

SATELLITE MONITORING OF URBAN SPRAWL AND ASSESSING THE IMPACT OF LAND COVER CHANGES IN THE GREATER TORONTO AREA

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ABSTRACT:

This research investigates the extent of land cover change, particularly urban sprawl, in the Greater Toronto Area (GTA) and the nature of the resulting landscape fragmentation, particularly with regard to the Oak Ridges Moraine (ORM), an ecologically important and sensitive area for the region. Three scenes of Landsat TM imagery were acquired from July/August 1985, July/August 1995 and July 2005. The TM images and TM5 textures were classified into seven land cover categories, i.e., low-density built-up, high-density built-up, construction sites, agriculture, forest, golf courses, parks/pasture and water using a maximum likelihood classifier. The overall accuracies were 90% for 1985, 93% for 1995 and 91% for 2005. Landscape fragmentation due to spatio-temporal changes was then evaluated using spatial metrics. The landscape composition results indicate that significant urban growth and sprawl occurred in the GTA. Comparison of the land cover classes over the 20 year period reveals a shift in dominance in the landscape through a clear increase in low-density built-up land cover categories coupled with a clear decrease in agricultural areas. The landscape configuration metrics calculated suggest increased fragmentation of both agricultural and low-density built-up areas during the two decades. Combined with the change in their proportions, this meant more isolation and attrition for the former, while the latter gained area through the appearance of more frequent and relatively smaller patches. In addition, the contagion and proximity indices indicate that agricultural areas were increasingly reduced in area, subdivided into smaller patches and became more dispersed over the given time period, while the opposite was true of suburban areas. The most extensive urban expansion onto the ORM occurred in municipalities within the region of York and therefore a thorough investigation of the impacts of this expansion is strongly recommended.

1. INTRODUCTION

Over the past few decades, there has been a rapid change of land cover in the Greater Toronto Area (GTA) in southern Ontario, Canada. In particular, the expansion of urban areas is due mainly to the GTA's increasing population. The urban growth trend is expanding towards and onto the Oak Ridges Moraine (ORM), an environmentally significant and sensitive area that lies north of Toronto. The ORM is the largest glacial remnant in Ontario and acts as a groundwater recharge/discharge area for approximately 65 watercourses. But the ORM has come under threat from urban expansion of the GTA in recent decades. The increase of built-up areas on the ORM has raised serious concern pertaining to water quality and quantity. Increased water withdrawal and contamination could impact those living in the GTA, fisheries, wildlife and conservation (NRC, 2007). Future urban growth within the surrounding municipalities will have significant impact on the important resources that the ORM provides and on the overall environmental quality of the region.

Previous studies have sought to combine change detection using remotely sensed data with impact analysis of these changes using landscape metrics, with the aim of taking into account the spatial distribution and arrangement of land cover changes. Some notable studies have been performed by Franklin et al. (2000), Narumalani et al. (2004), as well as Kamusoko and Aniya (2007). Herold et al. (2005, 2003 and 2002) have conducted extensive research on the use of spatial metrics to quantify the impact of urban growth in Santa Barbara, California. Studies like these have helped to provide urban and

environmental planners with the spatial and temporal information necessary to make more informed decisions about future land use. Given the ORM's ecological significance, such a study could provide valuable information to institutions such as the Government of Ontario, which enacted legislation in 2001 to protect the moraine (NRC, 2007). Therefore, the objective of this research is to map land cover changes during 1985, 1995 and 2005 using multi-temporal remote sensing and to assess the impact of urban land cover change on the environment using landscape metrics.

2. STUDY AREA AND DATA DESCRIPTION

The GTA is the most populous metropolitan area in Canada and is the sixth largest metropolitan area in North America (Wikipedia, 2008). It includes the city of Toronto and four regional municipalities (Durham, Halton, Peel and York) with a combined population of about five and a half million. In addition to its importance for water quality in the region, the ORM contains most remaining natural areas in the GTA bio-region including forests, wetlands and various plant and animal species, and provides for most of the recreational opportunities for the GTA's significant population.

