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Development of a Large Area Biodiversity Monitoring System Driven by Remote Sensing

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Abstract

Biodiversity is a multifaceted concept that often eludes simple operational definitions. As a result, a variety of definitions have been proposed each with varying levels of complexity and scope. While different definitions of biodiversity exist, the basic unit of measurement for the vast majority of studies is conducted at the species level. Traditional approaches to measuring species richness provide useful, yet spatially constrained information. Remote sensing offers the opportunity for large area characterizations of biodiversity in a systematic, repeatable, and spatially exhaustive manner.

Based on this review we examine the potential for a national biodiversity monitoring system for Canada driven by remote sensing, a country approaching 1 billion ha in area, with the aim of producing recommendations that are transferable for regional or continental applications. A combination of direct and indirect approaches is proposed, with four selected key indicators of diversity that can be derived from Earth observation data: productivity, disturbance, topography, and land cover. Monitoring these indicators through time at an ecosystem level has the potential to provide a national early warning system, indicating where areas of potential biodiversity change may be occurring. We believe the large area biodiversity monitoring system as outlined would provide an initial stratification of key areas where regional and local scale analysis can be focused and also provide context for species collections data.

A Introduction

I Importance of mapping and monitoring biodiversity

Human activities are hastening the loss of biological diversity across the planet. Researchers predict that the strongest overall driver of terrestrial biological diversity loss within the next century will result from land use change (Sala et al. 2000). The majority of this conversion process is driven by anthropogenic activities, which often alters ecosystem structure and function, and in turn, global biogeochemical cycles (Vitousek et al. 1997). One dramatic example of land use change has been the reduction in the world's humid tropical forests: Between 1990 and 1997, approximately 37 million hectares of forest were lost mainly due to the conversion of land for agricultural purposes (Achard 2002). Not only are these forests major contributors to the terrestrial carbon cycle (Dixon et al. 1994, Mahli et al. 1999), but they are often "biodiversity hotspots" that contain large number of species, many of which are endemic (Myers et al. 2000).

While the emphasis on biodiversity loss in the tropics is often ascribed to the high levels of species endemism and overall species diversity that can be found in those areas, other ecosystems important to the overall biodiversity of the planet are also worthy of examination. For example, the boreal forest biome covers approximately 13 million km^2 of the Earth's surface and represents one quarter of the world's forested lands (Olson et al. 1983; Apps et al. 1993). The functioning of the boreal forest has been demonstrated to be more closely tied to species composition than to climate (Chapin and Danell 2001). As such, large changes to the extent or composition of the boreal forest may have a dramatic impact on global climate, and as a result, may have dire repercussions for local and global species diversity. Distinct differences between forest characteristics in the countries that have boreal forest exist. For example, the Russian Federation and Canada have 77.5% of the primary forest and 70% of the modified natural forest, whereas the Nordic countries have 1.2% and 0% respectively (FAO 2005). Disturbance characteristics also vary across the boreal, where in Canada the combined losses in area are less than or equal to the total gains per year; in the Russian Federation the losses are greater than the gains; and in the Nordic countries the gains have been greater than the losses (FAO 2005). Boreal forests are typically composed of species that would elsewhere be considered pioneer species, capable of rapid migration into barren (disturbed) lands when the climate or environmental conditions allow. While not as species rich as tropical forests, identifying and monitoring how both anthropogenic and natural disturbances affect species richness and composition within the boreal forest is an important part of maintaining global biodiversity.

Recognizing persistent and global threats to biological diversity, 190 countries have stated their commitment to the Convention on Biological Diversity (CBD), by aiming to achieve reductions in biodiversity loss by 2010 (UNEP 2002). This global consensus identifies that the present loss of biodiversity is intimately linked with human development, and that the conservation and sustainable use of present biological diversity is paramount to current and future generations of all life on Earth. As a first step, the CBD states that participating nations should implement a system to identify and monitor components of biological diversity, along with the processes that significantly threaten its conservation or sustainable use (CBD 1992).

Unfortunately, the task of identifying and monitoring elements of biodiversity at large, regional or national scales, using traditional surveying techniques (e.g. ground or aerial based), remains logistically difficult and/or financially prohibitive to accomplish. Fortunately, Earth Observation (EO) satellites are uniquely capable of synoptically covering large areas of the planet in a repeatable and cost effective manner. Data from sensors onboard these satellites have already improved insights into the ecological processes that are understood to influence biological diversity (Berry and Roderick 2002, Running et al. 2004, Turner et al. 2005), and have allowed for the broad scale delineation of anthropogenic and natural disturbances driving the loss of global biological diversity (Achard et al. 2002, Potter et al. 2003). While traditional methods of inventorying and assessing biodiversity will still be required, remotely sensed data can augment such efforts.

In this communication, we begin by briefly examining definitions of biodiversity while providing examples of how biodiversity is typically assessed using remote sensing technology. We take advantage, and build upon, existing reviews which developed classification schemes to assess the range of methods available to detect, map, and monitor biodiversity using remotely sensed data. With the Canadian landmass as an example, we then develop and propose a national framework which may be applied to identify and monitor elements of biological diversity across the country driven principally from satellite data and other spatial information sources. Canada's large size enables the underpinnings of this example framework to be considered as portable, or as a basis for, other regional or continental biodiversity mapping and monitoring initiatives.

II Assessment of Biodiversity

Biological diversity, or "biodiversity", is a wide-ranging concept that has been defined in numerous ways. Strictly speaking the term biodiversity refers to the quality, range or extent of differences between the *biological* entities in a given set (Heywood and Watson 1995). A broader, more widely recognized definition is the one established in the CBD, which defines biodiversity as the variability among living organisms from all sources (including terrestrial, marine and aquatic ecosystems) and the ecological complexes of which they are part, including diversity within and between species and of ecosystems (CBD 1992). DeLong (1996) examined 85 variations of the term “biodiversity” in an attempt to provide a consistent and meaningful definition. Perhaps unsurprisingly, this investigation found various definitions of biodiversity that ranged in scope and differed in how diversity is characterized. While there are clearly many ways to partition the various biological elements of biodiversity, many texts on the subject concentrate on the measurement of *species* diversity, not genetic or ecological diversity (Huston 1994, Rosenzweig 1995, Gaston and Blackburn 2000, Hubbell 2001).

Given that only approximately 15% of the species estimated to exist have been taxonomically classified (Gaston 2000), it follows that some of the most basic questions regarding biodiversity often begin with determining species richness (the number of species) within a given area of study (Magurran 2004). However, while species richness is a relatively intuitive and theoretically tractable measurement, it is only one component of species diversity and by itself is not very informative (Pielou 1975). Consequently, researchers often use a combination of diversity measures such as species richness and evenness (the variability of species) to describe the biodiversity for a given area (Rosenzweig 1995, Hubbel 2001, Magurran 2004).

