Satellite Monitoring of Urban Land Cover Change in Stockholm Between 1986 and 2006 and Indicator-Based Environmental Assessment

Dorothy Furberg and Yifang Ban

Abstract Over the past few decades, there has been substantial urban growth in Stockholm, Sweden, now the largest city in Scandinavia. This research investigates and evaluates the evolution of land cover/use change in Stockholm between 1986 and 2006 with a particular focus on what impact urban growth has had on the environment using indicators derived from remote sensing and environmental data. Four scenes of SPOT imagery over the Stockholm County area were acquired for this study including two on 13 June 1986, one on 5 August 2006 and one on 4 June 2008. These images are classified into seven land cover categories using an object-based and rule-based approach with spectral data and texture measures as inputs. The classification is then used to generate spatial metrics and environmental indicators for evaluation of fragmentation and land cover/land use change. Based on the environmental indicators, an environmental impact index is constructed for both 1986 and 2006 and then compared. The environmental impact index is based on the proportion and condition of green areas important for ecosystem services, proximity of these areas to intense urban land use, proportion of urban areas in their immediate vicinity, and how impacted they are by noise. The analysis units are then ranked according to their indicator values and an average of the indicator rankings gives an overall index score. Results include a ranking of the landscape in terms of environmental impact in 1986 and 2006, as well as an analysis of which units have improved the least or the most and why. The highest ranked units are located most often to the north and east of the central Stockholm area, while the lowest tend to be located closer to the center itself. Yet units near the center also tended to improve the most in ranking over the two decades, which would suggest a convergence towards modest urban expansion and limited environmental impact.

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1 Introduction

Over the past few decades, there has been substantial urban growth in Stockholm, Sweden, now the largest city in Scandinavia. Growth in the area is due mainly to the increasing population, which rose by 18 % between 1986 and 2006. The environment in and around Stockholm may be in the process of becoming more fragmented, especially in terms of its green areas, also known as "green wedges". Therefore, it is important to map urban land-cover changes and assess the environmental impact of these changes on the environment in a timely and accurate manner.

The objective of this research is to investigate the extent and nature of land-cover change in Stockholm from 1986 to 2006 through object-oriented, rule-based classification of satellite data, derivation of fragmentation statistics and environmental indicators based the classifications and the compilation of an environmental impact index for comparative purposes. Results are expected to reveal where and how different areas of Stockholm County have changed in terms of the impact of urban development on the natural environment in recent decades.

2 Study Area and Data Description

Stockholm municipality covers an area of around 216 km^2, while Stockholm County, a much larger region, covers 6 519 km^2 (STOCKHOLMS STADS UTREDNINGS- och STATISTIIKKONTER AB 2011). The planning authorities in Stockholm have called this area of Sweden a "green big city region." (REGIONPLANE- och TRAFIKKONTORET 2002) Greater Stockholm's "green wedges" that lead from the countryside in towards the more central parts of the city and the green links between these wedges comprise the framework of the region's green structure. Stockholm recently won the 2010 Green Capital Award from the European Union and has a vested interest in preserving the balance between its green and built-up spaces. Yet the region's population continues to grow, putting added pressure on the natural environment and increasing demand for built-up areas. This study seeks to find out what has occurred in relation to green areas and in terms of urban growth within the county of Stockholm over a recent 20 year period.

Four scenes of SPOT imagery over the Stockholm area were acquired for this study: two on 13 June 1986, one on 5 August 2006 and one on 4 June 2008. The images were selected from the height of the vegetation growing season to

maximize the differences between built-up areas and vegetation in order to reduce detection of unreal changes caused by seasonal differences between years. Two scenes from 2006 were sought but an appropriate 2006 growing season image over the northern parts of Stockholm County was simply not available. The scene from 2008 is therefore used as a substitute. The SPOT imagery from 1986 was from SPOT 1 with a resolution of 20 m, while that of 2006 and 2008 was from SPOT 5 with a resolution of 10 m.

The specific study area is based on the extent of the satellite images and, excluding an edge buffer, includes all or part of the territory of 18 municipalities in Stockholm County (see Fig. 1). The total land area covered by the satellite images is approximately 2,220 km^2. The major land cover classes in the area are low-density residential areas (LDB), high-density residential built-up areas (HDB), industrial/commercial areas, forest, open land, forest and open land mixed, and water. The HDB class is somewhat unique in this study since much of the "high density built-up" areas in the city center of Stockholm are composed of buildings that have businesses on the ground floor but residences on the above floors. Therefore the HDB areas classified in the center of Stockholm do include some commercial areas, which could at the same time be classified as residential. In contrast, the industrial/commercial class includes for example industrial park areas as well as shopping centers.

A number of GIS datasets were collected including data on land cover, transportation networks and noise disturbed areas. This data was used in the construction and calculation of the environmental indicators.

3 Methodology

## 3.1 Geometric Correction and Mosaicking

The SPOT scenes from each date were geocorrected to vectors from the Swedish National Land Survey's (SNLS) GSD topographic map collection [Lantmäteriet (SNLS) 2010] using a polynomial approach with at least eight GCPs each. The pairs of images from the two different decades were then mosaicked together using PCI Geomatica.

