The Development of a Canadian Dynamic Habitat Index Using Multi-Temporal Satellite Estimates of Canopy Light Absorbance

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ABSTRACT

Monitoring patterns of fauna diversity across the landscape, both spatially and temporally, presents special challenges due to the dynamic nature of populations and complex interactions with the local and regional environment. One area where progress is being made is the development of relationships between regional biodiversity with indirect indicators or surrogates, such as vegetative production. In this paper we discuss implementation of a dynamic habitat index, originally developed in Australia, to Canadian conditions. The index, based on the fraction of photosynthetically active radiation (fPAR) absorbed by vegetation, a variable which is analogous to green vegetation cover, is derived solely from satellite data. The index utilizes time series of satellite observations of greenness to derive three indicators of the underlying vegetation dynamics; the cumulative annual greenness, the minimum level of perennial cover, and the degree of vegetation seasonality. We apply the index across Canada and compare the three components by ecozones, demonstrating that Canada's terrestrial environment can effectively be clustered into five major dynamic habitat regimes. These range from those with low cumulative greenness and highly seasonal variation in cover, to regimes which have high canopy light absorbance with limited seasonality and continuous annual green cover. By comparing data from multiple years, our analysis indicates that a number of these ecozones have experienced changes in their composition over the past six years. We believe this methodology can provide an initial stratification of large areas for biodiversity

monitoring and can be used to focus finer scale approaches to specific regions of interest or monitor regions too remote for comprehensive field surveys.

Key words: productivity, vegetation dynamics, large-area, ecozone, biodiversity, cluster analysis, dynamic habitat index, MODIS, fPAR, wildlife habitat

1. INTRODUCTION

Movement of fauna presents special challenges for the conservation of biodiversity as species are often dependent on a range of landscape ecosystems to provide food and habitat for their survival. Home range size and shape are among the most fundamental ecological parameters for species modeling and the analysis of factors influencing home range size has received constant research and management attention for the past quarter century. Understanding species use of space is vital for management and conservation to, for example, designate the size of management units to suit the species they are designed to protect (Hefindal et al. 2005).

The past two decades have seen the development of relationships between herbivore biomass and patterns of productivity based on the simple premise that the key requirements for existence of an organism are a supply of food to meet its metabolic needs and habitat for shelter and nesting (Olff et al. 2002, Berry et al. 2007). As survival and reproduction are often food limited, the availability of food in time and space is an important factor influencing the spatial organization of species (McLoughlin et al. 2000a). In addition, vegetation components also provide shelter and nesting resources for many animals (Cork and Catling 1996, Berry et al. 2007). As a result, temporal changes in the distribution and growth of vegetation is of major importance to the existence and persistence of fauna.

In areas were food is abundant and predictable in time (e.g., seasonality) and space (e.g., patchiness) small home ranges may be more likely to occur as animals are able to maximize energy intake over less area with or without territorial defense (McLoughlin et al. 2000b) and may be expected to have non-migratory movement patterns. In contrast, in areas with less food availability, more patchy distribution of vegetation or with seasonal depletion, species may have larger home ranges. These species may also, in some circumstances, face increases in competitor density and intruder pressure thus exhibiting dispersive behavior, surviving by relocating annually based on available food and habitat requirements (Berry et al. 2007, Woinarski et al. 1992). These types of relationships between home range, abundance and primary productivity / food availability have been developed for a range of species including Eurasian lynx where it was found that home range was inversely proportional to environmental productivity and seasonality (Herfindal et al. 2005). Similarly, Nilsen et al. (2005) found that leopard, wolf, and fisher home range sizes are all associated with measures of vegetation productivity including rainfall, soil nutrient status, and water availability. For African herbivores, East (1984) found measures of productivity could be associated with patterns of overall biodiversity distribution.

Land use change, disturbances such as harvesting, fire, and insect infestations and potential increases in climate variability further complicate the management of individual species. For example, a mountain pine beetle epidemic in Western Canada has affected an estimated 9.2 million ha in 2006, compared with 164,000

ha in 1999 (Westfall 2007). Similarly, overgrazing by animals, such as Caribou on lichen (Theaun et al., 2005), can result in landscape degradation persisting for as long as 50 years (Moser et al., 1979) due to the slow growth and ecological sensitivity of northern environments.

These factors place increasing demands on land managers who seek to ensure species protection whilst experiencing a general reduction in funds for assessing patterns of species diversity (Bailey et al 2004). As a result, cost effective methods are desperately needed to explain, predict, and map patterns of species abundance and movement in space/time and to better understand how particular ~~functional and~~ ecological groups of species respond to complex landscape disturbance and change.

One way of endeavoring to track resource availability through space and time is by utilizing readily-available information on vegetation and land use acquired by Earth observing satellites. Remote sensing offers an ideal technology to monitor and assess changes in vegetation cover and condition at a variety of spatial and temporal scales (e.g., Running et al. 2004). Leafy vegetation cover is the most fragile and therefore perhaps the single most vulnerable biotic component of terrestrial ecosystems with major disturbance events clearly discernable from remote observations (Potter et al. 2003, Fraser et al. 2005, Fraser and Latifovic 2005; Coops et al. 2006). Foliage burns relatively easily, can be readily blown down, cut to the ground, or consumed by herbivores. Shed leaves rapidly

decompose to blend in with background soil attributes. As a result, remote sensing of green vegetation cover provides a useful means to assess both current vegetative production as well as the detection of changes in production due to disturbance.

Since the launch of the first remote sensing satellites in the late 1970's green vegetation cover has been monitored daily (Myneni et al. 1998) across the globe, making available a time series of measurements that facilitate spatial-temporal analysis of vegetation production. A key metric of vegetation production from satellite imagery is the prediction of the fraction of photosynthetically active radiation (or fPAR) intercepted by vegetation, which is analogous to greenness cover (Knyazikhin et al. 1998) and ranging from zero (on barren land) to one (for dense cover). In theory, the higher the average fPAR level observed over the course of a seasonal plant growing cycle, the more dense the green leaf cover, and the less disturbed the vegetation cover. Conversely, the lower the average fPAR, the landscape is inferred to be less productive and subject to disturbance. fPAR is linearly related to the positive end of the more commonly used Normalized Difference Vegetation Index (NDVI), a measure of reflected radiation. Despite fPAR being less commonly applied, it is fPAR, not NDVI, that is required to calculate the rate at which carbon dioxide and energy from sunlight are assimilated into carbohydrates during photosynthesis of plant tissues, with summation of carbon assimilated by the vegetation canopy over time yielding the landscape gross primary productivity (Monteith 1972). Potter et al. (2003)

demonstrated that fPAR observed by daily satellite observations can successfully be used to monitor large-area ecosystem behavior. Over the entire globe, 10 years of greenness observations were analyzed to assess changes in the vegetation pattern due to a range of major ecosystem disturbances such as fire and insects. Nilsen et al. (2005) was among the first to link satellite measured greenness with measures of fauna diversity. They compared variations in the mean and seasonal greenness over a two year period with the home ranges of 12 carnivore species in the northern hemisphere to test the hypothesis of Harestad and Bunnell (1979) that species home ranges should decrease as a function of increasing productivity. Results indicated that the accuracy of prediction of 8 of the 12 species home range sizes was improved using the greenness observations.