The potential benefits of using satellite remote sensing to assess and monitor elements of biodiversity were suggested by researchers over a decade ago (Soulé and Kohm 1989, Noss 1990, Roughgarden et al. 1991, Davis et al. 1990, Lubchenco et al. 1991). Much of the available literature on remote sensing applications for mapping and monitoring aspects of biodiversity reveal certain commonalities. Chief among these is the unique ability of satellite imagery to synoptically monitor large areas in a timely, systematic, and repeatable manner (Stoms and Estes 1993, Innes and Koch 1998, Nagendra 2001, Turner et al. 2003, Kerr and Ostrovsky 2003). Recent studies utilizing remote sensing as a means of mapping, monitoring or modeling remote sensing are becoming more prevalent and are being conducted at various scales of inquiry.

Turner et al. (2003) categorized the use of remote sensing to quantify or model biodiversity components into “direct” and “indirect” approaches. Land cover maps — a direct approach — was considered a first-order analysis of species occurrence (Turner et al. 2003) as they implicitly or explicitly map the composition, abundance, and distribution of individual species or assemblages. In contrast, indirect approaches use remotely sensed imagery to measure environmental variables or indicators that are known or believed to influence aspects of biodiversity (Turner et al. 2003). These environmental parameters can include climatic and geophysical variables such as rainfall and topographic variation as well as the mapping of vegetation productivity or habitat mapping which are then statistically related to species abundance or occurrence data (Gontier et al. 2006). In a similar approach, Nagendra (2001) reviewed biodiversity monitoring applications that used remote sensing techniques and proposed three general categories of approaches. Again, direct and indirect approaches were highlighted; however, Nagenda (2001) also proposed a third approach which involved the development of direct relationships between spectral radiance values recorded from remotely sensed data and species distribution patterns recorded from field observations.

In the following sections we build on these reviews, with updated examples, and provide a short overview of these approaches. For detailed reviews in these topics readers are referred to Nagendra (2001), Turner et al. (2003) and Kerr and Ostrovsky (2003) for comprehensive summaries.

1 Direct Methods

Direct approaches to assess biodiversity are considered a first-order analysis of species occurrence (Turner et al. 2003). Direct approaches implicitly or explicitly map the composition, abundance, and distribution of individual species or assemblages. This is to say, “direct” approaches provide data that can be used to directly quantify elemental aspects of biodiversity (e.g., the classification of individual species or associations of species to derive maps of the pattern of species richness). In terrestrial applications such direct observations acquired from remotely sensed data are typically limited to the detection of larger plants (e.g., trees), or in open areas where crops, shrubs, or lichens form a spatially contiguous layer of vegetation (Nagendra 2001).

At sub-meter spatial resolutions, direct identification of certain tree species, through the detection of individual tree crowns, is becoming feasible. Imagery for these types of applications can be obtained from satellite based systems such as the IKONOS and Quickbird satellites, which offer multi-spectral imagery at resolutions of 4 m and 2.4 m, respectively, and panchromatic imagery at 1 m and 0.6 m, respectively (GeoEye 2006, DigitalGlobe 2006). Digital aerial photography likewise provides access to very high spatial resolution imagery, often as fine as 0.5 m (King 1995).

By digitizing traditional color and color infrared film, Key et al. (2001) were able to simulate high spatial resolution digital imagery with an average pixel size of 0.36 m. A staged multi-date spectral classification technique was used to discern four deciduous species that comprise 99% of the trees in their study area. Gougeon (1995) identified tree crowns from a range of boreal tree species in Canada using 0.36 m airborne scanner imagery. Results were encouraging with classification accuracy across the area of approximately 72%, with species specific accuracies depending on the tree size and a given species' spectral separability. Using high pulse rate laser scanners and image segmentation techniques, Hyyppä et al. (2001) were able to detect and resolve characteristics of individual trees such as height, location, and crown dimension. This information was then extrapolated to the stand level, where estimates of forest stand attributes were found to exceed conventional inventory methods.

Advances in radiometric and spectral resolution have also aided in the identification of individual species. Newer multispectral and hyperspectral sensors divide the electromagnetic spectrum into dozens or even hundreds of discrete bands, making it possible for a species' unique spectral signature to be discerned. Goodwin et al. (2005) utilized 0.8 m hyperspectral Compact Airborne Spectrographic Imagery 2 (CASI-2) imagery to assess the capacity of spectrally discriminating individual species in a native eucalypt forest in Australia. Results indicated that two species in particular were sufficiently spectrally and structurally distinct to allow for individual crowns and species mapping. Buddenbaum et al. (2005) utilized hyperspectral data to map species and age classes in coniferous forest stands in Western Germany. Using hyperspectral data alone, they achieved a classification accuracy of 66%, which was increased to 74% when stem density was included.

While still utilizing very high spatial resolution imagery, many authors have concluded that working at the species assemblage scale is appropriate and ensures accurate and reliable results (Trietz et al. 1992; Goodwin et al. 2005). As pixel size increases beyond that of individual trees or individual plant assemblages, tree crowns within a scene are no longer visible and stands of trees or shrubs become the smallest of discernable elements. If these spatially contiguous species assemblages are identified as having unique biodiversity value then their direct mapping remains possible. For example, Miyamoto et al. (2004) utilized digital camera imagery to map wetland species diversity as an indicator of overall biodiversity. High spatial resolution images were acquired and mosaicked with 27 specific species mixtures identified and classified, including key species groups considered to be of high biodiversity value.

2 Indirect Methods

In contrast, indirect approaches use remotely sensed data to measure environmental variables or indicators that are known or understood through biological principles to capture aspects of biodiversity (Turner et al. 2003). In practice this is the most common approach of assessing biodiversity using remotely sensed data acquired from either aircraft or spacecraft, as it provides quantifiable elements that can be readily and repeatedly obtained to relate to biodiversity. To examine the variety of indirect variables, or indicators, used to assess biodiversity, four broad categories can be defined which capture the majority of ongoing research in this area. These categories include indirect measures of: (i) the physical environment itself, such as climate and topography, (ii) vegetation production, productivity, or function, (iii) habitat suitability, with respect to its spatial arrangement and structure, and (iv) metrics of disturbance which can provide indirect measures of changes in biodiversity.

a Climate and Topography

Predicting biological diversity as a function of climate at both the regional (Currie and Paquin, 1987; Hawkins et al. 2003; O'Brian, 1998; Venevsky and Veneskaia, 2003) and global scale (Gaston, 2000; Kleidon and Mooney, 2000; Latham and Ricklefs, 1993) is well established. At regional scales, the degree of disturbance and fragmentation of the landscape may still apply, but these factors are generally muted in comparison to climatic effects (see Sarr et al. 2005). Temperature and moisture are two variables often utilized in climatic analyses, usually in the form of annual precipitation and evaporation (potential or actual). Ecologically it is worth considering analysis of climatic effects seasonally and in reference to how organisms directly respond (Mason and Langenheim, 1957). Johnson et al. (1998) used climate and satellite captured estimates of vegetation greenness from the meteorological satellites of the National Oceanic and Atmospheric Agency (NOAA) and the European Organization for the Exploitation of Meteorological Satellites (EUMETSAT) to predict areas of high bird species endemism with an accuracy approaching 89%. The study also incorporated digital elevation data, which was the top-ranking predictor for most of their analyses. However, those cases in which elevation data were not used, predictive accuracies of 70 – 88% were still achieved using surrogates such as rainfall and thermal variables (Johnson et al. 1998).