3.2 Classification of Satellite Data

3.2.1 Segmentation and Rules-based Classification

Various image processing and classification algorithms were tested and compared. The best results were obtained from an object- and rule-based classification approach using texture measures as well as spectral data as inputs. A pixel-based

Fig. 1 This image shows the
extent of the study area:
Stockholm county
municipalities included in the
study are outlined and labeled
in yellow with 2006 and 2008
SPOT imagery as backdrop
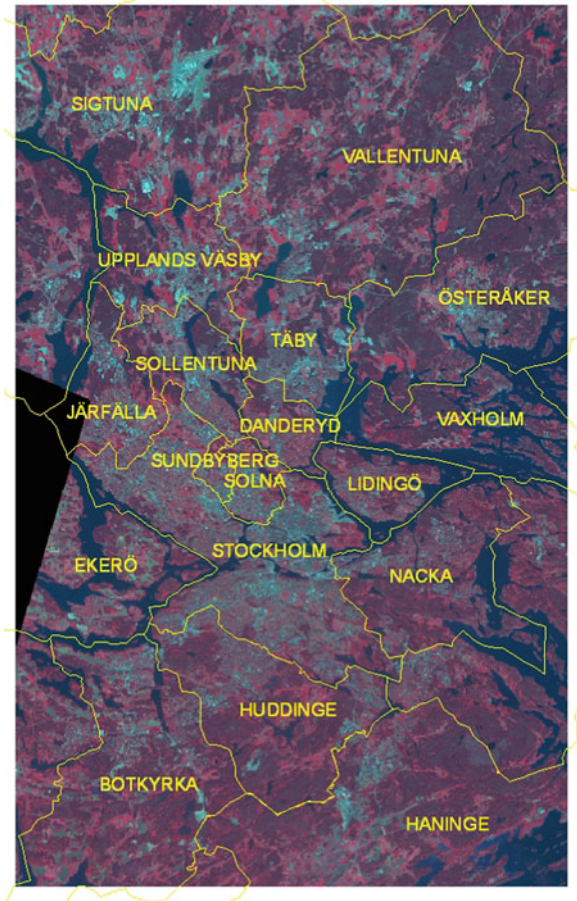
maximum likelihood classification was at first tested on the 2006 image (higher
resolution) without satisfactory results. Yet this initial classification was later used
as an additional input to the rules-based classification that followed. Based on
trials, the green, red and near-infrared spectral bands as well as mean, standard
deviation and correlation textures of the red band were selected as input data.
Texture measures were included since previous studies have shown that texture
measures such as grey-level co-occurrence matrix can improve the classification
accuracy of optical satellite imagery (Shaban and Dikshit 2001; de Martino et al.
2003; Herold et al. 2003).

Segmentation was performed on the two images using Definiens eCognition
software (Definiens AG 2007). Image segmentation can be defined as the division
of an image into spatially continuous, disjoint and homogeneous regions, also
known as objects. The procedure for the multi-scale image segmentation can be
described as a bottom-up region merging technique. It starts with each pixel which
is assumed to be an image object. Pairs of objects are merged to form larger

objects based on a homogeneity criterion which is comprised of color and shape components. A 'merging cost' is assigned to each possible merge. A merge takes place if the merging cost is less than a user-specified threshold, which is scale parameter in Definiens. The procedure stops when there are no more possible merges (Ban et al. 2010). In this study, the scale parameter was 20 and the homogeneity criteria were set at 0.1 for shape and 0.5 for compactness. These parameters were selected based on trials and provided the most appropriate objects for classification in that they most closely represented discrete areas of the different land cover types found in the region.

Rules were then sequentially constructed using an object's mean value of different input data to separate the different classes in order of easiest to separate to most difficult to separate. For example, water could be separated from everything else first based on values from the green spectral layer, then built-up areas were separated from non-built up based on values in the initial pixel-based classification, and so on. Areas that were satisfactorily classified early on were then excluded when performing the more fine-tuned rule-based classifications that were subsequently necessary for land cover categories that are often difficult for a single classification algorithm to distinguish. The process could therefore be considered as a type of sequential-masking classification. Once the segmentation-based classifications of the two dates were completed, accuracy assessments were performed using at least 600 random sample vector points for each land cover class.

3.2.2 Incorporation of Existing GIS Data

The GSD Topographic map was used to fill in data gaps so that analysis units located on the outskirts of the study area might have compleste classification information. Other existing GIS data sources for the Stockholm region were considered for incorporation into or improvement of the classification but for various reasons did not prove suitable. The SNLS has a land cover classification (from GSD Topographic map, Lantmäteriet [SNLS] 2010, 5 × 5 m), but this data does not provide as much detail when compared with the classification from 2006 (even though the resolution is better) and the map collection has no historical land cover data. Swedish Corine Landcover data (Lantmäteriet 2002) was not used for similar reasons. Its precision is measured at 85 % while the segmentation-based classifications in this research reach over 90 %.