Landsat TM imagery was acquired as input data for the analysis from three different years: 18 July and 12 August 1985, 30 July and 24 August 1995 and 2 and 25 July 2005. Two adjacent scenes were necessary for each year in order to cover the whole GTA. The images were carefully selected from the height of the full vegetation growing season to reduce the unreal changes

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caused by seasonal differences between years and to maximize the differences between built-up and non-built-up areas. The major land cover classes in the area are: low-density built-up (residential areas), high-density built-up (including roads and industrial areas), construction sites, agriculture, forest, golf courses, parks/pasture and water. Due to their spectral similarities, it was necessary to combine parks and pasture into one class. The agriculture class, on the other hand, was subdivided into several classes for classification due to their spectral diversity, and then aggregated together for change detection.

3. METHODOLOGY

3.1. Geometric Correction & Mosaicking

The images from each date were geocoded to the vectors from Canada's National Topographic Data Base (NTDB) using a polynomial approach with eight GCPs each. Images from the two dates for a given year were then mosaicked together using PCI Geomatica.

3.2. Texture analysis

Past studies have shown that spatial information or image texture is an important characteristic used to identify objects or regions of interest in an image (Haralick et al., 1973), and that texture measures such as grey-level co-occurrence matrix (GLCM) can improve the classification accuracy of optical satellite imagery (De Martino et al., 2003) and SAR data (Ban & Wu, 2005). In this research, various texture measures were tested and GLCM mean, standard deviation and correlation textures were selected based on trials.

3.3. Classification of Satellite Data

The maximum likelihood algorithm (MLC) was used to classify the images. A class for roads was also initially classified, which was later aggregated with high density built-up due to the confusion between roads and high density built-up areas. The number of training pixels used for the classification of each land cover category ranged from 1000 - 6000.

TM 3, 4, and 5 were selected for land cover classification as they represent the majority of variance in TM data. To improve the classification, mean, standard deviation and correlation textures of TM5 were included in the classification. Once the classifications of the three dates were completed, accuracy assessments were performed using 500 random sample vector points for each land cover class.

3.4. Quantification of Landscape Pattern and its Importance for Process

An important concept that has been established in the field of landscape ecology is that a landscape's pattern strongly influences its ecological processes and characteristics (McGarigal & Marks, 1995, Turner, 1989, Forman & Godron, 1986). Another is that habitat fragmentation is a common process related to landscape change that often negatively affects both its structure and function. This phenomenon has been identified as one of the greatest threats to biodiversity worldwide (Botequilha Leitao & Ahern, 2002). Most human land uses, such as urban development, roads and agriculture, cause habitat fragmentation. For the purposes of this study, habitat fragmentation is defined as being comprised of three major components: loss of original habitat (attrition), reduction

in habitat size (shrinkage) and increasing isolation of habitat patches (Botequilha Leitao & Ahern, 2002). Shrinkage, isolation and attrition are spatially quantifiable characteristics of a landscape that can be measured by landscape metrics. These were calculated for the GTA at each of the different points in time and the results compared to see how the landscape and land uses have changed over the past two decades. The specific metrics used are discussed in the next section.

The GTA is a fairly heavily-managed landscape, that is, there is little natural habitat – areas not directly influenced by people – in the region. To begin with in 1985, agricultural lands, being the most dominant land cover class with maximal connectedness constitute the matrix in this case, while the other classes comprise the patches and sometimes corridors**. Forest is the only land cover class that could qualify as natural habitat. Therefore it is not so much habitat fragmentation that is of concern in this study (since this has already to a large extent happened in the GTA), but it is the fragmentation of vegetated-areas or the loss of vegetation-covered areas that is at stake. These vegetated areas help several natural and necessary processes in the GTA, especially with regard to water supply, such as infiltration, filtration and prevention of erosion. Urban or even suburban development, particularly on the ORM, could hinder or disrupt these processes and negatively impact the water supply in this region.