Mackey et al. (2004) and Berry et al. (2007) developed, for the Australian continent, an integrated index, using satellite observations to track landscape productivity on a monthly time step, and assess how biomass is partitioned and made available as food and other habitat resources for fauna. The premise of the approach was that while some animal species are resident within a single landscape ecosystem, many vertebrate and invertebrate animal species are highly mobile, principally due to food and habitat requirements. Such species often move over large distances which may be regular, principally driven by seasonal changes, or irregular, with dispersive or nomadic movement reflecting less predictable changes (Gilmore et al. 2007). The integrated index was derived using measures

of mean annual, minimum, and seasonal variation in fPAR and was applied over the entire country for monthly observations in 2003. By comparing and monitoring the different proportions of these three greenness components, changes in vegetation production and seasonality can be assessed, which in turn provide insights into species habitat and forage conditions present for that year. Berry et al. (2007) found significant information about the structure and cover of Australian vegetation was conveyed by the fPAR derived index. Approximately 70% of the continent is arid and was well characterized by low minimum cover. The majority of the evergreen forest canopy maintained a high annual fPAR, and low annual variation in fPAR. This was support by additional evidence that as annual fPAR increases, the height and projected foliage cover of the woody component (i.e., trees and shrubs) of the vegetation also increases (Berry and Roderick 2002). In contrast, areas dominated by agricultural crops had moderate annual fPAR, large variations and low annual minimum cover. The authors concluded that vegetation related habitat resource availability, can readily be tracked through time using remotely sensed data, and it can be quantified in terms of carbon or energy assimilation over ecologically relevant timeframes (Berry et al. 2007).

In this paper we further develop the concept of a broad-scale integrative index of habitat suitability derived from information on vegetation greenness and cover for Canada. Our approach builds on the work of others, specifically Mackey et al. (2004) and Nilsen et al. (2005) who, as described above, utilized indices derived

from satellite based estimates of fPAR as a surrogate for environmental productivity. First we develop and present the fPAR data available for this application over Canada, and further develop the components of the index originally proposed by Mackey et al. (2004), to produce a Dynamic Habitat Index (DHI), as detailed in the Methods section. Once developed, we apply the dynamic habitat index over the entire Canadian land mass using data acquired from 2000 – 2005. Using information on the terrestrial ecozones of the country we then compare and contrast the dynamic habitat index values, utilizing cluster analysis investigate patterns between and within zones. Finally, we compare the annual dynamic habitat index from 2000 – 2005 against the long term mean to assess if any years are likely to have either resulted in decreased or increased home ranges of fauna based on variations in annual productivity. The application and future development of the index will then be discussed within the context of other biodiversity related research within Canada.

2. DATA

2.1 Fraction of Photosynthetically Active Radiation (fPAR) intercepted by vegetation

Globally, MODIS, on board the TERRA and AQUA platforms, is a critical tool providing a monitoring capacity of the Carbon cycle as part of the NASA Earth Observing System (Zhao et al. 2005). The MODIS sensors, launched in 1999 and 2001, provide near daily coverage of the globe at 1-km resolution in 36 spectral bands (Heinsch et al. 2006) and include state of the art geo-location,

atmospheric correction and cloud screening provided by a dedicated science team (Justice et al. 2002). Based on the MODIS satellite data, NASA provides a suite of atmospherically, geo-registered, data products on a routine basis, including fPAR, which is calculated from daily surface reflectances in a more rigorous way than previously was the case with other sensors (Tian *et al.*, 2000). As opposed to NDVI, fPAR is derived from a physically based model which describes the propagation of light in plant canopies and it can be used to retrieve a number of biophysical parameters including leaf area index (Tian *et al.* 2000). As a result, estimates of fPAR utilise a number of spectral bands (up to 7), not simply the red and near infrared reflectances as in the NDVI, and the retrieval algorithm takes into account sun angle, background reflectance, and view angle influences, whereas the algorithm to predict many other vegetation indices (including NDVI) do not. Still, fPAR estimates may be in error when following a recent fire (Steinberg et al., 2006), or where snow accumulates on the canopy (Yang et al., 2006).To minimize the influence of cloud and snow cover, atmospheric variation, and other confounding environmental conditions, the maximum daily fPAR is selected for each 8-day period and these 8-day composites are combined into monthly maximum fPAR products and mapped at a spatial resolution of 1-km. Global fPAR monthly images from 2000 to 2005 were accessed from Boston University MODIS product portal (http://cliveg.bu.edu). MODIS data collections began on Day 56 of 2000. To fill in the first 55 days following the start of the collection, we obtained averaged values for those dates as recorded over the following full five year's of data. As a result,

12 monthly composites were analysed for each year to derive the three annual

components of the index. In total 72 monthly composites were analysed over the

6 year period.

2.2 Ecological stratification

To obtain descriptions of the various biomes across Canada, we utilized the

National Ecological Framework of Environment Canada (Rowe and Sheard

1981). Stratification of biomes are based on a classification system whereby

each region is viewed as a discrete ecological system, with interactions between

geology, landform, soil, vegetation, climate, wildlife, water and human factors

considered. Reviews of the history ~~and the applications of~~ ecological

regionalization in Canada are given by Bailey et al. (1985) amongst others.

Ultimately, seven levels of generalization are available with 15 terrestrial

"ecozones" forming the broadest of the classes (Rowe and Sheard 1981, Wiken

1986, Ironside 1991). The ecozone level of stratification was used for our initial

analysis with each ecozone varying in shape, size, topography and climate and

thereby containing unique components of Canada's overall biodiversity (Table 1).

Table 1: List of the 15 terrestrial ecozones in Canada, and a brief summary of general landform, climate, vegetation and wildlife characteristics. Also shown is the total ecozone area and % of the total Canadian population that reside within the ecozone.

Ecozone	Climate	Vegetation / productivity	Wildlife (mammals/ birds)	Land Area (km^2) %of Total Area	Canadian population (%)
Arctic Cordillera	Extremely cold, dry; continuous permafrost	Mainly unvegetated; some shrub–herb tundra	Polar Bear (along coast), Arctic Hare; Northern Fulmar, Common Ringed Plover, Snow Bunting	230 873 2%	<0.01
Northern Arctic	Very cold, dry; continuous permafrost	Herb–lichen tundra	Peary Caribou, Muskox, Wolf, Arctic Hare; Red-throated Loon, Brant, ptarmigan, Greater Snow Goose	1 361 433 14%	0
Southern Arctic	Cold, dry; continuous permafrost	Shrub–herb tundra	Barren-ground Caribou, Wolf, Grizzly Bear, Arctic Fox, Arctic Ground Squirrel, lemming; Arctic Loon, ptarmigan, Snowy Owl	773 041 8%	0
Taiga Plain	Cold, semiarid to moist; discontinuous permafrost	Open to closed mixed forest	Moose, Woodland Caribou, Wood Bison, Wolf, Black Bear, Red Squirrel; Northern Shrike, Spruce Grouse	580 139 6%	0
Taiga Shield	Cold, moist to semiarid; discontinuous permafrost	Open evergreen and deciduous, lichen, shrub, tundra	Moose, Barren-ground Caribou, Wolf, Snowshoe Hare, Red Squirrel; Red-necked Phalarope, Northern Shrike	1 253 887 13%	0
Hudson Plain	Cold to mild, semiarid; discontinuous permafrost	Wetland; some herb, lichen tundra, evergreen forest	Woodland Caribou, Moose, Black Bear, marten, Arctic Fox; Canada Goose	353 364 4%	0
Boreal Shield	Cold, moist	Evergreen forest, mixed evergreen, deciduous forest	White-tailed Deer, Moose, Black Bear, Canada Lynx, marten, Red Squirrel; Boreal Owl, Blue Jay	1 782 252 18%	10