While elevation is a relatively static variable compared to other biophysical parameters such as climate, its function as a key biodiversity gradient has been well documented (Rosenzweig 1995). For example, in the tropics, the species diversity of many plants and animals has shown a unimodal shaped patterns, with the highest species diversity often occurring at mid-elevations in various studies (Rosenzweig 1995). In contrast, Patterson et al. (1998) showed a decreasing trend in bat and bird species richness as elevation increased. Elevation has also been correlated with levels of productivity. Within the 15 vegetation communities of the Santa Catalina Mountains of Arizona, a steeper decrease in productivity from high-elevation forests to mid-elevation woodlands was found, along with a less steep decrease in productivity from dry woodlands through desert grassland into desert (Whittaker and Niering 1975). Undoubtedly, various species richness-elevation patterns exist, some of which are likely influenced by the size of the area sampled (Rahbek 1997). Regardless of the shape that a given species richness-elevation relationship may take, elevation remains a key variable in explaining regional differences in biodiversity.

Fortuitously, the past decade has seen an increase in our capacity to map and monitor aspects of climate and the physical environment. In 2000, NASA and the US National Imagery and Mapping Agency (NIMA) launched the Shuttle Radar Topography Mission (SRTM) on the Space Shuttle. SRTM radar obtained elevation data for 80% of the land surface of the Earth between ± 60º latitude which for the first time provides consistent elevation data over the land at 90 m spatial resolution, world-wide, with vertical resolution in the order of 5 m (Farr and Kobrick 2000). Other global datasets that cover all latitude ranges are also freely and readily available (Gesch et al. 2001).

b Vegetation production, productivity, or function.

The integrated response of vegetation to climate is expressed as growth, or net primary production (NPP). A direct correlation between productivity and species richness is expected as areas of high NPP have more resources to partition among competing species, thereby supporting a greater number of species and larger populations than areas with low NPP (Walker et al. 1992). Using remotely sensed data, vegetation production can be assessed through relationships with standing biomass or foliage vigour, such as prediction of leaf area index (LAI), tree volume or biomass, or photosynthesis through the fraction of light absorbed by the vegetation (fPAR). The Normalized Difference Vegetation Index (NDVI), which is the normalized ratio of the red and infrared reflectance, provides an indication of photosynthetic activity of chlorophyll based vegetation (Tucker 1979) and has been used extensively to assess and predict biophysical parameters of forests (Wulder 1998), and as a means of examining how environmental changes affect the distribution of both plants and animals (Pettorelli et al. 2005). Time series of NDVI data derived from the Advanced Very High Resolution Radiometer (AVHRR) has been successfully used in many studies to provide estimates of the interannual variability of global vegetation activity and in relating small-scale (large area) variations in vegetation to climate (Myneni et al. 1997). More recently, the Enhanced Vegetation Index (EVI), a similar index, but one which is less affected by atmosphere or saturation at higher biomass contents, has also been related to production, both regionally and globally (Huete et al. 2002).

Vegetation indices such as NDVI and EVI, and derivatives such as LAI and fPAR, allow for the investigation of relationships between ground-based measures of species richness and satellite-based measures of vegetation productivity and function (Berry and Roderick 2002, Running et al. 2004). For example, the relationship between avian species diversity and annual vegetative biomass was evaluated in Senegal using broad scale NDVI data (Jorgensen and Nohr 1996) with success. Skidmore and Said (2003) predicted mammal and bird species richness using the NDVI derived from NOAA satellites, but noted that climate parameters were better predictors of species richness than the NDVI alone. Bonn et al. (2004) used NDVI to investigate the relationship between species richness and productivity, and found that higher productivity levels do lead to higher species richness. More recently Waring et al. (2006) utilized EVI data over the continental US to predict woody species richness, as measured using the USDA Forest Service Forest Inventory and Analysis data and found significant relationships between total species numbers at the ecosystem level and maximum annual EVI. At regional levels moderately strong correlations have been established between plant species richness and NDVI values in California, again using NOAA AVHRR data with the accuracy of the results dependent on season and the species life form (Walker et al. 1992).

c Habitat suitability, habitat pattern and structure

While climate and productivity have been linked to broad global patterns of biodiversity (Willig et al. 2003, Hawkins et al. 2003), finer scale spatial patterns such as land use and land cover, forest structural stage, and their associated spatial patterns, are increasingly being investigated as potential predictors of species diversity and abundance at regional and local scales (Fahrig 2003). In forested environments, the vertical structural complexity has been linked with forest biodiversity (Hansen et al. 1995, Imhoff et al. 1997). Various applications in remote sensing have become increasingly successful at mapping and monitoring these spatial structures. For example, Light Detection And Ranging (LiDAR) is a technology that has been successfully applied to estimating elements of forest structure that have traditionally only been available in a more generalized or empirical manner (Lim et al. 2003; Wulder 1998). LiDAR uses a laser pulse, typically sent from an aircraft, which is intersected by vegetation cover or may penetrate through to the ground, to produce points which have location and elevation information (x, y, and z positions). The point clouds that are generated may be processed to generate ground elevation models and a depiction of the above ground vegetation (Lim et al. 2003). Attributes that may be generated include both tree or stand height characteristics, canopy closure, and estimated attributes such as volume and LAI. Analysis techniques may also be applied to develop from the point data information on the distribution of vegetation at a given location, although the sensor types and analysis techniques may vary (Lefsky et al. 1999, Coops et al. 2006a). These structural estimates can then be linked to population and abundance models, allowing for the estimation of bird diversity (Bradbury et al. 2005). The combination of LiDAR and spectral information may be used to delineate tropical tree species based on their unique structural and spectral components. Such advances would provide scientists with data needed to undertake hypotheses testing on patterns and processes associated with tropical forest structure, or provide high spatial resolution data for depiction of floristic composition or species richness in tropical forests (Gillespie et al. 2004).

Land degradation and biodiversity loss caused by the drivers of both land cover and land use change have been mapped by Earth observation satellites at least since the inception of the Landsat series in the early 1970s (Cohen and Goward 2004). As mentioned previously, land cover maps depicting individual or assemblages of species are critical to biodiversity assessments because they represent a "first-order" analysis of species occurrence (Turner et al. 2003). Additionally, land cover data may prove useful as a predictive variable when trying to assess habitat diversity of various species not directly imaged by the remote sensor system.

