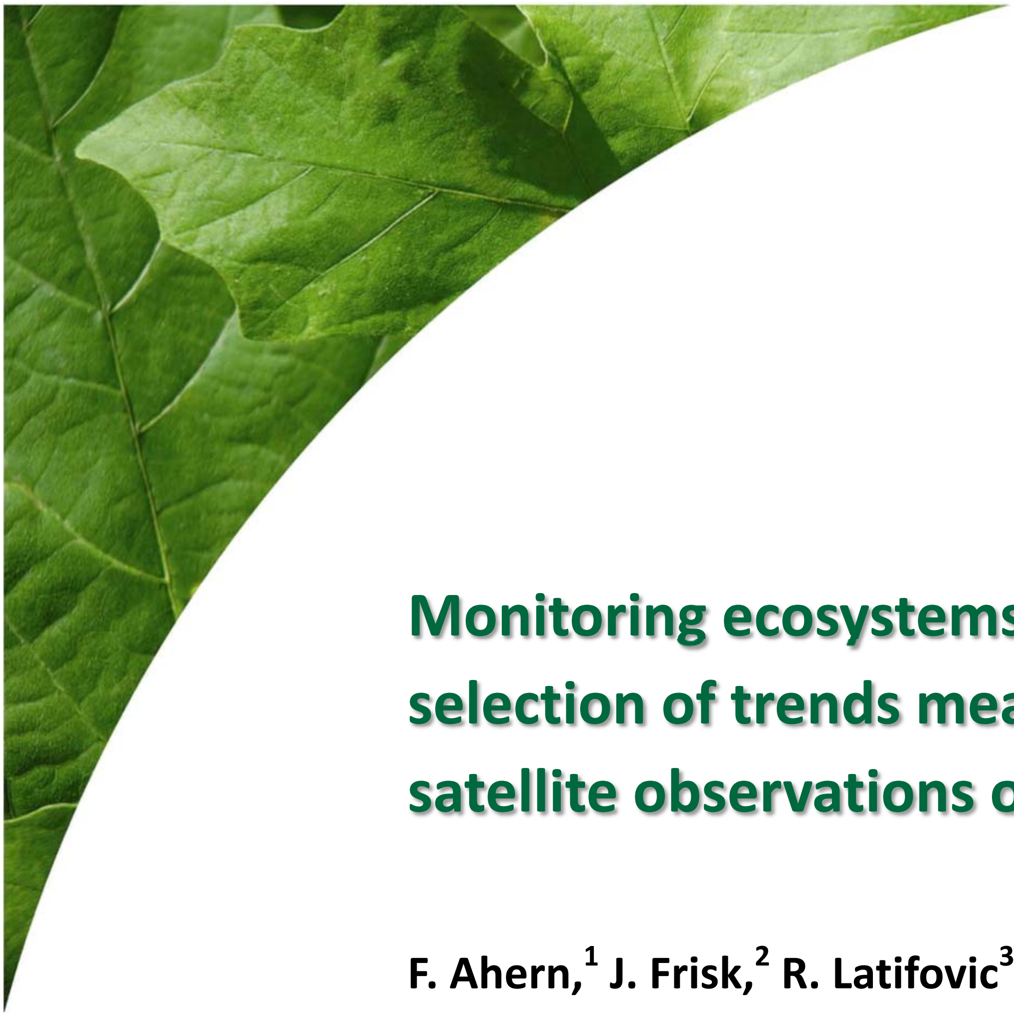

Monitoring ecosystems remotely: a selection of trends measured from satellite observations of Canada

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Canadian Biodiversity: Ecosystem Status and Trends 2010
Technical Thematic Report No. 17
Published by the Canadian Councils of Resource Ministers

[1] TerreVista Earth Imaging, Cormac, Ontario
[2] Environment Canada
[3] Canada Centre for Remote Sensing
[4] Canadian Forest Service, Natural Resources Canada

Library and Archives Canada Cataloguing in Publication

Monitoring ecosystems remotely: a selection of trends measured from satellite observations of Canada.

Issued also in French under title:
Surveillance à distance des écosystèmes : sélection de tendances mesurées à partir d'observations par satellite du Canada.
Electronic monograph in PDF format.
ISBN 978-1-100-22458-9
Cat. no.: En14-43/17-2013E-PDF

This report should be cited as:
Ahern, F., Frisk, J., Latifovic, R. and Pouliot, D. 2011. Monitoring ecosystems remotely: a selection of trends measured from satellite observations of Canada. Canadian Biodiversity: Ecosystem Status and Trends 2010, Technical Thematic Report No. 17. Canadian Councils of Resource Ministers. Ottawa, ON. v + 66 p.
http://www.biodivcanada.ca/default.asp?lang=En&n=137E1147-1

PREFACE

The Canadian Councils of Resource Ministers developed a Biodiversity Outcomes Framework[1] in 2006 to focus conservation and restoration actions under the *Canadian Biodiversity Strategy*.[2] *Canadian Biodiversity: Ecosystem Status and Trends 2010*[3] was the first report under this framework. It assesses progress towards the framework's goal of "Healthy and Diverse Ecosystems" and the two desired conservation outcomes: i) productive, resilient, diverse ecosystems with the capacity to recover and adapt; and ii) damaged ecosystems restored.

The 22 recurring key findings that are presented in *Canadian Biodiversity: Ecosystem Status and Trends 2010* emerged from synthesis and analysis of technical reports prepared as part of this project. Over 500 experts participated in the writing and review of these foundation documents. This report, *Monitoring biodiversity remotely: a selection of trends measured from satellite observations of Canada*, is one of several reports prepared on the status and trends of national cross-cutting themes. It has been prepared and reviewed by experts in the field of study and reflects the views of its authors.

Acknowledgements

This project could not have been carried out without the enthusiastic and unflagging support of the first author's colleagues across Canada. The Canada Centre for Remote Sensing provided the majority of the data used. He wants to thank Jean-Marc Chouinard for providing managerial support from the start, and to scientists Rasim Latifovic, Robert Fraser, Richard Fernandes, Bert Guindon, Ian Olthof, Darren Pouliot, and Hongxu Zhao for many helpful discussions. Without exception they willingly provided the data from their projects that he asked for and answered all the questions he had. Gunar Fedosejevs and Arvon Erickson helped him acquire the archival MSS data from the early Landsat satellites that were so useful in extending the timeframe back to the 1970s. Scientists at the Canadian Forest Service were equally helpful. Mike Wulder and Nicholas Coops (at UBC) provided national products, and help using them, from their BioSpace project. We also thank the reviewers of this report.

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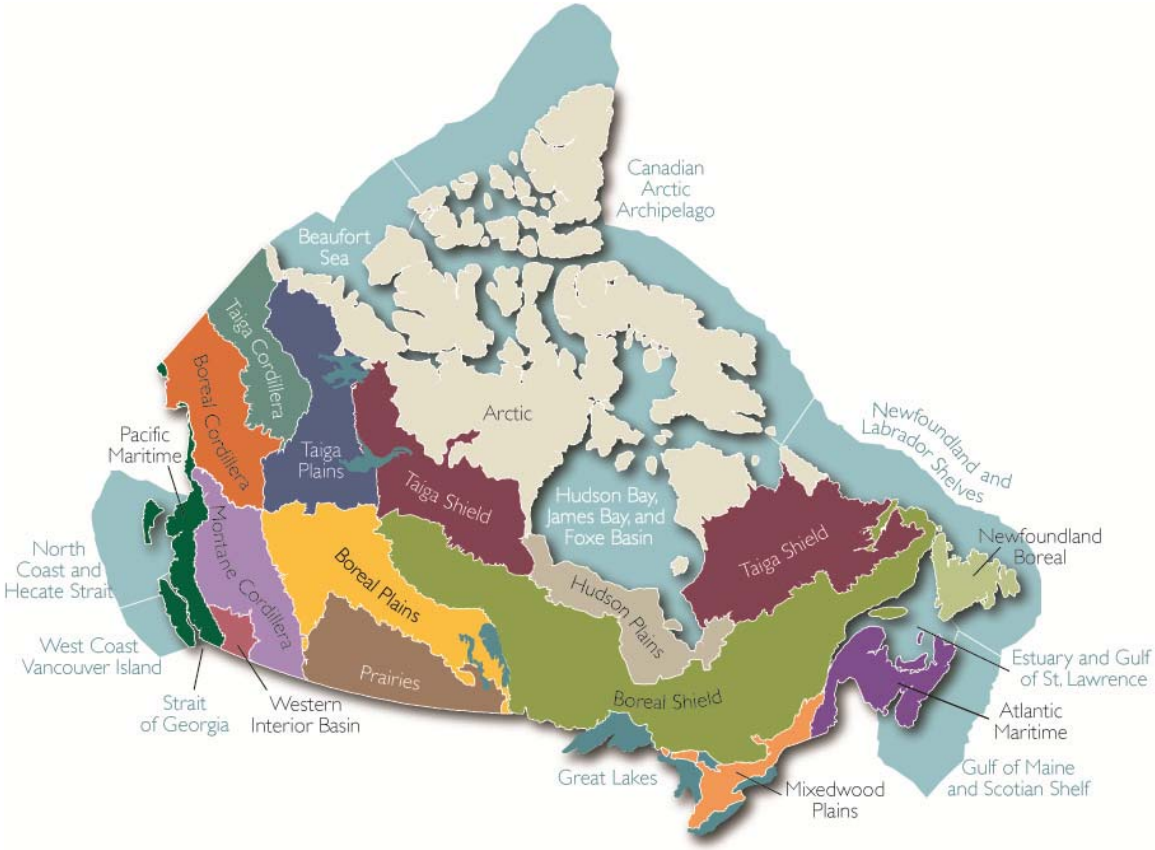
[1] Environment Canada. 2006. Biodiversity outcomes framework for Canada. Canadian Councils of Resource Ministers. Ottawa, ON. 8 p. Available at http://www.biodivcanada.ca/default.asp?lang=En&n=F14D37B9-1.

[2] Federal-Provincial-Territorial Biodiversity Working Group. 1995. Canadian biodiversity strategy: Canada's response to the Convention on Biological Diversity. Environment Canada, Biodiversity Convention Office. Ottawa, ON. 77 p.

[3] Federal, Provincial and Territorial Governments of Canada. 2010. Canadian biodiversity: ecosystem status and trends 2010. Canadian Councils of Resource Ministers. Ottawa, ON. vi + 142 p. Available at http://www.biodivcanada.ca/default.asp?lang=En&n=83A35E06-1

Ecological Classification System – Ecozones⁺

A slightly modified version of the Terrestrial Ecozones of Canada, described in the *National Ecological Framework for Canada,*[4] provided the ecosystem-based units for all reports related to this project. Modifications from the original framework include: adjustments to terrestrial boundaries to reflect improvements from ground-truthing exercises; the combination of three Arctic ecozones into one; the use of two ecoprovinces – Western Interior Basin and Newfoundland Boreal; the addition of nine marine ecosystem-based units; and, the addition of the Great Lakes as a unit. This modified classification system is referred to as "ecozones⁺" throughout these reports to avoid confusion with the more familiar "ecozones" of the original Framework.[5]



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[4] Ecological Stratification Working Group. 1995. A national ecological framework for Canada. Agriculture and Agri-Food Canada, Research Branch, Centre for Land and Biological Resources Research and Environment Canada, State of the Environment Directorate, Ecozone Analysis Branch. Ottawa/Hull, ON. 117 p. Report and national map at 1:7 500 000 scale.

[5] Rankin, R., Austin, M. and Rice, J. 2011. Ecological classification system for the ecosystem status and trends report. Canadian Biodiveristy: Ecosystem Status and Trends 2010, Technical Thematic Report No. 1. Canadian Councils of Resource Ministers. Ottawa, ON. Available at www.biodivcanada.ca/default.asp?lang=En&n=E0DDE11F-1

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EXECUTIVE SUMMARY

This Technical Thematic Report summarizes the results of four major remote sensing analyses for the ecozones$^+$ of Canada: (1) Land Cover Change, 1985 to 2005; (2) Normalized Difference Vegetation Index (NDVI) 1985 to 2006; (3) Average Dynamic Habitat Index, 2000 to 2006; and (4) Indicators of Forest Fragmentation, circa 2000. The period of analysis is depends on the information used to assess each theme. Major findings are listed here:

- There was a net increase in the area of Fire Scars in Canada between 1985 and 2005 of approximately 146,000 km^2, a 200% increase over the area of Fire Scars in 1985. There was, however, a decrease in Fire Scars during the last five years of the analysis (2000 to 2005).
- Within the Agricultural Land class of the Boreal Plains Ecozone$^+$, a net area of approximately 5,020 km^2 of Cropland/woodland (7.5% of the 1985 Cropland/woodland area) transitioned to the more intensive Cropland class from 1985 to 2005.
- Urban area in the Golden Horseshoe region of Ontario increased from 1,111 km^2 in 1974 to 1,436 km^2 in 1990, with an average increase of 20 km^2/year. The average rate of expansion increased to 23 km^2/year between 1990 and 2005, with urban area increasing to 1,778 km^2. The rate of urban expansion in the Lower Fraser Valley of British Columbia occurred at an average rate of 6 km^2/year, increasing from 498 km^2 in 1975 to 680 km^2 in 2007.
- Peak annual NDVI, an indicator of the amount and vigour of green vegetation, increased significantly over 22% of Canada between 1985 and 2006. Increasing NDVI was most evident in the north where processes are strongly climate driven, while trends in the south were less ubiquitous and found to be more driven by changes in land cover.
- Seasonal variation in greenness, one of the three components of the Dynamic Habitat Index, was highly sensitive to changes in altitude, and has the potential to be a sensitive indicator of shifts in vegetation ranges though the current time series is too short to analyze trends.
- Forest density is highest in the boreal region of Canada.

INTRODUCTION

Remote sensing is "the science, technology and art of obtaining information about objects or phenomena from a distance" (CCRS, 2005). This report focuses on remote sensing information obtained from satellite sensors which measure reflected or emitted radiation from the earth's surface. Remote sensing data, when verified and complemented with field-based data, can provide consistent and repeatable measurements of ecosystems, allowing for analysis of change over time. Satellite data is less costly and time intensive than direct field observations and is available for areas that may be otherwise inaccessible. Satellite data are also useful for putting the results of direct field measurements into a broader context.

At the outset of the Ecosystem Status and Trends Report (ESTR), a review of remote sensing activities and available datasets for examining ecosystem status and trends in Canada was conducted. Considerations for appropriate measurements and datasets included the spatial and temporal resolution, the length of the archive, and the timeliness of the information. High resolution data (<10 m) provides fine scale information, but the volume of data makes analysis time intensive. This scale of data is also not available for long term analyses. Medium resolution data (10 to 100 m), such as Landsat imagery provides fairly detailed information but still requires time- and data- intensive analysis. Landsat imagery is collected for the same area every 16 days (limiting seasonal specificity[6]) with archives going back to the 1970s. Use of high and medium resolution satellite information is therefore most useful for monitoring specific areas of concern, relying on *a priori* knowledge of sensitive areas, and likely missing areas of unexpected change. Coarse resolution data (>100 m) provides broad scale information consistently across Canada, with archives going back to the 1980s, resampled daily (allowing for seasonal specificity in measurements). Coarse resolution data will only detect large scale changes; making this is a more reactive as opposed to proactive approach to monitoring.

Based on the results of this review, the following information was collected and analyzed by ecozone+ for ESTR: broad scale land cover change across Canada from 1985 to 2005; case studies on urbanization in two of Canada's fastest growing urban areas; trends in vegetation productivity (NDVI) across Canada from 1986 to 2006; status of a recently developed Dynamic Habitat Index for Canada (derived from fPAR, another measurement of vegetation productivity); and status of two forest-related indicators of forest fragmentation (forest density and forest edge density). This paper presents the results of these analyses by ecozone+. It was intended for this information to be incorporated into the individual ecozone+ reports with other information. This report does not provide a review of all remote sensing information in Canada. It focuses on information available across Canada, and therefore, further relevant remote sensing information specific to a particular ecozone+ may also be included in those reports.

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[6] Cloud-free Landsat images are required for most analyses. So, as a given scene is only resampled every 16 days, a cloud-free image may not be available within a specific time period.

LAND COVER CHANGE

Broad land cover change 1985 to 2005

The Canada Centre for Remote Sensing (CCRS) has produced a consistent land cover time series (1985, 1990, 1995, 2000, 2005) for Canada derived from coarse (1 km resolution) satellite data from the National Oceanic and Atmospheric Administration (NOAA) – advanced high-resolution radiometer (AVHRR) sensors (Latifovic and Pouliot, 2005). This is the longest land cover dataset that covers all of Canada, providing a unique ability to consistently track long term trends.

Methods

Satellite data are assigned to land cover categories during a process called image classification (Cihlar et al., 1998). Land cover types are differentiated based on spectral signatures (patterns of absorption and reflectance of the electromagnetic spectrum) which result from pigment content, leaf structure, and plant structure (Fleishman and Mac Nally, 2007).

CCRS developed a robust methodology to produce land cover maps from 1985 to 2005 through the detection of changes to a pre-existing, widely accepted 1995 base map produced by Cihlar *et al.* (1999). Areas of change detected by comparison with the 1995 base map were reclassified for each year of the series, updating the 1995 map as opposed to creating new maps. This methodology maintains high consistency in land cover between maps. The methodology for the detection and reclassification of changes is described in detail in Latifovic and Pouliot (2005).

The 12-class map produced by CCRS was simplified to nine classes for the purposes of ESTR (Appendix 1). The 'Disturbance' class from the CCRS 12-class legend was renamed, 'Fire Scars[7], the three forest classes were combined into the 'Forest' class and the 'Cropland' and 'Cropland/Woodland' classes were combined and renamed 'Agricultural Land' (Appendix 1). Land cover changes were examined for six of these classes.[8] Land cover and land cover change results were summarized by ecozone$^+$ for the purposes of ESTR.

Quality checks and limitations

Errors in the data can be introduced in many stages. Errors in the 1995 base map may be carried into the change maps derived from this base map. There may also be errors in the satellite input data (AVHRR), in the change detection process, or in the re-classification of detected changes.

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[7] The Fire Scars class contains both new (<5 years) and old (>5 years, but not yet reclassified) burned areas. It may also include very large areas of harvest or mining, and severe insect defoliation.

[8] The Urban, Snow/ice/glacier and Inland Water classes were not part of the change analysis. See Appendix 1 for further details.

A visual comparison of the land cover results against higher resolution (30 m) Landsat imagery showed that the expected dynamics of disturbance followed by revegetation were captured by the land cover change analysis (Latifovic and Pouliot, 2005). This visual comparison also showed that the spatial shape and extent of large disturbances classified by the land cover change analysis differed considerably, in some cases, from the Landsat image due to the coarse resolution of the AVHRR data.

CCRS also conducted a quantitative comparison of the land cover results presented in this report with the Satellite Database for the Land Cover of Canada (SILC), a higher resolution (30 m) Landsat database which covers 9% of the Canadian land mass in 2000. In order to make comparisons between the two datasets, the SILC database was reclassified at a 1 km resolution, classifying each 1 km pixel as the dominant 30 m pixel within. Comparisons with the SILC showed that the overall accuracy of the 2000 land cover map was 61.5%, while the accuracy of reclassified areas identified in the change detection process was only 44.0% (Latifovic and Pouliot, 2005). These accuracy values for the 2000 land cover map are likely underestimates of the overall accuracy as the analysis was restricted to areas included in the SILC database, which are primarily of highly variable topography and therefore prone to classification errors (for example, mountainous areas and transition zones between broad biomes).

Extra caution should be taken when interpreting these results for ecozones$^+$ with large mountainous areas (such as the Pacific Maritime Ecozone$^+$), or ecozones$^+$ with large grassland areas (such as the Prairies Ecozone$^+$) as large fluctuations in moisture availability from year to year result in dramatically different surface appearances of grassland areas (Davidson and Wang, 2004 in Latifovic and Pouliot, 2005). Land cover changes in areas made up of several small parcels of different classes (such as the Mixedwood Plains and the Prairies ecozones$^+$) will not be detected as changes will likely occur at a scale too small to be detected at this coarse resolution.

In summary, this dataset is most effective at detecting large scale change in land cover. The results for every ecozone$^+$ should be corroborated with other information, particularly for smaller scale changes.

Results

General land cover for 2005 is shown in Figure 1. During the period from 1985 to 2005, changes were primarily detected in the Forest and Fire Scars classes (Figure 2, see Appendix 2 for a breakdown by ecozone$^+$). Fire Scars increased from 1990 to 2000 followed by a decrease from 2000 to 2005. The net change from 1985 to 2005 was an increase of approximately 200% (~146,000 km^2). A net decrease in Forest area by approximately 4% (~158,000 km^2) was observed during the same period (1985 to 2005). The majority of this decrease (3.5 out of 4.0%) transitioned to Fire Scars. The remainder of the net decrease in Forest area during this period is attributed to transitions to Low Vegetation and Barren (< 1%), Shrubland (< 1%), and Agricultural Land (<0.1%). Decreases in Forest area during the time period appear to be concentrated in the southwestern Taiga Shield, and northwestern Boreal Shield (Figure 3).

Further examination of the components of the Agricultural Land class in the Boreal Plains Ecozone$^+$ reveals a trend of transition from the 'Cropland/Woodland' component into the 'Cropland' component (Figure 4). From 1985 to 2005, 7.7% (~5,150 km^2) of Cropland/Woodland was lost, most of which (~5,020 km^2) was converted to Cropland. Land cover statistics for 2005, and a summary of change from 1985 to 2005 are presented in Appendix 2.