3.3 Methods for Landscape Change Analysis

Two methods for landscape change analysis were employed in this study. First, spatial metrics were used to evaluate land cover change and specifically fragmentation for the whole study area. The metrics used are described in Sect. 3.3.1 and the results provided under Sect. 4.3.1. The second method is intended to

estimate environmental impact of the land cover change and consists of the calculation of five environmental indicators and their compilation into an environmental impact index. Explanation of the environmental indicators and the index is given in Sect. 3.3.2 and the results in Sect. 4.3.3. These two methods are not connected but are intended to provide complementary information.

To give an idea of how green and urban areas changed according to existing administrative boundaries in the study area, the percent change in large forested areas and in urban areas per municipality or parish is provided in Sect. 4.3.2. This information provides a bit more insight into the change over the whole of the study area and may be useful for city planning, since the focus of the information from the environmental indicators is in general on the less developed, more natural areas of the region.

3.3.1 Fragmentation Statistics

Evaluation of landscape fragmentation due to spatio-temporal changes was evaluated using selected spatial metrics generated from the Fragstats software (McGarigal et al. 1995) based on the classifications. The seven original land cover classes were aggregated to three classes: urban, natural and water classes for generation of the metrics. Forest, Open land, and Forest and open land mixed were aggregated to the natural class; HDB, LDB and Industry/Commercial to the urban class; while water remained its own class. This was done in order to minimize issues related to the difference in resolution between classifications being compared. The metrics calculated and used in this study are class area percentage (CAP), patch density (PD), area-weighted mean shape index (AWMSI), area-weighted mean perimeter to area ratio (AWMPAR) and connectance index (CONNECT). The area-weighted shape metrics are used since they give more weight to larger patches and thus the influence of the original difference in resolution of the classifications is thereby further minimized. AWMSI equals the sum of all patch perimeters divided by the minimum perimeter given a maximally compact patch with the same area multiplied by proportional patch abundance. AWMPAR is composed of the sum of the ratios of patch perimeter to area multiplied by proportional patch abundance. CONNECT measures connectivity of the land cover type and is defined based on the number of functional joinings between patches of the corresponding patch type, where each pair of patches is either connected or not based on a user-specified distance criterion. This statistic is reported as a percentage of the maximum possible connectance given the number of patches in the land cover class. A one kilometer distance was set for calculation of connectance based on trials and using the water class as a control group (the assumption being that the water class changes minimally over the 20 year period). The metrics values are then used for comparative evaluation rather than as stand-alone measurements.

3.3.2 Construction of a Comparative Index using Environmental Indicators

The purpose of the environmental impact index is to assess and compare the condition of the large green areas that provide several of the Stockholm region's essential ecosystem services. Bolund and Hunhammar (1999) have described a number of these specific to the Stockholm area, including air filtration, rainwater drainage, microclimate regulation and noise reduction. The unit of analysis for the environmental impact indicators and index is the large forested area or LFA. LFAs are defined according to information from several of the Stockholm Regional and Traffic Planning Authority's regional planning documents (for example STOCKHOLMS LÄNS LANDSTING REGIONPLANEKONTORET 1985 and REGIONE- och TRAFIK-KONTORET 1996) and one in particular on green structure in and around Stockholm:

> Green high value areas are large, coherent spaces that have specific importance within the categories of social, natural science and cultural environment values. They are the most important parts of a [green] wedge. They should be large, at least 3 square kilometres, so that they are big enough to preserve regional qualities, even qualities that are sensitive to disturbances and edge effects, and biological diversity (REGIONPLANE- och TRAFIKKONTORET 2008).

In this study, large forested areas were determined from the classifications by combining two land cover classes: "forest" and "forest and open land mixed". All areas that were greater than 3 km^2 were checked against the satellite imagery and road network to ensure that they did indeed fulfil the criteria outlined above. There were 30 of them in the study area extent in 1986 and 33 of them in 2006 (three of those from 1986 became divided due to the construction of new roads).

The Stockholm Regional and Traffic Planning Authority's report on Stockholm's green structure, having established the requirement for size of large green areas (>3 km^2), goes on to specify a further requirement important for ecosystem services:

> [Green] wedges should have a minimum width of 500 meters. This width is needed to accommodate several different types of natural areas that can act as connectivity routes for flora and fauna. This width also provides for variable natural areas for people to enjoy, including undisturbed environments. This width is also important for creating the "city breeze" that leads to the air exchange between the city's hard surface areas and the cooler natural spaces (REGIONPLANE- och TRAFIKKONTORET 2008).

These criteria were the basis for selecting the five indicators of the environmental impact index, namely: Area, Perforation, Proximity to intense urban land use, Urban perimeter and Noise. These indicators and the rationale for using them are explained below.

