods which are used for analyzing urban sprawl have been identified. However only ten have been tested for their suitability: class area (CA), number of patches (NP), edge density (ED), area weighted mean patch fractal dimension (AWMPFD), built-up density, contagion, Shannon's entropy, urban growth, classification new developments, and the land use change detection. The method Markov Cellular Automata Chain model has not been conducted because of the lack of software. For nine of the ten applied methods the scale influence was tested, the influence of scale has not been tested for the method land use change detection.

The landscape metric class area (CA) is a useful indicator of urban sprawl as it provides information on the growth of the built-up area. Scale influences this indicator, however the reaction is linear. It should be noticed that when applying this method on a low resolution, the area identified as built-up decreases significantly, as small and isolated patches disappear when larger areas are aggregated.

The suitability of the landscape metrics number of patches (NP) and edge density (ED) does not add much information to the analysis of urban sprawl. These two metrics are vague indicators, which only underlines the findings of contagion and Shannon's entropy. The calculation of these two landscape metrics is easy and not time consuming, however their effectiveness can be described as limited. These landscape metrics should only be used in combination with the landscape metrics contagion and Shannon's entropy. They cannot be used solely, as no real conclusion can be drawn from these indicators.

The AWMPFD is a suitable methodology for analyzing urban sprawl with a GIS. It provides useful information about the shape of the patches. However only when the appropriate scale is used. When landscapes are being aggregated on a low resolution, they lose their distinctive forms, which is the case for the 500 meter resolution map for the Green Heart. Thus when up scaling, the form and shape of a landscape changes, accompanied by a loss of information.

The contagion index and Shannon's entropy are both useful indicators for analyzing urban sprawl. They measure the landscape configuration and composition, i.e. the aggregation and dispersion of the patches. However contagion is a difficult landscape metric because of its response to scale, i.e. there is no ability to estimate the change of the metric if the scale is changed.

The methods built-up density, urban growth, the classification of new development, and the landscape change detection all underline the expansion of the built-up area. They are not entirely comparable, however they do correlate with each other. All three methods provide insight into the direction of the urban sprawl. Differences can be found in the approach, density, growth per time step, classification of the type of growth, and the probability land use changes. These methods are very useful and suitable for analyzing urban sprawl. They provide information on the direction of the urban sprawl, and development patterns become recognizable. However scale has its influence on these methods. The development patterns which are recognized on a high resolution, the 5 and 50 meter resolution, remain unnoticed in the low resolution analysis, the 500 meter resolution.

When the Green Heart area is analyzed on a 5 meter resolution, the description of the urban sprawl of the area would be different than for the 500 meter resolution, although there is some resemblance. Looking at the 5 meter resolution analyses it can be concluded that the sprawl is moderate, the urban area is not completely dispersed, and some core areas of built-up can be found. In time, only a small shift towards a more scattered and disperse development occurs. The structure of the urban patches are not rectangular and simple, neither highly complex, so somewhere in between. Also distinctive urban development patterns are detectable. However, looking at the 500 meter resolution it can be concluded that far less sprawl has occurred. Although the absolute and relative built-up growth is higher than for the 5 meter resolution analysis, the total urban area is in the 500 meter resolution 45% smaller when compared to the 5 meter resolution. The built-up patches are rectangular and very simple. The area consists, like the 5 meter resolution, of moderate dispersed urban areas, with some larger core areas. Also the development is slowly developing towards a dispersed pattern (instead of a more compact pattern). However distinctive development patterns are not detectable for the 500 meter resolution analysis. Which are detectable for the 5 and 50 meter resolution analysis.

Concluding: scale has a significant influence on the measurement of urban sprawl with GIS methods. However what is not discussed and analyzed more thoroughly is the influence of the amount of classes on the landscape metrics. Therefore it is strongly recommended to add the influence of the amount of classes to the conceptual model as a influencing variable of the landscape metrics, when analyzing urban sprawl with a GIS.