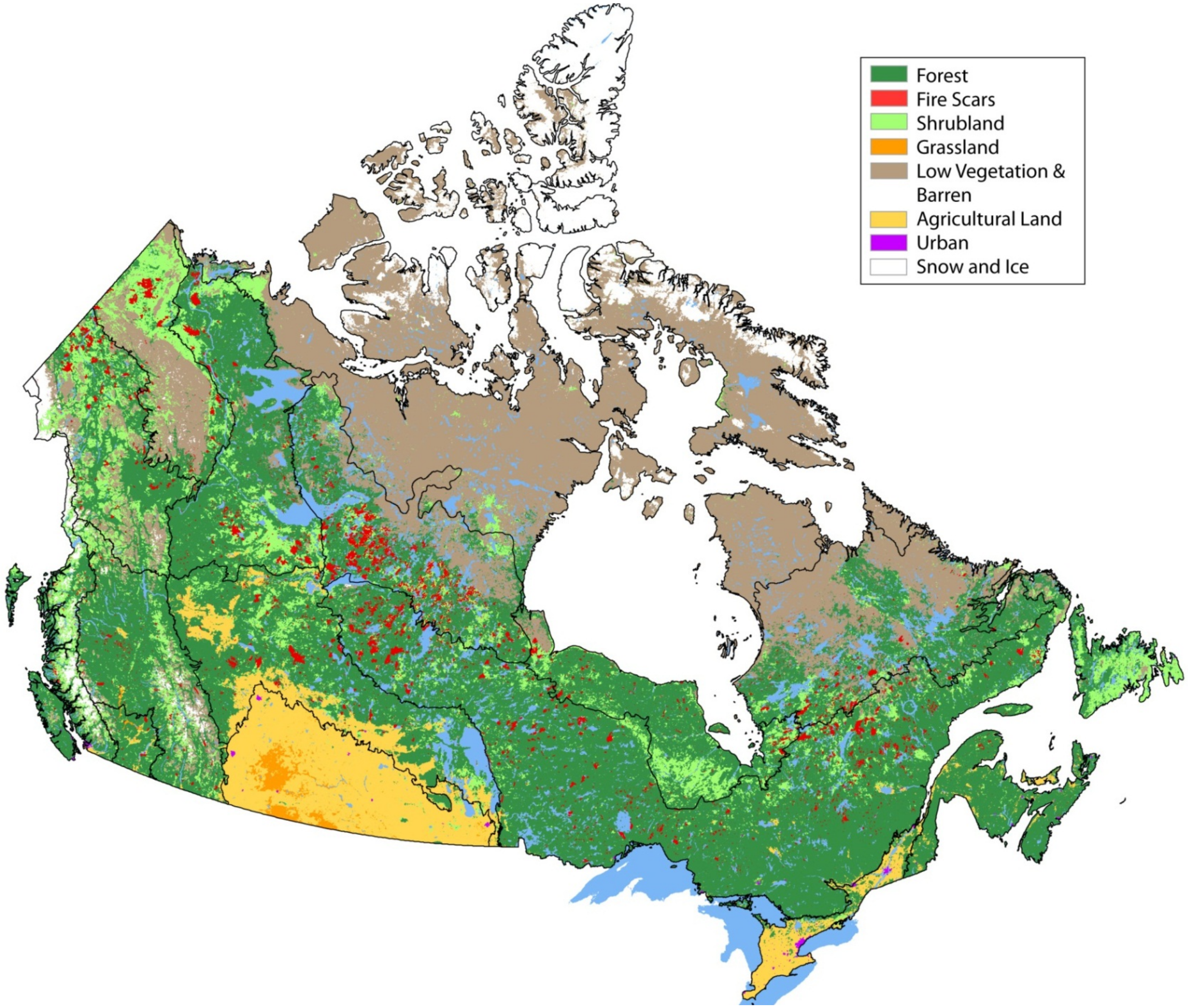

Figure 1. Broad (1 km resolution) land cover classification for Canada, 2005.
Source: Derived from Latifovic and Pouliot (2005)

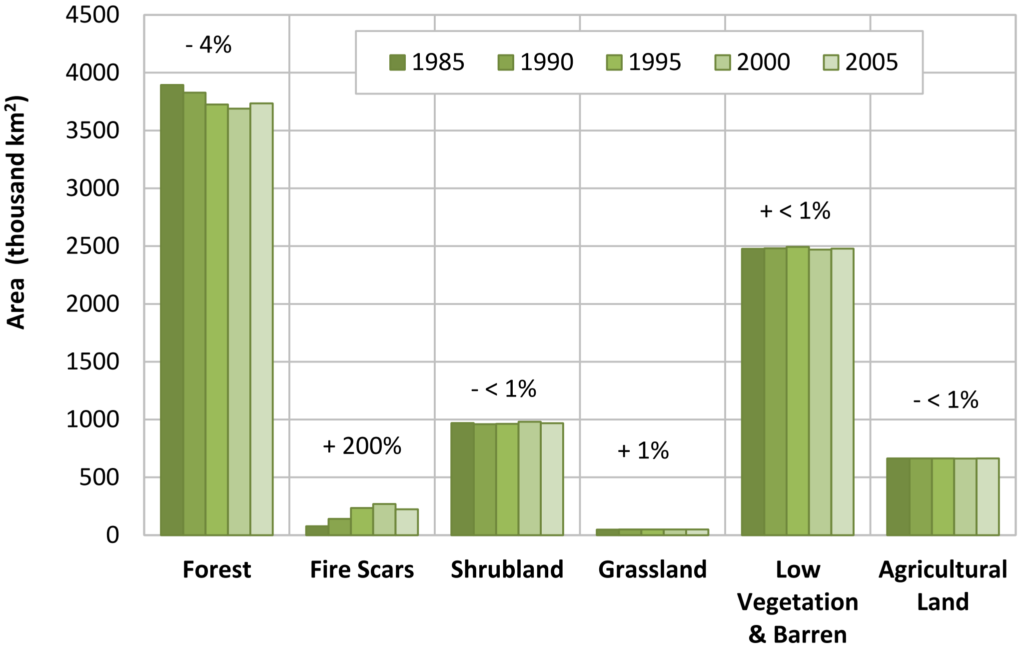

Figure 2. Area by land cover class for all of Canada, 1985, 1990, 1995, 2000 and 2005. Labels are the total percent change for each land cover class between 1985 and 2005. Source: Derived from land cover statistic produced by Latifovic and Pouliot (2005)

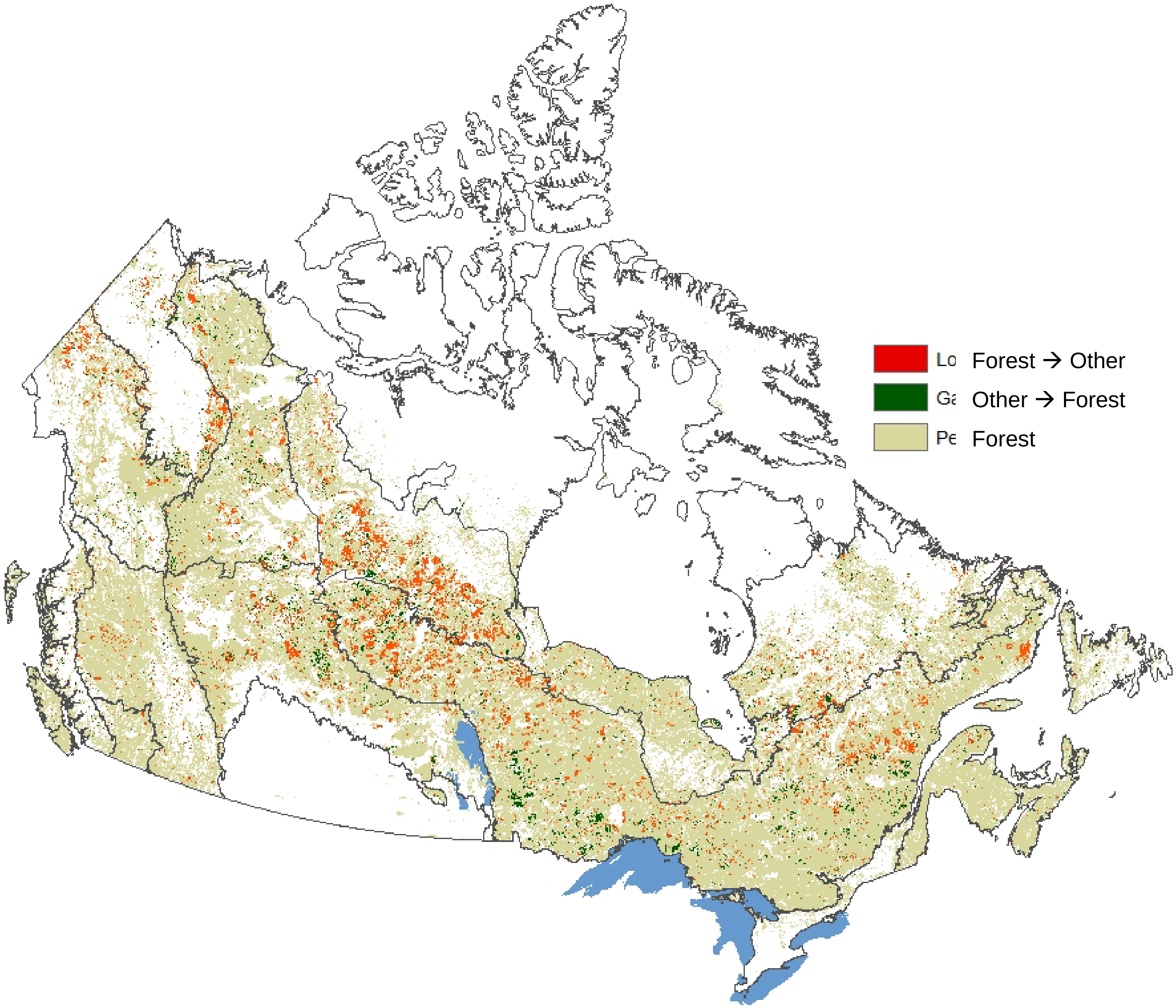

Figure 3. Areas of transition between Forest and other classes, 1985 to 2005.
Most transitions occurred between areas of Forest and areas of Fire Scars.
Source: Derived from land cover maps produced by Latifovic and Pouliot (2005)

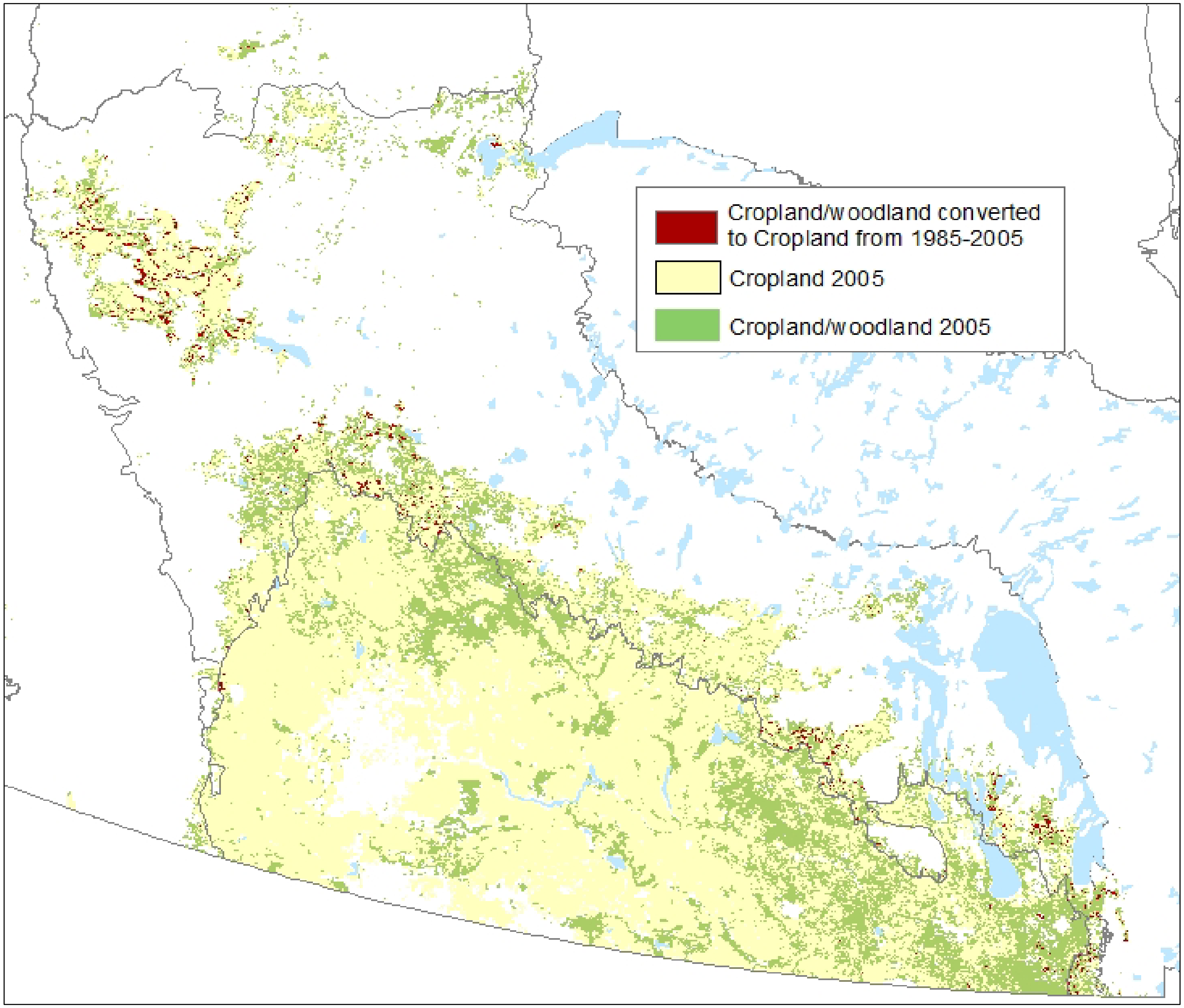

Figure 4. Transitions from Cropland/Woodland to Cropland in the Boreal Plains and Prairies ecozones⁺, 1985 to 2005.
Source: Derived from land cover maps produced by Latifovic and Pouliot (2005)

Discussion

The primary changes in land cover shown by this analysis are in the Fire Scar and Forest classes. The occurrence of fire is influenced by several factors, primarily weather/climate, fuel, topography, and human influences (Flannigan and Wotton, 2001; Flannigan et al., 2005; Parisien et al., 2006). The increase in Fire Scars to 1995 is consistent with the data presented in the Technical thematic report on large fires in Canada (Krezek-Hanes et al., 2011) which show a general increase in area burned from the 1960s to 1990, with extreme fire years in 1989, 1994, and 1995. The increase in area burned from the 1960s to 1990 has been linked the expanded use of forests by humans during this time and to warmer temperatures across the country (Podur et al., 2002; Gillett et al., 2004; Skinner et al., 2006; Girardin, 2007). For further discussion on trends in fires in Canada, including annual area burned, fire severity, and seasonality, see Krezek-Hanes et al., (2011).

The shift in the components of Agricultural Land from Cropland/Woodland to Cropland in the Boreal Plains Ecozone$^+$ is the result of woodlots and other woodlands being converted to cropland. This finding is supported by the Wildlife Habitat Capacity on Agricultural Land in Canada National Thematic Report (Javorek and Grant, 2011) which shows that the area of land classified as All Other Land[i] in the agricultural area of the Boreal Plains Ecozone$^+$ decreased between 1986 and 2006. The Wildlife Habitat Capacity, a multi-species assessment of broad-scale trends in the potential ability of the agricultural landscape to provide suitable habitat for populations of terrestrial vertebrates, also declined significantly in the Boreal Plains Ecozone$^+$ during this period (Javorek and Grant, 2011).

Urbanization case studies

Most of Canada’s population growth between 1996 and 2001 occurred in four main regions: the Lower Fraser Valley and southern Vancouver Island in British Columbia (Pacific Maritime Ecozone$^+$); the Edmonton-Calgary corridor (Prairies Ecozone$^+$); Toronto’s Golden Horseshoe region (Mixedwood Plains Ecozone$^+$); and the Greater Montreal area (Mixedwood Plains Ecozone$^+$) (Gurin, 2003). Population growth can be accommodated through densification of existing urban areas or through expansion into previous non-urban areas (or ‘urbanization’ as defined for the purposes of this analysis). Unlike some other types of land cover change, urbanization is most often permanent (McKinney, 2002). Urbanization can impact biodiversity in numerous ways, including:

- direct loss of habitat, including forests, wetlands, and agricultural land;
- changes to the water cycle, including excess runoff following precipitation and lack of water during droughts as a result of the impermeability of built-up areas; and

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[i] As defined by the Census of Agriculture, which roughly corresponds to the Cropland/Woodland category used here

- imposing barriers to plant and wildlife dispersal.

Two of the four main regions of population growth, the Golden Horseshoe of Ontario and the Lower Fraser Valley of British Columbia, were chosen for this case study. Landsat imagery has a greater resolution than AVHRR satellite data (used to show broad land cover changes in the previous section) and has become more readily available for studies of this scale in recent years. Landsat imagery was analysed specifically for this report.

The Golden Horseshoe

The Golden Horseshoe region in southern Ontario extends around the western end of Lake Ontario from Pickering to Niagara, including the Greater Toronto Area and the cities of Burlington and Hamilton. It is part of the Lake Erie Lowland Ecoregion of the Mixedwood Plains Ecozone$^+$ where the natural land cover is typically broadleaf and mixedwood forests (Ecological Stratification Working Group, 1995). This region contains intensive agriculture and has undergone prolonged and extensive urban development since the 1950s. It is currently the most populous and heavily urbanized region of Canada (Statistics Canada, 2012), and is also home to the majority of Ontario's species at risk (Wilson, 2008), with birds and species that require wetland habitats making up the majority of these at risk species (David Suzuki Foundation and Ontario Nature, 2011). Ecology and conservation issues include threats to forests and plants, a need to conserve wetlands, water quantity and quality, and invasive species (Environment Canada, 2005).

Although this area has no natural limits to growth, in 2005 the Government of Ontario established a large greenbelt area (more than 7,600 km^2) surrounding the Golden Horseshoe with zoning restrictions to protect agricultural and natural lands from urban sprawl (Government of Ontario, 2005; Ministry of Municipal Affairs and Housing, 2005).

The Lower Fraser Valley

The Lower Fraser Valley of British Columbia follows the Fraser River from just past Mission and Abbotsford in the east to its outlet in the Strait of Georgia. It includes the city of Vancouver and surrounding suburbs. It is part of the Lower Mainland Ecoregion of the Pacific Maritime Ecozone$^+$. Climate is mild and very wet and natural vegetation is dominated by forests of coastal Douglas fir, western hemlock, and western red cedar (Ecological Stratification Working Group, 1995). The flat-lying Fraser delta is ideal for agriculture, and except for a number of large peat bogs, agricultural land has replaced the natural land cover throughout most of the delta (Environment Canada, 2005). As in the case of the Golden Horseshoe, the wetlands of the Lower Fraser Valley represent the most threatened and diverse ecosystems. The area once had numerous peat bogs, but most are gone or greatly reduced. The Burns Bog, near Richmond, is the largest remaining peatland (Hebda et al., 2000).

The Lower Fraser Valley has strong geographic constraints to urbanization with elevation rising steeply to the north of the Fraser River, and the United States border stopping Canadian urbanization to the south. To the east, the Fraser valley narrows rapidly. These factors restrict further expansion of urban areas primarily to the broad Fraser River delta, with the exception of North and West Vancouver, which climbs the mountains to the north.

Methods

For both the Golden Horseshoe and the Lower Fraser Valley case studies, baseline land cover maps for 1990 with land cover boundaries already visually interpreted from Landsat TM imagery were obtained from MDA Federal (formerly EarthSat). Landsat MSS images (80 m resolution) for 1974/1975 and Landsat TM images (30m resolution) for 2005/2007 were obtained from CCRS. Both the resolution and spectral separation of the 1974/1975 Landsat MSS images are lower than the 1990 and 2005/2007 Landsat TM images due to improvements in the TM sensor over the previous MSS sensor.

A false colour infrared colour composite image was created for both the 1974/1975 Landsat MSS images and the 2005/2007 Landsat TM images to improve visual interpretation. Urban area was delineated manually through a visual comparison with the 1990 map, assuming that for 1974/1975 Urban area was contained within the 1990 extent and for 2005/2007 Urban extent expanded beyond that of 1990.

Once the map revisions were completed, changes in Urban area and the resulting changes in the other land cover classes were calculated. Changes between the other land cover classes were not detected in this process (for example, conversion of Forest or shrub to Agriculture). Confidence in the results of this process is very high for changes in Urban area and medium-high for the categorization of land cover in 1975 that was converted to urban area by 1990 (land cover converted to Urban area from 1990 to 2005 was already defined in the 1990 map obtained from MDA Federal). We estimate the accuracy of the area totals to be greater than 90%.

Results

The Golden Horseshoe, Ontario

There was a substantial increase in Urban or barren area and a corresponding loss of Agricultural land and, to a lesser extent, Forest or shrub land in the Golden Horseshoe region from 1974 to 2005 (Figure 5, Figure 6). A total of 210 km^2 of Agricultural land was converted to Urban or barren land during the first period from 1974 to 1990 (a rate of 13 km^2/year) and a further 305 km^2 was converted from 1995 to 2005 (a rate of 20 km^2/year). When the loss of forest land and wetlands is added, the total urbanization rate between 1974 and 1990 was 20 km^2/year, increasing to 23 km^2/year between 1990 and 2005.

The increase in Urban area during this period was concentrated in the area surrounding Toronto, with greater growth between 1990 and 2005 (Figure 6). On the south side of Lake Ontario, the there was more modest growth. Hamilton also grew more between 1990 and 2005 than between 1974 and 1990. Urban growth on Niagara Peninsula was minimal during the study period.