3.5. Limitations of landscape metrics and core set of indices used

There is abundant recent literature that has urged caution in the use of landscape metrics, because they are often strongly correlated and can be confounded (Botequilha Leitao & Ahern, 2002 and McGarigal & Marks, 1995). Li and Wu (2004) pointed out the variable responses of certain landscape indices to changes in spatial pattern, such as evenness and fractal dimension, as well as the difficulty in interpreting them since they do not consider the association of proportions with patch types and often represent more than one aspect of spatial pattern. They stressed that simple metrics such as patch size, edge, inter-patch distance and proportion are more likely to generate meaningful inferences. It was therefore decided that this study would look at a core set of "simpler" indices that for the most part each measure one component of either landscape composition or spatial pattern. Botequilha Leitao & Ahern (2002) analyzed several comparative studies and reviews of the many landscape metrics available (e.g. Li & Reynolds, 1994 and Riitters et al., 1995) and proposed a core set of metrics that describe landscape structure and key associated spatial processes. A modified version of this core set of metrics is used in this study for assessing landscape fragmentation and is listed in Table 1.

Composition metrics measure inherent landscape characteristics such as proportion, evenness and dominance. Configuration metrics, on the other hand, quantify the spatially-explicit characteristics of the landscape, such as ratio of area-to-perimeter, edge contrast and location of patch types in relation to one another. The configuration metrics used here can benefit from some further explanation. The patch shape index (PSI) corrects for the size problem of the perimeter-area ratio index by adjusting for an almost square standard and is thus the simplest and perhaps most straightforward measure of overall shape complexity (McGarigal & Marks, 1995). The total edge

** See Forman and Godron (1986) for more information on the patch/corridor/matrix model.

contrast index (TECI) measures the degree of contrast (difference) between a class of patches and their neighborhoods (*Ibid.*). For reference, forest and high density built-up areas have high contrast, while agricultural areas and golf courses do not. This is a relative indicator and in our case measures the degree of contrast in the edge of a specific class. The proximity index equals the sum of patch area (m²) divided by the nearest edge-to-edge distance squared (m²) between the patch and the focal patch, of all patches of the corresponding patch type whose edges are within a specified distance (in this case, 1000 m) of the focal patch. PI increases as the neighborhood is increasingly occupied by patches of the same type and as those patches become closer and more contiguous (or less fragmented) in distribution (*Ibid.*). Contagion can be considered a measure of land cover class dispersion and interspersions, which are both low when contagion is high – a sign that patches are generally aggregated. For specific details on how the metrics are calculated, see McGarigal & Marks (1995).

Landscape Composition Metrics	Description
Patch Richness (PR)	Number of classes present in the landscape
Class Area Proportion (CAP)	Proportion or percentage of each class in the landscape
Number of Patches (NP)	Total number of patches of a specified land cover class
Patch Density (PD)	Number of patches per square kilometer
Mean Patch Size and Stan. Dev. (MPS and PS_SD)	Average patch size and stand. dev. of a class of patches
Landscape Configuration Metrics	Description
Mean Patch Shape Index and Standard Deviation (PSI_MN and PSI_SD)	Class average and standard deviation of the ratio of perimeter to minimum possible perimeter given the number of cells in the patch
Total Edge Contrast Index (TECI)	Quantifies edge contrast (degree of contrast between a patch and its neighbors) as a percentage of maximum possible
Mean Proximity Index and SD (MPI and MPI_SD) – search radius: 1 km	Measures relative distance between patches of the same class
Contagion (CONTAG)	Relative aggregation of patches of different types at the landscape scale

Table 1. Core Set of Landscape Metrics Used

In this study, the scale is truly on a landscape or regional level at which we detect broad land cover changes over significant periods of time (two decades). The grain is the satellite image resolution – that is, each classified pixel is 28.5m x 28.5m. The extent is the area of the GTA, approximately 7,200 km². The scale (grain and extent) is the same for all three classifications, a circumstance which minimizes problems or errors stemming from scale. The use of this core set of landscape metrics is in an overall sense valid in this case because they are being used only *comparatively* between three points in time. They are relative rather than stand alone indicators of fragmentation. They therefore can inform us about the spatio-temporal trends in the GTA landscape.