For example, Kerr et al. (2001) used land cover derived by the sensor onboard the Systeme Probatoire pour l'Observation de la Terre (SPOT), called VEGETATION (or VGT), along with environmental measurements of potential and actual evaportranspiration, and net primary production to predict butterfly species richness across Canada. Their findings revealed that over 90% of butterfly species richness could be explained by the number of land cover types (habitat heterogeneity) per quadrat at each of three quadrat scales examined. Luoto et al. (2004) used habitat composition (i.e. land cover type), structure (e.g. edge length, mean patch size, etc.), and topographic metrics derived from a Landsat TM land cover classification and digital elevation models, to predict bird species richness in boreal agricultural-forest mosaics in Finland. Their habitat-composition model explained 60.8% of the variation in species richness, but decreased to 48.4% when applied to the model test area. However, their habitat-structure model explained 58.8% of the variation in species richness, which actually increased to 61.7% when applied to the test area.

However, care should be taken when using land cover maps as predictive variables for ascertaining species richness. In a study aimed at predicting species richness of mammals in Great Britain using satellite derived land cover maps, Cardillo et al. (1999) found that land cover generally explained less than half of the variation in mammal species richness and occurrence. As noted by the authors, the reason for this limited performance is most likely attributable to species specific behavioral responses, and to factors independent of land cover type. Studies such as these clearly demonstrate a need to fully comprehend the specific life history characteristics of the species being modeled, and to ensure that the data being utilized is commensurate for the intended purposes.

In addition to the capacity to measure the various land cover types that represent a species' specific habitat, remote sensing technology also allows for the mapping of spatial patterns in vegetation cover over the landscape. Ecosystems do not cover the landscape uniformly; rather they occur in landscape elements or patches (Forman 1995) where a patch is considered as a homogeneous component that differs in some measurable way from neighboring patches

(McGarigal and Marks 1995). Structural components of the landscape that can be quantified include the size distribution of patches, dispersion of patch types throughout the landscape, contrast among patches, patch shape complexity, contagion or clumping of patch types, and corridors between patches (McGarigal and Marks 1995, Franklin and Dickson 2002). Such landscape metrics can provide vital information on the function of ecological systems, as well as patterns of biodiversity (Farr 1998). A number of studies have examined the effect of forest loss and changes in spatial configuration on biodiversity and ecological functioning (Villard et al. 1999; Collingham and Huntley, 2000; Cooper and Walters, 2002; Mac Nally and Horrocks, 2002, Fahrig 2003). In riparian systems patches are often defined by native or natural vegetation left along streams as buffers. Alternatively in a more arid and agricultural systems, patches may be defined by the field size, areas of exposed soil, or remnant vegetation. The variety and relative abundance of different patch types can provide critical information and include patch richness, patch diversity, and diversity indices.

If these types of patch descriptions are to be assessed through time then it is critical to ensure that there is quality control and rigor in the estimates to provide confidence in the results. Manual interpretation of forest boundaries for example, is often highly subjective, and thus produces unique, rather than consistent datasets and as a result the monitoring of patch based attributes derived from manual-based methods is problematic (Edwards and Lowell 1996). A key benefit of digital assessment of patches in the landscape is the consistent and repeatable manner at which these are derived, which ensures more consistent, and thus accurate, estimates through time (Franklin and Dickson 2002). Such rigor in the selection of ecological indicators is seen as an important aspect of any operational biodiversity monitoring program (Dale and Beyeler 2001, Smyth and James 2004, Beever 2006).

Given that patch-based indicators are readily extractable from digital imagery, through the use of software such as Fragstats (McGarigal and Marks 1995), the interpretation of these landscape metrics and their relevance to landscape pattern and ecological function, and ultimately biodiversity, becomes feasible on an operational level when combined with the synoptic, systematic, and repeatable nature of Earth observation satellite data.

d Metrics of disturbance

Disturbances occur over a range of spatial and temporal scales, and at differing intensities (Coops et al. 2006b). Disturbances often play an essential role in regulating competitive exclusion and enhancing the spatial heterogeneity of vegetation communities, both of which enhance diversity (Huston 1994, Spies and Turner 1999). At the fine scale a small disturbance may increase the heterogeneity of a landscape and increase habitat niches. For example a wind throw event which opens the forest floor to sunlight, which promotes the growth of herbaceous plants, grasses, and bushes, thereby improving habitat quality for a variety of organisms, such as pollinating insects, ungulates and bears (Franklin and Dickson 2002). A more severe disturbance event, such as a large fire, allows early seral species that colonize quickly after disturbance to proliferate, followed by late seral species that increase in abundance and dominance through time (Linke et al. 2006). Optimal diversity occurs, therefore, when disturbances are sufficiently frequent to limit dominance while also allowing sufficient time for colonization by all species (Connell 1978, Sarr et al. 2002).

Disturbance regimes over time act to define a landscape and are intrinsically linked to landscape spatial pattern and thus changes in biodiversity. If disturbance patterns change, then changes in biodiversity patterns may also be expected to change. Forman (1995) describes five disturbance processes that result from alteration of landscape pattern, such as perforation, dissection, fragmentation, shrinkage, and attrition. Of these processes fragmentation in particular is important as it is often the most common, and leads to smaller and more distant patches as well as increases the edge/area ratios. Fragmentation therefore has a direct result on biodiversity as organisms that are sensitive to patch size or edge are directly affected. For example, highly vagile species, such as carnivorous birds, are more likely to perceive a landscape as connected, whereas less vagile bird species, such as woodpeckers and chickadees, may perceive the connectivity between their preferred habitat patches as fragmented and inaccessible (D'Eon et al. 2002). The varied thrush (*Ixoreus naevius*) for example is a bird species that avoids forest edges (Hansen et al. 1991). If a large percentage of this bird's forest habitat were fragmented, its ability to survive would markedly diminish. Likewise species that require large connected landscapes are also affected by fragmentation such as the elk (*Cervus elaphus*) which requires large amounts of adjoining, connected, habitat (Silbaugh and Betters 1997, Franklin and Dickson 2002).

Remote sensing technology has been shown to be successful at monitoring disturbance (Foody et al. 1996; Rignot et al. 1997) particularly disturbance events which results in stand replacement such as fire, clear cut harvesting, and wind throw. By comparison disturbances events which happen (comparatively) slowly through time such as thinning, infestation and succession are more difficult, due to more subtle changes in the spectral responses. Their accurate detection is therefore more difficult (Coops et al. 2006b). Disturbance studies have been undertaken globally, regionally and locally. Cohen et al. (2002) undertake a broad scale disturbance study in western Oregon using Landsat spectral data collected between 1972 and 1995 using a Tassel Cap Transformation (TCT) (Healy et al. 2005) to estimate the annual change in clear cut logging and wildfire, the two ubiquitous disturbance events in the region. Clear-cut harvest and wildfire occurred over 19.9% and 0.7% of western Oregon respectively with rates of harvest over time generally being lowest in the early 1970s, peaking in the late 1980s and early 1990s, and then decreasing near 1970s levels by the mid-1990s. It was concluded that comparing the managed disturbance regimes with historical wild disturbance regimes can aid in understanding the relative impact of management regimes on ecosystems (Cohen et al. 2002) and subsequently the species and animal biodiversity of the region.