Atlantic Maritime	Cool, wet	Mixed deciduous, evergreen forest	White-tailed Deer, Moose, Black Bear, Coyote, Raccoon; Blue Jay, Eastern Bluebird	183 978 2%	9
Mixed wood Plain	Cool to mild, moist	Mixed deciduous, evergreen forest	White-tailed Deer, Red Fox, Raccoon, Striped Skunk, beaver, Grey Squirrel; Great Blue Heron, Blue Jay	138 421 1%	51
Boreal Plain	Cold, moist	Mixed evergreen, deciduous forest	Woodland Caribou, Mule Deer, Moose, Black Bear, beaver, Muskrat; Boreal Owl, Blue Jay	679 969 7%	3
Prairies	Cold, semiarid	Grass; scattered deciduous forest	Mule Deer, White-tailed Deer, Pronghorn, Coyote, Prairie Dog; Sage Grouse, Burrowing Owl	469 681 5%	14
Taiga Cordillera	Cold, semiarid; discontinuous permafrost	Shrub, herb, moss, tundra	Dall's Sheep, Grant's Caribou, Black Bear, Grizzly Bear; Peregrine Falcon, Ptarmigan	264 480 3%	<0.01
Boreal Cordillera	Moderately cold, moist	Largely evergreen forest; tundra, open woodland	Moose, Dall's Sheep, Grizzly Bear, Black Bear; Ptarmigan, Spruce Grouse	459 680 5%	0
Pacific Maritime	Mild, temperate, very wet to cold alpine	Coastal evergreen forest	Black Bear, Grizzly Bear, Mountain Lion; Black Oystercatcher, Tufted Puffin	205 175 2%	9
Montane Cordillera	Moderately cold, moist to arid	Evergreen forest, alpine tundra, interior grassland	Woodland Caribou, Mule Deer, Moose, North Armerican Elk, Mountain Goat; Blue Grouse, Steller's Jay	479 057 5%	3

3. METHODS

Mackey et al. (2004) proposed a dynamic habitat index, for Australian conditions, based on three indices calculated from a single year (2003) of MODIS monthly fPAR: the annual mean fPAR, the annual minimum fPAR, and the coefficient of variation of fPAR. By comparing and monitoring the different proportions of these three fPAR components, changes in vegetation production and seasonality can be assessed, designed to provide insights into species habitat and forage conditions present for that year. In our approach we apply a similar methodology to that outlined by Mackey et al. (2004); however, modified slightly to be more applicable for Canadian conditions and vegetation types. Three indices of an annual sequence of MODIS monthly fPAR are computed: (a) the cumulative annual fPAR, providing an indication of overall site greenness; (b) the minimum annual apparent cover, providing an indication of the base level of cover observed at a location, and; (c) the variation of the greenness , estimated as the coefficient of variation (standard deviation divided by the mean). We utilize the full historical archive of MODIS data and compute the three fPAR components for each year from 2000 – 2005, as well as a long term index representing the average components over the 6 year time period. The rationale for each of the components is explained in more depth below.

3.1 Annual Cumulative Greenness

As previously noted, strong linkages have been demonstrated between canopy light absorbance, or greenness, and species home ranges and abundance. Researchers have integrated greenness over a specific monthly period, growing season, or for the entire year to create surrogate variables for overall landscape greenness. These integrated indices of landscape greenness have been shown to be related to ~~terrestrial~~ net primary productivity (Goward et al. 1985) and are based on both a strong underlying theoretical basis and significant empirical correlations (Sellers 1985, Fung et al. 1987, Potter et al. 1993) and found to be significant indicators of vegetation production over a variety of land cover types such as forests (Coops et al. 1999), grasslands (Wang et al. 2004), crops (Groten 1993), as well as over a range of scales (Waring et al. 2006). To estimate the annual integrated greenness we sum the monthly fPAR observations over the 12 months for each year to produce an annual greenness component for each year between 2000 – 2005. These components were then averaged to produce a long term annual cumulative greenness component.

3.2 Annual Minimum Cover

In addition to the overall greenness of a site, the capacity of the landscape to support adequate levels of green vegetation cover over the entire year is an important factor for food access and habitat. The continual provision of food and habitat resources throughout the year is of particular interest to wildlife conservationists, as changes in the amount and quality of available vegetative

cover influences behavior of many herbivorous species, and ultimately, the carnivorous species which prey upon them (Schwartz et al. 2006). Locations without significant snow cover in autumn will maintain a cover of green biomass into winter providing accessible food resources and habitat. Provision of cover at different times of the year has been shown to influence female and male home ranges differently. For example the home ranges of male deer remain constant with changes in cover with males remaining to protect territory; whereas, female deer increase their home ranges as they are more able to move and select new areas based on increased green cover (Cimino and Lovari 2003). Change in green cover is detectable from satellite observations by estimating the minimum amount of green cover over the year. In areas which are snow covered for significant portions of the year in the minimum green cover will be zero. In contrast, areas which experience no snow cover and maintain varying degrees of vegetated cover throughout the year will have positive annual greenness values.

3.3 Seasonal variation in landscape greenness

Finally, the seasonal pattern of vegetation development at a given location often depends on the climate and geography. For example, the arctic and sub-arctic tundra regions of Canada have a much shorter growing season than the forests or grasslands in the more temperate regions. Such context needs to be considered when applying dynamic indices of habitat productivity to a given landscape, as seasonality through its effects on essential resources such as food, water, and nutrients, is expected to exert selective pressure on life history

traits (Boyce 1979, McLoughlin et al 2000b). Many researchers have utilized

information on seasonality, such as data on rainfall, solar radiation, and

evapotranspiration to estimate the length of the growing season and the

seasonal variation experienced at a site across the growing season (Reed et al.

1994, Zhang et al. 2003). From satellite derived greenness we capture this

seasonality as the greenness coefficient of variation (standard deviation divided

by the mean greenness for the year). Sites having high seasonality will have

large variations in greenness over the annual cycle compared to their mean

value, such as productive agriculture land cover and seasonal herbaceous

landscapes. Sites with low seasonality are indicative of areas that have

consistent vegetation production throughout the year such as evergreen forests.