Since all of the LFAs established for 1986 and 2006 based on the size requirement meet the width criteria (500 m), the first indicator (Area) is simply based on the size of the large forested area. The assumption here is that larger green areas are more resistant to disturbance, more resilient if disturbed and provide ample shelter for flora and fauna. The second indicator (Perforation) is a measure of the physical condition of the LFAs, specifically their degree of intactness or perforation. Have they been disturbed by clear cut areas or roads? The degree of perimeter is used as a measure of

perforation of the area (using both internal and external perimeter). The length of perimeter of the LFA is divided by the minimum possible length given the same area (i.e. as a perfect whole circle). The third indicator measures the proximity of LFAs to intense urban land use. Dense urban and industrial areas produce pollution in the form of heat, emissions and contaminants which larger forest areas are to some extent able to compensate for (Bolund and Hunhammar 1999). But their proximity places pressure on these green areas. This proximity index (I_{prox}) is intended as a rough measure of that pressure. It is calculated as the area weighted distance between each LFA and all HDB and industrial/commerical areas, with both the size of the urban areas and that of the LFA taken into account ($I_{prox} = A_{LFA} * \sum (D^2/A_U)$) where A_{LFA} = area of large forested area, D = distance between LFA and urban patch, A_U = area of urban patch (centroids of LFAs and HDB/Industrial/Commercial areas are used to calculate distances). The fourth indicator (Urban perimeter) takes into account the immediate vicinity of the LFAs or the composition of their perimeter. Depending on the type of land cover there, they will be more insulated from or more exposed to various stressors. The percent of the LFA's perimeter that borders urban land use is calculated since this type of land cover will place the most pressure on the green area. Finally, the fifth indicator or degree of disturbance from noise in the LFA is measured based on a dataset created by the Stockholm Regional and Traffic Planning Authority, which indicates outdoor noise levels across the county. The amount of area per LFA exposed to noise levels above 55 dB (The World Health Organisation's limit for outdoor noise, WHO 1999) is calculated.

The method for compiling the index is simple in order to ensure as much transparency as possible. No weighting system of the indicators was used since a just system of weights is difficult to establish and defend and would require at the very least consultation and decisions from a panel of local experts. Instead a balance among the indicators selected was sought. Once all indicators were calculated, the analysis units were ranked according to each indicator. An average of the indicator rankings was taken to provide an overall index score.

The major advantage of the index and indicators is that they are comparative (the same methods and standards are used to derive them from each classification for each analysis unit). They can therefore be used as a measure of the differences between 1986 and 2006. Calculation of valid stand-alone indicator values is more difficult and not attempted here.

4 Results and Discussion

4.1 Geometric Correction and Mosaicking

The results from the geometric correction of the satellite images were satisfactory. The average X RMS error for the 2006 image was 3 m and the average Y RMS error was 3.3 m; for the 2008 image these were 2.6 and 3.1 m respectively. For the

1986 images, the average X RMS was measured at 4.4 m, while the average Y RMS error was 6.8 m.

4.2 Classification of Satellite Data

The results of the segmentation-based classifications over the Stockholm region are reported in Table 1. The overall accuracies were 92 % for both 1986 and 2006.

The texture features were instrumental in creating rules that ultimately successfully assigned objects to the correct land cover types. This was especially true when it came to isolating built-up areas such as LDB from other types of mixed but natural landscape and HDB from industrial areas. In regard to the lower resolution of the 1986 imagery, the objects generated by the segmentation for 1986 were for the most part of a similar size as those for 2006, but the 2006 segmentation did have a greater amount of smaller objects which led to a slightly more detailed classification, especially when it came to correctly isolating forest and open land mixed.

4.3 Landscape Change Analysis

4.3.1 Fragmentation Statistics

Looking at the change in class area percentage between 1986 and 2006, natural land cover dropped and urban areas increased by approximately 1.5 % of the whole landscape or just over 33 km^2. Urban areas increased by just under 10 % while natural areas decreased by 2 %. Both the natural and urban land cover areas became worse in terms of connectivity and their patch density and shape complexity increased over the 20 year period (see Table 2). The change in shape complexity and connectivity is shown graphically in Fig. 2.

If we look at the changes in the fragmentation statistics in conjunction with the changes in CAP, we get a better idea of the nature of the change in the natural and urban land cover classes. Natural areas decreased both in terms of land area as well as connectivity while patch density increased. These are indications that natural areas were becoming more fragmented through shrinkage or attrition of patches. The fact that patch shapes became more irregular would also suggest that previously larger natural patches were reduced by perforation or division in ways that increased their perimeter relative to area, such as by roads and/or clear-cuts. Urban areas on the other hand increased in terms of land area and patch density but decreased in connectivity. This suggests that new patches appeared out in the natural landscape and relatively near existing built-up areas, but not in direct conjunction with existing urban patches. The increase in shape complexity also supports the idea that several new, smaller and less compact patches came into existence.