4. RESULTS & DISCUSSION

4.1 Geometric Correction & Mosaicking

The multi-temporal Landsat TM images were geometrically corrected with RMS errors averaging 0.2 (pixel) for the six images and no greater than 0.26. The results from the image mosaicking were also for the most part satisfactory, although there were some tonal matching issues associated with the 1985 mosaic. The differences in tones for similar land cover classes with this image led to some of the problems the MLC algorithm had in distinguishing a certain type of agriculture from a certain kind of forest (see the footnote on the next page).

4.2 Classification

The results of the classifications are reported in Table 2, while the confusion matrix produced from the 1995 classification is shown in Table 3 (located after References).

1985 Overall Accuracy: 90.1%
1985 Overall Kappa Statistic (KS): 0.89%

LC class	KS	Producers Acc.	Users Acc.
Water	1	95.2%	99.58%
Forest	0.92	97.4%	93.12%
Parks/Pasture	0.95	85.4%	95.96%
Golf courses	0.98	77.4%	97.98%
Agriculture	0.61	94.8%	66.2%
HDB	0.88	88.6%	89.5%
LDB	0.93	94.6%	94.04%
Construction	0.98	87.4%	98.2%

1995 Overall Accuracy: 93.08%
1995 Overall Kappa Statistic (KS): 0.92%

LC class	KS	Producers Acc.	Users Acc.
Water	1	92%	100%
Forest	0.96	98.6%	96.67%
Parks/Pasture	0.84	91.40%	85.58%
Golf courses	0.96	86.60%	96.44%
Agriculture	0.85	94.80%	86.97%
HDB	0.88	92.60%	89.9%
LDB	0.95	95.20%	95.39%
Construction	0.95	93.40%	95.7%

2005 Overall Accuracy: 91.05%
2005 Overall Kappa Statistic (KS): 0.9%

LC class	KS	Producers Acc.	Users Acc.
Water	1	89%	100%
Forest	0.92	95.8%	92.65%
Parks/Pasture	0.90	84.8%	91.38%
Golf courses	0.97	91.6%	97.03%
Agriculture	0.77	89.6%	80.14%
HDB	0.90	86.6%	90.97%
LDB	0.80	99%	82.09%
Construction	0.99	92%	99.14%

Table 2. Accuracy Reports for the Three Classifications

The overall accuracies were: 90% for 1985, 93% for 1995 and 91% for 2005. The texture features were instrumental in helping the maximum likelihood classifier to distinguish land cover types such as golf courses from parks/pasture and agricultural areas. Because the category of parks/pasture was mixed to varying degrees with agriculture in each of the classifications and because of the difficulty this would have caused in

interpreting the landscape metrics (particularly in regard to spatial measures), these two categories were aggregated into what is termed “managed” land cover. Judging from the classifications and the assigned proportions of these two categories, it was determined that municipal parks in their true sense made up around 1% of the landscape. It is therefore estimated that managed land cover is composed of between 96-98% agricultural areas, while parks make up the other 2-4%.

4.3 Landscape metrics and trends for the GTA between 1985 and 2005

Since it is not possible or even perhaps relevant to discuss every statistic calculated, we will focus our attention on the clearest and most relevant information provided by the metrics in Tables 4 and 5. Most analysis will be devoted to changes in the classes of managed land cover (agriculture & parks) and LDB since these categories often showed the clearest and most significant trends.