3.4 The Canadian Dynamic Habitat index (DHI)

The annual cumulative greenness , annual minimum fPAR, and the coefficient of

variation of fPAR were computed for each year (2000 – 2005) from the monthly

fPAR layers. In addition, the long term mean of each indicator was calculated by

averaging the annual value over the 6 year period. Ecozone boundaries were

then used as a stratification layer, whereby yearly and long term means for each

of the three components were calculated per ecozone. In order to differentiate

how the component values for the 15 terrestrial ecozones behaved, the ecozone

averages from each of the three long term components were analyzed using

cluster analysis. Cluster analysis has been widely applied to a variety of research

problems, and provides a basis for classifying objects by joining pairs with the

highest level of similarity into new combined groups. This process is then repeated until a single group remains and provides a means of hierarchically classifying ecozones based on key attributes. The 15 ecozone averages for the three long term dynamic habitat index components were clustered based on the Euclidean distances between clusters using equation 1,

$$\boxed{} \qquad\qquad (1)$$

where $\boxed{}$ is the Euclidian distance between cluster $\square$ and all other clusters in terms of $\boxed{}$ and $\square$, representing long term integrated fPAR, minimum fPAR, and fPAR coefficient of variation, respectively. A hierarchical grouping tree is then produced to graphically represent how larger groups can be developed based on combining similarly behaving ecoregions.

In addition to undertaking cluster analysis, we compared the three dynamic habitat components from each year to their long term respective means to establish if any major structural changes to habitat may have occurred at an ecosystem level over the 6 year MODIS archive. To make this comparison, we follow a similar approach of Potter et al. (2003) and Mildrexler et al. (2007) whereby significant changes in the annual satellite record can be detected as deviations from the long term mean using thresholds derived from scaling the differences (standard deviations) between annual and long term values. This

approach assumes that a sustained disturbance event can be defined as any

decline in average annual fPAR that lasts for at least 12 monthly observations at

any specific pixel location. Another assumption is that the structure of the

vegetation has been severely altered or destroyed during the disturbance event

at a magnitude that lowers fPAR for at least one seasonal growing cycle.

Therefore, any ecozone that had a significant variation from the long term mean

in any of the three components was flagged, and the total number of annual

deviations summed and compared. Ecozones with the highest number of

deviations from the long term mean are therefore likely to be regions where there

has been significant deviation in the 3 index components over the past 6 years.

4. RESULTS

The distribution of the terrestrial ecozones across Canada are shown in Figure 1,

and the three components of the dynamic habitat index are shown in Figure 2(a)-

(c), with the combined dynamic habitat index displayed in Figure 3. By assigning

key attributes of habitat variability to different components the combined index

provides information on the overall patterns of landscape productivity, and by

inference, aspects of biodiversity and habitat quality. In northern Canada, the

Arctic Cordillera and the Northern Arctic ecozones experience significant polar

darkness measured in weeks to months, with permanent snow cover typically

occurring from September to June. Extremely low temperatures combined with

an average precipitation of less than 200 mm per year severely limit major

vegetation development resulting in very low annual cover. Figure 2(a) indicates

the overall greenness of these landscapes is very low, resulting in a low

integrated annual cumulative greenness. Similarly the amount of minimum cover

is also very low (Figure 2b). Away from the outcrops and rock, and further south

into the southern arctic, soil conditions improve and, in the spring and summer,

large flushes in vegetation cover occur resulting in increasing overall greenness
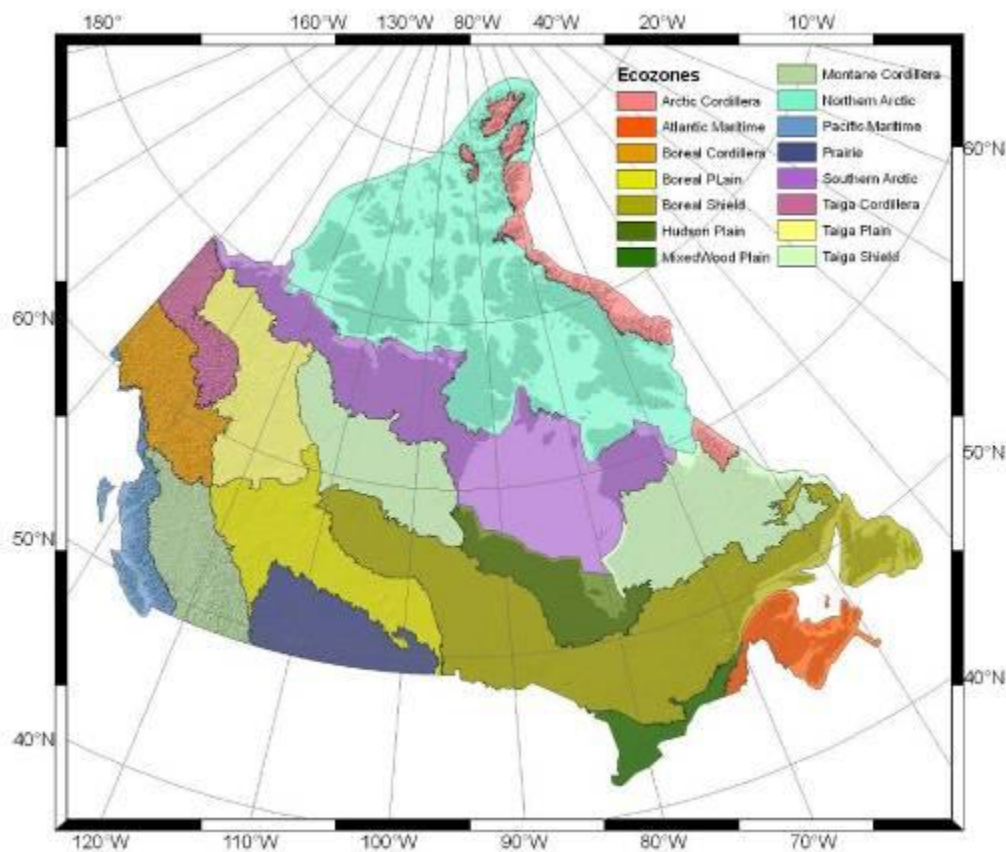
and high seasonality (Figure 2c).

Figure 1: Coverage of the 15 terrestrial ecozones across Canada. Ecozone boundaries are highlighted in grey. Select urban locations are noted as are main elements of the Canadian road network.

The Prairie ecozone, typified by post-glacial landscapes with low rolling

topography and flat areas (resulting from historic lake bed sedimentation), the

dynamic habitat index follows the same general trends as the Arctic Cordillera

and Northern Arctic ecozones. Similar to the Arctic, the Prairie ecozone will have snow cover in winter; however, in the summer the region ~~contains the majority of the country's productive~~ agricultural cropland, rangeland, and pasture. As a result, the cumulative greenness is much higher than the northern ecozones, and the seasonality is comparatively less. In the west of the country the Pacific Maritime ecozone contains principally evergreen needle-leaf forests which have permanent foliage cover throughout the year, with sustained high levels of production resulting in permanent, high levels of greenness. This consistently high annual greenness is related in the low seasonality (Figure 2c). The Montane Cordillera ecozone has highly variable climate and vegetation types, ranging from alpine tundra and dense conifer forests to ~~dry sagebrush and~~ grasslands. As a result, the region is typified by high seasonality, and average levels of minimum cover and annual greenness .