Table 1 Accuracy scores and confusion matrices for the segmentation-based 1986 and 2006 classifications

1986 overall accuracy: 92.4 %
1986 overall kappa statistic: 0.91
1986 confusion matrix:

Land cover class	Water	LDB	HDB	Industry/commercial	Forest	Forest and open land mixed	Open land	Totals	User's accuracy (%)
Water	721	0	0	0	1	0	0	722	99.86
LDB	0	662	18	18	0	21	3	722	91.69
HDB	0	9	570	41	0	1	2	623	91.49
Industry/commercial	0	2	15	498	0	0	1	516	96.51
Forest	0	25	1	4	703	36	9	778	90.36
Forest and open land mixed	1	18	2	5	2	513	35	576	89.06
Open land	1	9	3	35	1	35	670	754	88.86
Totals	723	725	609	601	707	606	720	4691	
Producer's accuracy (%)	99.72	91.31	93.6	82.86	99.43	84.65	93.06		

2006 overall accuracy: 92.1 %
2006 overall kappa statistic: 0.91
2006 confusion matrix:

Land cover class	Water	LDB	HDB	Industry/commercial	Forest	Forest and open land mixed	Open land	Totals	User's accuracy (%)
Water	744	0	0	0	0	0	0	744	100.00
LDB	0	684	61	12	1	3	3	764	89.53
HDB	4	21	509	23	0	0	0	557	91.38
Industry/commercial	0	9	27	524	2	0	5	567	92.42
Forest	8	8	1	2	714	44	11	788	90.61
Forest and open land mixed	0	18	1	0	0	551	7	577	95.49
Open land	0	24	5	40	33	8	727	837	86.86
Totals	756	764	604	601	750	606	753	4834	
Producer's accuracy (%)	98.41	89.53	84.27	87.19	95.20	90.92	96.55		

4.3.2 Land Cover Change

Municipalities or parishes where percentage of LFAs changed significantly (a drop or increase of more than approximately 2 %) between 1986 and 2006 are listed in Table 3. Negative changes in percent are due mainly to either clearing of forest and/or division of existing LFAs while positive changes are mainly due to areas of regrowth. Those administrative units that lost the most in terms of square kilometers of LFA were Österåker-Östra Ryd, Täby and Boo. Those that gained the most were Vaxholm, Huddinge and Norrsunda. These findings on areas of improvement/deterioration from the perspective of administrative boundaries coincide more or less with the findings from the environmental impact index (the environmental perspective) as discussed below.

Municipalities or parishes where percentage of urban areas changed significantly (either a drop or increase of more than approximately 1 km^2) between 1986 and 2006 are listed in Table 4. Positive changes in percentage are mainly due to areas of urban expansion. Negative changes, on the other hand, are mainly due to improved detection of small green areas (such as lawns, trees and small parks lining streets and subdivisions) in and amongst urban areas in the 2006 classification. This indicates that urban areas were slightly overestimated in the 1986 classification and therefore that the percentage increases calculated are conservative and thus reliable. The administrative units that experienced the most increase in terms of square kilometers of urban areas were Österåker-Östra Ryd, Boo and Vaxholm. Looking at loss of LFA area and increase in urban area together, it appears that Österåker-Östra Ryd and Boo gained urban areas at the expense of sections of LFAs. Vaxholm on the other hand experienced increases in both, which suggests that urban development did not occur in direct contact with the LFA there, rather parts of it were allowed to regrow.

4.3.3 Environmental Impact Index Results

The environmental impact indicator results consist of a series of tables that can be provided by the authors upon request. In general, positive changes in area and perforation signified regrowth of forest in that particular LFA. Changes in rank for the proximity to intense urban land use indicator depended mainly on the location of new industrial/commercial or HDB areas. Negative changes in the percent of urban perimeter indicator were caused by construction of new LDB areas or roads in direct proximity to LFAs. Positive changes in the area affected by noise were most often due to loss of part of the area in the LFA affected by noise.

Each LFA is ranked according to each indicator and a subsequent average ranking across the indicators provides its overall environmental impact index score. These overall index scores are shown in Table 5 for both years.

North Vallentuna has the highest ranking in both years primarily due to the fact that it has very little or no urban perimeter and that it is relatively far from most intense urban land use areas. Boo, Skarpnäck, and Danderyd_Täby had consistently

Table 2 Class area percentage and selected fragmentation metrics

Class level	CAP	PD	AWMSI	AWMPAR	Connectance
Units	%	#/km^2	None (index)	None (ratio)	None (index)
Natural					
1986	71	0.25	11	43	1.18
2006	69.5	0.46	19	73	0.92
Urban					
1986	15.9	0.16	24	106	0.83
2006	17.5	0.45	39	191	0.52
Water					
1986	13	0.07	10	69	1.00
2006	13	0.08	10	72	1.00
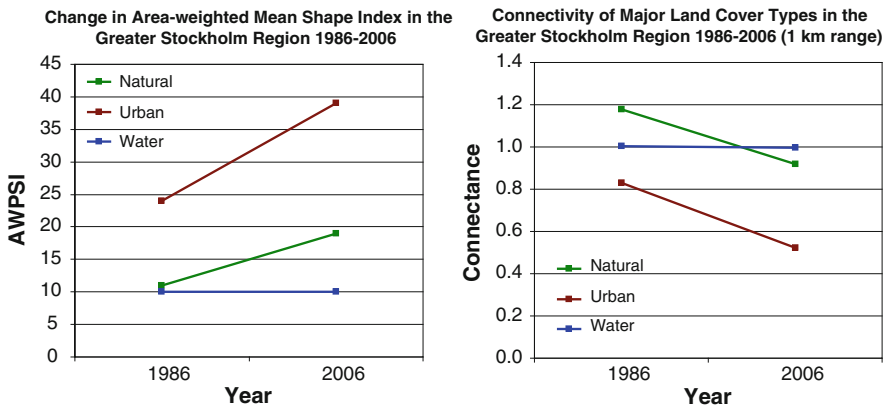
Fig. 2 Change in AWMSI (*Left*) and connectivity (*Right*) of major land cover types between 1986 and 2006