In addition to the use of spectral responses in the visible and near infrared regions of the electromagnetic spectrum, the thermal infrared region is also an important source of information – particularly related to disturbance. Generally, a negative relationship is expected between vegetation indices responding to reduced cover and surface temperature (Goward et al. 1985, Price 1990). The basis for this relationship lies in the unique spectral reflectance and emittance properties of vegetation relative to bare ground with vegetated surfaces having a lower temperature than soil resulting in land surface temperature (LST) decreasing with an increase in vegetation density through latent heat transfer (Mildrexler et al. In press). The coupling of LST and NDVI was found to improve land cover characterization for regional and continental scale land cover classification (Lambin and Ehrlich 1995, Nemani and Running 1997, Roy et al. 1997). Running et al. (1994) suggested that the addition of LST to spectral vegetation indices could increase the discrimination of regional land cover classes. Findings from Borak et al.'s (2000) research supports this suggestion, showing that LST with NDVI improved the statistical relationship between their temporal and spatial change detection metrics. Lambin and Ehrlich (1996) explored the biophysical justification for such a combination and recommended land cover/land use studies utilize the LST-NDVI feature space to provide information on more biophysical attributes and processes of land surfaces than vegetation indices alone. Goetz (1997) reported that the negative correlation between LST and NDVI, observed over a range of scales, was largely related to changes in vegetation cover and soil moisture and indicated that the surface temperature can rise rapidly with water stress. Mildrexler et al. (In press) utilize this relationship in their proposed disturbance index which can be applied to MODerate-resolution Imaging Spectroradiometer (MODIS) 16-day EVI and 8-day LST to detect the location and spatial extent of broad scale (~1 km^2) disturbance events such as forest fires and the incremental process of recovery of disturbed landscapes. A bibliographic summary of selected examples of direct and indirect methods is presented in Table 1.

Insert table 1 about here:

3 Spectral Association Methods

Nagenda (2001) highlighted methods which develop direct relationships between spectral radiance values recorded with remote sensors, and species distribution patterns recorded from field observations. These techniques provide a growing area of focus in biodiversity research, particularly due to the increasing availability of data with higher spectral, spatial, and temporal resolutions. Remotely sensed data with higher spectral resolution can allows for individual species to be identified based on their unique spectral characteristics (Wulder et al. 2004). When this data is available, spectra acquired at a particular location may be related to the number and variety of either species, or species assemblages of the area. In the case of tropical areas, which have a significant diversity with respect to species richness and habitats, such techniques are proving to be invaluable. Clark et al. (2005) investigated the utility of high spectral and spatial resolution data for mapping of tropical rain forests, and achieved 92% accuracy when mapping individual tree crowns using 30 optimally selected bands with a spatial resolution of 1.6m. Hyperspectral imagery has been used to provide a more detailed discrimination of tropical mangrove forests (Held et al. 2003), which has been found difficult to accomplish with medium spatial resolution (~30 m) data (Green et al. 1998). In a similar approach Schmidtlein and Sassin (2004) utilized hyperspectral airborne imagery of grasslands in Germany to derive species composition and floristic gradients. Changes directly observed in the spectra along the floristic gradients were correlated to changes in species composition and plant function responses using statistical techniques with reasonable success ($r^2 > 0.66$).

B A Conceptual Approach to Map and Monitor Canadian Biodiversity

I Introduction to Approach

As evidenced above, there are a variety of approaches to map and monitor biodiversity using remote sensing technology. It also becomes evident that for any broad scale biodiversity monitoring framework that encompasses a range of biota, including trees and understorey vegetation, as well as avian and mammalian species, that the mapping of indirect estimates of biodiversity provides the most realistic, flexible, and cost effective approach. With the second largest landmass of any country in the world Canada contains a wide variety of environments resulting in extensive plant and animal species diversity. As would be expected for a northern, higher latitude nation, species richness has been found to be highest in the warmer, southern latitudes, of the country (Currie 1991, Kerr and Currie 1995, Francis and Currie 2003). Out of a total of 177 terrestrial regions, 14 ecosystems have been classified as high risk for biodiversity loss (Environment Canada 1994) and include endangered areas such as the Gary Oak ecosystem and the Carolinian woodlands (Figure1).

Insert Figure 1 about here:

Not surprisingly, this high risk for biodiversity loss is linked to human induced land use change associated with residential development and conversion of the land for agricultural purposes (Kerr and Cihlar 2004). The newly promulgated Species at Risk Act (SARA) aims to provide legal protection of Canada's wildlife and biodiversity. As of April 2006, the Committee on the Status of Endangered Wildlife in Canada (COSEWIC) – now formally associated within the SARA process – listed 39 species of mammals, birds, reptiles, amphibians, fish, anthropods, molluscs, vascular plants, mosses, and lichens as being either extirpated, endangered, or threatened (see Table 2). International commitments, such as the 1992 Rio Convention on Biological Diversity, and 1981 Ramsar Convention on Wetlands, which have been in force since 1993 and 1986 respectively, clearly outline Canada's international responsibility to preserve its own biodiversity for the common global good.

Insert Table 2 about here:

In designing and developing a conceptual model for assessing and monitoring biodiversity, Canada-wide, we considered the following rationale:

- The scheme should be national in approach and cover as much of the Canadian land mass as possible,
- The system is deigned to be appropriate for characterization of the vegetated terrestrial biosphere,
- The system should have two initial foci; an assessment of the current vegetative biodiversity across the country and a monitoring component to assess changes in vegetative biodiversity through time.
- Utilize available remotely sensed datasets (if possible data which is available free of charge, or at nominal cost).
- Provide regional and national emphasis, rather than provide local level results, with the system being scalable, and
- Encourage linkages with ongoing Canadian efforts charged with investigating biodiversity across a range of scales (such as programs related to habitat, forests, wetlands, and agricultural ecosystems)

II The Four Components

The four major components of the proposed model are designed to capture the four major indirect estimates of biodiversity as highlighted in the literature. These components are topography, vegetation function / production, land cover fragmentation, and disturbance. These four components are developed in Table 3. Based on the key rationale listed above it is apparent that a relatively broad spatial pixel is required to ensure regular image revisit times, as well as realistic data volumes. As a result, a nominal spatial resolution of 1 km is proposed, due in part to the availability of data at this spatial resolution from the SPOT VGT or MODIS sensors, as well as AVHRR data, which has been available since the early 1980's (Latifovic et al. 2005). In the following section desired datasets, a general methodology of how the data is proposed to be processed, and expected results from each component will be described. The final section will describe a proposed integration strategy for combining these four components into a unified scheme for regional application.