Integrated Annual Productivity

High

Low

A

Minimum Annual Cover

High

Low
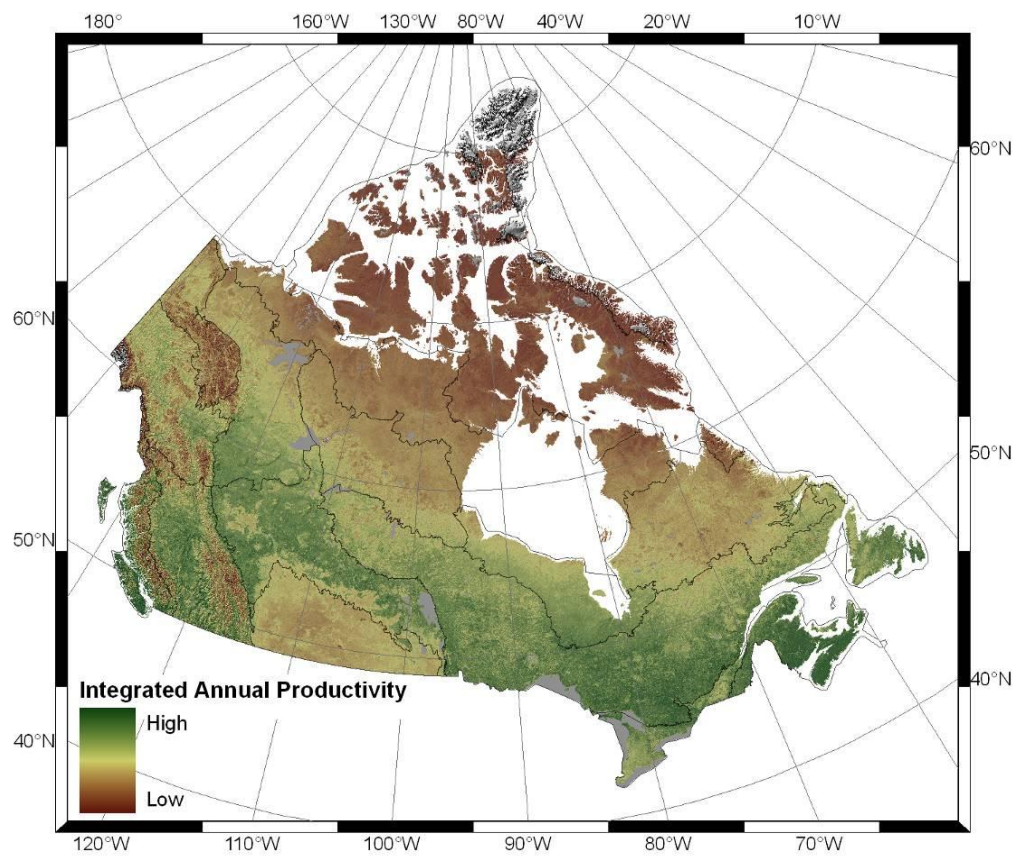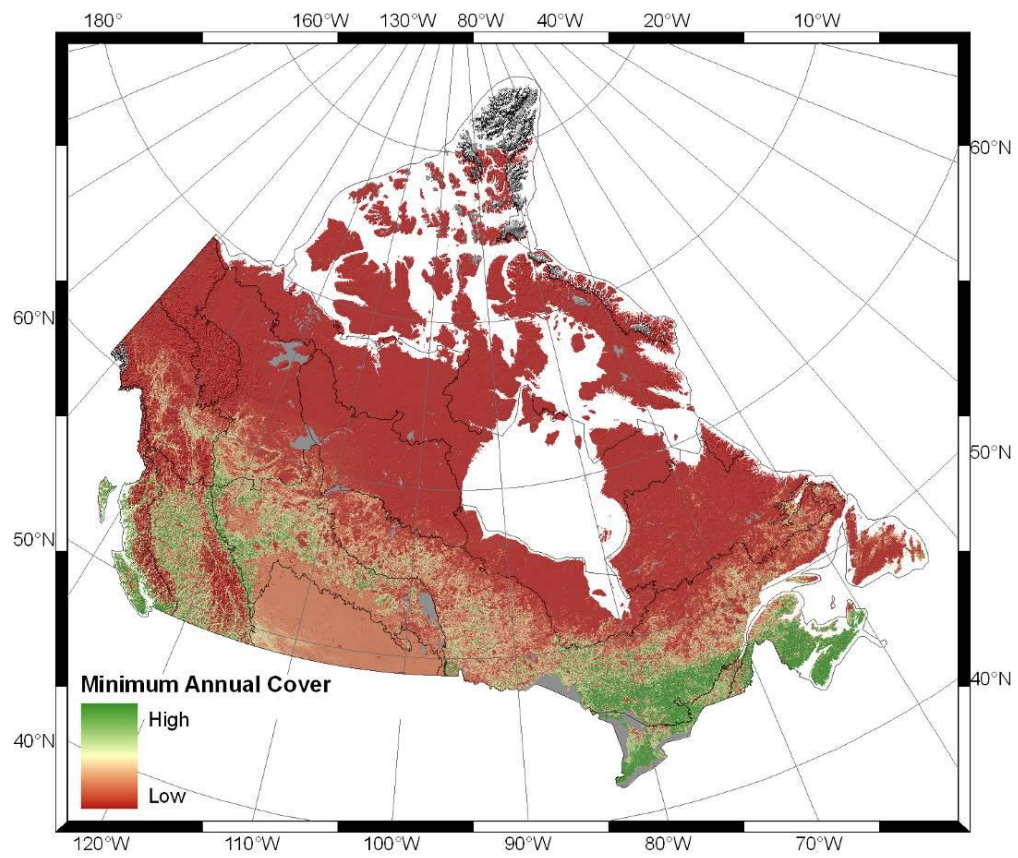
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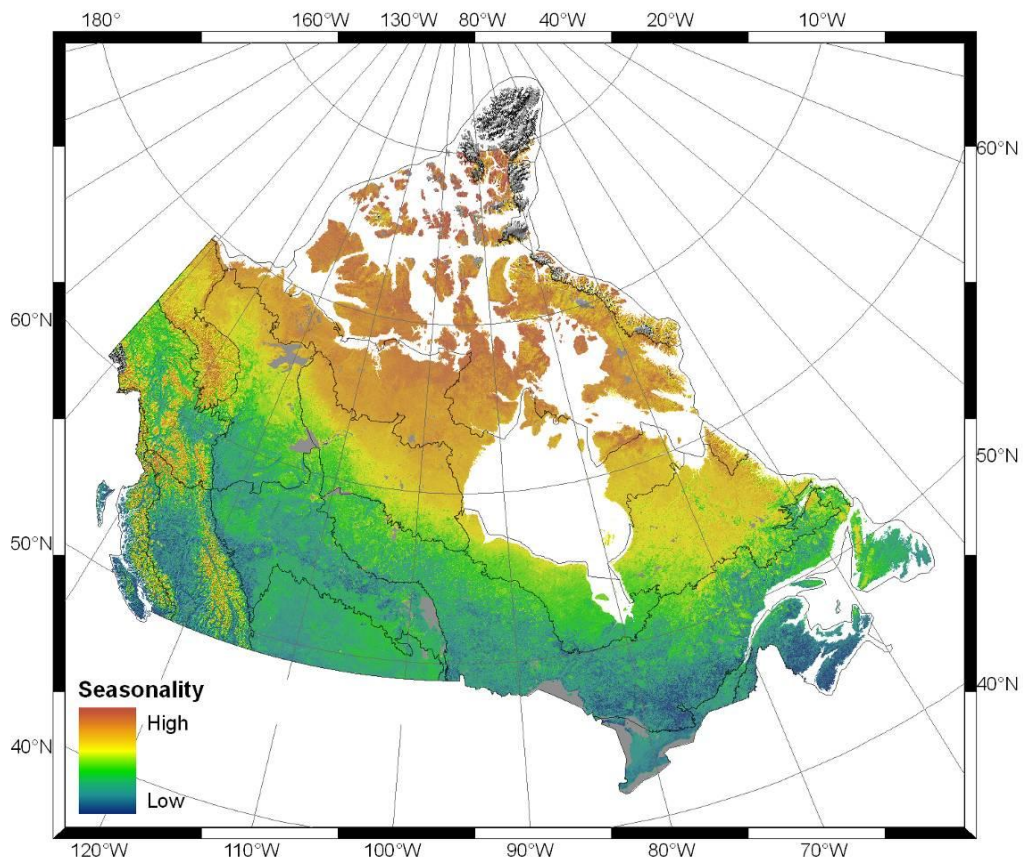
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Figure 2: The Canadian dynamic habitat index components; (a) annual greenness, (b) minimum annual cover; and (c) seasonality averaged over the 6 years of observations.