Table 3 Significant changes in percent of large forested areas per municipality/parish

Municipality/parish	Percent 1986	Percent 2006	Difference %	Difference km^2
Boo	25.5	21.9	−3.6	−1.6
Ed	29.1	32.5	3.4	1.3
Huddinge	44.4	48.1	3.7	2.7
Lovö	9.6	12.4	2.8	1.3
Norrsunda	20.6	23.7	3.0	2.3
Trångsund	26.3	30.6	4.3	1.5
Täby	10.4	6.4	−4.0	−2.8
Vaxholm	16.5	19.3	2.8	3.1
Viksjö	19.6	16.2	−3.4	−0.5
Österåker-Östra Ryd	39.6	37.8	−1.7	−3.7

Table 4 Significant changes in percent of urban areas per municipality/parish

Municipality/parish	Percent 1986	Percent 2006	Difference (%)	Difference (km^2)
Boo	15.1	25.4	10.4	4.7
Botkyrka	17.8	19.4	1.6	1.5
Bromma	54.6	48.8	−5.8	−1.6
Farsta	54.1	42.0	−12.1	−2.1
Huddinge	16.8	19.6	2.8	2.0
Norrsunda	2.8	5.1	2.3	1.8
Saltsjöbaden	12.1	17.5	5.4	1.5
Solna	47.5	41.0	−6.5	−1.4
Trångsund	15.9	19.6	3.7	1.3
Täby	26.2	28.2	2.0	1.4
Vallentuna	3.6	5.4	1.8	2.9
Vaxholm	3.3	6.4	3.1	3.4
Österhaninge	12.6	14.5	1.9	2.1
Österåker-Östra_Ryd	6.2	10.5	4.3	9.2

Table 5 Environmental impact index: average ranking in order of best (1) to worst (30) for 1986 compared to 2006

ID	Parish/municipality	1986 ranking	2006 ranking	ID	Parish/municipality	1986 ranking	2006 ranking
26	North Vallentuna	1	1	5	West Norrsunda	16	13
30	East Vallentuna	2	10	22	Huddinge	17	7
11	Vaxholm	3	2	7	Trångsund	18	6
14	Central Österåker	3	17	27	Viksjö	18	20
18	Central Vallentuna	3	5	2	Haninge	20	17
4	West Österåker	6	12	17	Norrsunda Vallentuna	21	26
16	Ed	7	9	9	East Nacka	22	16
20	East Österåker	8	29	21	Flemingsberg	23	24
10	Lovö	9	3	19	Sankt Mikael	24	22
25	North Norrsunda	10	15	24	Sollentuna_Fresta	24	10
6	North Österåker	11	13	23	West Nacka	26	28
12	Sollentuna_Järfälla	12	7	28	Jakobsberg_Kallhäll	27	24
1	Huddinge_Botkyrka	13	21	3	Boo	28	30
29	Täby_Vallentuna	13	4	8	Skarpnäck	28	22
15	Ed_Kallhäll	15	26	13	Danderyd_Täby	28	18

low rankings for nearly all indicators in 1986 and this was again the case for Boo in 2006, while Danderyd_Täby moved up dramatically as a result of forest regrowth on its northern side.