Class level:	CAP	NP	PD	MPS	PS_SD
Units	%	patches	# / km ²	km ²	km ²
Forest***:					
1985	21	8614	0.45	0.19	2.0
1995	23	2052	0.11	0.84	4.9
2005	23	2741	0.14	0.64	5.7
Managed land					
(96-98% agriculture / 2-4% parks):					
1985	60	2130	0.11	2.13	91.3
1995	52	10495	0.54	0.38	22.2
2005	43	8657	0.45	0.38	8.1
LDB:					
1985	9	1187	0.06	0.51	3.8
1995	12	5927	0.31	0.15	5.0
2005	18	11103	0.58	0.13	7.2
HDB:					
1985	5	541	0.03	0.61	3.5
1995	6	7049	0.37	0.07	1.5
2005	6	6467	0.34	0.07	1.5
Golf courses:					
1985	1	590	0.03	0.15	0.3
1995	2	709	0.04	0.17	0.3
2005	4	8433	0.44	0.03	0.1
Construction sites:					
1985	0.6	840	0.04	0.06	0.1
1995	0.7	1540	0.08	0.03	0.1
2005	0.8	822	0.04	0.07	0.2
Water:					
1985	5	318	0.02	1.17	14.1
1995	5	148	0.01	2.39	20.1
2005	5	195	0.01	1.83	17.5

Table 4. GTA Landscape Composition Metrics

With regard to the landscape composition metrics, the most significant proportional results are in regard to loss of agricultural lands in favor of low density built-up areas and golf

*** Forested areas generally remained the same or unaffected during this two decade period. The statistics and graph show an increase in forested areas between 1985 and 1995 due to a slight under-detection of forested areas in the 1985 classification and a slight over-detection of forested areas in the 1995 and 2005 classifications. The differences in detection of forested areas were due to the spectral qualities of each of the satellite images, e.g. it was more difficult for the algorithm to distinguish forested areas from a certain type of agriculture since they had very similar spectral values in the 1985 satellite imagery. This makes the forest class appear more “patchy” or fragmented in the 1985 statistics.

courses, see Table 5 and Figure 1. The decrease in managed or agricultural lands held a fairly steady rate of between 8 and 9% of the landscape per decade. LDB areas increased by about 3% between 1985 and 1995 and by 6% between 1995 and 2005. Golf courses increased by less than a percentage point between 1985 and 1995 but doubled in area between 1995 and 2005. The good news is that forested areas remained relatively unchanged, holding steady at around 22% of the landscape**. High density built-up areas and construction sites increased only slightly (less than a percentage point each) over this time period.

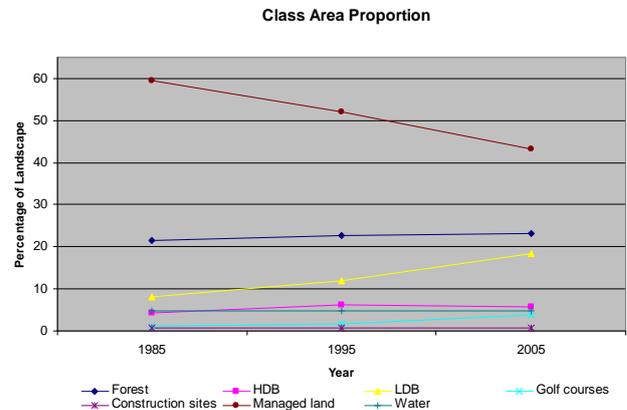


Figure 1. Percentages of land cover classes in the GTA over the time period 1985 – 2005

The proportion change information combined with the NP and PD metrics gives more specific information in regard to how managed land and LDB areas were altered. The number of patches and patch density for managed land increased five times over between 1985 and 1995, indicating increased isolation in addition to shrinkage from its CAP reduction. Its proportion decreased again in 2005 combined with a drop in number of patches and patch density, which would indicate attrition (outright loss) of agricultural areas. For LDB, nearly the opposite was true with increases in both CAP and NP/PD over the 20 year period. While the LDB areas increased, the rise in patch number and density indicated that areas appeared as many new patches, not as additions to or consolidation with existing patches, a phenomenon which produces a more “percolated” or “patchy” landscape. Mean patch size dropped, particularly between 1985 and 1995 (see Figure 2), but also slightly between 1995 and 2005, reinforcing the conclusion that the addition of LDB areas was leading to more fragmentation, rather than aggregation, of the landscape.