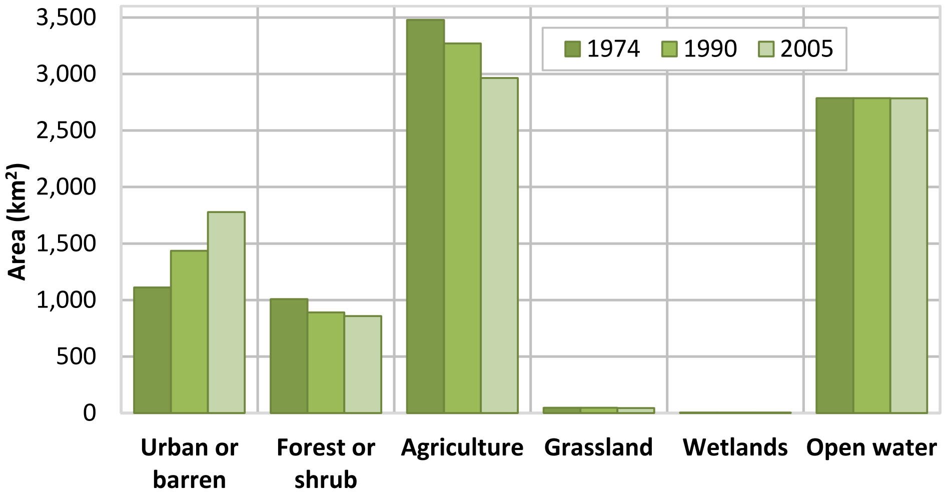


Figure 5. Land cover changes in Ontario's Golden Horseshoe, 1974, 1990 and 2005.
The graph shows a 60% total increase in urban or barren land.
Note: image resolution in 1974 was lower than in 1990 and 2005

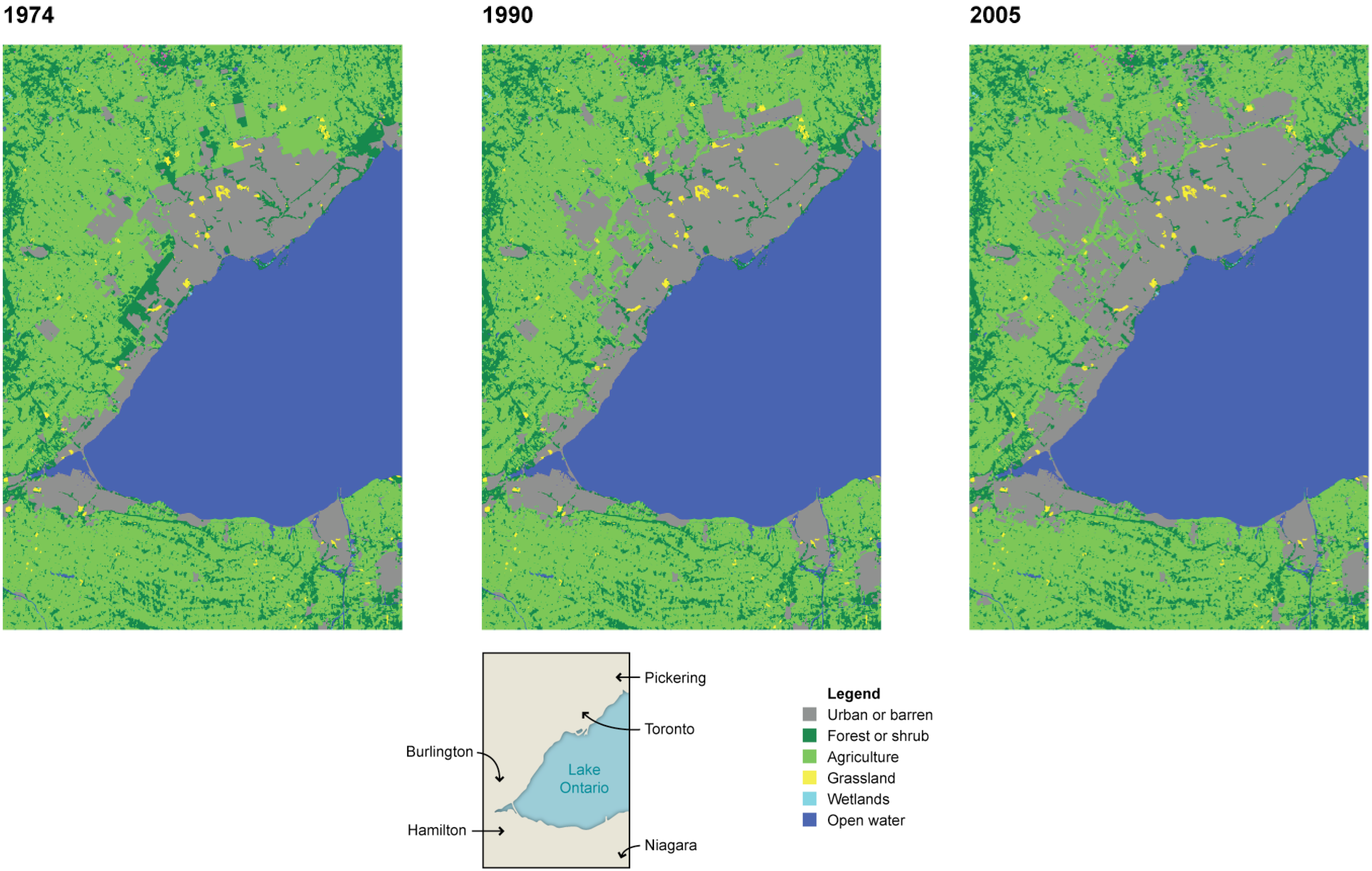


Figure 6. Changes in land cover in Ontario's Golden Horseshoe, 1974, 1990, and 2005.

The Lower Fraser Valley, British Columbia

Urban expansion in the Lower Fraser Valley occurred primarily in former areas of Forest or shrub land (Figure 7, Figure 8). Expansion also occurred, to a lesser extent, in Agricultural land areas. A total of 87 km^2 of Forest or shrub land was converted to Urban or barren land between 1975 and 1990 (a rate of 6 km^2/yr) and 62 km^2 of Forest or shrub land was converted to Urban area from 1990 to 2007 (a rate of 4 km^2/yr). The average urbanization rate for all land cover types between 1975 and 2007 was 6 km^2/year.

Growth in the Lower Fraser Valley did not follow the same pattern as in the Golden Horseshoe. The city of Vancouver itself has grown laterally as much as it can. North Vancouver expanded to the west, but is not growing substantially. There was also not much urban expansion in Richmond during the study period. Further upstream on the Fraser River, however, expansion of Urban area is evident. On the south shore, the Surrey to Delta area expanded considerably, while on the north side, Urban area filled in between Burnaby and New Westminster, as with the area between Port Moody and Port Coquitlam. Even more distant from Vancouver, the Abbotsford-Clearbrook area expanded noticeably (Figure 8).

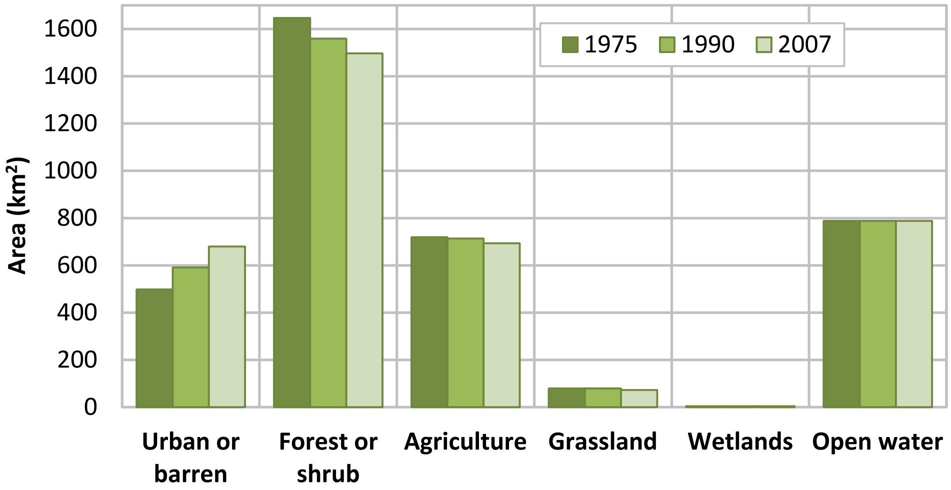


Figure 7. Land cover changes in the Lower Fraser Valley of British Columbia, 1975, 1990 and 2007. The graph shows a 37% total increase in urban or barren land.
Note: image resolution in 1974 was lower than in 1990 and 2007

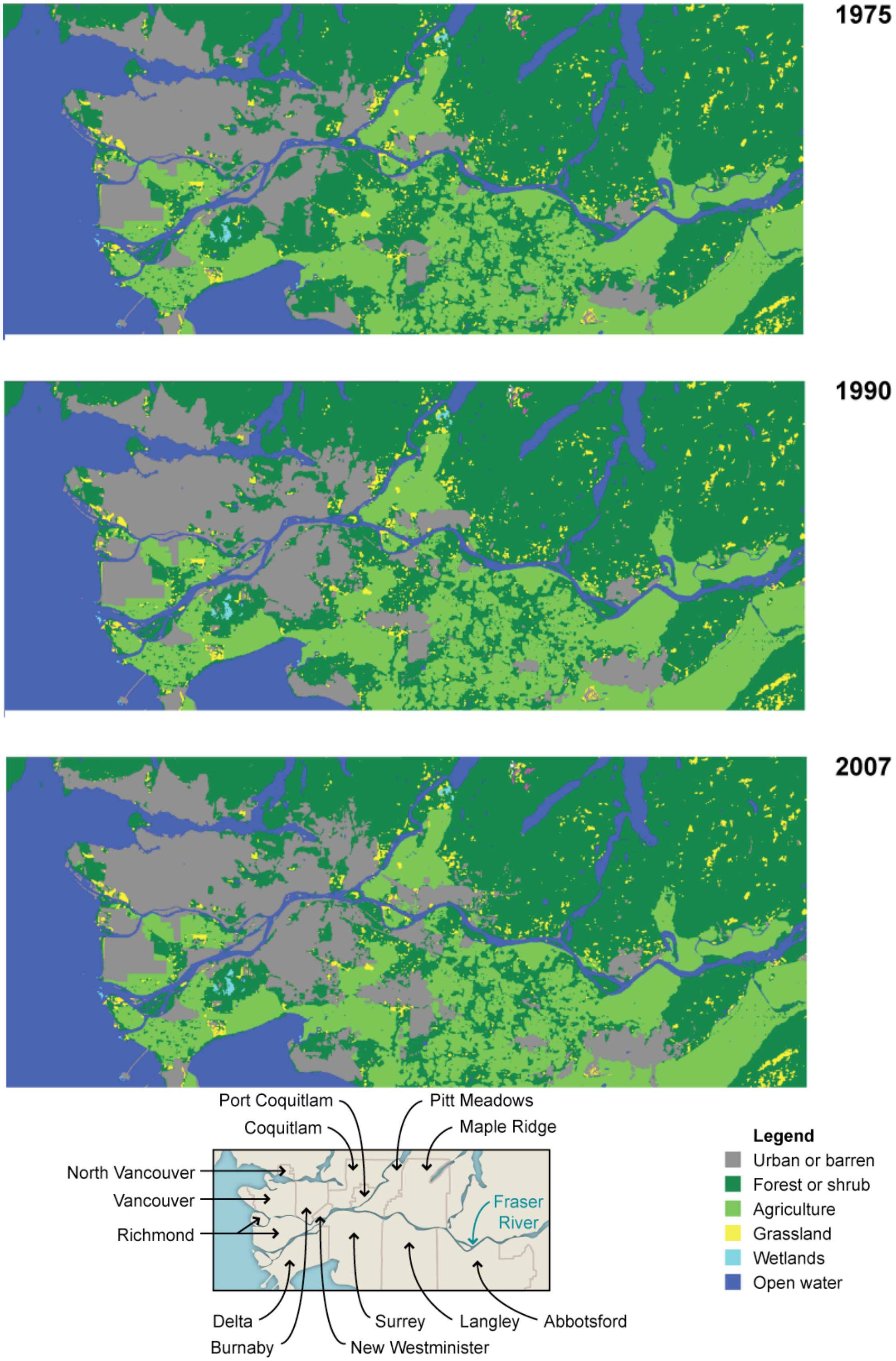


Figure 8. Changes in land cover in the Lower Fraser Valley, 1975, 1990, and 2007.

Discussion

These two studies show an increase in Urban area since the 1970s, particularly in the Golden Horseshoe region of Ontario. Urban expansion in the Golden Horseshoe occurred primarily at the expense of Agricultural land (also found by Cheng and Lee (2008)), and to a lesser extent, forest. Expansion is most dramatically seen centered around Toronto. The Government of Ontario's Greenbelt Plan (Ministry of Municipal Affairs and Housing, 2005) came into effect in 2005 with an aim to protect a large area (>7,600 km^2) surrounding the Golden Horseshoe from further urbanization. The population growth rate of the Greater Golden Horseshoe (which, as defined by Statistics Canada, includes areas beyond this analysis, north to the Georgian Bay and east to Kawartha) between 2001 and 2006 was 8.4%. Growth in this region accounted for 84% of Ontario's population increase and 39% of Canada's population increase during this period (Statistics Canada, 2012). Further analysis of urbanization in this region will be important to examine how effective the Greenbelt Plan is at slowing the increase in Urban area and encouraging "smart growth" (densification as opposed to expansion, see for example, Canadian Mortgage and Housing Corporation, 2005).

Urban expansion in the Lower Fraser Valley since 1975 has taken place primarily in areas of Forest or shrub land. In the thirty years leading up to the 2001 census, the population in Vancouver and surrounding area grew almost 70%, with the majority of that growth occurring outside the core cities of Vancouver, Burnaby, and New Westminster (Gurin, 2003). Between 2001 and 2006, the population growth rate was 6.5%, greater than the Canadian average of 5.3%. This trend matches those areas that have also shown the greatest urbanization. Future urban expansion in the Lower Fraser Valley and will likely continue in the more distant communities up the valley as the city of Vancouver and the nearby suburbs have reached geographic limits to sprawl.

NORMALIZED DIFFERENCE VEGETATION INDEX 1985 TO 2006

Earth observation researchers developed the Normalized-Difference Vegetation Index (NDVI) early in the era of satellite observations and it is now a popular and robust indicator of the amount and vigour of green vegetation. NDVI measures the contrast between the reflectance of red solar radiation, which is absorbed by chlorophyll, and the reflectance of near-infrared (NIR) solar radiation, which is reflected by the internal structure of leaves. NDVI most directly represents gross primary photosynthesis (Tucker, 1979; Sellers 1985 and Myneni et al. 1995 in Pouliot et al., 2009) and can be used as a proxy of green leaf area (Myneni et al., 1998). The NDVI is calculated for a given area using the following formula:

$$\mathrm{NDVI} = \frac{\mathrm{NIR} - \mathrm{Red}}{\mathrm{NIR} + \mathrm{Red}}$$

where:

NIR = intensity of near-infrared radiation reflected

Red = intensity of red radiation reflected

NDVI values range from -1 to +1, with clouds, water, and snow resulting in negative values, barren areas of rock and soil resulting in values close to zero, and densely vegetated areas resulting values close to 1. Different types of vegetation also have different characteristic NDVI values. For example, early-succession broadleaf vegetation has a higher NDVI value than late-succession conifers (Myneni and Williams 1994 in Pouliot et al., 2009).

There are several different global NDVI datasets compiled from Advanced Very High Resolution Radiometer (AVHRR) sensors. Different processing of AVHRR data and/or analyses during different time periods may show different or even contradictory NDVI trends (Alcaraz-Segura et al., 2010). The dataset used here was developed by CCRS (Pouliot et al., 2009) from 1 km resolution AVHRR data (Latifovic et al., 2005). They analyzed trends in annual peak NDVI during a 22 year period (1985 to 2006) and their results are examined at an ecozone^{+}-level here. Changes in NDVI are discussed as a proxy for changes in primary productivity.

Methods

Pouliot et al. (2009) developed a complete and rigorous approach for processing the newly developed 10-day composite 1 km AVHRR satellite data and analyzing the output. The data were spatially averaged to 3 km resolution and annual peak growing season values were calculated by averaging the three highest NDVI values from all July-August composite images. Significance of the trend analyses conducted for each location was assessed at the 95% confidence level using the Mann-Kendall test. Only locations with significant trends are shown in the maps. Detailed methods are described in Pouliot et al. (2009).

This CCRS dataset has improved corrections and a higher resolution than the Global Inventory, Monitoring, and Modeling Studies dataset, currently the most widely used dataset of global NDVI.

Significant trends ($p < 0.05$) are summarized here by ecozone^{+} and visually compared to the 1995 land cover map (see Land cover change on page 3) to facilitate discussion of NDVI trends relative to the land cover.

Pouliot et al. (2009) also examined the influence of climate and land cover change on the observed NDVI trends. The influence of climate was examined by calculating a Climate Trend Impact Index (CTII) for each region based on correlation between gridded monthly temperature and precipitation data (Mitchell 2005 in Pouliot et al., 2009) and annual peak NDVI. An analysis of the influence of land cover change on NDVI was conducted for regions where Landsat time series data (Regions 5, 6, 8 in Figure 9) or Census of Agriculture data (Region 7 in Figure 9) was available. These results are presented here by ecozone^{+}.

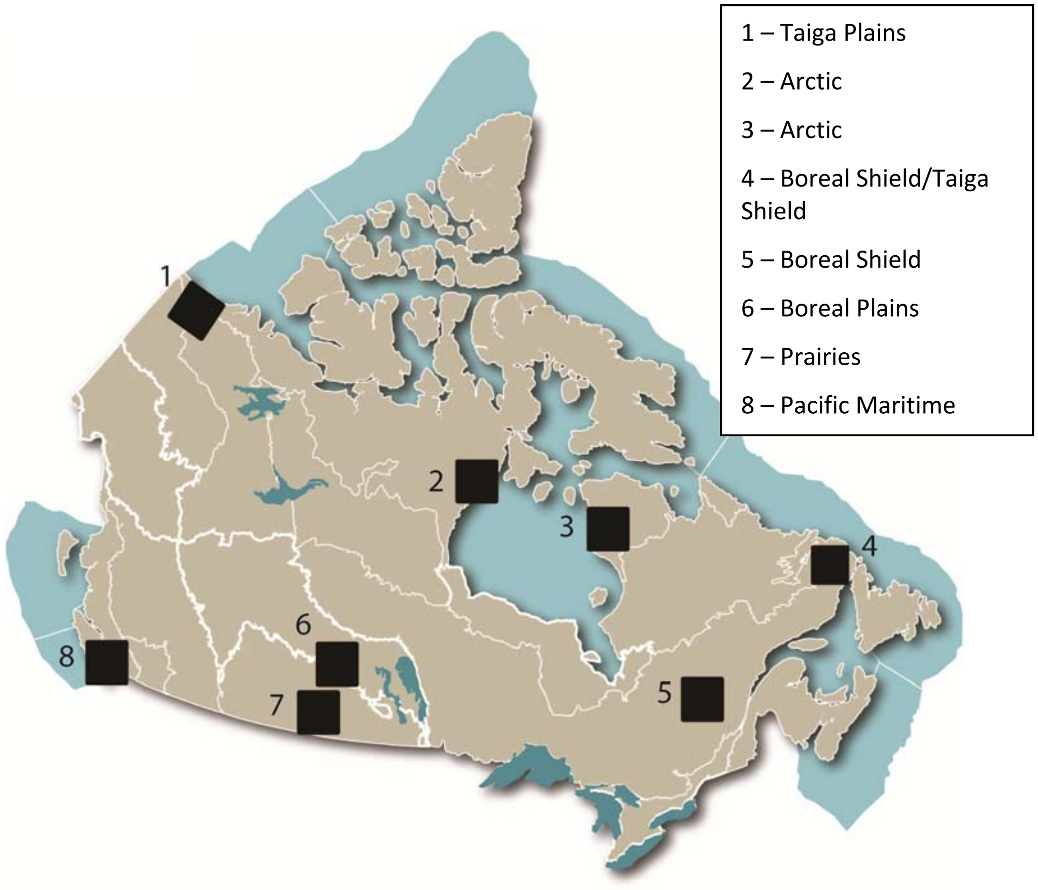


Figure 9. Study regions used to address the impacts of climate forcing and land cover on NDVI trends. Regions 1 to 4 are considered 'northern' while Regions 5 to 8 are considered 'southern'.
Source: adapted from Pouliot et al. (2009)

Quality checks and limitations

In areas where soil is visible, soil reflectance can affect the NDVI value. The appearance of soil changes based on moisture content and, as a result, soil moisture influences NDVI in areas where there is low to moderate vegetation with visible soil (Huete and Jackson, 1987; Huete and Jackson, 1988). Another limitation of NDVI is that it becomes less sensitive to changes in greenness as its value increases. For example, a larger increase in greenness is required to increase NDVI by the same increment the closer the value is to 1 (Gilabert et al., 1996; Santin-Janin et al., 2009).

Two quality checks were conducted on the 1 km AVHRR NDVI dataset used in this analysis (Pouliot et al., 2009). The first quality check involved a quantitative comparison of this NDVI dataset with an NDVI dataset derived from high resolution (30 m) Landsat data for two tundra regions (Region 1 in the Taiga Plains Ecozone$^+$ and Region 3 in the Arctic Ecozone$^+$, see Figure 9). The NDVI trends from the 1 km AVHRR NDVI dataset corresponded well with the Landsat data with a mean absolute error of 4.5% in Region 1 and 6.8% in Region 3.

The second quality check involved examining NDVI trends in all areas burned between 1960 and 2004 (forest fire databases from Fraser et al., 2004 and Zhang et al., 2004a,b in Pouliot et al., 2009) within the eight regions to verify that the expected dynamic of burning and regrowth was observed. NDVI trends were all found to be negative in areas recently affected by fire (1994 to 2004), likely a result of reduced vegetation present. Trends were positive in areas affected by fires from 1980 to 1990 as regeneration would have dominated. Trends were generally positive or close to zero in areas affected by fire prior to 1980 (1960 to 1980). These results suggest reasonable agreement between expected and observed NDVI trends.

Results

Twenty-two percent of Canada's land area showed a significant positive NDVI trend ($p < 0.05$) while only 0.5% showed a significant negative NDVI trend (Figure 10). There was a small area in the Prairies Ecozone$^+$ near the Alberta, Saskatchewan, and United States borders with a negative trend. In addition, a number of patches with negative trends were found in the western Boreal Shield and Taiga Shield ecozones$^+$, the southern Taiga Plains Ecozone$^+$, and the western-central Montane Cordillera Ecozone$^+$ corresponding to areas of mountain pine beetle kills.

Figure 10. Significant (p <0.05) trends in peak annual NDVI from 1985 to 2006.
Source: Adapted from Pouliot et al. (2009)

While broadly distributed across the country, the largest positive trends were found in regions of arctic tundra and taiga, alpine tundra, the Pacific coast, and the eastern prairies. The Newfoundland Boreal Ecozone+ had the greatest percent of its area showing positive trends with positive trends over nearly 41% of the ecozone+ (Figure 10, Table 1).