The environmental impact index scores are shown graphically in Fig. 3 for 1986 and 2006. This figure displays clearly some of the geographic differences in the ranking scores. In 1986, the lowest ranked analysis units tend to be nearer the central Stockholm area, while the highest ranked units tend to be on the northern and eastern outskirts of the study region. The configuration in 2006 is more difficult to characterize, with the
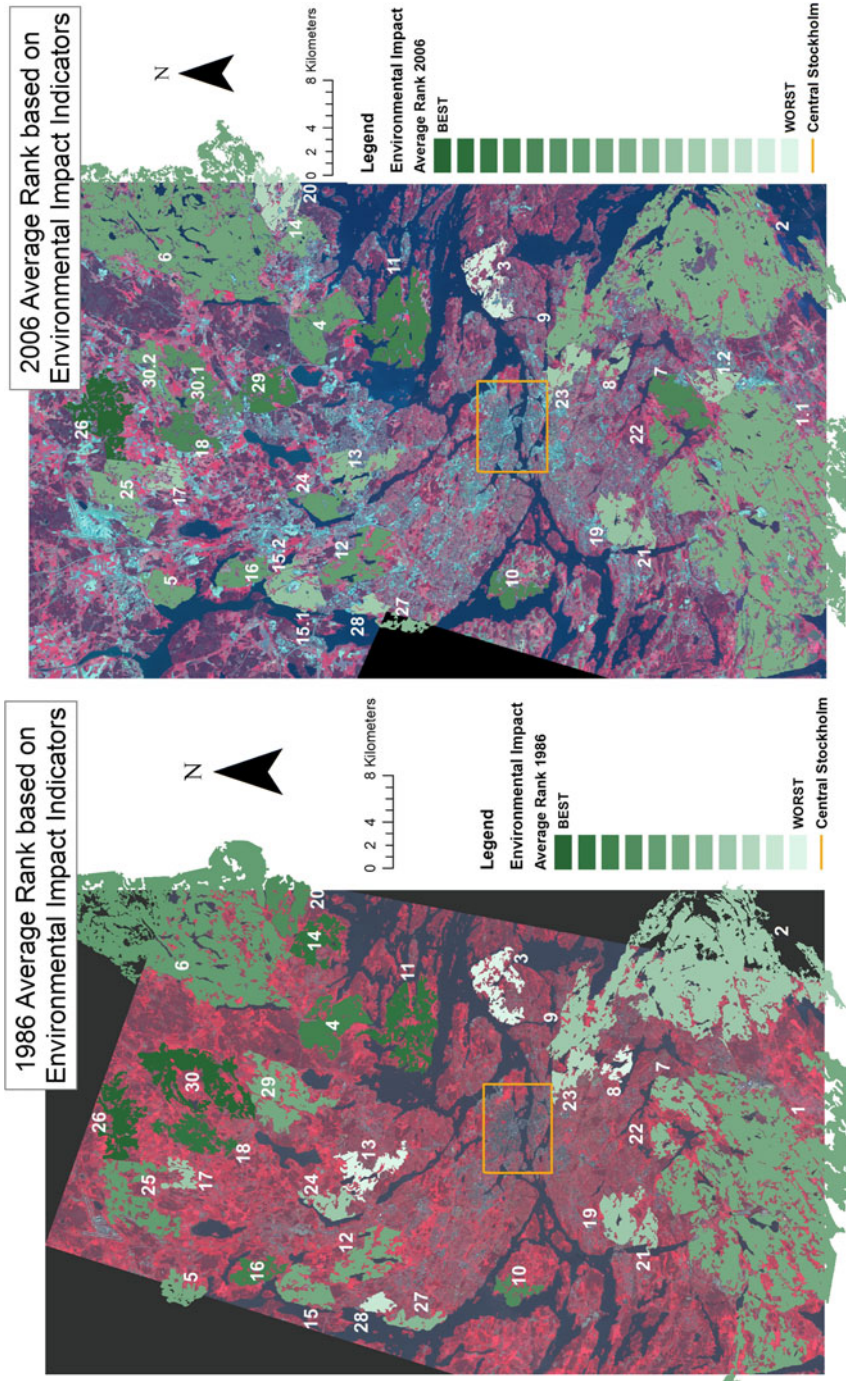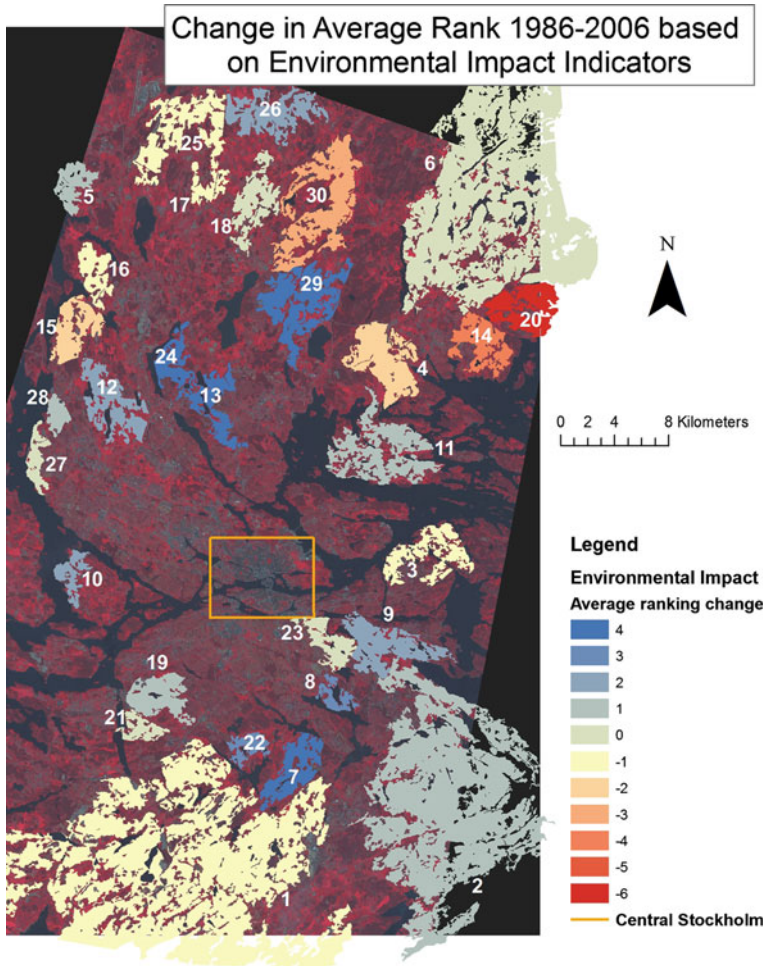
Fig. 3 Environmental impact index average rank per LFA for 1986 (*Left*) and 2006 (*Right*)

Fig. 4 Change in average ranking between 1986 and 2006 based on the Environmental Impact Indicators

highest and lowest ranked units more evenly scattered throughout the study area. There does not seem to be any trend according to size either, apart from the fact that the smaller LFAs tend to be either the highest or lowest ranked units while the larger LFAs tend to rank in the middle. This is true of both years.