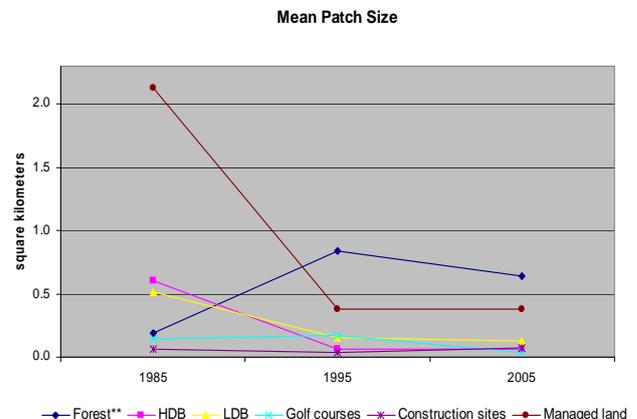


Figure 2. Mean patch size of land cover classes in the GTA over the time period 1985 – 2005

Turning our attention to the landscape configuration metrics (Table 5), we see that several of the metrics results confirm increased fragmentation of the landscape due to urban development. The MPI dropped for managed land but increased for LDB areas over the given time period, see Figure 3. As mentioned previously, an increase indicates that the neighborhood is more extensively occupied by patches of the same type as those patches become closer and more contiguous (or less fragmented) in distribution, which was the case for LDB. The opposite was true for managed land, where surrounding neighborhoods were increasingly occupied of patches of other categories, probably of an urban nature, and agricultural patches became more dispersed.

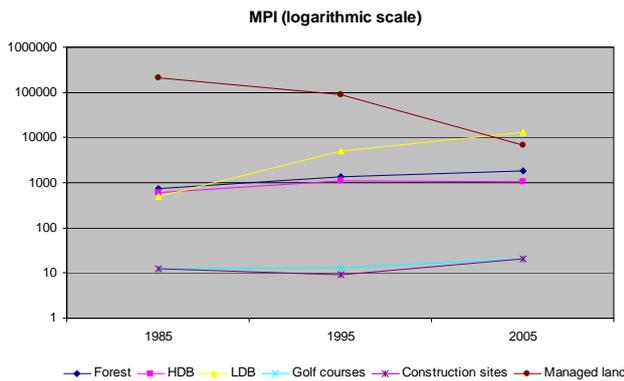


Figure 3. Mean proximity index for land cover classes in the GTA over the time period 1985 – 2005

Class level:	PSI_MN	PSI_SD	TECI	MPI	PL_SD
Units	none	none	%	none	none
Forest**:					
1985	1.75	0.76	53	734	3395
1995	2.71	1.72	55	1367	4371
2005	2.38	1.52	57	1796	7668
Managed land					
1985	1.77	1.98	61	212278	379511
1995	1.51	0.95	63	89474	167438
2005	1.56	1.02	60	6872	18434
LDB:					
1985	2.33	1.18	66	504	2996
1995	1.58	0.89	63	5076	19621
2005	1.57	0.97	62	12937	45010
HDB:					
1985	2.42	1.41	64	606	2173
1995	1.50	0.85	65	1095	4796
2005	1.51	0.81	51	1072	4968
Golf courses:					
1985	2.07	0.62	52	12	63
1995	2.10	0.76	46	13	50
2005	1.53	0.54	52	21	62
Construction sites:					
1985	1.64	0.49	51	13	40
1995	1.44	0.47	50.2	9	28
2005	1.52	0.48	50.4	21	53
Water:					
1985	1.62	0.94	69	984	5325
1995	1.71	1.21	64	2362	6558
2005	1.62	1.13	65	2427	7257

Landscape level: CONTAG (%)

1985: 62	1995: 57	2005: 52
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Table 5. GTA Landscape Configuration Metrics

At the landscape level, the contagion values indicate that the different land cover types in the GTA became increasingly disaggregated and interspersed over the 20 year period, a sign of increased landscape fragmentation.