The analysis of climate forcing by Pouliot et al. (2009) showed moderate linear relationships for all regions in Figure 9 with temperature variables more strongly correlated with NDVI trends in northern regions (Regions 1 to 4) and precipitation more strongly correlated in the southern regions (5 to 8). The CTII showed that trends in NDVI for northern regions were more strongly influenced by climate than southern regions.

Results of the analysis of the impact of land cover change show that the positive NDVI trend in the south is driven primarily by changes in land cover, particularly on Vancouver Island in the Pacific Maritime Ecozone+ where vigorous succession following logging has led to increasing NDVI , and in the Prairies Ecozone+ where increases in NDVI correspond with increases in cropland area (Pouliot et al., 2009).

Table 1. Area of increasing and decreasing NDVI trends by ecozone+ from 1985 to 2006

Ecozone+	**Area with ↑ Trend (km^2)**	**Area with ↓ Trend (km^2)**
Arctic	2,281,558 (12.2%)	3,303 (0.1%)
Taiga Plains	116,163 (22.7%)	7,470 (1.5%)
Taiga Shield	415,278 (36.5%)	8,730 (0.8%)
Boreal Shield	335,205 (21.0%)	14,742 (0.9%)
Atlantic Maritime	33,408 (16.5%)	720 (0.4%)
Mixedwood Plains	15,876 (13.8%)	666 (0.6%)
Boreal Plains	130,554 (20.8%)	3,861 (0.6%)
Prairies	157,491 (35.1%)	1,116 (0.2%)
Taiga Cordillera	118,449 (35.3%)	189 (0.1%)
Boreal Cordillera	103,833 (23.8%)	594 (0.1%)
Pacific Maritime	63,864 (32.2%)	387 (0.2%)
Montane Cordillera	122,391 (29.8%)	4,527 (1.1%)
Hudson Plains	16,713 (4.9%)	405 (0.1%)
Western Interior Basin	16,713 (30.1%)	1,035 (1.9%)
Newfoundland Boreal	43,290 (40.9%)	0 (0%)
All of Canada	**1,967,535 (22.3%)**	**47,745 (0.5%)**

Arctic

Areas in the Arctic Ecozone$^+$ with notable increases in NDVI include the northern portion of Banks Island, the Dundas and Sabine peninsulas of Melville Island, the south shore of Bowman Bay on Baffin island, the area along the northwestern shore of Hudson Bay, and the Labrador Peninsula within the Arctic Ecozone$^+$, particularly the lower elevations bordering Ungava Bay (Figure 10). All of these areas (within the Arctic Ecozone$^+$) correspond to tundra vegetation.

The CTII calculated for Regions 2 and 3 (Figure 9 on page 19) by Pouliot et al. (2009) revealed that NDVI trends in these regions of the Arctic Ecozone$^+$ were strongly influenced by climate. In general, NDVI in northern regions (Regions 1 to 4, Figure 9) was negatively correlated with precipitation and positively correlated with temperature (Pouliot et al., 2009).

Olthof et al. (2008) examined NDVI trends in a portion of the Arctic Ecozone$^+$ corresponding roughly to Region 3 in Figure 9 using the same AVHRR NDVI dataset analyzed here along with high resolution (30 m) Landsat data. They found that lichen-dominated communities had consistently lower NDVI trends than vascular plant dominated communities, though all showed increasing trends. This is consistent with ground studies (for example, Arft et al., 1999; Sturm et al., 2001; Hollister et al., 2005; Tape et al., 2006; Walker et al., 2006) and was attributed to increasing vigour and biomass of vascular plants and some impairment of lichen growth due to drying (Olthof et al., 2008).

Taiga Plains

An extensive area of strong NDVI increase was found in the northern region of this ecozone$^+$, corresponding to a large area of conifer forest north of Great Bear Lake to the east of the Mackenzie Valley (Figure 10). A similar but smaller patch of increasing NDVI was found in the lower Mackenzie Valley. Further south, areas of increasing NDVI were more isolated. An area of decreasing NDVI was found west of Great Slave Lake which does not correspond to any recent burns.

Region 1 (Figure 9) in the climate forcing analysis by Pouliot et al. (2009) is within the Taiga Plains Ecozone$^+$. The CTII calculated for this region revealed that NDVI is strongly influenced by climate, with a higher CTII than any other region analyzed. In general, NDVI in northern regions (Regions 1 to 4) was negatively correlated with precipitation and positively correlated with temperature (Pouliot et al., 2009).

Olthof et al. (2008) examined NDVI trends in a portion of the Taiga Plains Ecozone$^+$ corresponding roughly to Region 1 in Figure 9 using the same AVHRR NDVI dataset analyzed here along with high resolution (30 m) Landsat data. They found that lichen-dominated communities had consistently lower NDVI trends than vascular plant dominated communities, though all showed increasing trends. This is consistent with ground studies (Arft et al., 1999; e.g. Sturm et al., 2001; Hollister et al., 2005; Tape et al., 2006; Walker et al., 2006) and was attributed to increasing vigour and biomass of vascular plants and some impairment of lichen growth due to drying (Olthof et al., 2008).

Taiga Shield

NDVI trends increased over a sizeable area in the northeastern portion of the ecozone$^+$ (Figure 10). Increases were most pronounced south of Ungava Bay, which is dominated by tundra vegetation, and in southern Labrador, which is dominated by coniferous forest and shrubland. The area between these two "hotspots" also exhibited a positive, but less pronounced trend during this period. The positive trend identified south of Hamilton Inlet and Lake Melville in Labrador has not been identified in most other studies except for Slayback et al. (2003) whose analysis suggests that the increases in NDVI trends in this area were recent. A sizeable area of increasing NDVI trends was also found in the northwestern portion of the Taiga Shield. This area is predominantly covered with coniferous forests, but shrub and tundra vegetation are also found there.

Region 4 in the climate forcing analysis by Pouliot et al. (2009) is contained within the eastern portion of the Taiga Shield Ecozone$^+$. The CTII calculated for this region revealed that NDVI there was strongly influenced by climate, though not as strongly as in the Taiga Plains and Arctic ecozones$^+$. In general, NDVI in northern regions (Regions 1 to 4, Figure 9) was negatively correlated with precipitation and positively correlated with temperature (Pouliot et al., 2009).

Boreal Shield

The area of significant positive NDVI trend observed in southern Labrador continued into the eastern Boreal Shield Ecozone$^+$ in Quebec, predominantly in areas of coniferous forest, but also in shrubland (Figure 10). The positive trend in this region has not been identified in most other studies, except for Slayback et al. (2003) whose analysis suggests that the increases in NDVI trends in this area are recent. Isolated areas of increasing NDVI were found further west in central Quebec with the greatest increases in areas of shrubland. Further west, a significant patch of mixedwood forests just north of Lake Superior showed increasing trends, as well as a similar patch just west of Lake Nipigon. Further west still, there were many isolated patches of positive NDVI trends found and a smaller number with negative NDVI trends. NDVI trends in this area are related to the dynamic process of wildfire and regeneration that is common in the western portion of the Boreal Shield Ecozone$^+$. Not all increases in NDVI found in this region were the result of post-fire regeneration. In an analysis of recently burned and unburned sites using the same AVHRR NDVI dataset within the boreal forest region of central Canada, Alcaraz-Segura et al. (2010) found NDVI increases in all recently burned (since 1984) sites and 50% of unburned sites analyzed.

Regions 4 and 5 (Figure 9) in the climate forcing analysis by Pouliot et al. (2009) correspond to the northeastern and southcentral Quebec portions of the Boreal Shield Ecozone$^+$. The CTII calculated for these regions revealed that NDVI in the northeastern region of the Boreal Shield was strongly influenced by climate, while NDVI in the southcentral Quebec region of the Boreal Shield was less influenced by climate. In general, NDVI in northern regions (Regions 1 to 4) was negatively correlated with precipitation and positively correlated with temperature while regions in the south (Regions 5 to 8) were positively correlated with precipitation and negatively correlated with temperature (Myneni and Williams, 1994 in Pouliot et al., 2009).

Atlantic Maritime

NDVI increased significantly in areas of mixed forest along the Gaspé Peninsula and on most of Cape Breton Island (Figure 10). Increasing trends may be associated with commercial logging that has increased the proportion of broadleaf trees but more detailed studies are necessary to test this hypothesis. It is important to note that deciduous and mixed deciduous forests, which make up a large portion of this ecozone$^+$, have NDVI values close to the saturation point (Gilabert et al., 1996; Santin-Janin et al., 2009; Myneni and Williams, 1994 in Pouliot et al., 2009) (see Quality checks and limitations on page 19) which makes detection of small changes in NDVI difficult.

Mixedwood Plains

This ecozone$^+$ is dominated by human modification of the landscape through urban development, extensive agriculture, and commercial logging. A few areas of negative NDVI trends west of Toronto were found and are likely associated with urban development. Extensive areas of positive NDVI trends were found mostly in areas of agricultural land (Figure 10). A more detailed analysis is necessary to attribute a cause and interpret ecological significance.

Boreal Plains

Significant NDVI trends were extensive but scattered (Figure 10). Much of the area found with positive trends was in agricultural areas, as well as some patches of strong positive trends in the forest and shrubland south and west of Lake Athabasca. Two small patches of strong negative NDVI trends appear to be associated with the Athabasca oil sands development.

Prairies

A small area of the Prairies Ecozone$^+$ in southern Alberta between Pakowki Lake and the Saskatchewan border showed a strong negative NDVI trend. Much of the remainder of this ecozone$^+$ showed significant positive NDVI trends, particularly pronounced in Alberta west of Lethbridge and in Saskatchewan west of Moose Jaw (Figure 10).

In an arid area like the Prairies Ecozone$^+$ moisture plays a major role in the value of NDVI, because the greenness of vegetation in this ecozone$^+$ is very sensitive to the amount and timing of precipitation. It is possible that the increase in greenness that followed the drought of 2000 to 2002 (Bonsal and Regier, 2007) may be responsible for the positive trend in NDVI. Increasing NDVI trends in the Saskatchewan portion of this ecozone$^+$ were found to be highly correlated with increasing cropland area, suggesting that land cover is an important driver of NDVI trends in this ecozone$^+$ (Pouliot et al., 2009).

Increases in NDVI in this ecozone$^+$ have also been shown by Slayback et al. (2003), Zhou et al. (2001), and Tateishi and Ebata (2004).

Taiga Cordillera

NDVI increased significantly in the area of shrub and tundra vegetation south of the Mackenzie Mountains, and to the west of the Mackenzie Valley (Figure 10).

Boreal Cordillera

An extensive but patchy area of increasing NDVI was found in the central region of this ecozone+, corresponding to an area of patchy conifer, shrub, and tundra vegetation (Figure 10). Although a CTII was not calculated within this ecozone+, it is likely the NDVI trends are correlated with climate as significant warming (particularly in the winter) is occurring in this ecozone+ (Zhang et al., 2011) and most of the Boreal Cordillera remains as intact wilderness (ESTR Secretariat, In Prep.).

Pacific Maritime

NDVI increased over extensive areas within this ecozone+ (Figure 10). In particular, most of Vancouver Island showed a significant NDVI increase. Increases in NDVI trends on Vancouver Island (Region 8 in Figure 9) were found to be highly correlated with changes in land cover. This increase in NDVI is likely a result of logging followed by vigorous succession (Pouliot et al., 2009).

Montane Cordillera

NDVI increased over much of the ecozone+, particularly at higher elevations in areas dominated by shrub and tundra vegetation (Figure 10). At lower elevations, increases in NDVI were found primarily in areas of mixedwood forest. These low elevation areas of increasing NDVI may represent mixtures of mature forest and cutblocks at early successional stages which have higher NDVI values than mature conifer forest. Negative trends in central British Columbia corresponded to an area of known mountain pine beetle damage that has been affecting the area since approximately 1994 (BCMF, 2003 in Pouliot et al., 2009). The extent of the area with negative NDVI trends (Figure 10) is smaller than the corresponding area of mountain pine beetle kill due to the resolution of AVHRR data, local variations in damage severity, and the position of the disturbance event in the time series. More recent damage (2003 to 2006) can be missed because these points may be seen as outliers in the robust trend analysis (Pouliot et al., 2009).

Hudson Plains

Relatively little of this ecozone+ showed significant NDVI trends. Those areas where NDVI increased were in the lowland portion of the ecozone+ dominated by wetlands (Figure 10).

Western Interior Basin

NDVI increased in this ecozone+ in areas of mixed forest and may result from regeneration after extensive forest harvesting (Figure 10). NDVI decreased significantly over approximately 2% of its area, scattered throughout the ecozone$^+$ in areas that are primarily classified as conifer forest. The cause of these negative trends is not known. Negative NDVI trends may be an indication of drying within the ecozone$^+$, though an analysis of the Palmer Drought Severity Index for this ecozone$^+$ from 1950 to 2006 found no significant changes during this period (Zhang et al., 2011).

Newfoundland Boreal

The greatest proportion of area with increasing NDVI was found in this ecozone$^+$ (41%) (Figure 10 and Table 1). Much of northcentral Newfoundland showed an increase in NDVI. This appears to be centered to the south of the town of Grand Falls-Windsor. This is an area of extensive shrub and poor forest cover. It is possible that warming climate conditions are enabling this climate-limited vegetation to increase in density and vigour.

Discussion

Several long-term studies of NDVI derived from data from the AVHRR sensor on the NOAA polar orbiting weather satellites have shown statistically significant increases in the north from Alaska to Ungava Bay during various periods from the 1980s to present (Myneni et al., 1997; e.g. Los et al., 2000; Kawabata et al., 2001; Zhou et al., 2001; Slayback et al., 2003; Goetz et al., 2005). The scientific consensus attributes these changes to the effects of climate change, particularly climate warming. More detailed studies have shown increases in herb and shrub vegetation (Arft et al., 1999; e.g. Sturm et al., 2001; Hollister et al., 2005; Tape et al., 2006; Walker et al., 2006; Olthof et al., 2008; Olthof and Pouliot, 2010) which would in turn cause long-term increases in NDVI. Together with in-situ observations, the NDVI trends provide supporting evidence that the effects of climate change are already occurring in northern regions.

Further south, areas of increasing trends in NDVI warrant further study as NDVI trends vary with the time period analysed and the dataset used. While no studies show extensive areas of decreasing NDVI, some studies using the 8 km resolution GIMMS AVHRR dataset (Goetz et al., 2005; Bunn and Goetz, 2006) identified more patches of negative NDVI trends in boreal forests, attributed to potential factors such as fire, drought stress, nutrient limitation, or insect and disease damage, than found in this study. A comparison between these two datasets showed that the GIMMS dataset may be biased towards negative trends (Alcaraz-Segura et al., 2010). As these results indicate a potential for reduced primary productivity in boreal forest areas (affecting the carbon balance), it is important to follow up on the extent to which this is occurring.

In conclusion, this study indicates a real greening of the north that is likely related to climate change, the normal burn-and-regeneration cycle in the boreal forest, and a possible greening related to a change of the forest age distribution in the commercial forest zone. Greening in the settled agricultural and urban areas is also observed and warrants more study.

AVERAGE DYNAMIC HABITAT INDEX, 2000 TO 2006

The Canadian Dynamic Habitat Index (DHI) is a composite image of three indicators of vegetation dynamics. It is a relatively new remote sensing index based on a data set that begins in 2000, with potential uses for this index still being tested and refined. The DHI as presented here is currently a point in time measure; trends are not yet shown.

The three indicators that make up the Canadian DHI are: (1) cumulative annual greenness; (2) minimum annual fPAR; and (3) seasonal variation in greenness (Coops et al., 2008). All three indicators are derived from estimates of the fraction of photosynthetically-active radiation that is absorbed by the earth's surface (fPAR), obtained from the MODIS sensors launched in 1999 and 2001 (Heinsch et al., 2006). fPAR ranges from 0 to 1 with higher values of fPAR averaged over the growing season corresponding to more densely vegetated productive landscapes and lower values of fPAR averaged over the growing season corresponding to less productive landscapes (Coops et al., 2008). The fPAR of areas covered in snow approaches zero, though areas of shadow and chlorophyll absorption by conifers will still contribute to a positive fPAR value.

Although fPAR is similar to NDVI, the estimation of fPAR is more directly related to plant physiology than NDVI as it is calculated from a physically based model of the propagation of light in plant canopies (Coops et al., 2008). fPAR also does not have the same issues with saturation at higher values as the NDVI (Coops et al., 2009b) (see Quality checks and limitations on page 19). Estimates of fPAR utilize a number of spectral bands from the MODIS sensor (up to 7) whereas the NDVI is based on two spectral bands, the red and near infrared (see NDVI on page 17).

The DHI was first developed in Australia (Mackey et al., 2004) and has been adjusted for use in Canada by Coops et al. (2008). Their results form the basis of this section and have been summarized by ecozone$^+$ for the purposes of the ESTR.

Methods

Coops et al. (2008) obtained estimates of 1 km resolution monthly maximum fPAR values derived from data collected by MODIS sensors on the Terra and Aqua satellites from the NASA Earth Observing System from 2000 to 2005. This data is calibrated by NASA to take sun angle, background reflectance, and view angle into account, and is made available publicly. Monthly maximum fPAR values are used in order to minimize the influence of cloud and snow cover, atmospheric variation, and other confounding environmental conditions. From these values, Coops et al. (2008) calculated the three components of the DHI, for each year:

1. C**umulative annual fPAR:** the integrated annual fPAR, based on the monthly maximum fPAR values for the year. This has been interpreted as the cumulative annual greenness;
2. **Annual minimum fPAR:** the minimum value out of the monthly maximum fPAR values in a year. This has been interpreted as the minimum annual green vegetation

cover. However, this interpretation is not accurate in winter because of the effects of shadows, so we have avoided this interpretation;

3. **Annual coefficient of variation of fPAR**: the standard deviation of the monthly maximum fPAR values in a year, divided by the mean of the monthly maximum fPAR values in a year. Interpreted as the annual degree of vegetation seasonality.

They then calculated an average over the six-year dataset for each of the three components and produced a map for each component and one composite map (Coops et al., 2008). Their results are further analysed by ecozone+ here. As the data represent a six-year average, it currently only provides an estimate of the status in each ecozone+ without providing any information on trends.

Quality checks and limitations

Significant algorithm refinement of the MODIS sensor has been conducted since its inception (Yang et al., 2006a), however, limited validation has been conducted on the fPAR estimates specifically (Yang et al., 2006b).

We noted a minor but distinct seam along the 60th parallel in the annual minimum cover component that may have resulted from some change in processing algorithm at that latitude. This does not affect our interpretation, since that component is so low at that latitude.

Results

The three components of the DHI are shown separately in Figure 11a to c. Vegetation dynamics by component are summarized by ecozone+ in Table 2.

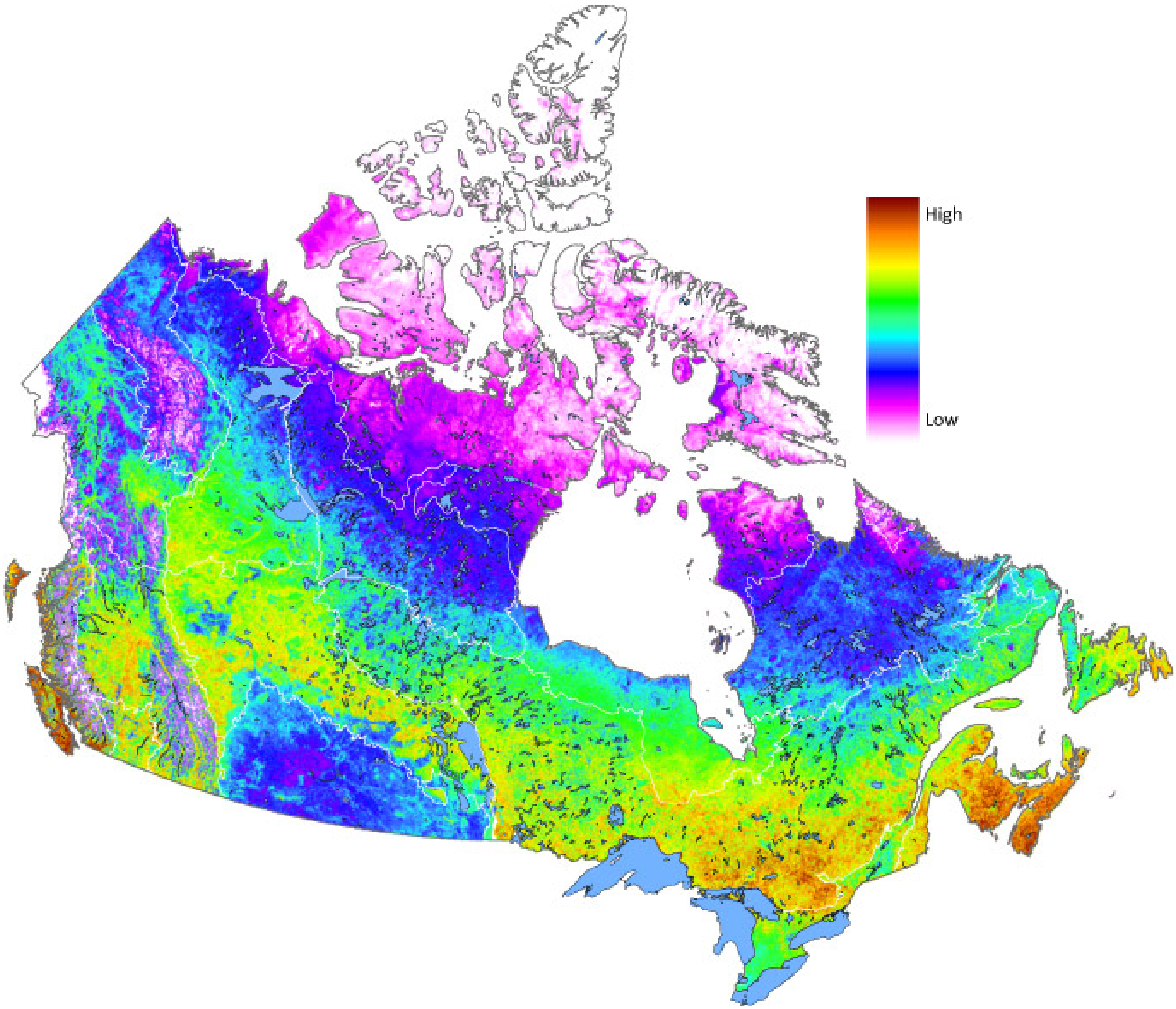
From the national perspective of average cumulative annual greenness (Figure 11a) it is apparent that the most productive regions are Canada's forests, with the greatest greenness in the southern maritime climates (both Atlantic and Pacific with greenness decreasing toward the tree line). The altitude effect of Canada's high mountains is apparent, as is the influence of aridity of Canada's prairie region.