The change in environmental impact average ranking per LFA is shown in Fig. 4. This figure indicates which regions have improved the most in general in terms of environmental impact and which have improved the least. Several of the more centrally located LFAs moved up in rank mainly due to improved standing for the proximity to intense urban land use indicator, since most of the new industrial/commercial and HDB areas were constructed more towards the outskirts

Table 6 Most improved and most deteriorated LFAs according to change in ranking per environmental impact indicator

Indicator	Most improved	Most deteriorated
Area	13. Danderyd_Täby	29. Täby_Vallentuna
Perforation	29. Täby_Vallentuna	20. East Österåker
Proximity to intense urban land use	10. Lovö	30. East Vallentuna
Urban perimeter	29. Täby_Vallentuna	14. Central Österåker
Noise	29. Täby_Vallentuna	11. Vaxholm
		13. Danderyd_Täby

of the study region. Those that dropped in rank the most did so due to increases in LDB areas in their immediate vicinity, such as in the case of East Österåker (20), or due to increased proximity to intense urban land use as well as division or fragmentation, as in the case of East Vallentuna (30). However, this figure is misleading in the case of Täby_Vallentuna (29). This LFA lost a significant portion of its area due to construction of new roads and urban areas. Yet this circumstance led to its improvement in terms of perforation, urban perimeter and noise. Had the area indicator carried more weight in taking the average of indicators, the change would not have been positive for this LFA.

The most improved and deteriorated LFAs per indicator are listed in Table 6. As discussed earlier, LFA Danderyd_Täby improved most in terms of area thanks to a section of forest regrowth on its north side. Täby_Vallentuna (29) deteriorated most due to the loss of about 50 % of its area due to construction of new roads and the resulting fragmentation. This loss, however, in effect led to its improvement in ranking in terms of perforation (the remaining area was more compact than the previous whole), for urban perimeter (the previous perimeter was more intricate and skirted LDB areas) and in terms of noise (less area now affected). East Österåker (20) worsened most in terms of perforation due to construction of new LDB areas that increased the length of its perimeter. For the proximity indicator, Lovö (10) improved most by default since no new industrial/commercial or HDB areas were constructed anywhere near it and it changed very little in area. East Vallentuna (30) on the other hand worsened most in this category because of the combination of the fact that it became divided in two which meant a drop in area coupled with the construction of new industrial/commercial areas relatively close by. Central Österåker (14) deteriorated most in terms of urban perimeter since it became increasingly surrounded by new LDB areas. However, Vaxholm (11) and Danderyd_Täby (13) did not really become much worse in terms of exposure to noise; the change is due mainly to a better delineation of these LFAs in the 2006 classification, which very slightly increased the area affected by noise.

5 Conclusion

This research investigates land-cover change in Stockholm between 1986 and 2006 and analyzes the impact of those land cover changes with the help of spatial metrics and environmental indicators. They results of the statistics and index

rankings reveal how green and urban areas evolved between 1986 and 2006 and in what manner the city has expanded, especially with regard to the surrounding natural resources.

Urban areas increased and natural land cover types decreased by about 1.5 % or 33 km^2 of the study area. The landscape change metrics indicated that both became more fragmented: natural areas became more isolated or shrank whereas new small urban patches came into being. The most noticeable changes in terms of environmental impact and urban expansion were in the east and north of the study area. Although a good deal of the urban expansion between 1986 and 2006 occurred in the northwest, the LFAs in that area were relatively small. There are larger and more far reaching LFAs in the northeast and these registered more of the effects of the urban development.

The results from the environmental impact index showed that the best average ranking scores occur in the northern and eastern portions of the study area. The worst tended to be closer to the center of the Stockholm region with a few exceptions. When it came to negative changes in rankings, areas in the northeast dropped the most. This shift in the northeast was mainly due to construction of new LDB areas. Generally, in terms of changes in rankings between 1986 and 2006, the most improved analysis units are those that are closest to the central Stockholm area, while the least improved or worsened units tend to be on the outskirts of the study area due to the fact that the urban expansion has occured mostly in the suburban areas.

It is important to keep in mind that the changes in many of these analysis units according to the indicators were for the most part subtle. The Stockholm area would not be considered densely urban when compared to other major cities or capitals and it has exceptional endowments in terms of green areas and water. What may be worth noting is that the changes (especially those that were negative) were not worse or more extreme in terms of environmental impact or urban expansion. This in itself serves as an indication that the regional planning authorities have made progress towards their goal of preserving the balance between Stockholm's green and urban areas over the past few decades.

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