Other configuration metrics were also calculated, notably: mean and standard deviation for patch compaction (i.e., mean distance between each cell in the patch and the patch centroid) and mean and standard deviation of nearest neighbor distance (i.e., distance between patches of the same class). However, these share some similarities to PSI and MPI respectively, and thus are not presented or commented upon here.

5. CONCLUSION AND RECOMMENDATIONS

As we have seen, low density urban areas increased significantly in the GTA between 1985 and 2005 at the expense of mainly agricultural areas. The loss of these agricultural or vegetated areas means a more extensive cover by artificial surfaces and less natural services provided by vegetation such as infiltration, filtration and protection against erosion. Increased urban development could in essence compromise (hinder or disrupt the natural processes that provide) a good quality water supply to the region ensured by the ORM, not to mention the additional pollution. A thorough investigation of these impacts is therefore highly recommended, especially concerning the portion of the ORM that lies within the region of York where there was clear suburban expansion onto the moraine in the municipalities of Aurora and Richmond Hill (see Figure 4, situated after References). On a positive note, the forested areas in the region have remained relatively untouched by the urban growth trend. Let us hope that this remains true for the decades to come as well.

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Land cover classes	Water	Forest	Parks/Pasture	Golf courses	Agriculture	HDB	LDB	Construction	Totals
Water	460	0	0	0	0	0	0	0	460
Forest	7	493	0	1	5	0	4	0	510
Parks/Pasture	0	2	457	59	14	1	0	1	534
Golf courses	0	1	9	433	6	0	0	0	449
Agriculture	3	0	27	7	474	1	8	25	545
HDB	28	1	4	0	0	463	12	7	515
LDB	2	3	3	0	0	15	476	0	499
Construction	0	0	0	0	1	20	0	467	488
Totals	500	500	500	500	500	500	500	500	4000

Table 3. 1995 Classification Confusion Matrix

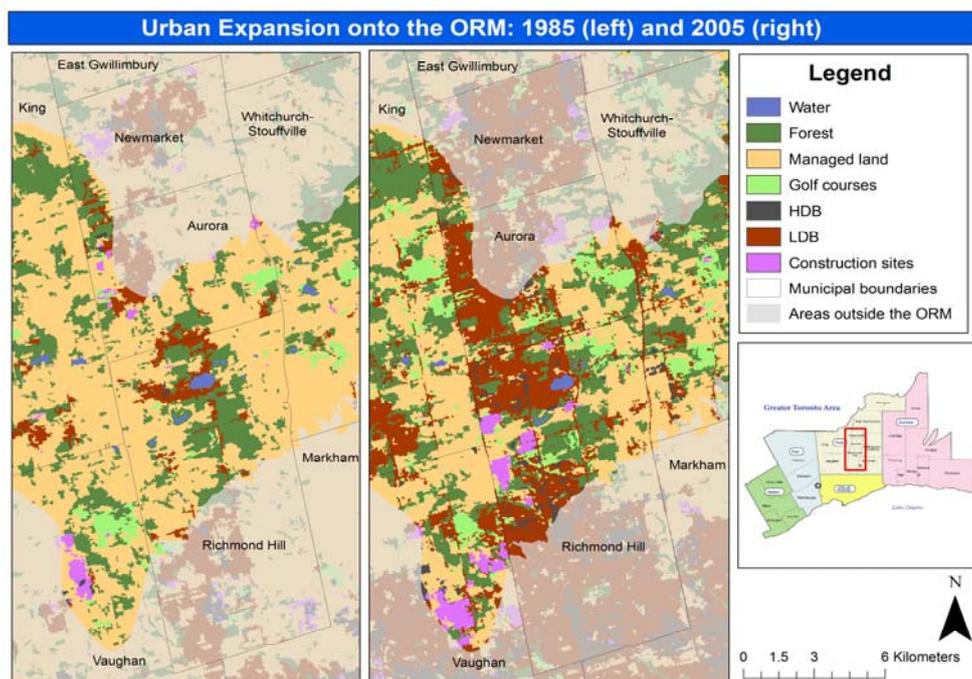


Figure 4. Illustration of Urban Expansion onto the ORM between 1985 and 2005