The national pattern of average annual minimum fPAR (Figure 11b) is similar to the average cumulative greenness, however it is greatly compressed toward the south. In other words, the minimum cover is quite low throughout the country except in the south and at low elevations. The highest values of average minimum fPARcover occur in a swath of forest across eastern Canada. This corresponds to a band of dense mixed forest. In this area, fPAR is relatively high, even in winter, because of the shadowing effects of all trees, as well as the chlorophyll absorption by conifers.

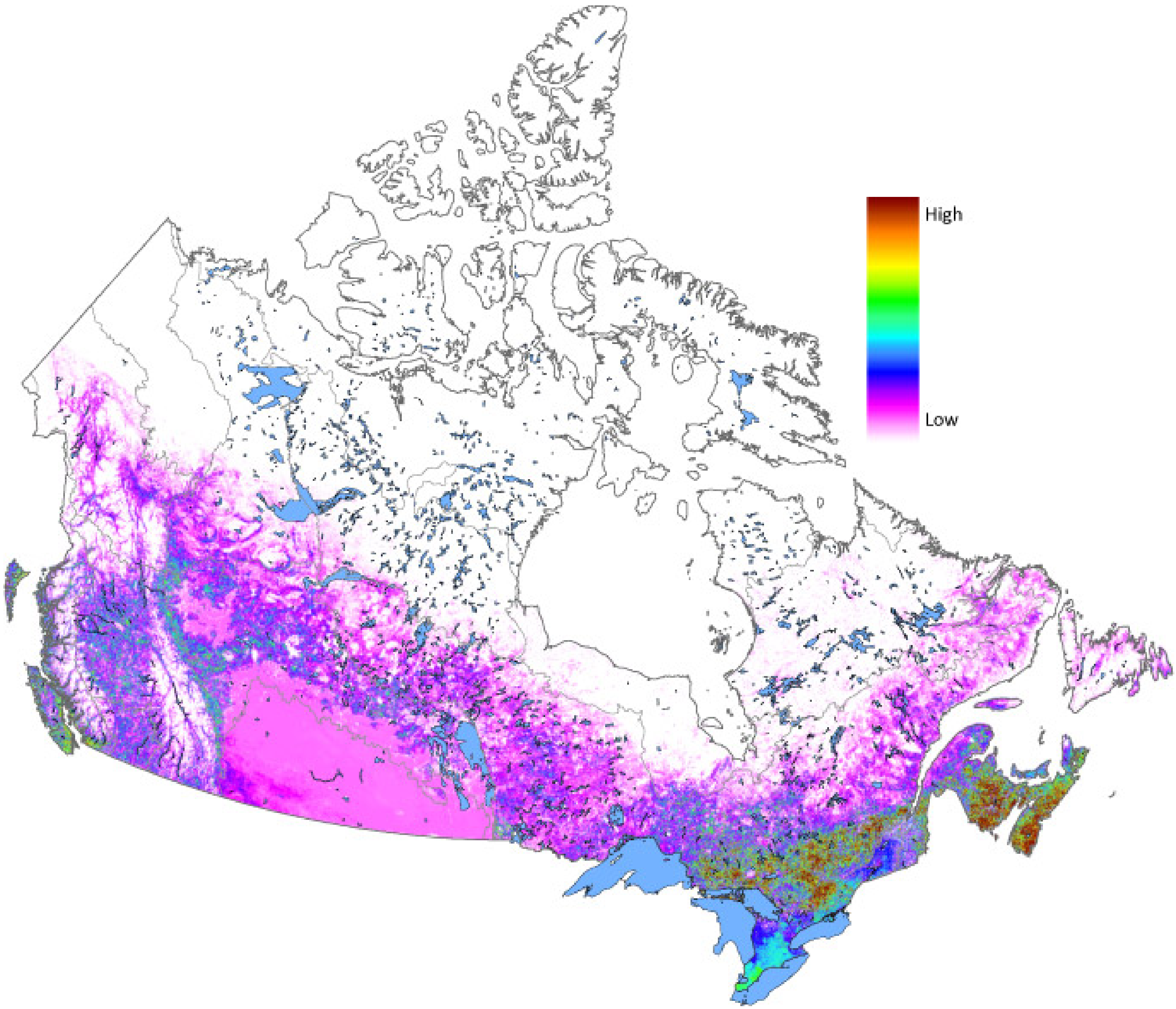
The average seasonal variation in greenness (Figure 11c) shows different patterns than the other two components of the DHI. Most dramatically, there is no difference between the prairie region and the forests. The seasonal variation increases towards the north and at higher altitudes in the south. This increase is the result of lower mean fPAR in these areas, rather than an increase in the standard deviation. This component shows some subtle and unexpected variations within ecozones^{+}, described briefly in Table 2. When this component is inspected closely, it is apparent that it is very sensitive to relatively small variations in altitude.

Coops et al. (2008) also found that the Boreal Plains, Mixedwood Plains, and Hudson Plains ecozones (using the National Ecological Framework (Ecological Stratification Working Group, 1995)) had the highest variation in the DHI during looking at each year from 2000 to 2005.

a. Cumulative annual greenness (2000 to 2005 average)



b. Minimum annual fPAR (2000 to 2005 average)



c. Seasonal variation in greenness (2000 to 2005 average)

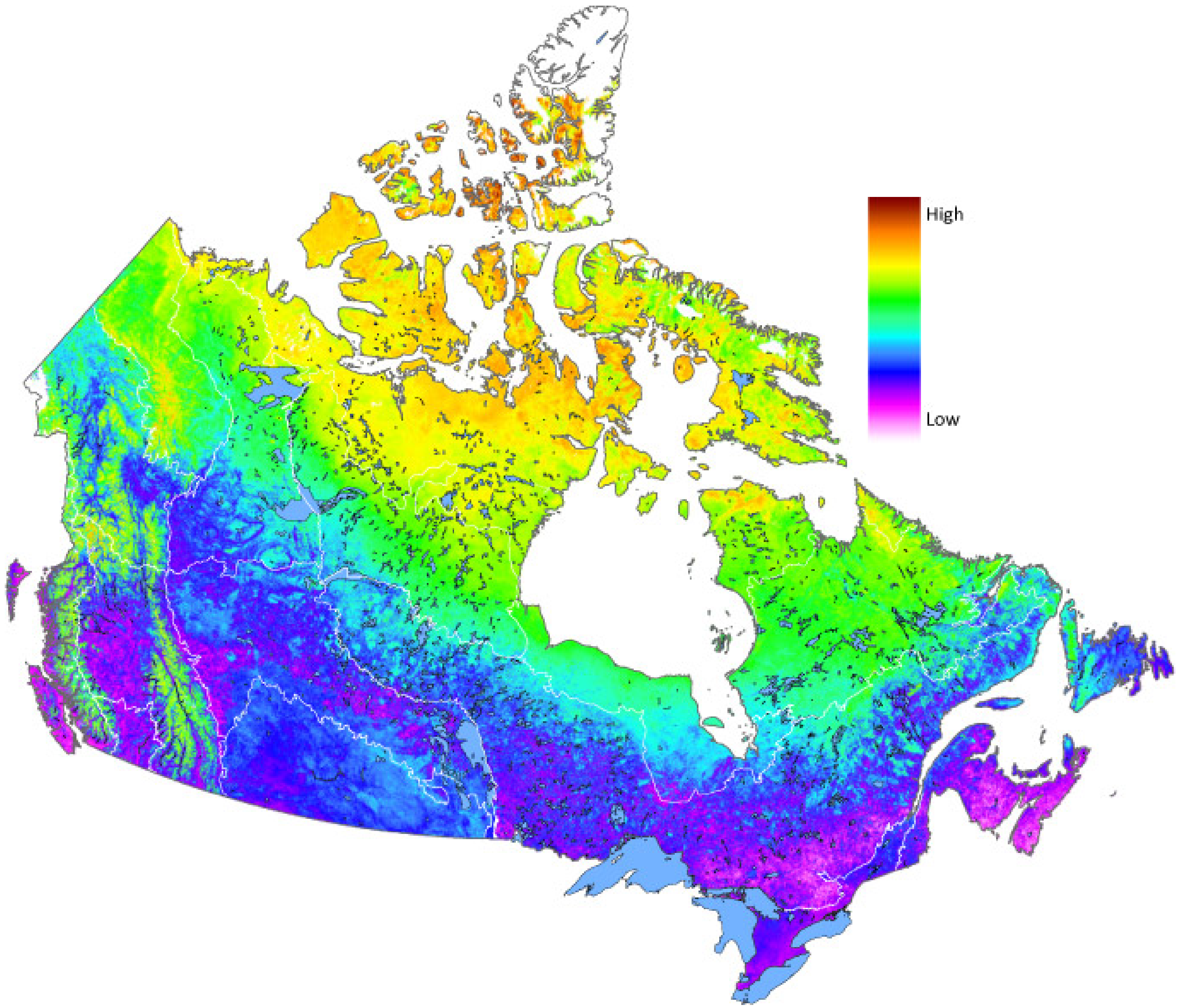


Figure 11. Vegetation dynamics in Canada's ecozones⁺ by Dynamic Habitat Index components, averaged over 2000 to 2005 DHI components are (a) cumulative annual greenness, (b) minimum annual fPAR and (c) degree of vegetation seasonality. Source: adapted from Coops et al. (2008)

Table 2. Characteristic vegetation dynamics by ecozone⁺ (averaged from 2000 to 2005)

Ecozone⁺	**Cumulative annual greenness**	**Minimum annual fPAR**	**Annual degree of vegetation seasonality**
Arctic	Variable: very low in the Arctic Cordillera, higher on western Banks Island, the Great Plain of the Koukdjuak on Baffin Island and Ungava	Very low	High except slightly lower in some locations, such as Ungava.
Taiga Plains	Low to medium: decreasing from south to north	Very low to low	Decreasing toward south: some interesting patterns in Quebec and Labrador, especially around Hamilton inlet.
Taiga Shield	Variable: high in south, low in north; effects of elevation are evident.	Low but increasing toward south	High in north becoming medium in south; effects of elevation are particularly evident.
Hudson Plains	High in south becoming medium along the shore of Hudson Bay.	Low throughout	Grading from high in north to low in south.
Boreal Shield	High in south becoming lower toward north, particularly in northwest where fire is frequent	Variable: very low in north to very high in south	Grading from high in north to low in south. Lowest in southernmost Canadian Shield in eastern Ontario.
Atlantic Maritime	High to very high in southern New Brunswick and Nova Scotia	Variable: low in Gaspé and northern Cape Breton to very high in southern New Brunswick and Nova Scotia	High except lower in northern Cape Breton and parts of Gaspé.
Mixedwood Plains	Low in urban areas, medium in agricultural areas, and high in forested areas	Variable: highest in SW Ontario and Manitoulin Island; lowest south of Georgian Bay and north of Lake Simcoe.	Low throughout
Boreal Plains	Variable; lowest in agricultural areas	Variable; lower in agricultural areas; lowest in patches that may be burn scars	Variable: higher in agricultural areas and in patches that may be burn scars
Prairies	Medium to low: highest in forested Cypress Hills	Uniformly low	Uniformly medium
Taiga Cordillera	Variable: very low in mountains; higher in northern Yukon	Low	Varies with elevation
Boreal Cordillera	Variable: very low near mountain tops; highest in northern BC	Low; higher in valleys	The elevation effect is very pronounced: highest at highest elevation and lower in valleys
Pacific Maritime	Variable: very low on mountain tops to very high in coastal regions of Vancouver and Queen Charlotte Islands	Very low on mountain tops to high in coastal regions of Vancouver and Queen Charlotte Islands	The elevation effect is very pronounced: highest at highest elevation and lower in valleys

Ecozone^{+}	**Cumulative annual greenness**	**Minimum annual fPAR**	**Annual degree of vegetation seasonality**
Montane Cordillera	High except at highest elevations and dry valleys.	Variable	Low except high at high elevations
Western Interior Basin	High except in dry interior valleys.	Variable	Low except high at high elevations
Newfoundland Boreal	High in east to medium to high in west.	Low except coastal fringe	Pronounced elevation effects

Discussion

Each of the three components of DHI provides information about vegetation production. The values of fPAR integrate the effects of various factors on productivity. Forests that consist primarily of evergreen trees, for example, will have a higher cumulative annual fPAR, a higher minimum annual fPAR, and a lower degree of seasonality than a forest consisting of primarily deciduous trees. Productivity (and therefore fPAR) tends to increase with increasing temperature, though will be reduced by periods of drought.

The DHI provides a potential approach for using standard earth observation products to monitor long-term vegetation productivity trends (from 2000). Specific uses for this relatively new dataset are still being explored and tested. One key area of research is in using the DHI components to predict patterns of biodiversity. This research is based on the assumption that the distribution and abundance of species across landscapes is driven by key environmental parameters (Turner et al., 2003), with vegetation productivity being one of these key parameters (MacArthur, 1972). Coops et al. (2008) argue that direct measurements of fPAR, which is included in the three DHI components, provide better estimates of vegetation productivity than the more traditionally used NDVI. It would be interesting to compare similar indicators of productivity based on NDVI data in order to better compare these methods.

Andrew et al. (2011) examined the ability of the DHI components to explain patterns of butterfly community composition and species affinities in Canada. They found that these components on their own were not a good predictor, but suggested they could be used to improve predictions of community composition within the qualitatively defined ecozones and ecoregions of Canada (Ecological Stratification Working Group, 1995). Coops et al (2009a)(2009c) used the DHI components to predict the species richness of breeding birds in the United States, and, in conjunction with land cover and topography, in Ontario with more promising results. The ability to predict species distribution and the relevant parameters for predicting species distribution are species dependent. In many cases, this type of analysis more specifically predicts potential species distribution, as opposed to actual species distribution (Kerr and Ostrovsky, 2003).

Using remotely sensed data to indirectly describe broad patterns of biodiversity could be used to develop an "early warning system" of large scale changes in biodiversity (Duro et al., 2007). The utility of the DHI components in this type of work remains to be seen. Other potential uses may also be developed.

INDICATORS OF FRAGMENTATION: FOREST DENSITY AND FOREST EDGE DENSITY

To allow for a meaningful discussion of landscape changes over time, changes in the total area of various land cover classes (for example, the first section of this report starting on page 3) should be discussed in conjunction with changes in the pattern of land cover classes (such as homogeneity). This discussion fits within the theme of fragmentation. Habitat fragmentation has played a significant role in conservation research since the 1970s (Haila, 2002; Manning et al., 2004). A widely accepted definition of fragmentation (or the process of fragmentation) is the division of contiguous habitat into smaller pieces (Fleishman and Mac Nally, 2007). Fragmentation results in a decrease in connectivity, an increase in edge density, and an increase in isolation of remnant areas. Analyses of fragmentation impacts are complex as the different components of fragmentation are often confounded (Haila, 2002; Lee et al., 2002; Manning et al., 2004) and results are highly species dependent (Flaspohler et al., 2001; Ries and Sisk, 2004; Villard et al., 2007).

The completion of a high resolution (30 m) map of Canada's forested region circa 2000 by the Canadian Forest Service under the joint Earth Observation for Sustainable Development (EOSD) initiative has provided a detailed dataset of Canada's forest cover. This dataset has enabled Canadian Forest Service, in conjunction with the University of British Columbia, to derive spatial statistics on Canadian forest cover at a number of resolutions (Wulder et al., 2008b). Of the fragmentation statistics reported by Wulder et al., (2008b), two are presented here by ecozone$^+$ for ESTR: (1) the proportion forested pixels within a 1 km^2 analysis unit (that is, forest density); and (2) the length of all edges between forest and non-forest pixels within each 1 km^2 analysis unit (that is, forest edge density).

These analyses should be considered as broad-brush, entry-level fragmentation data sets. As this analysis is currently for one time period, the results are primarily a description of the patterns of forest within each ecozone$^+$.

Methods

The EOSD land cover maps were produced from 30 m Landsat data collected between 1999 and 2002 from May to October (90% obtained within one year of the 2000 target date) (Wulder et al., 2008a). Each pixel was classified in one of 23 categories. Further discussion of the classification process can be found in Wulder et al., (2008a).

Detailed methodology can be found in Wulder et al. (2008b). The "proportion of forest area" (referred to as "forest density" in this report) and "forest edge density" metrics are summarized by ecozone$^+$ here. Regions classified as 'Treed' in the EOSD dataset (>10% tree cover (Wulder and Nelson, 2003)) were reclassified as 'Forest' and all other regions were reclassified as 'non-forest' for the purpose of these analyses (Wulder et al., 2008a). Forest density represents the proportion of forested pixels (30 m resolution) within each 1 km^2 analysis unit while the forest edge density metric represents the total length of all of the edges between forested pixels and non-forested pixels within a 1 km^2 analysis unit.

Quality checks and limitations

Pre-existing data are often used for validation of remotely sensed data sets (for example, the Satellite Database for the Land Cover of Canada database was used to validate the land cover change maps outlined in the first section of this report on page 3) (Wulder et al., 2007). The EOSD data set from which the forest and edge density calculations were drawn was validated using airborne video data collected specifically for the validation process of this data set. A 31,000 km^2 sub-sample of the EOSD data set was analyzed on Vancouver Island in the Pacific Maritime Ecozone$^+$ (Wulder et al., 2007) with a systematic stratified random sampling approach outlined in Wulder *et al.* (2006). The coniferous treed class (a sub classification of "Forest"), which made up 71% of the area sampled was found to have a classification accuracy of 86%.

A distinct visual seam is noted at the Ontario-Quebec border in the forest edge density map. While not large numerically, this seam introduces an element of caution into the interpretation; greater confidence should be placed in differences highlighted within a single province than between provinces. This seam could also reflect a difference in forest management policy between the two provinces.

In the interpretation of the following results, it is also important to note that these metrics are not a measure of human influence; they are a measure of landscape characteristics which may result from either natural or anthropogenic processes. For example in wetland or alpine areas, forest edge density will be relatively high due to the natural heterogeneity of the landscape, not as a result of human influences (Wulder et al., 2008b).

Results

Results of the forest density analysis are presented in Figure 12 and the results of edge density analysis are presented in Figure 13. These results are discussed by ecozone$^+$ below.

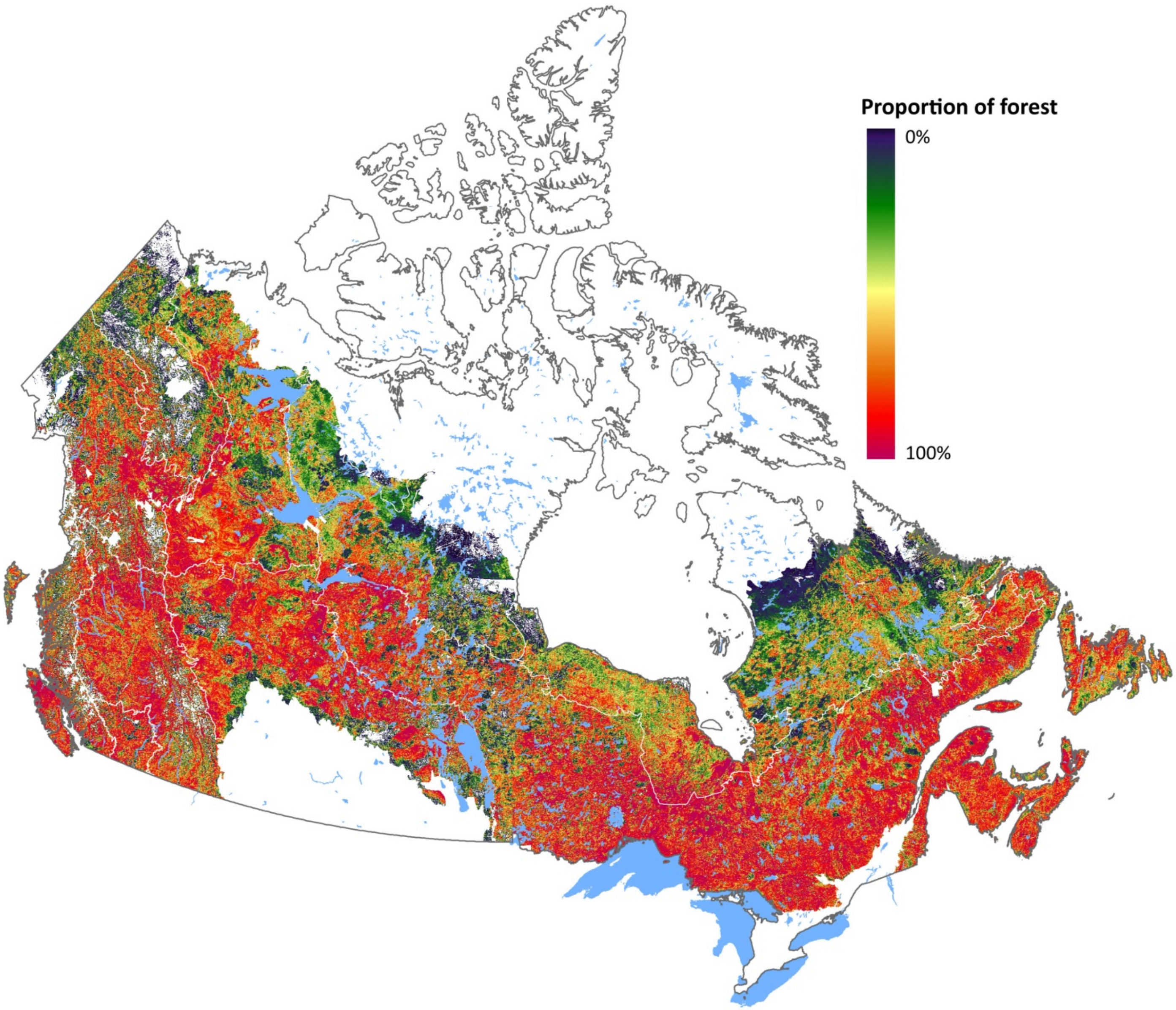


Figure 12. Forest density in the forested region of Canada circa 2000.
Forest density is the proportion of 30 m^2 pixels that are forested in each 1 km^2 analysis unit.
Source: derived from the EOSD land cover of 2000 data set created by CFS (Wulder et al., 2008b)