South of the Arctic ecozones, the Taiga Plains and the Taiga Shield ecozones are principally boreal coniferous forests which, like the Pacific Maritime, do not experience major seasonal variations in foliage cover. As a result, the annual cover is relatively high, and the seasonality less compared to the northern ecozones. These ecozones are also relatively productive, and feature a rich diversity of plants, birds, and mammals compared to the Sub-arctic and Arctic ecozones, as is evident in the high greenness values. To the east, the wetland

dominated Hudson Plain ecozone shows a very high annual production, high levels of annual cover, and moderate seasonality. The deciduous and evergreen Mixedwood Plains ecozone and the Atlantic Maritime ecozones again show high levels of annual greenness cover, likely reflecting the mix of agriculture and woodlands in the region. Southern portions in these ecozones have greater cumulative greenness, and less pronounced seasonality due to the more moderate climate. Figure 3 visualizes the three components of the DHI jointly, highlighting where the components are correlated, and where they differ. In this visualization, increasing intensities of seasonality were assigned to the red band, increasing annual greenness to the green band, and increasing levels of minimum cover to the blue band. The extensive light blue areas represented the most productive land with high minimum cover and little seasonality, whereas the darker purple areas, dominant in the Prairies, experience moderate productivity, moderate seasonality, and low minimum cover. The bright red arctic ecozones are highly seasonal, with low minimum cover, and low productivity.
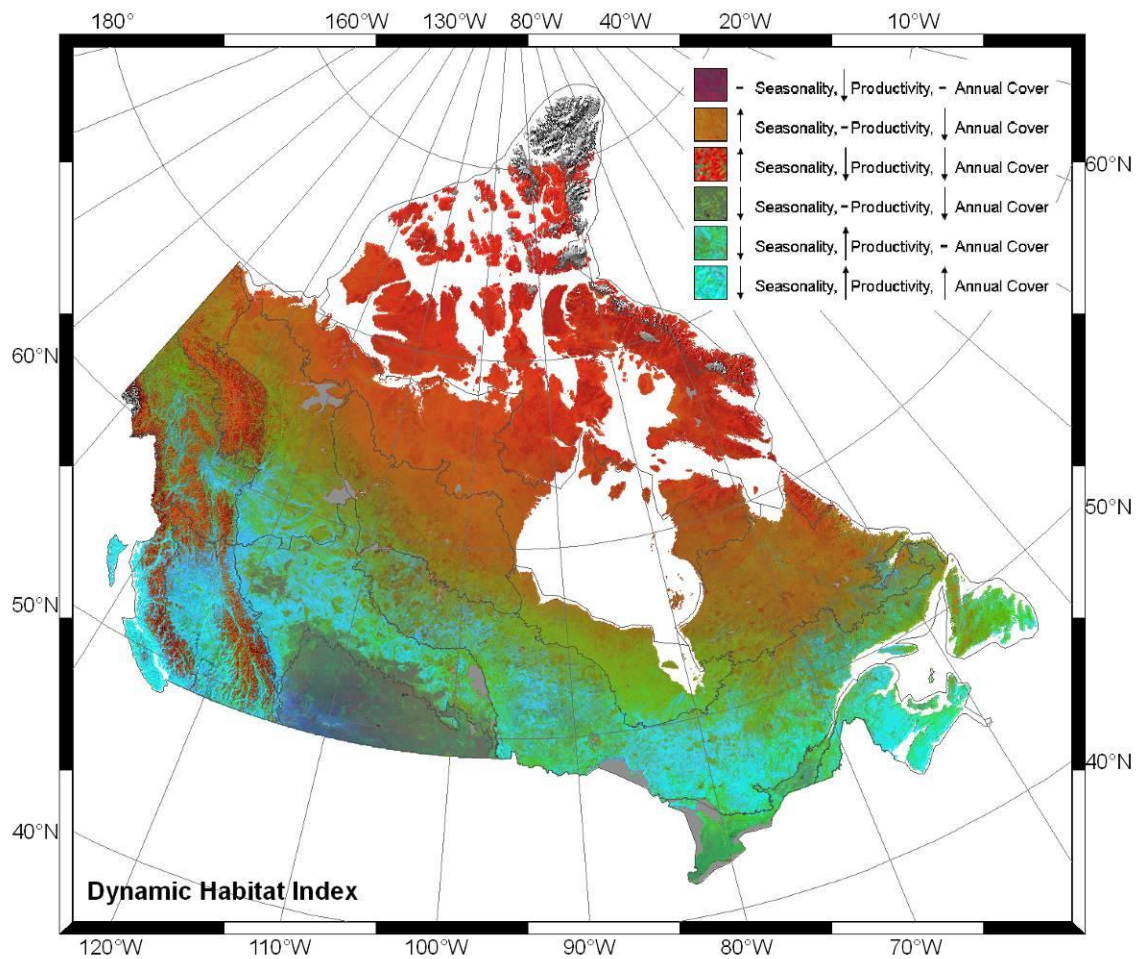
Figure 3: The combined dynamic habitat index derived from the long term (2000 – 2005) components. Ecozone boundaries are highlighted in grey. The composite image was developed by assigning the annual integrated greenness to the green band, the annual cover to the blue band, and the seasonality to the red band. Bright red areas have low annual mean fPAR, low annual minimum fPAR and high seasonal variability. Thus, bright red areas indicate locations where the small of amount of annual greenness that occurs was evident for only part of the year, Bright cyan areas have a high mean, a high minimum and low variability and represents locations with vegetation that was consistently green throughout the year. Darker blue indicates landscapes with a low mean, a high minimum, and low variability. Orange areas indicate moderate landscape greenness that varies throughout the year. Green areas are high annual production, a high landscape greenness and low seasonality. Symbology: ↑High, ↓Low and –moderate.