Insert Table 3 about here:

1 Topography

The Canadian landmass is characterized by large topographic variation across the country, although outside of British Columbia, elevation ranges are limited (Wulder and Seemann 2001). In highly diverse mountainous environments, such as those found in British Columbia, topography is a key driver of changes in precipitation and temperature regimes which in turn influence vegetation composition and production. We propose to utilize topographic information acquired by the SRTM mission, providing 90m spatial resolution topographic information consistently across the country from 49 ° to 60° N. Above 60° N where STRM data is not available we will utilize the best available datasets, with a failsafe available in the GTOPO30 dataset (Gesch et al. 2001) which provides topographic information at 1000 m spatial resolution.

In many environments, information on elevation is an obvious choice for helping discriminate land cover classes (Strahler et al. 1978), as discrimination of cover types whose distributions are influenced by variation in elevation is improved with the inclusion of terrain information (Franklin and Peddle, 1989; Franklin et al. 1994). Improved remote sensing classification accuracies have been reported with the direct incorporation of terrain information into the classification. Elumnoh and Shrestha (2000) incorporated digital terrain information into classification of 13 land cover classes and classification accuracy improved 7% with terrain data particularly in discriminating lowland agriculture fields from highland forest classes. In regions with mountainous and highly variable terrain shadows can cause problems in the classification of imagery. Low sun angles and the resulting cast shadows on steep slopes reduced the reflectance recorded by the sensor and therefore can result in less accurate discrimination of variables such as growth stage or age (Sader et al. 2001). One recommendation for dealing with the effect of shadows and low sun angles in highly mountains terrain is to stratify the image by aspect and the use information on terrain in the classifier. The approach has been found to increase the overall accuracy of land cover classification in predominantly forested, high-elevation study area of British Columbia, Canada (Wulder et al. 2004); however, this approach needs to be applied on a scene by scene basis due to variable sun and view angle combinations at each overpass (Wulder et al. 2004).

We propose to capture topographic variation over the continent using indices of relative relief such as an elevation residual approach Wilson and Gallant (200) or a terrain roughness index (Riley et al. 1999). The elevation residual approach, for example, uses a local window to assess the relative change in elevation of the central cell to its neighbours. The output of the procedure is the difference from the mean divided by the standard deviation and measures the relative topographic position as a fraction of the local relief and so is normalized to the local surface roughness. The deviation ranges between ±1 with low numbers indicative of flat terrain within flat areas, and higher numbers indicative of significant elevation change within the local neighbourhood (Wilson and Gallant 2005).

2 Dynamic Habitat Index (DHI)

As discussed, a strong link exists between productivity and species richness, so a capacity to track landscape productivity at regional or continental scales through space and time can provide critical information for the movement and characterisation of biodiversity. We propose to utilize remote sensing generated estimates of fPAR, which vary between 0 and 1, and provide an indication of the photosynthetic capacity of the landscape. This information is available at 16-day or monthly time steps, at 1 km spatial resolution, from the MODIS sensor, for the entire globe since 2000 (Running et al. 2004).

In Australia Mackey et al. (2004) developed a simple integrated index using monthly fPAR data from the MODIS sensor to track landscape productivity on a monthly time step, and from these monthly variations assess how biomass is partitioned and made available as food and other habitat resources for animals. The approach developed by Mackey et al. (2004) is based on three indices calculated from monthly estimates of fPAR including 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 components, changes in vegetation habitat and production for species biodiversity can be better understood. The approach was modified (Coops et al. In review) which involved the utilization of long term fPAR data acquired by averaging seven years of MODIS fPAR observations over Canada. From these seven year averages the temporal variations in each of the fPAR metrics was assessed. Generally arctic grasses and shrub ecosystems in the north of the country have low levels of minimum production and low overall productivity, but are highly variable throughout the year. Crops also have high annual variability;

however, they have a much higher annual mean productivity, coupled with a low minimum productivity when fallow. Evergreen forests typically are temporally stable and maintain some productivity throughout the year; whereas, deciduous forest, are often equally productive, however much more seasonal. A schematic diagram of where different environments within Canada, occur within this three dimensional fPAR spaces is shown in Figure 2. A more detailed description of the behaviour of the three fPAR components for Canadian ecosystems is available in Coops et al. (In review).

Insert Figure 2 about here:

3 Land Cover

Information on current land cover will be extracted from the Canadian Forest Service and Canadian Space Agency Earth Observation for Sustainable Development of Forests (EOSD) products. EOSD products depict the land cover of the forested ecozones of Canada, based on circa 2000 Landsat Enhanced Thematic Mapper (ETM+) imagery. The EOSD mapping area was defined as the forested ecozones of Canada (which represent approximately 60 % of the country) requiring over 450 scenes to cover the mapping area. Accounting for image extension outside of the defined mapping area results in approximately 80 % of Canada being mapped (Wulder et al. 2006). The heterogeneous nature of the forested area of Canada is reflected in these summary values, indicating the association of lakes and wetlands with the forested land. National Forest Inventory statistics report that the forested and other wooded lands represent approximately 402 MHa (or ~40 %) of the country (NRCan 2006). In order to complete the EOSD imagery was ortho-rectified to produce a consistent image base for processing (Wulder et al. 2002) and a top-of-atmosphere approach applied to account for the influence of sun illumination on pixel radiometric response (after Peddle et al. 2003). An unsupervised classification (i.e., k-means) using a clustering approach was followed by manual labelling of classes. In total 23 land cover classes are defined, focused on the forested environment, as well as classes for “no data”, cloud, shadow, snow/ice, rock/rubble/bedrock, exposed land, and water. The remaining classes include classes for shrub, herbs, bryoid, wetland, and coniferous, broadleaf and mixed wood forest types. A summary of the methods applied and the EOSD classes are available in Wulder et al. (2003).

In addition to providing information on the land cover of an individual pixel, the EOSD land cover classification will be used to assess the landscape pattern. Landscape pattern will be quantified from measures of the composition and structure of landscape patches within each 1 x 1 km cell. From the 25 x 25 m pixels of land cover, patch relationships that affect landscape dynamics, such as diversity, complexity, association, and connectivity will be calculated. The variety and relative abundance of patch types are measures of composition and include patch richness, patch diversity, and diversity indices. The size distribution of patches, dispersion of patch types throughout the landscape, contrast among patches, patch shape complexity, contagion or clumping of patch types, and the corridors between patches are structural components of the landscape that can be quantified (McGarigal and Marks 1995, Urban 1998).

4 Disturbance

The timing, location, and magnitude of major disturbance events can also be critical when assessing and monitoring biodiversity, with changes associated with wildfire, insect epidemics, flooding, climate change, and harvesting as well as human induced activities such as land clearing and changes in land use. To assess disturbance we will apply a disturbance index, modified from Mildrexler et al. (In press). The disturbance algorithm utilizes MODIS LST and EVI data from 2000 to 2006 and is based on consistent radiometric relationships between LST and EVI computed on a pixel-by pixel basis (Mildrexler et al. In press). The algorithm computes the long-term monthly LST and EVI from the seven years of data and compares the actual monthly observations to the long term averages to detect changes in land surface energy partitioning while avoiding the high natural variability associated with tracking LST at daily or weekly time frames. A set of thresholds are then developed, specific for individual ecozones, which allow the index to be tuned to changes in disturbance conditions over Canada. Initial verification of the approach confirms it is sensitive to large stand replacing disturbance events such as wildfire, as well as insect infestations such as Mountain Pine Beetle outbreak in British Columbia. In addition, the index appears capable of detecting increases in vegetation vigour such as irrigation in agricultural areas, as well as gradual woody encroachment in the Arctic and eastern Canada following large scale disturbance.