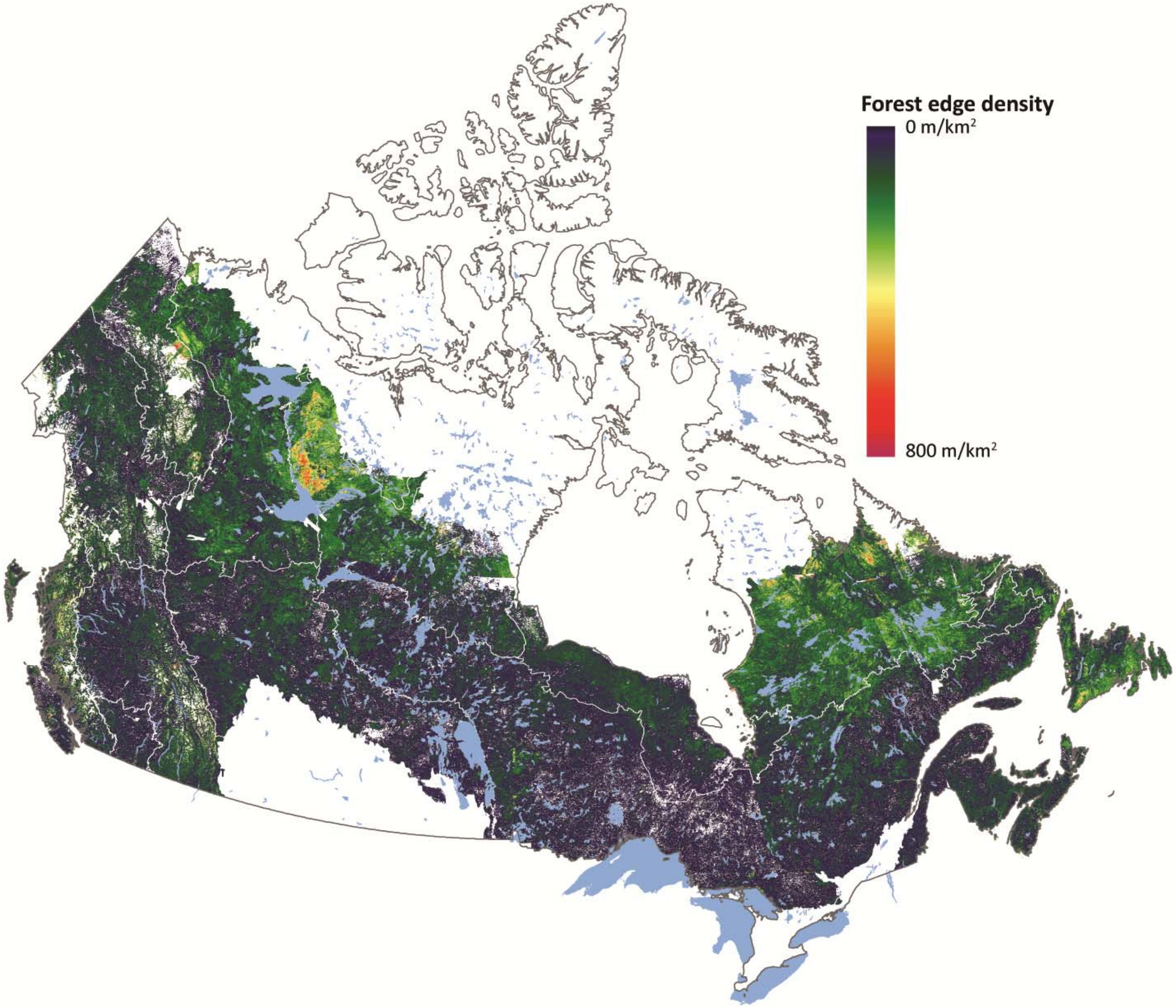


Figure 13. Forest edge density in the forested region of Canada, circa 2000.
Forest edge density is the total length of all edges between forested pixels (30 m resolution) and non-forested pixels within a 1 km^2 analysis unit.
Source: derived from the EOSD land cover of 2000 data set created by CFS (Wulder et al., 2008b))

Taiga Plains

There is a large variation in latitude, elevation, and climate in the Taiga Plains Ecozone$^+$. It is an area of frequent large wildfires and thus the vegetation is made up of a patchwork of fire scars at different stages of regeneration. Forest density in much of this ecozone$^+$ was found to be greater than 50% (Figure 12). Lower forest densities were found immediately south of Great Slave Lake, the uplands near Norman Wells, in a large burn scar west of Lac la Martre, and in portions of the lower reaches of the Mackenzie Valley. The forest edge density in the Taiga Plains Ecozone$^+$ was found to be higher than more southerly forests, with a typical value of 250 m/km^2, increasing to 500 to 600 m/km^2 in the area of tundra surrounding the eastern foothills of the Mackenzie Mountains (Figure 13).

Taiga Shield

The western portion of the Taiga Shield Ecozone$^+$ is approximately two-thirds forest and one-third tundra. The majority of the forest area in this ecozone$^+$ was found to have a forest density greater than 50% while areas of tundra and fire scars were found to have forest densities of 30% or less (Figure 12). Forest edge density in the western portion of the ecozone$^+$ was typically around 250 m/km^2 (Figure 13). A large area just north of Great Slave Lake was found to have edge densities up to 650 m/km^2, likely corresponding to a transition region between forest and tundra land covers.

The eastern portion of the ecozone$^+$ is approximately one-third forested and two-thirds tundra. As in the west, the forested portion includes many fire scars. Forest density greater than 50% was found for the majority of the forested area in the eastern portion of the ecozone$^+$, while forest density closer to 30% or less was found in areas of tundra and fire scars (Figure 12). In contrast to the western portion, the forest density decreased to less than 10% at the northern extreme of this ecozone$^+$, suggesting the eastern portion of the ecozone$^+$ includes more severe growing conditions than the western portion. As in the west, typical values of forest edge density were around 250 m/km^2 with a few small areas in the northern extreme of this ecozone$^+$ with forest edge densities up to 650 m/km^2 (Figure 13). These may be associated with areas of poor drainage and a greater density of wetlands.

Boreal Shield

Forest is the dominant land cover in the Boreal Shield Ecozone$^+$ with numerous fire scars of varying ages. Many of the areas of lower forest densities corresponded to young fire scars (Figure 12). Forest edge density, while low throughout this ecozone$^+$ (0 to about 150 m/km^2), was slightly greater in the north, particularly in regions most affected by wildfires (Figure 13). Notable in this ecozone$^+$ was the large area of low forest density and high forest edge density surrounding the nickel smelter in Sudbury.

Atlantic Maritime

The Atlantic Maritime Ecozone^{+} is relatively small with a dominant land cover of mixed forest. Agricultural land has replaced the forest in much of Prince Edward Island, the Annapolis Valley of Nova Scotia, and the Saint John valley of New Brunswick. High forest density was found for most of this area (Figure 12). Of note is an area of low forest density found in the region of Cape Breton Highlands National Park. This area of low density may be the result of forests within the park being left to regenerate naturally after severe spruce-budworm outbreaks in the 1970s and early 1980s while forests outside of the park were salvaged-logged, though this hypothesis has not been confirmed.

The density of forest edges in the Atlantic Maritime Ecozone^{+} was found to be low (Figure 13), ranging from 0 to about 150 m/km^{2} throughout much of the region. Edge density increased to about 270 m/km^{2} in the Northern Cape Breton highlands.

Boreal Plains

Considerable area in the Boreal Plains Ecozone^{+} has been converted to agriculture, as evidenced in the lower density of forest found around the periphery of the Prairies Ecozone^{+} and in the Peace River area associated with the towns of Dawson Creek, Grand Prairie, Peace River, and Valleyview (Figure 12). A very large wildfire that burned about 2,000 km^{2} north of Whitecourt in 1998 also corresponded to an area of low forest density. Areas with high elevation and irregular terrain including the uplands of Riding Mountain National Park, Duck Mountain Provincial Park, and the Porcupine Hills and Pasquia Hills typically exhibited high forest density.

The density of forest edges generally ranged from 0 to about 150 m/km^{2}, with some areas up to 250 m/km^{2} (Figure 13). A visual comparison with the original EOSD land cover map (before simplification to 'forest' and 'non-forest') within the Boreal Plains Ecozone^{+} showed that the density of forest edges in homogeneous uncut forest was generally below 100 m/km^{2}, while areas of forest containing many cutblocks had forest edge densities ranging between 100 and 200 m/km^{2}. In many areas that are not subject to logging, natural edges, such as contact with water bodies and wetlands, produced edge densities between 100 and 200 m/km^{2}.

Taiga Cordillera

The dominant land cover of the Taiga Cordillera Ecozone^{+} is shrub at lower elevations and tundra in the Mackenzie and Stikine Mountains and the Canadian portion of the Brooks Range. A large area of this ecozone^{+} was found to have very low to low forest density (Figure 12) due to large, essentially treeless upland areas. At lower elevations, most areas contained scattered and open forests rather than continuous, high density forests. A significant area with relatively high forest density was found, however, in the lowlands between the Mackenzie Mountains and the Brooks Range. Forest edge density was generally low throughout the ecozone^{+} (Figure 13) (0 to about 150 m/km^{2}). Some areas, however, had edge densities approaching 300 m/km^{2}, particularly in the lowlands to the west of Fort Good Hope.

Boreal Cordillera

The Boreal Cordillera Ecozone$^+$ exhibits strong altitudinal zonation of its vegetation, from dense conifer forests in the valleys, progressing to shrubs and stunted trees to tundra and finally to snow and ice on the peaks. The forest density was found to be quite heterogeneous (Figure 12), but generally correlated with altitude gradient with the highest forest densities at the lowest elevations. Forest edge density was typical of other boreal forest regions (Figure 13), ranging from 0 to about 250 m/km^2.

Pacific Maritime

The vegetation in the Pacific Maritime Ecozone$^+$ exhibits strong altitudinal zonation. Forest density was found to be very high in the Queen Charlotte Islands, on Vancouver Island, and at lower elevations along the Pacific coast (Figure 12). Forest edge density increased with increasing altitude, reaching values as high as 650 m/km^2 reaching the altitudinal treeline. This high edge density may also result from the geometry of the mountains themselves; several drainage channels within a single 1 km^2 analysis unit would result in high forest edge densities.

Montane Cordillera and Western Interior Basin

The Western Interior Basin and Montane Cordillera ecozones$^+$ are largely indistinguishable based on forest and forest edge density and are summarized together here. Growing conditions for forests are ideal in these ecozones$^+$, with the exception of the dry interior valleys of the Western Interior Basin Ecozone$^+$. Forest density was found to be strongly skewed toward high-density classes in both ecozones$^+$, with more analysis units with very low forest density found in the Western Interior Basin (Figure 12) as a result of the open forests of the dry interior valleys. The area of mountain pine beetle mortality was not yet visible in these landscape metrics as of the year 2000. The northernmost regions of the Montane Cordillera Ecozone$^+$ were found to have large areas with very high forest density, likely due to an absence of logging.

In these ecozones$^+$, the density of forest edges was inversely correlated with forest density, areas with lower forest density typically had higher forest edge density (Figure 13), likely a result of the fragmentation from industrial logging in these two ecozones$^+$.

Hudson Plains

The vegetation of the Hudson Plains Ecozone$^+$ is dominated by conifer forest, with a belt of shrubland and wetland covering a poorly drained band toward the south of the ecozone$^+$, and a predominance of tundra vegetation in Wapusk National Park to the north of York Factory. Forest density was found to be low in much of the Hudson Plains Ecozone$^+$ (Figure 12) as a result of the many small bodies of open water and non-forested wetlands. The variable landscape was also reflected in the forest edge density (Figure 13), with a large part of the ecozone$^+$ showing forest edge densities in the range of 250 m/km^2.

Newfoundland Boreal

Forest density in the Newfoundland Boreal Ecozone+ was found to be greater than 50% for most of the ecozone+ (Figure 12). Two large patches of low density forest found east of Corner Brook and Deer Lake on the Buchans Plateau appear to be old fire scars. A large area of low density forest centered on Bay du Nord Wilderness Reserve also appears to be an old burn scar.

Forest edge density in this ecozone+ was found to be relatively high (Figure 13): greater than 350 m/km^2 for most of the area classified as shrub; and greater than approximately 600 m/km^2 in the Long Range Mountains. This suggests a very heterogeneous forest/shrub matrix, with many edges.

Discussion

As the EOSD dataset is currently only available for the 2000 time period, the main result of this analysis is descriptive. The full-resolution forest density image shows numerous areas of lower forest density, particularly smaller patches affected by industrial logging, and larger patches affected by forest fires. Industrial-scale forestry also appears to increase the edge density from less than 100 m/km^2 in uncut areas of homogeneous mature forest to a range between 100 and 200 m/km^2 in areas with an extensive pattern of cutblocks. The edge density is also higher in the northern portion of the Boreal Shield Ecozone+ where the forest becomes less continuous and prone to larger fires.

The utility of this dataset is currently limited to describing the characteristics of forests at a point in time. A time series, produced every ten years for example, would enable monitoring of trends in the forest.

CONCLUSION

This paper used both coarse and medium resolution remote sensing data as a means of assessing the status and trends of biodiversity in Canada's ecosystems. The three analyses that examine trends over time showcase some of the changes in Canada's landscapes over the last thirty years, including a net increase in the area of Fire Scars between 1985 and 2005, and point to an intensification of agriculture, particularly within the Boreal Plains Ecozone+ (should be corroborated with finer scale information). Particularly striking is the finding that primary productivity has increased significantly ($p < 0.05$) on 22% of Canada's land mass between 1985 and 2006 while only decreasing significantly on only 0.5% of Canada's land mass.

Data on ecosystem status was analyzed by ecozone+ from two newer datasets, the fPAR dataset from the MODIS sensor which is used to create the DHI, and the EOSD dataset derived from Landsat data for the forested region of Canada showing status of forest and forest edge density. The utility of these measures of ecosystem status for future ecosystem monitoring remain to be seen.

It is important to recognize that remote sensing experts, who compile and analyze the data, are not typically also experts in ecology; and ecology experts, who interpret the findings and put them into context, are not typically also remote sensing experts. It is therefore very important that these two groups work together closely, ensuring that the most biodiversity relevant questions are asked and answered with remote sensing data, while understanding the limitations. There are a wide range of users of remote sensing data and one dataset can be used for many purposes and analyzed in many different ways. As we move forward with using remote sensing information for ecological monitoring, it is important that user groups and remote sensing data providers get together to make sure that the data is useful to all and the right questions are being asked and answered to meet monitoring objectives.

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APPENDIX 1

Land cover classification scheme used for the Land Cover Change analysis for the ESTR

Class	Description
Forest	Tree crown density > 10%. Includes: – Conifer Forest (>80% needleleaf trees) – Broadleaf Forest (> 80% broadleaf trees) – Mixed Forest (20-80% of tree species are either needleleaf or broadleaf trees)
Shrubland	Tree crown density < 10%, shrub cover > 40% *Note: Most wetlands will be included here*
Grassland	Tree or shrub cover <10%, herbaceous vegetation present
Agricultural Land	Includes: – Cropland (land covered with typically annual herbaceous crops, may contain <10% shrubs or trees. Includes low, medium and high biomass crops) – Cropland/woodland (contains a mix of cropland, forest, shrubland, grassland or built-up areas in which no one component comprises >70% (by area) of the landscape)
Low Vegetation and Barren	Includes areas vegetated with lichens, heather, herbs, shrubs (<40% of vegetation is shrubs, otherwise it will be classified as "Shrubland"), bare soils, or rock outcrops
Fire Scars	Includes: – New disturbance (fire scars < 5 years old) – Old disturbance (fire scars > 5 years old, but not yet classified as another vegetation type. *Note: while old and new fire scars make up the majority of this class, areas of harvest, mining, and severe insect defoliation may also be included*
Urban	Land covered by buildings and other artificial structures. Confusion with other non-vegetated classes may occur for small urban areas. *Note: Urban area in this report is status as of 1996-1997 from the National Atlas. AVHRR data is too coarse to map changes in urban area over time.*
Snow/ice/glacier	Land covered with permanent ice or snow. *Note: Errors exist in this class for the Pacific Maritime and Boreal Cordillera ecozones*[+]*. These errors have been corrected in the 2005 land cover map, but are not corrected in the transition matrices. Changes in this class over time therefore cannot be discussed.*
Inland Water	Land covered with water in liquid form *Note: The 'inland water' class extent is taken from the National Atlas. Changes in inland water are not mapped due to the dynamic nature and high variability of this class.*

APPENDIX 2

Land Cover as of 2005 and land cover change from 1985 to 2005 presented by ecozone+.

Arctic

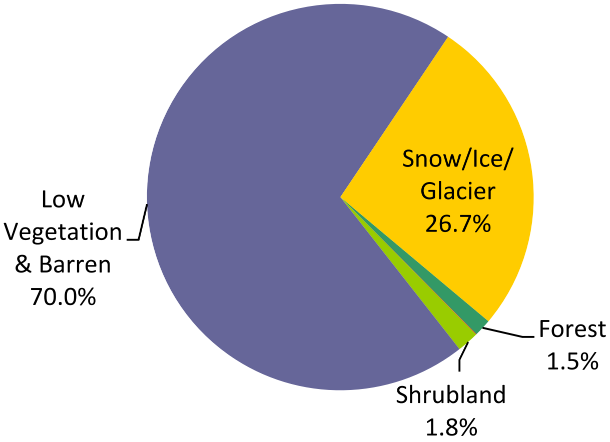

Figure 14. Land cover in the Arctic Ecozone+, 2005.
Land area in the Fire Scars class is very small (<0.001%). Total land area is 2,355,196 km^2.

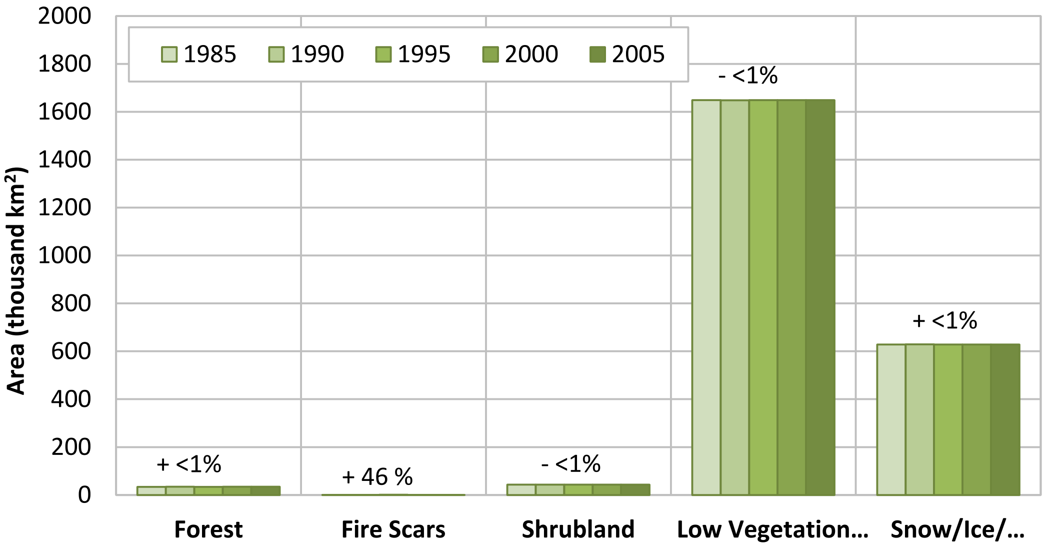

Figure 15. Area by land cover class across the Arctic Ecozone+, 1985, 1990, 1995, 2000 and 2005. Labels are the total percent change for each land cover class between 1985 and 2005.

Taiga Plains

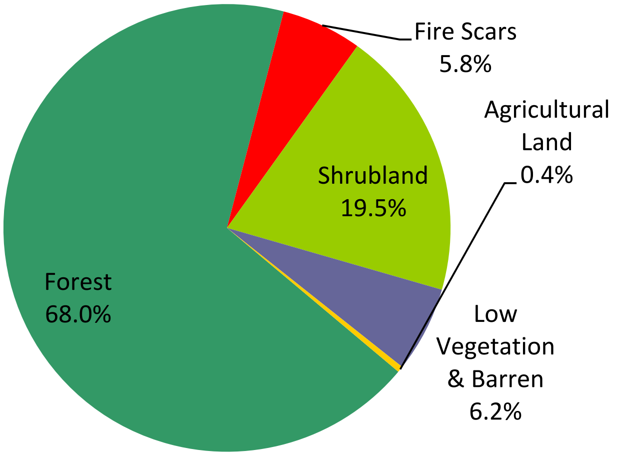

Figure 16. Land cover in the Taiga Plains Ecozone⁺, 2005.
Total land area is 510,388 km². Urban land area is very small (<0.01%), and is the extent from the National Atlas as of 1996-1997.