8 References

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Appendix

Conversations regarding the boundaries of the Green Heart of 1990 and 1993.

- *Dennis Weijers to Gerth Molenaar, Randstedelijk Rekenkamer. May 31, 2012.*

“Goedendag mevrouw/meneer van de Randstedelijke Rekenkamer,

ik ben Dennis Weijers, master student Geographical Information Management and Applications (MSc programma van de universiteiten Delft, Enschede, Utrecht en Wageningen). Ik ben momenteel bezig met mijn thesis. Het onderwerp van mijn thesis is het analyseren van de urban sprawl van het Groene Hart.

In het rapport: “Het Groene Hart - Een haalbare kaart” staat op pagina 18 een figuur die vier verschillende grenzen van het Groene Hart laat zien. Onder de figuur staat: “Het figuur is door het RPB samengesteld op basis van de volgende bronnen: Werkcommissie Westen des lands (1958), Ministerie van VROM (1990), Ministerie van VROM (1993) en Ministerie van VROM et al. (2004)”.

Nu vroeg ik mij de volgende dingen af:

- Is deze kaart manueel ingetekend of zijn er ook shapefiles (uitwisselingsformaat van geografische informatie, natuurlijk mag een andere uitwisselingsformaat zoals .tab van mapinfo ook)?
- Wie heeft deze kaart gemaakt, en zou deze persoon mij deze kaart als ze bestaan in een uitwisselingsformaat van geografische informatie mij kunnen verstrekken zodat ik deze kan gebruiken in mijn thesis?

Ik hoop dat u mij verder kunt helpen.

Met vriendelijke groeten,
Dennis Weijers”

- *Response Gerth Molenaar to Dennis Weijers. May 31, 2012.*

“Beste Dennis,

In reactie op je vraag kan ik je het volgende melden. Figuur 1 komt uit het boek dat in de voetnoot staat vermeld. Het PBL (Planbureau voor de Leefomgeving) heeft ons daarbij geholpen door het afzonderlijk beschikbaar stellen van het figuur. Overigens zijn ook de figuren 2 en 3 met behulp van het PBL tot stand gekomen, en wel specifiek voor ons rapport.

Hoe zij zelf deze figuur 1 hebben opgebouwd in termen van GIS, kan ik niet zeggen. Wij kennen alleen het plaatje zoals afgedrukt in ons rapport. Voor nadere informatie lijkt het mij het handigst om zelf contact op te nemen met het PBL. Het is inmiddels alweer drie jaar geleden dat dit speelde, vandaar dat wij niet meer precies scherp hebben wie van het PBL ons daarbij destijds hebben geholpen.

Met vriendelijke groet,

Gerth Molenaar”

dr. G. Molenaar
directielid

Randstedelijke Rekenkamer
Teleportboulevard 110
1043 EJ Amsterdam
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- *Answer PBL (Planbureau voor de Leefomgeving), June 6, 2012.*

"Beste Dennis,

Ik heb de oorspronkelijke bestanden uit de publicatie achterhaald. Het zijn 4 contouren waarvan de jaartallen helaas niet overeenkomen met de legenda van de kaart in het boek. Dit heeft volgens één van de schrijvers waarschijnlijk te maken met publicatiedatum en effectuering. De grenzen van vóór 2002 zijn niet hard. Voor het jaar 1990 is een eigen gemaakte contour gebruikt en daar is geen data van. De zuid-oost grens is nogal arbitrair bij de provinciegrens gelegd.

Voor de achtergronden van beleidskeuzes en de keuzes die gemaakt zijn voor het samenstellen van de kaart moet ik je doorverwijzen naar de schrijvers van het rapport. Maarten Piek is degene die de kaarten samengesteld heeft en waarschijnlijk de beste informatiebron. Hij werkt tegenwoordig bij het ministerie van I&M".

Met vriendelijke groet,

Arjan van der Put
Informatieadviseur

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