4.1 Ecozone characterization by Dynamic Habitat Index

Custer analysis on the 15 terrestrial ecozones indicates that many of the ecozones follow similar patterns with respect to the three habitat index components (Figure 4). At the 40% merging level (indicated by linking distance), 5 clear groupings of ecozones are evident. The first cluster characterizes habitats which are highly variable with respect to their annual green cover, have no perennial cover, and have very low annual greenness. This cluster is typical of Arctic Cordillera and the Northern Arctic ecozones. A second habitat cluster is slightly less restrictive with respect to its cumulative greenness and with more patchy perennial cover compared to the northern arctic. This cluster is typified by the Southern Arctic ecozone. A third habitat cluster comprises the Taiga Plain, Taiga Shield, Prairie, and Taiga Cordillera - all of which have moderate cumulative greenness, and experience a high degree of seasonality associated with either a highly productive crop cycle, or periods of snow cover. This highly variable seasonality has the effect of reducing the overall greenness of these ecozones compared to the denser and more productive forests of the more southern boreal and coastal ecozones. The fourth major cluster of ecozones includes evergreen forests, and wetlands, which are highly productive year round, resulting in high annual cumulative greenness, with limited seasonality and continuous green cover throughout the year. This habitat is common across much of Canada including large areas of the Boreal Shield, Boreal Plain, Mixedwood Plain, Pacific Maritime, Montane Cordillera, and Hudson Plain ecozones. The final cluster is a small area in Canada's east typified by

productive forested landscapes, with high annual cumulative greenness, limited

seasonality and a very high annual minimum cover indicative of a high biomass

ecozone. The Atlantic Maritime ecozone is alone within this unique habitat
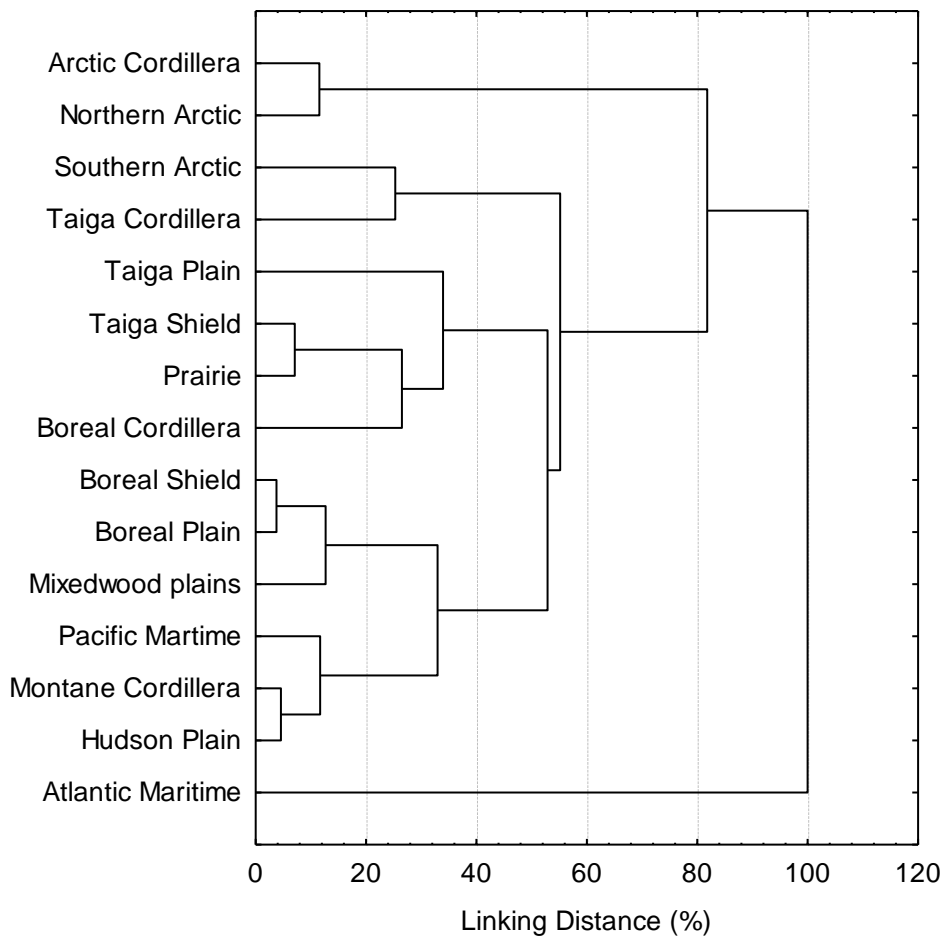
cluster.

Figure 4: A hierarchical tree derived from cluster analysis on the 15 terrestrial ecozones indicates that many of the ecozones follow similar patterns with respect to the three habitat index components. Note the formation of five large clusters at the 40% relative Euclidean distance.
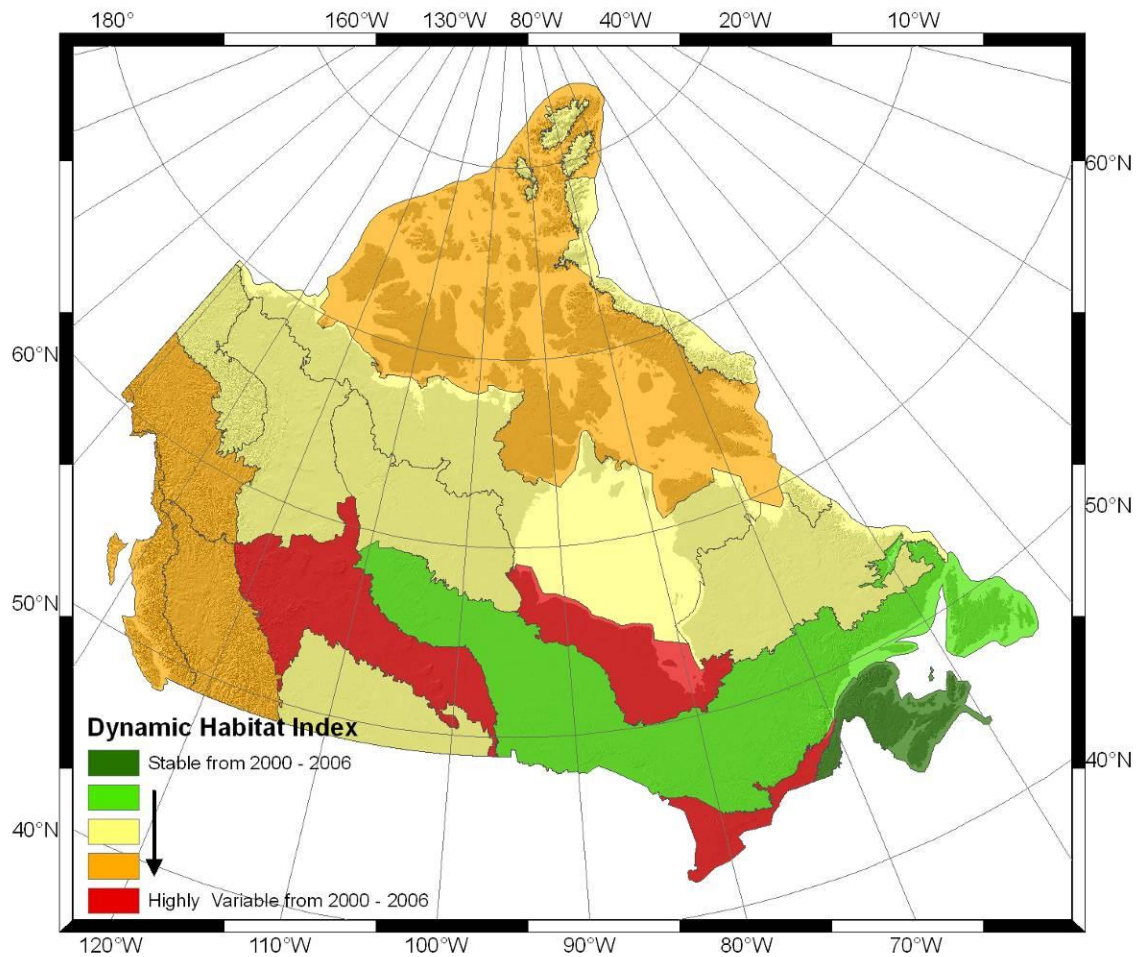
Figure 5: Relative score of the occurrence of major deviations from the long term of the three dynamic habitat components from 2000 – 2005. Three ecozones are highlighted which have the highest number of deviations from the long term mean: the Boreal Plain, Hudson Plain and Mixedwood plains. Other ecozones which are subject to a high degree of variability are the Montane Cordillera, Pacific Martime, Boreal Cordilleria, and Southern and North Arctic ecozones.

