The development of a Canadian dynamic habitat index using multi-temporal satellite estimates of canopy light absorbance

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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 (Herfindal 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 (Ofll 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 and Ferguson, 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 avail-
able food and habitat requirements (Berry et al., 2007;
Woinarski, 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 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 tech-
nology 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 obser-
vations (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 1970s 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 (Knyszikhin 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 could 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 2-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.
2. Data

2.1. Fraction of photosynthetically active radiation 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., 2003). 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 utilize 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 5-year’s of data. As a result, 12 monthly composites were analyzed for each year to derive the three annual components of the index. In total 72 monthly composites were analyzed 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) (available at www.ec.gc.ca/soer-ree/English/Framework/NarDesc/canada_e.cfm). 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 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, 1993). The ecorezone level
<table>
<thead>
<tr>
<th>Ecozone</th>
<th>Climate</th>
<th>Vegetation/productivity</th>
<th>Wildlife (mammals/birds)</th>
<th>Land area (km²), % of total area</th>
<th>Canadian population (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arctic Cordillera</td>
<td>Extremely cold, dry; continuous permafrost</td>
<td>Mainly unvegetated; some shrub–herb tundra</td>
<td>Polar Bear (along coast), Arctic Hare; Northern Fulmar, Common Ringed Plover, Snow Bunting</td>
<td>230,873; 2%</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Northern Arctic</td>
<td>Very cold, dry; continuous permafrost</td>
<td>Herb–lichen tundra</td>
<td>Peary Caribou, Muskox, Wolf, Arctic Hare; Red-throated Loon, Brant, ptarmigan, Greater Snow Goose</td>
<td>1,361,433; 14%</td>
<td>0</td>
</tr>
<tr>
<td>Southern Arctic</td>
<td>Cold, dry, continuous permafrost</td>
<td>Shrub–herb tundra</td>
<td>Barren-ground Caribou, Wolf, Grizzly Bear, Arctic Fox, Arctic Ground Squirrel, lemming, Arctic Loon, ptarmigan, Snowy Owl</td>
<td>773,041; 8%</td>
<td>0</td>
</tr>
<tr>
<td>Taiga Plain</td>
<td>Cold, semiarid to moist; discontinuous permafrost</td>
<td>Open to closed mixed forest</td>
<td>Moose, Woodland Caribou, Wood Bison, Wolf, Black Bear, Red Squirrel; Northern Shrike, Spruce Grouse</td>
<td>580,139; 6%</td>
<td>0</td>
</tr>
<tr>
<td>Taiga Shield</td>
<td>Cold, moist to semiarid; discontinuous permafrost</td>
<td>Open evergreen and deciduous, lichen, shrub, tundra</td>
<td>Moose, Barren-ground Caribou, Wolf, Snowshoe Hare, Red Squirrel; Red-necked Phalarope, Northern Shrike</td>
<td>1,253,887; 13%</td>
<td>0</td>
</tr>
<tr>
<td>Hudson Plain</td>
<td>Cold to mild, semiarid; discontinuous permafrost</td>
<td>Wetland; some herb, lichen, shrub, tundra</td>
<td>Woodland Caribou, Moose, Black Bear, marten, Arctic Fox; Canada Goose</td>
<td>353,364; 4%</td>
<td>0</td>
</tr>
<tr>
<td>Boreal Shield</td>
<td>Cold, moist</td>
<td>Evergreen forest, mixed evergreen, deciduous forest</td>
<td>White-tailed Deer, Moose, Black Bear, Canada Lynx, marten, Red Squirrel; Boreal Owl, Blue Jay</td>
<td>1,782,252; 18%</td>
<td>10</td>
</tr>
<tr>
<td>Atlantic Maritime</td>
<td>Cool, wet</td>
<td>Mixed deciduous, evergreen forest</td>
<td>White-tailed Deer, Moose, Black Bear, Coyote, Raccoon; Blue Jay, Eastern Bluebird</td>
<td>183,978; 2%</td>
<td>9</td>
</tr>
<tr>
<td>Mixedwood Plain</td>
<td>Cool to mild, moist</td>
<td>Mixed deciduous, evergreen forest</td>
<td>White-tailed Deer, Red Fox, Raccoon, Striped Skunk, beaver, Grey Squirrel; Great Blue Heron, Blue Jay</td>
<td>138,421; 1%</td>
<td>51</td>
</tr>
<tr>
<td>Boreal Plain</td>
<td>Cold, moist</td>
<td>Mixed evergreen, deciduous forest</td>
<td>Woodland Caribou, Mule Deer, Moose, Black Bear, beaver, Muskrat; Boreal Owl, Blue Jay</td>
<td>679,969; 7%</td>
<td>3</td>
</tr>
<tr>
<td>Prairies</td>
<td>Cold, semiarid</td>
<td>Grass; scattered deciduous forest</td>
<td>Mule Deer, White-tailed Deer, Pronghorn, Coyote, Prairie Dog; Sage Grouse, Burrowing Owl</td>
<td>469,681; 5%</td>
<td>14</td>
</tr>
<tr>
<td>Taiga Cordillera</td>
<td>Cold, semiarid; discontinuous permafrost</td>
<td>Shrub, herb, moss, tundra</td>
<td>Dall's Sheep, Grant's Caribou, Black Bear, Grizzly Bear; Peregrine Falcon, Ptarmigan</td>
<td>264,480; 3%</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Boreal Cordillera</td>
<td>Moderately cold, moist</td>
<td>Largely evergreen forest; tundra, open woodland</td>
<td>Moose, Dall's Sheep, Grizzly Bear, Black Bear; Ptarmigan, Spruce Grouse</td>
<td>459,680; 5%</td>
<td>0</td>
</tr>
<tr>
<td>Pacific Maritime</td>
<td>Mild, temperate, very wet to cold alpine</td>
<td>Coastal evergreen forest</td>
<td>Black Bear, Grizzly Bear, Mountain Lion; Black Oystercatcher, Tufted Puffin</td>
<td>205,175; 2%</td>
<td>9</td>
</tr>
<tr>
<td>Montane Cordillera</td>
<td>Moderately cold, moist to arid</td>
<td>Evergreen forest, alpine tundra, interior grassland</td>
<td>Woodland Caribou, Mule Deer, Moose, North American Elk, Mountain Goat; Blue Grouse, Steller's Jay</td>
<td>479,057; 5%</td>
<td>3</td>
</tr>
</tbody>
</table>