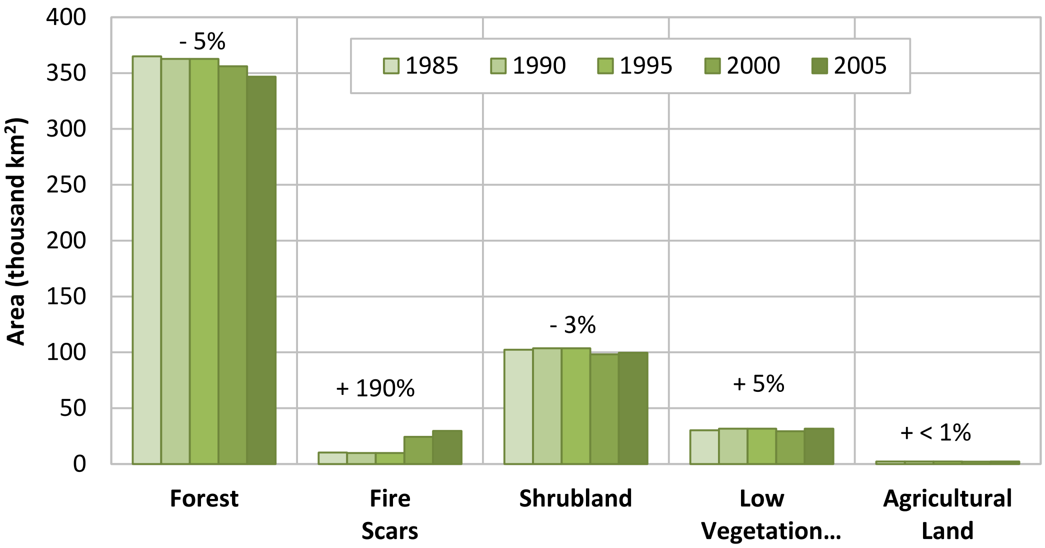

Figure 17. Area by land cover class across the Taiga Plains Ecozone⁺, 1985, 1990, 1995, 2000 and 2005. Labels are the total percent change for each land cover class between 1985 and 2005.

Taiga Shield

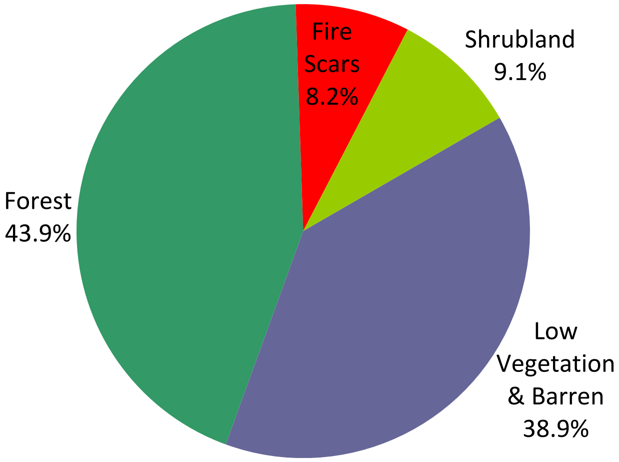

Figure 18. Land cover in the Taiga Shield Ecozone⁺, 2005.
Land areas in urban, Agricultural Land andSsnow/Ice/Glacier classes are very small (<0.01%) and there is no Grassland. Total land area is 1,124,419 km^2.

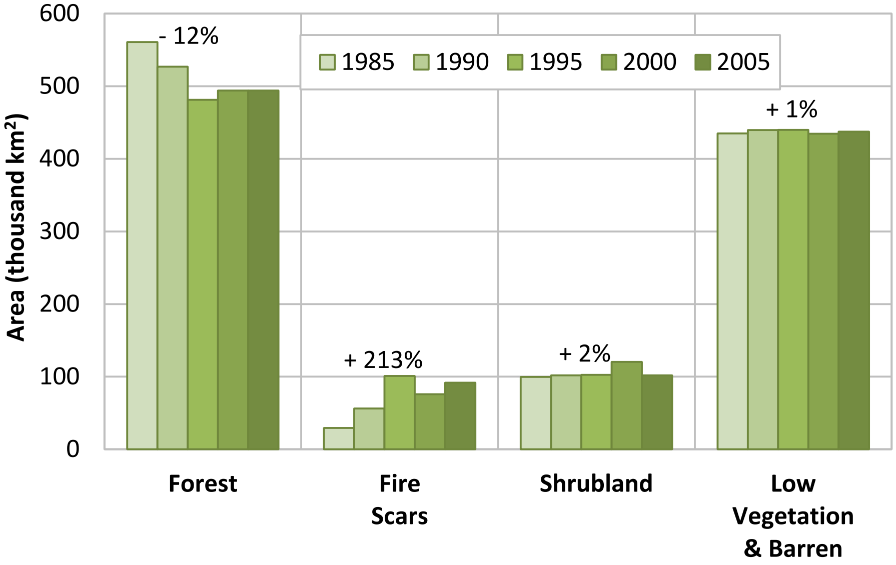

Figure 19. Area by land cover class across the Taiga Shield Ecozone⁺, 1985, 1990, 1995, 2000 and 2005. Labels are the total percent change for each land cover class between 1985 and 2005.

Boreal Shield

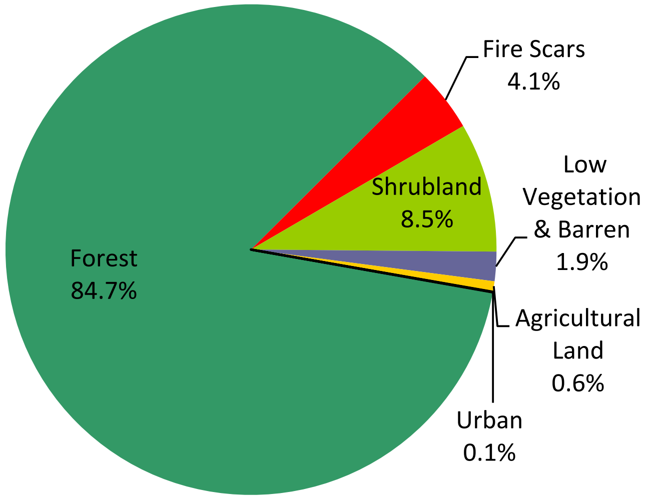

Figure 20. Land cover in the Boreal Shield Ecozone⁺, 2005.
Land area in the Grassland class is very small (<0.01%). Total land area is 1,597,782 km^2. Note that urban area is the extent from the National Atlas as of 1996-1997.

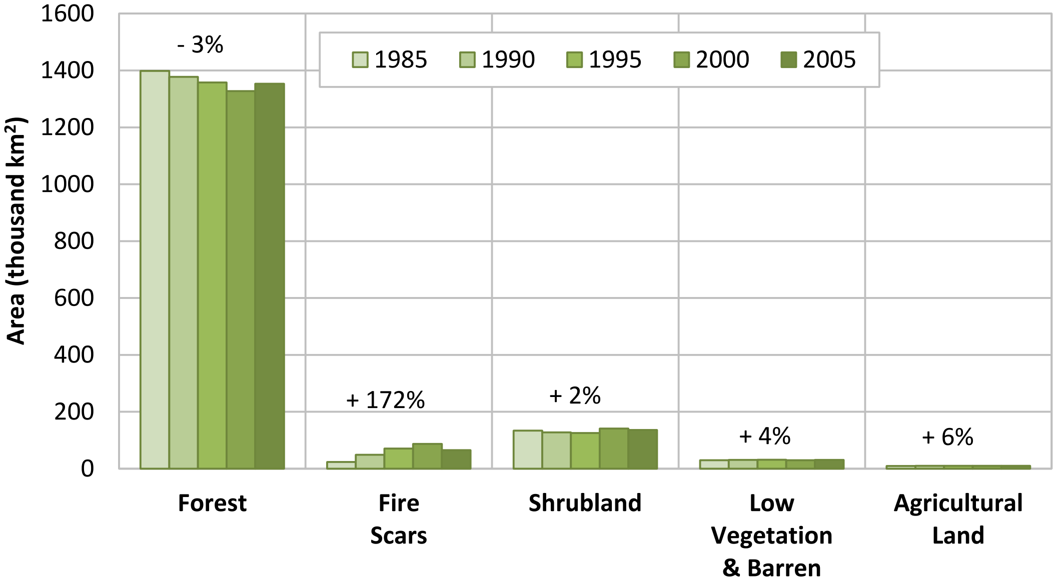

Figure 21. Area by land cover class across the Boreal Shield Ecozone⁺, 1985, 1990, 1995, 2000 and 2005. Labels are the total percent change for each land cover class between 1985 and 2005.

Atlantic Maritime

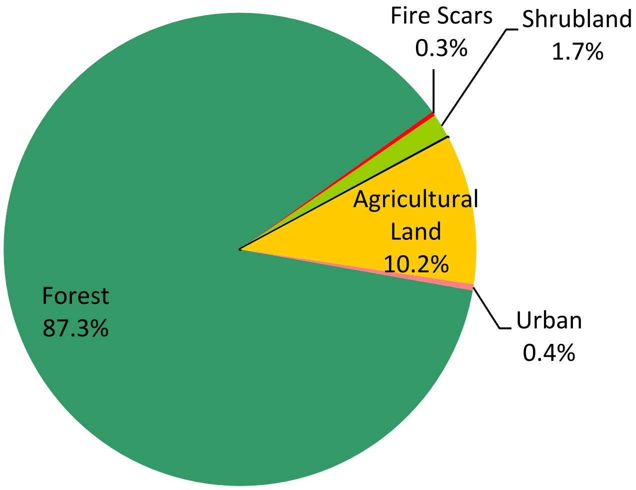

Figure 22. Land cover in the Atlantic Maritime Ecozone⁺, 2005.
Total land area is 196,049 km². Land area in the Grassland and Low Vegetation and Barren classes are very small (<0.01%). Note that urban area is the extent from the National Atlas as of 1996-1997.

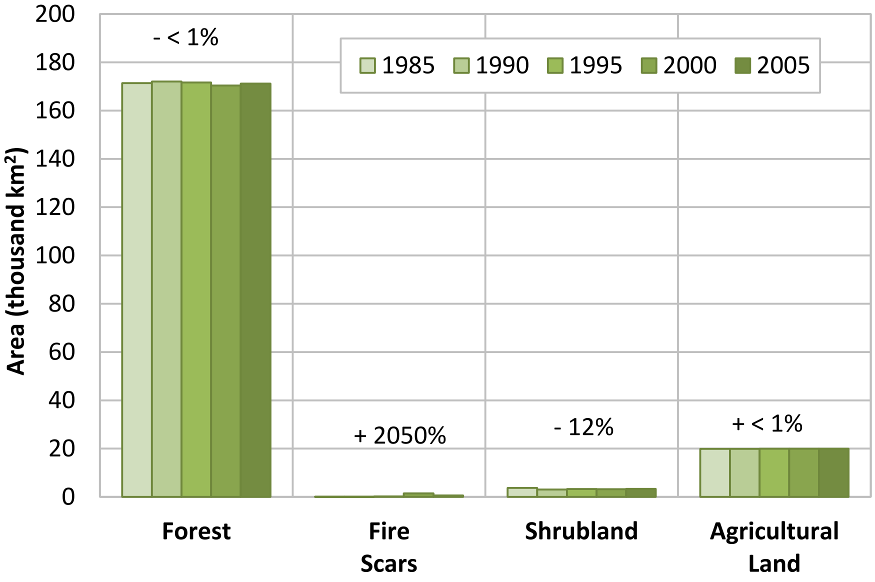

Figure 23. Area by land cover class across the Atlantic Maritime Ecozone⁺, 1985, 1990, 1995, 2000 and 2005.
Labels are the total percent change for each land cover class between 1985 and 2005.

Mixedwood Plains

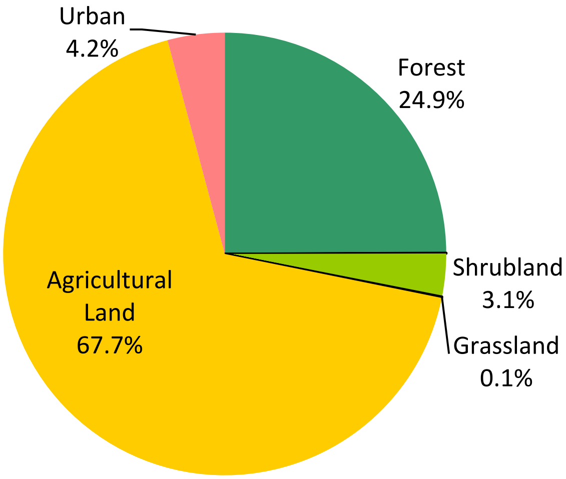

Figure 24. Land cover in the Mixedwood Plains Ecozone$^+$, 2005.
Land area in the Low Vegetation and Barren and Fire Scars classes are very small (<0.1%). Total land area is 111,675 km^2. Note that urban area is the extent from the National Atlas as of 1996-1997.

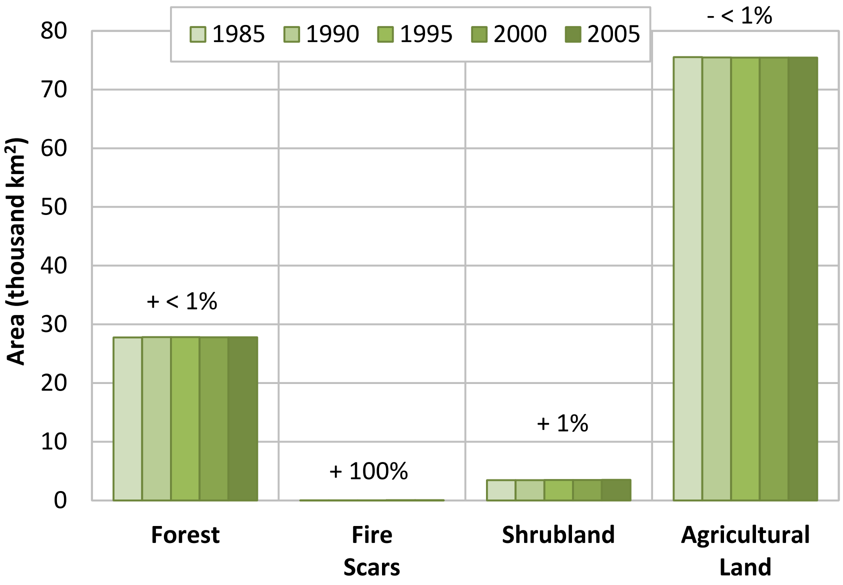

Figure 25. Area by land cover class across the Mixedwood Plains Ecozone$^+$, 1985, 1990, 1995, 2000 and 2005.
Labels are the total percent change for each land cover class between 1985 and 2005.
Though the area of Fire Scars increased by 100% during this period, the total area of Fire Scars in 2005 was only 36 km^2.

Boreal Plains

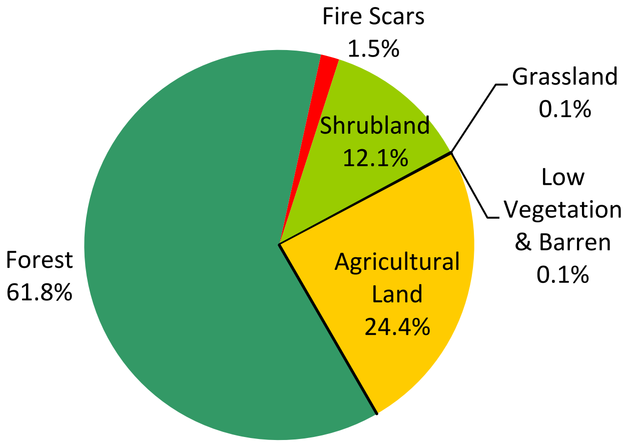

Figure 26. Land cover in the Boreal Plain Ecozone^{+}, 2005.
Land area in the Urban class (extent from the National Atlas as of 1996-1997) is very small (<0.01%).
Total land area is 628,102 km^{2}.

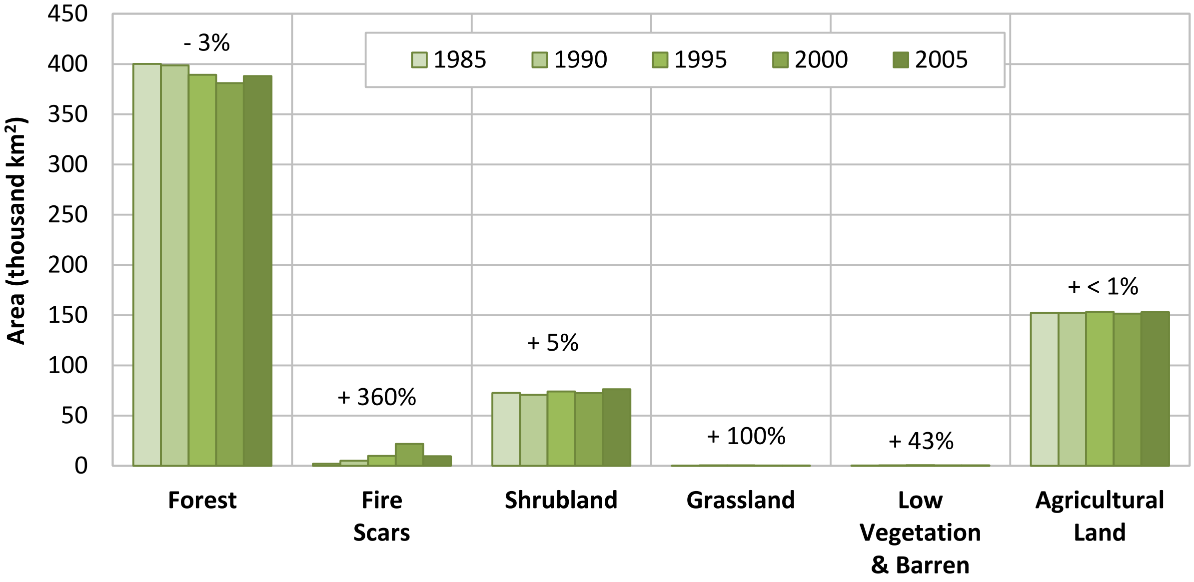

Figure 27. Area by land cover class across the Boreal Plain Ecozone^{+}, 1985, 1990, 1995, 2000 and 2005. Labels are the total percent change for each land cover class between 1985 and 2005.

Prairies

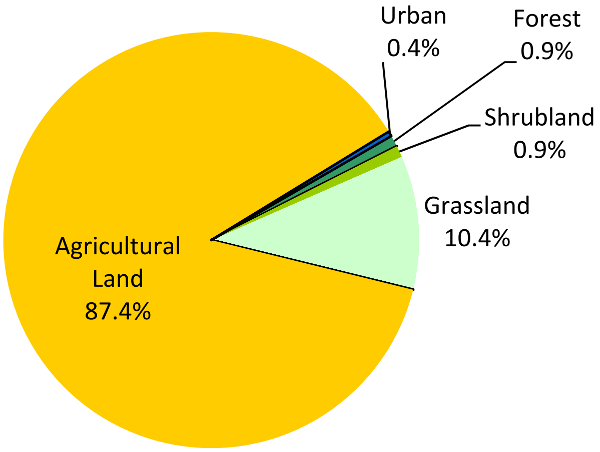

Figure 28. Land cover in the Prairies Ecozone^{+}*, 2005.*
Land area in the Low Vegetation and Barren and Fire Scars classes are very small (<0.01%). Total land area is 451,699 km^{2}*. Note that urban area is the extent from the National Atlas as of 1996-1997.*

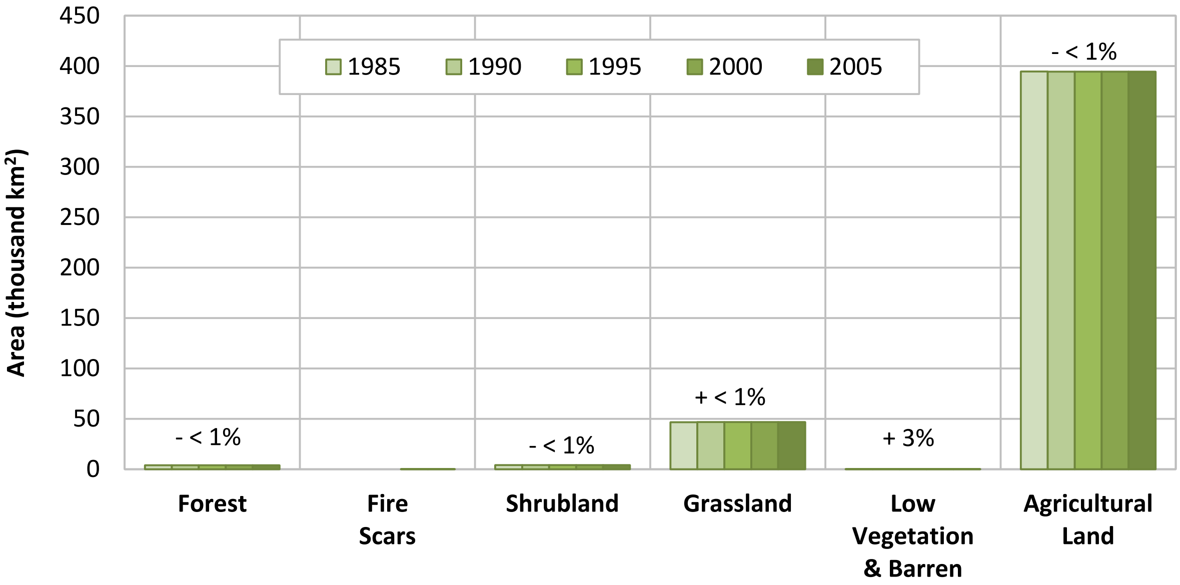

Figure 29. Area by land cover class across the Prairies Ecozone^{+}*, 1985, 1990, 1995, 2000 and 2005.*
Labels are the total percent change for each land cover class between 1985 and 2005.