A graphic example of each of the four components to be used in the Canadian biodiversity approach are summarised in Figure 3.

Insert Figure 3 about here:

III Implementation

International stewardship and reporting requirements (as exemplified by the CBD (CBD 2002)) promote the development of biodiversity monitoring systems that can be applied over regional and continental areas in a systematic and repeatable manner. The information generated from a biodiversity monitoring system that is representative of broad scale conditions provides strategic information for the entire country while also producing insights into fine scale disturbance locations that may be prioritized for further investigations. The broad regional characterizations will also provide baseline information on ecological conditions, against which changes can be determined and national species collection data can be compared against. The synoptic capabilities and range of environmental datasets made available by Earth observation satellites allow for such a monitoring system to be implemented.

Based upon the findings presented in this review, terrestrial vegetation biodiversity monitoring approaches applicable at the regional to continental level can be examined using the following datasets: elevation, productivity, disturbance, and land cover. In order to summarize and logically articulate the patterns in these four key indicators across Canada, results will be grouped within ecozones and ecoregions (Wiken 1986, Ecoregions Working Group 1989). Long term archives for the disturbance index and the dynamic habitat index will be derived from seven years of EVI, LST and fPAR data from MODIS onboard the TERRA and AQUA satellites. Digital elevation data from the SRTM will serve as the primary topographical stratification layer, with coarser resolution Global 30 Arc Second Elevation Data (GTOPO30) used to fill in missing areas not covered by the SRTM (as is not collected ±60 degrees latitude). MODIS datasets are freely available from the Land Processes Distributed Active Archive Center (LPDAAC; http://edcdaac.usgs.gov/main.asp), with both the SRTM and GTOPO30 data freely available from the US Geological Survey's EROS Data Center (ftp://e0srp01u.ecs.nasa.gov and http://edc.usgs.gov/products/elevation/gtopo30/gtopo30.html respectively).

In Figure 4 how the datasets derived from remotely sensed imagery will be utilized to provide a synoptic, systematic and repeatable biodiversity monitoring program is presented. The EVI and LST data will be used to calculate the Disturbance Index (DI) on a per pixel basis for terrestrial regions across Canada. Provisions exist to examine the DI on a 16-day, monthly, and annual basis, which will allow end users to select an appropriate level of temporal resolution for their given needs. A number of stratification layers will then be used to determine the long term mean and disturbance thresholds, which will allow the DI to be more responsive to disturbances specific to particular biogeoclimatic conditions. For example, our implementation of the DI will be tailored for a particular land cover type (e.g. coniferous forest), level of fragmentation (e.g. highly fragmented), elevation range (e.g. 200-400 m ASL), and ecoregion (e.g. Fraser Plateau). Finally, the Dynamic Habitat Index (DHI) will characterise the productivity regime within the ecoregion, and provide insights to what type of biodiversity is expected to exist, which in turn relates to available resources, suitable habitat cover, animal foraging behaviour, and other aspects that may influence regional biodiversity, and if the region is changing significantly as defined by the DI.

Insert Figure 4 about here:

C Conclusion

International commitments such as the Convention on Biological Diversity require that countries establish a means of inventorying and monitoring elements of biodiversity, and the processes that may impact them. Countries such as Canada that cover large and often inaccessible terrain will require biodiversity assessment techniques that are robust enough to be used in a variety of applications and spatial scales, while remaining scientifically rigorous and defensible. While conventional field based techniques will continue to dominate the mainstay of biodiversity research, they are costly and often logistically difficult to conduct over large areas. Fortunately, elements of biodiversity have been shown to be amenable to remote sensing technologies and associated techniques. For example, data from Earth observation satellites are now routinely used to create land cover maps. Such maps can be used to provide, or enable inference of, the number of individual species (or assemblages) within an area, which allows for key elements of biodiversity to be quantified such as species composition, richness, and evenness. Land cover maps can also be used to create habitat coverage maps for individual species, whose level of fragmentation can be analyzed to provide further insights into a given areas' ability to support certain species. Observations of variables known or believed to affect levels of biodiversity such as climate, productivity, and topography can also be synoptically monitored in a systematic and repeatable fashion. These "indirect" elements of biodiversity are often statistically related to "direct" elements such as species richness. Disturbance indices utilizing optical and thermal sensors onboard Earth observation satellites can be developed to reveal areas of vegetation undergoing broad scale disturbance or recovery. Such indices can act as a coarse filter biodiversity change detection system, whereby fine filter techniques utilizing higher spatial and spectral resolution sensors and/or more sophisticated techniques can be focused for further investigation.

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TABLES AND FIGURES

Table 1.

Global Scale Indicator of biodiversity	Approach	Description of Methodology	Author(s)
Land cover	Direct	Land cover change in global humid tropical forests between '97-'99	Achard et al. 2002
Land cover	Direct	Global landcover derived from 1km AVHRR data	Loveland et al. 2000
Land cover	Direct	MODIS used to derive global 1km land cover product	Friedl et al. 2002
Species home range	Indirect Productivity	FPAR used to explain intrapopulation variation in home range size among 12 species of carnivore	Nilsen et al. 2005
Land cover disturbance index (utilizes vegetation productivity and structural measures)	Indirect Disturbance	Change detection algorithm using BRDF to assess land cover change caused by fire	Roy et al. 2005
Vegetation productivity	Indirect Productivity	MODIS NPP product (derived from NDVI and other RS variables) is used to assess global net primary productivity	Running et al. 2004
Land cover disturbance index (utilizes vegetation productivity and structural measures)	Indirect Land Cover	Change detection algorithm (MODIS Vegetative Cover Conversion) comprised of a series of spectral, textural and shape indices used to assess land cover changes	Zhan et al. 2002
Continental Scale			
Indicator of biodiversity	**Approach**	**Description of Methodology**	**Author(s)**
Land cover	Direct	Decision tree classifier based on various optical/thermal and temporal metrics	Defries et al. 1998
Land cover	Direct	NDVI from March-October 1990 from the AVHRR are used to produce an unsupervised classification of vegetated and barren land	Loveland et al. 1991
Species-energy relationship	Indirect Productivity	NDVI used to model the structure of the species-energy relationship for birds in southern Africa	Bonn et al. 2004
Land cover disturbance index (utilizes vegetation productivity and structural measures)	Indirect Disturbance	NDVI and (thermal) hotspot algorithm used to detect forest fires throughout Canada	Fraser et al. 2000
Species richness	Indirect Land cover	Land cover diversity used as a predictor of butterfly species richness throughout Canada	Kerr et al. 2001
Regional Scale			
Indicator of biodiversity	**Approach**	**Description of Methodology**	**Author(s)**
Land cover	Direct	Landsat TM, DEM, population census, and various other datasets used to classify a final land cover product	Vogelmann et al. 1998
Land cover	Direct	Landsat TM data used with species occurrence data to identify areas where land use and conservation conflicts might exist and to investigate how land use constraints may aid in conservation area selection.	Wessels et al. 2000
Species endemism	Indirect Disturbance	Comparing T/NDVI with DNA divergence data to find relationship with biodiversity hotspots in tropical Africa	Fjeldsa et al. 1996
Species richness / Land cover	Indirect Elevation	Threatened endemic bird populations in Brazil mapped by processing historical range maps, RS derived forest cover, and DEM	Harris et al. 2005