Also shown is the total ecozone area and % of the total Canadian population that reside within the ecozone.
of stratification was used for our initial analysis with each ecozone containing unique components of Canada’s overall biodiversity (Table 1).

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 to 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 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 and 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

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 the following equation

\[ D(i) = \sqrt{\sum_{j=1, j \neq i}^{15} (t_i - t_j)^2 + (m_i - m_j)^2 + (c_i - c_j)^2} \]

(1)

where \( D(i) \) is the Euclidean distance between cluster \( i \) and all other clusters in terms of \( t, m, \) and \( c \), 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 three index components over the past 6 years.

4. Results

The distribution of the terrestrial ecozones across Canada are shown in Fig. 1, and the three components of the dynamic habitat index are shown in Fig. 2a–c, with the combined dynamic habitat index displayed in Fig. 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. Fig. 2a indicates the overall greenness of these landscapes is very low, resulting in a low integrated annual cumulative

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Fig. 1 – Coverage of the 15 terrestrial ecozones across Canada. Ecozone boundaries are highlighted in grey. Selected urban locations are noted as are main elements of the Canadian road network.
greenness. Similarly the amount of minimum cover is also very low (Fig. 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 (Fig. 2c).

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
Fig. 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.
summer the region 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 (Fig. 2c). The Montane Cordillera ecozone has highly variable climate and vegetation types, ranging from alpine tundra and dense conifer forests and grasslands. As a result, the region is typified by high seasonality, and average levels of minimum cover and annual greenness.

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. Fig. 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.

4.1. Ecozone characterization by dynamic habitat index

Cluster analysis on the 15 terrestrial ecozones indicates that many of the ecozones follow similar patterns with respect to the three habitat index components (Fig. 4). At the 40% merging level (indicated by linking distance), five 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

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Fig. 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.
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.

We propose that if the dynamic habitat index of individual ecoregions was highly variable from 2000 to 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 ecoregions: the Boreal Plain, Mixedwood Plain, and Hudson Plain, have the highest number of deviations from the long-term mean (Fig. 5). 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 ecological indicators 8 (2008) 754–766
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 three 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, 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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