Taiga Cordillera

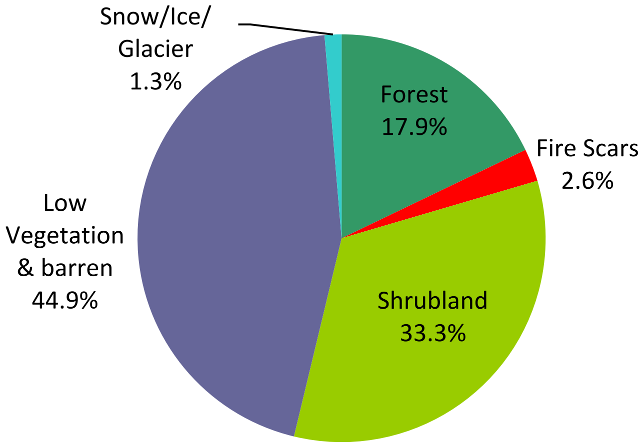

Figure 30. Land cover in the Taiga Cordillera Ecozone⁺, 2005.
Land area in the Grassland class is very small (<0.01%). Total land area is 336,528 km²

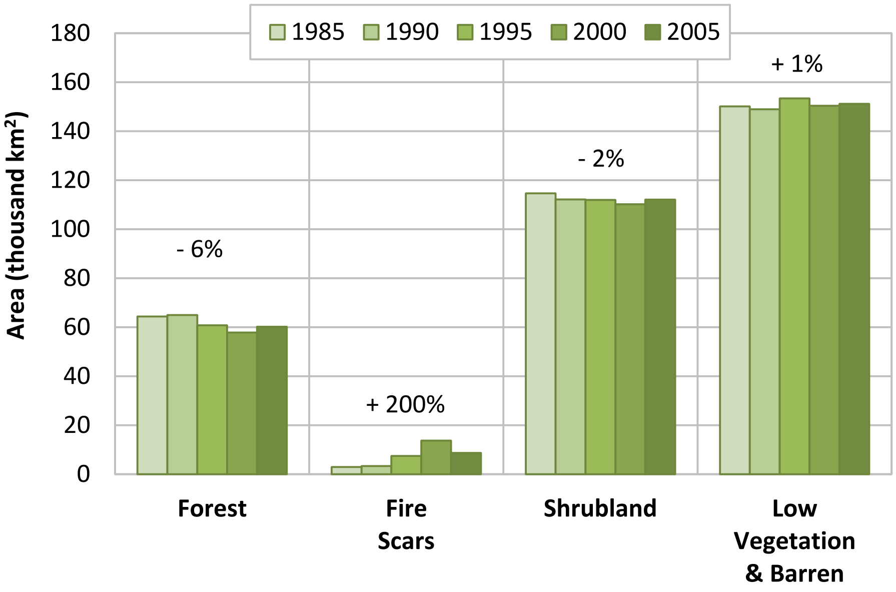

Figure 31. Area by land cover class across the Taiga Cordillera Ecozone⁺, 1985, 1990, 1995, 2000 and 2005.
Labels are the total percent change for each land cover class between 1985 and 2005.

Boreal Cordillera

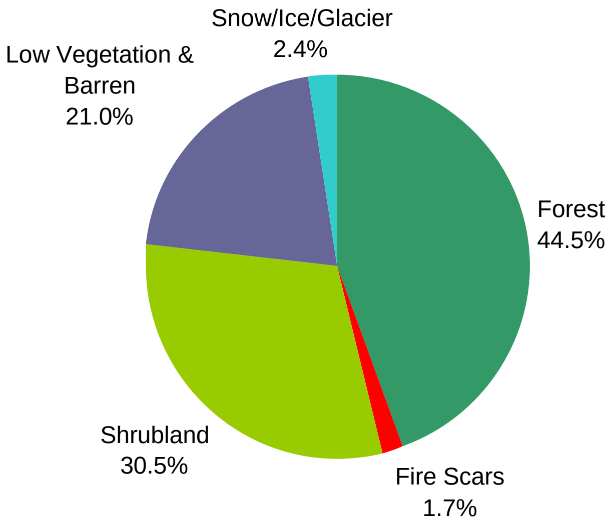

Figure 32. Land cover in the Boreal Cordillera Ecozone⁺, 2005.
Land area in the Urban class (extent from the National Atlas as of 1996-1997) is very small (<0.01%).
Total land area is 422,213 km^2.

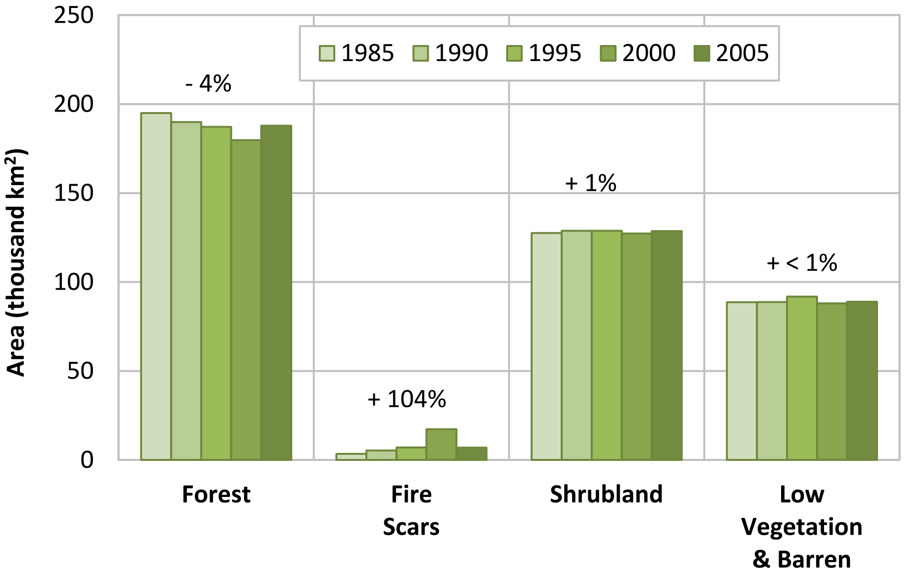

Figure 33. Area by land cover class across the Boreal Cordillera Ecozone⁺, 1985, 1990, 1995, 2000 and 2005.
Labels are the total percent change for each land cover class between 1985 and 2005.

Pacific Maritime

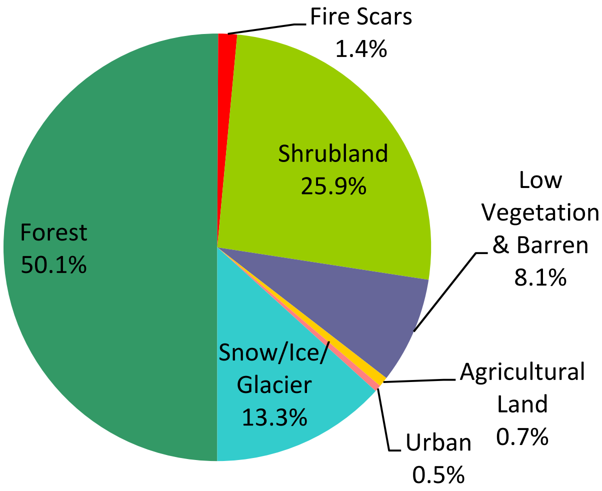

Figure 34. Land cover in the Pacific Maritime Ecozone⁺, 2005.
Total land area is 177,207 km². Note that urban area is the extent from the National Atlas as of 1996-1997.

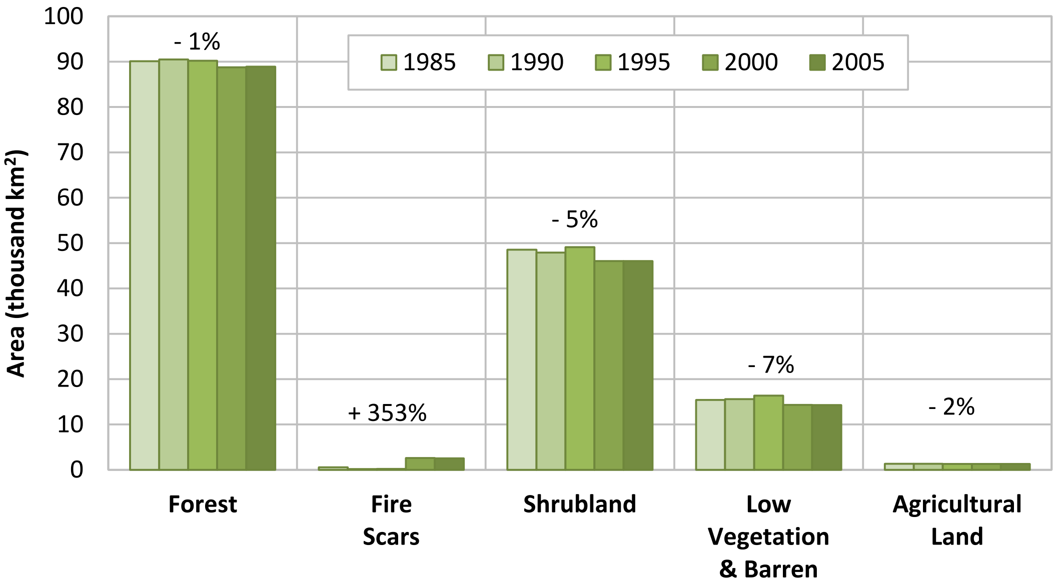

Figure 35. Area by land cover class across the Pacific Maritime Ecozone⁺, 1985, 1990, 1995, 2000 and 2005.
Labels are the total percent change for each land cover class between 1985 and 2005.

Montane Cordillera

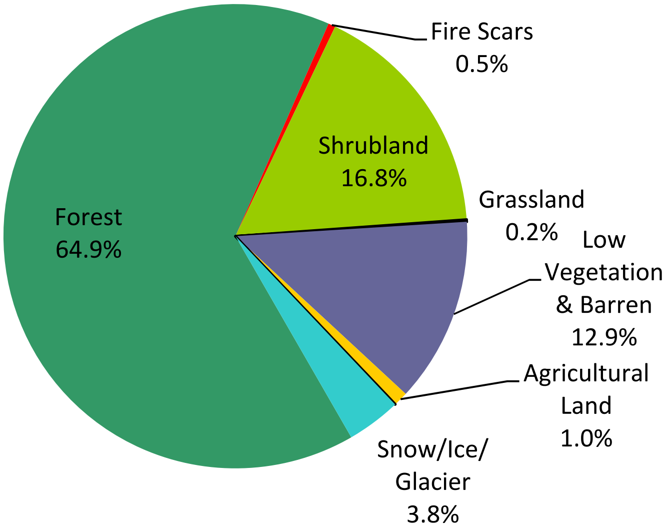

Figure 36. Land cover in the Montane Cordillera Ecozone^{+}, 2005.
Land area in the Urban class (extent from the National Atlas as of 1996-1997) is very small (<0.01%).
Total land area is 410,155 km^{2}.

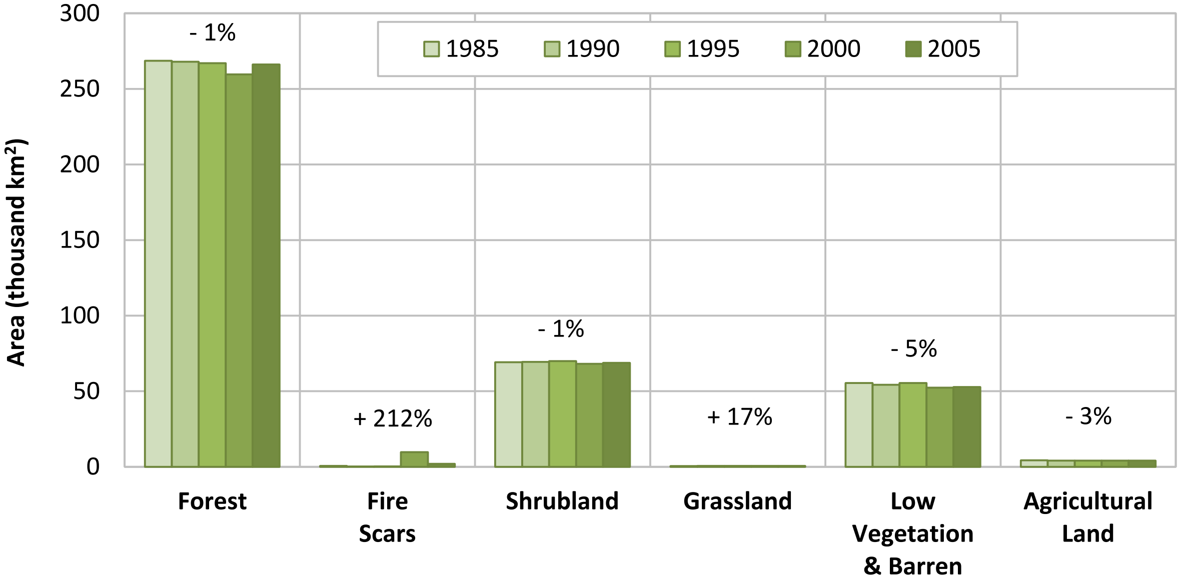

Figure 37. Area by land cover class across the Montane Cordillera Ecozone^{+}, 1985, 1990, 1995, 2000 and 2005.
Labels are the total percent change for each land cover class between 1985 and 20055.

Hudson Plains

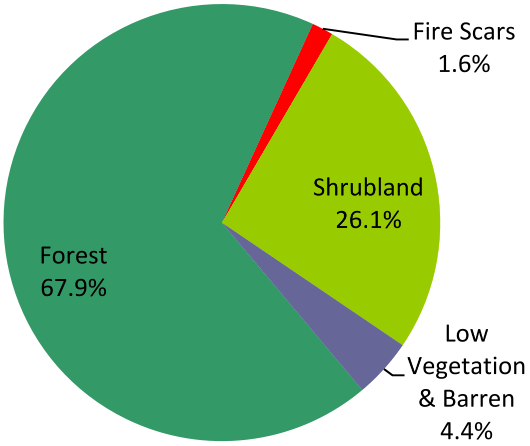

Figure 38. Land cover in the Hudson Plain Ecozone+, 2005.
Land area in the Agricultural Land class is very small (<0.01%). Total land area is 337,595 km^2.

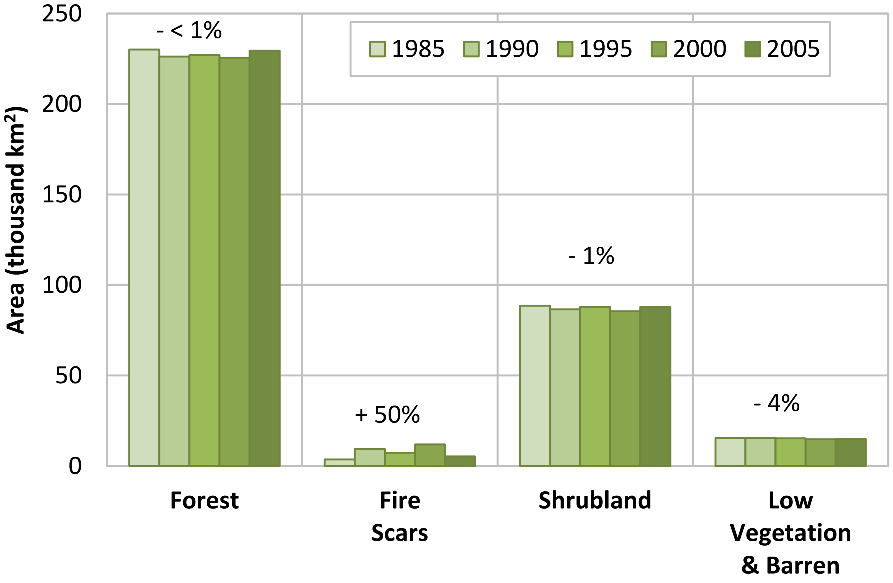

Figure 39. Area by land cover class across the Hudson Plain Ecozone+, 1985, 1990, 1995, 2000 and 2005.
Labels are the total percent change for each land cover class between 1985 and 2005.

Western Interior Basin

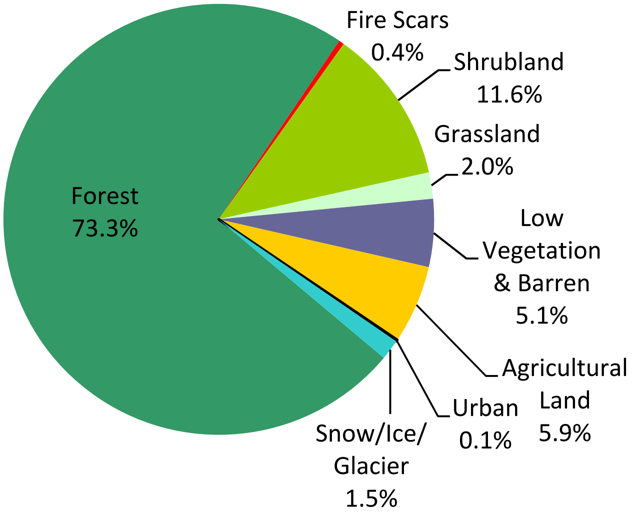

Figure 40. Land cover in the Western Interior Basin Ecozone⁺, 2005.
Total land area is 55,279 km^2. Note that urban area is the extent from the National Atlas as of 1996-1997.

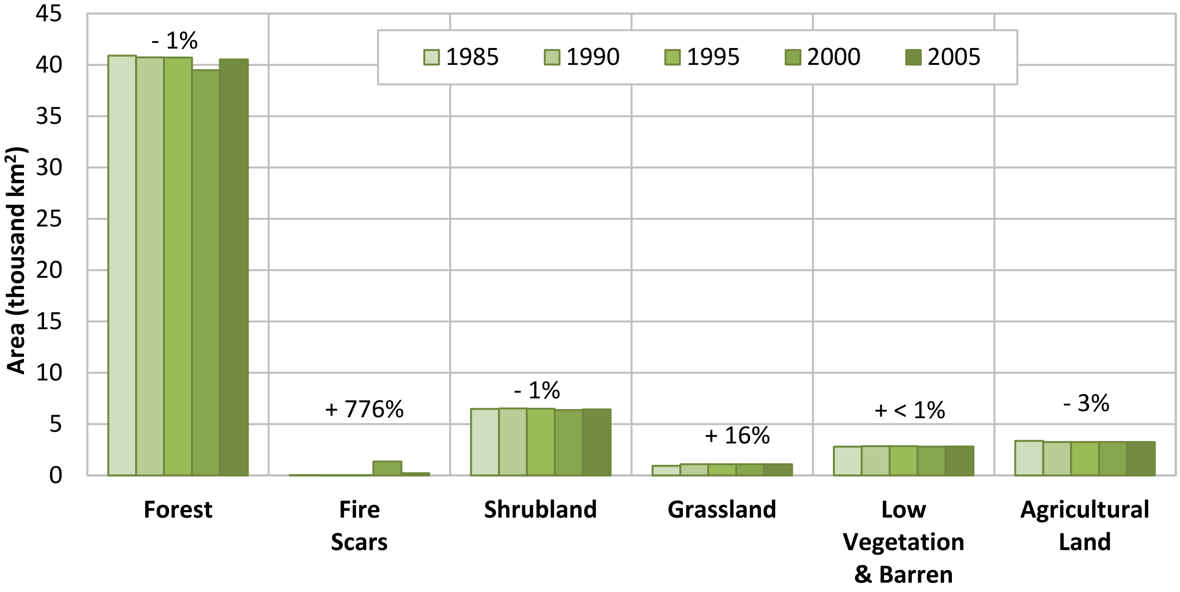

Figure 41. Area by land cover class across the Western Interior Basin Ecozone⁺, 1985, 1990, 1995, 2000 and 2005.
Labels are the total percent change for each land cover class between 1985 and 2005.

Newfoundland Boreal

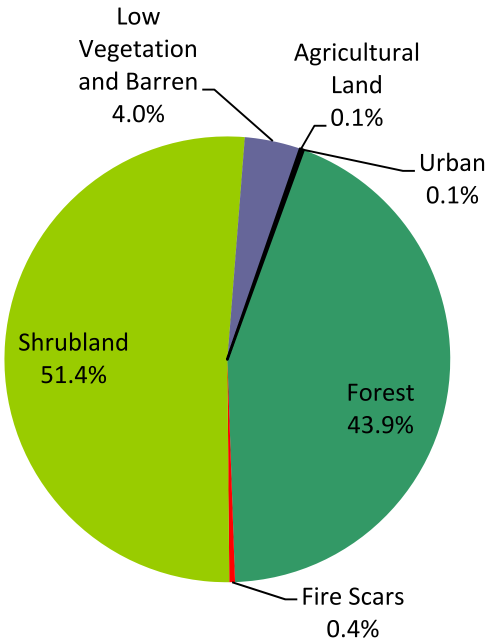

Figure 42. Land cover in the Newfoundland Boreal Ecozone⁺, 2005.
Total land area is 98,396 km2. Note that urban area is the extent from the National Atlas as of 1996-1997.

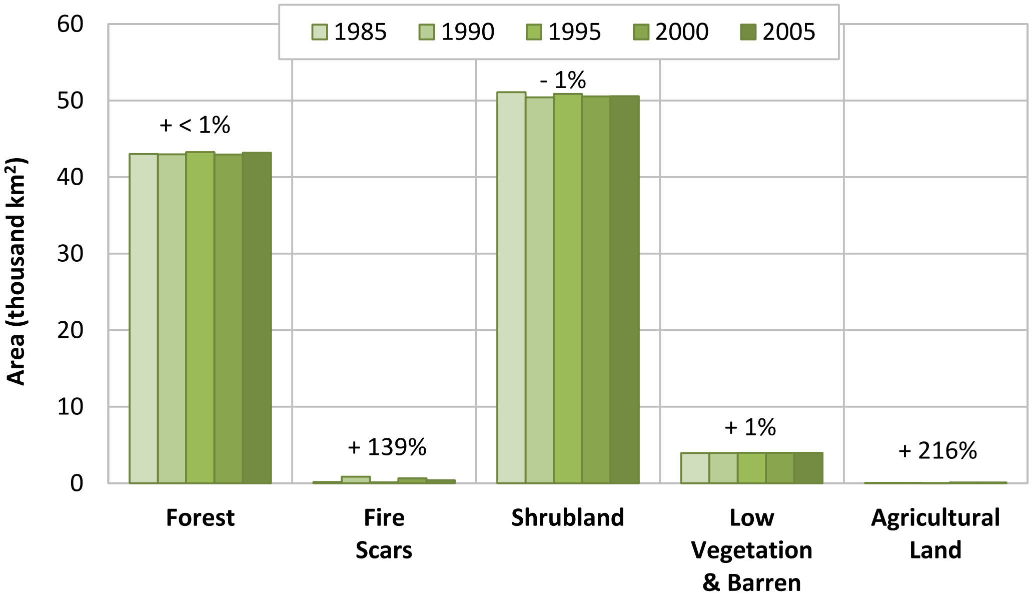

Figure 43. Area by land cover class across the Newfoundland Boreal Ecozone⁺, 1985, 1990, 1995, 2000 and 2005.
Labels are the total percent change for each land cover class between 1985 and 2005.