We propose that if the dynamic habitat index of individual ecoregions was highly variable from 2000 – 2005, the region may have experienced, or be characterized by, highly variable habitat and food supply, and this may be indicative of changes in species richness and movement patterns of fauna. Three

ecozones: the Boreal Plain, Mixedwood Plain, and Hudson Plain, have the highest number of deviations from the long term mean. The Boreal Plain forms a transition between urban and agricultural to more northerly forested regions and as a result is composed of transitional, heterogeneous, elements of both. As a result, there is within ecozone heterogeneity in cover and greenness characteristics spatially and temporally. Over the Boreal Plains inter- and intra-annual variation in precipitation will impact all dynamic habitat index components; for instance, precipitation will drive summer maximum greenness for cropped areas, winter minimum greenness cover, and overall variation. With mixed and coniferous forest dominated areas in the Boreal Plains seasonality is further impacted. The transitional nature of the Boreal Plains, coupled with agricultural access and human access to forests, results in fragmented forests, with the influence of forest patches upon overall within pixel greenness characteristics being further variable seasonally. Similarly, dynamic habitat index depictions of the Mixedwood Plain ecozone are also highly variable with the landscape composed of complex mosaic of land uses and related land cover and greenness potentials. The Mixedwood Plain, located in southern Ontario and Quebec, is highly urbanized with a patchwork of residual forests, farms, and a dense road network. Deciduous forests and agricultural cropping practices will lead to a high inter- and intra-annual variation in greenness, further exacerbated by variations in precipitation and climate. In contrast, the Hudson Plain is largely removed from anthropogenic influences located on the remote southern reaches of Hudson's Bay. The Hudson Plain ecozone is a complex mosaic of wetlands and forests.

Wetlands, while often considered as a land cover, are more of a landscape condition. For instance, based upon seasonal or annual precipitation, a forested area may be saturated (wetland forest) or dry. These fluctuations in landscape conditions also influence the greenness conditions captured to depict open water, fens, bogs, and wetlands, all intermixed with forested or upland low vegetation areas. Much of the vegetation in the Hudson Plain ecozone is low and easily covered with snowfall; further, snow and ice conditions also vary spatially and temporally. As a result, all 3 dynamic habitat index greenness components are impacted resulting in high variability in the index over time. Other ecozones showing a lesser, yet notable, degree of variability are the Montane Cordillera, Pacific Maritime, Boreal Cordillera, and Southern and North Arctic ecozones.

5. DISCUSSION

The dynamic habitat index presented here utilizes an indirect approach (Turner et al. 2003) to map and monitor environmental parameters believed to influence aspects of biodiversity. In general, environmental parameters can include climatic and geophysical variables, such as rainfall and topographic variation, as well as indices of vegetation production and land cover, both of which are often statistically related to species abundance or occurrence data (Nilsen et al. 2005). Employed in long time series, and over the entire landmass of Canada, the dynamic habitat index provides a baseline of the natural variability in productivity for a range of biogeoclimatic zones. Such areas can now be effectively partitioned allowing for a more comprehensive, consistent, and nuanced

understanding of the spatiotemporal variations in productivity for a variety of biogeoclimatic zones across Canada. Additionally, as the index utilizes remotely sensed measures of productivity, there exists a significant opportunity to explore linkages with previous experimental, descriptive, and theoretical work correlating productivity and general ecosystem functioning with species richness and/or composition (Rosenzweig and Abramsky 1993, Loreau et al. 2001).

Analyzing temporal changes in the annual dynamic habitat index should allow significant departures from the long term mean to effectively delineate regions undergoing disturbances (e.g., wild fires), or recovery events. Stratification of any of the three components then provides information on the overall potential effect on species home ranges, food supply, and habitat. We believe this type of information is important to managers charged with maintaining species habitat and populations. For example, changes to species competitive behaviors and health have been associated with reductions in environmental health associated with drought and mineral nutrient efficiencies. In these temporarily resource poor environments, the competitive ability and consequently the survival rates of some species may be reduced (Grime 1973). As a result, large deviations from the long term mean of the habitat suitability index calculated over several temporal scales may serve as an excellent indicator of change in species composition and diversity within a given area. Furthermore, regional deviations are spatially delineated, giving biodiversity researchers a coarse resolution indication of what

geographic regions are undergoing disturbance and thus a methodology to track landscape changes at continental scales through space and time. As the index is derived from remote sensing observations it can be applied over large management units where it is not feasible to conduct thorough surveys and monitoring programs (Bailey et al., 2004). By providing a coarse, initial stratification of changes in habitat condition, moderate or high spatial resolution satellite imagery, combined with ground based programs, can then be utilized to undertake fine scale investigations of the regions of interest. This then allows local scale interactions such as habitat fragmentation, and land cover change, both demonstrated at local levels to be related to extinction rates (Simberloff 1992, Pimm et al. 1995, Brooks and Balmford 1996, Brooks et al. 2002, Pimm and Raven 2000) to be more fully investigated. The 1 km spatial resolution of the MODIS imagery used in this study will have an impact upon the nature of the disturbances captured (Moody and Woodcock 1994), with small and isolated events more likely to be missed than small yet non-isolated disturbances. At the national and regional scale of this investigation, small and isolated events (e.g., highly localized insect or beaver activities) are not of particular importance and are better captured using more high spatial resolution change detection approaches (Coops et al. 2006). Harvesting activities are typically spatially constrained and, especially over time, are likely to be captured (Moody and Woodcock 1994). All within pixel cover conditions (i.e., roads, harvests, agricultural clearings) have an influence upon resultant greenness values, as a result, it is not the size of a single disturbance event that is of singular

importance, it is the amalgam of activities that enable or relate conditions or disturbances characteristics.

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