Table 2:

Ecozone	Taxonomic Class	Common Name	Scientific Name	COSEWIC Status
Boreal Shield Terrestrial Ecozone (~1.8 million km^2)	Arthropods	Monarch	*Danaus plexippus*	Special Concern
	Birds	Peregrine Falcon (anatum subspecies)	*Falco peregrinus anatum*	Threatened
	Fish (freshwater)	Aurora Trout	*Salvelinus fontinalis timagamiensis*	Endangered
	Mammals (terrestrial)	Wolverine (Eastern population)	*Gulo gulo*	Endangered
	Reptiles	Spotted Turtle	*Clemmys guttata*	Endangered
	Vascular Plants	American Ginseng	*Panax quinquefolius*	Endangered
Prairie Terrestrial Ecozone (~520,000 km^2)	Arthropods	Yucca Moth	*Tegeticula yuccasella*	Endangered
	Birds	Burrowing Owl	*Athene cunicularia*	Endangered
	Fish (freshwater)	Western Silvery Minnow	*Hybognathus argyritis*	Threatened
	Mammals (terrestrial)	Swift Fox	*Vulpes velox*	Endangered
	Reptiles	Prairie Skink	*Eumeces septentrionalis*	Endangered
	Vascular Plants	Small White Lady's-slipper	*Cypripedium candidum*	Endangered
Pacific Maritime Terrestrial Ecozone (~195,000 km^2)	Amphibians	Oregon Spotted Frog	*Rana pretiosa*	Endangered
	Arthropods	Sand-verbena Moth	*Copablepharon fuscum*	Endangered
	Birds	Spotted Owl (caurina subspecies)	*Strix occidentalis caurina*	Endangered
	Fish (freshwater)	Salish Sucker	*Catostomus catostomus*	Endangered
	Mammals (terrestrial)	Vancouver Island Marmot	*Marmota vancouverensis*	Endangered

Table 3:

	Topography	**Production**	**Land cover and fragmentation**	**Disturbance**
Image spatial resolution / grain	90 m < 60° N 1000 m > 60°N	1000 m	25 m	1000m
Image extent	Canada Wide	All vegetated areas	All forested areas	Canada Wide
Type of remotely sensed data	RADAR	MODIS fPAR	Enhanced Thematic Mapper (ETM+)	MODIS EVI / LST
Platform	Shuttle	Terra / Aqua	Landsat	Terra / Aqua
Temporal Capacity	Single	Monthly / Annual	Once	8-day
Ownership / cost	Free	Free	Free	Free
Size of Dataset	250 MB	100 MB	300 MB	1 TB per year
Processing strategy	Elevation Residuals	Dynamic Habitat Index (DHI)	Image classification, Pattern indices	16-day Disturbance Index against long term mean
Processing strategy references	Wilson and Gallant (2000)	Mackey et al. (2004), Coops et al. (In review)	Wulder et al. (2003).	Mildrexler et al, (In press)

Figure 1:

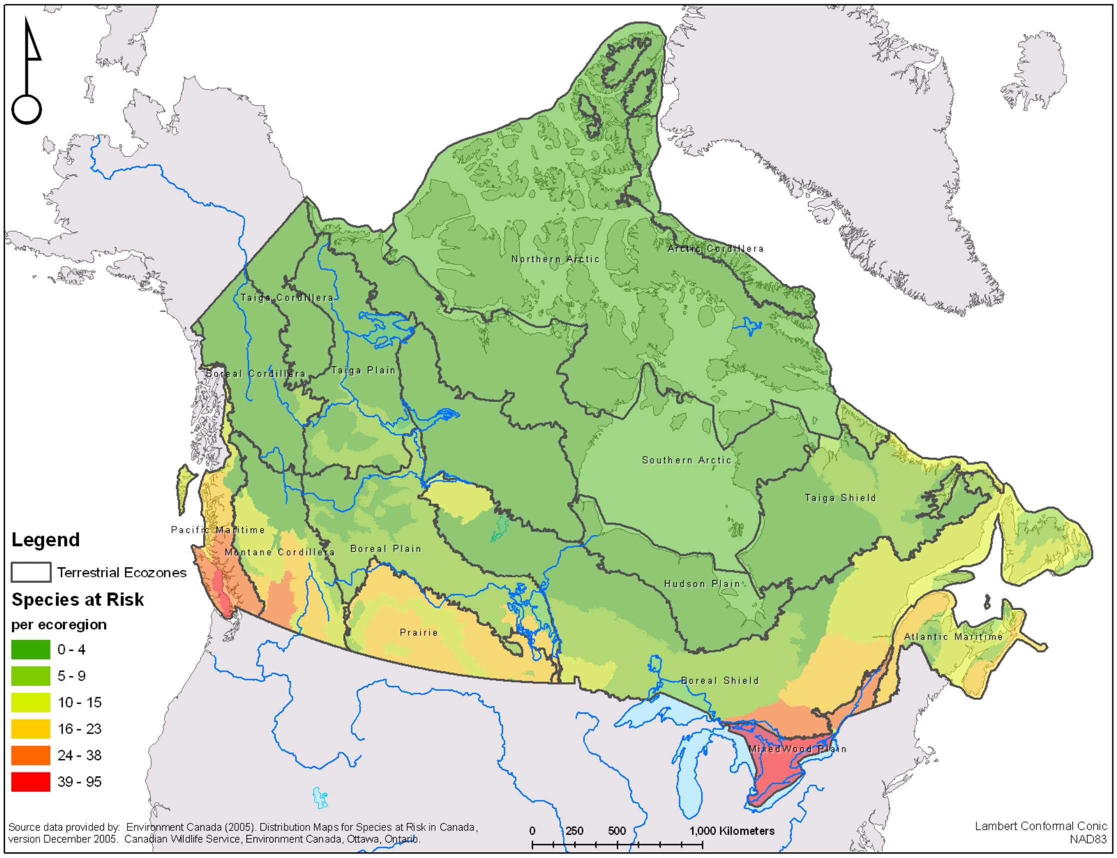
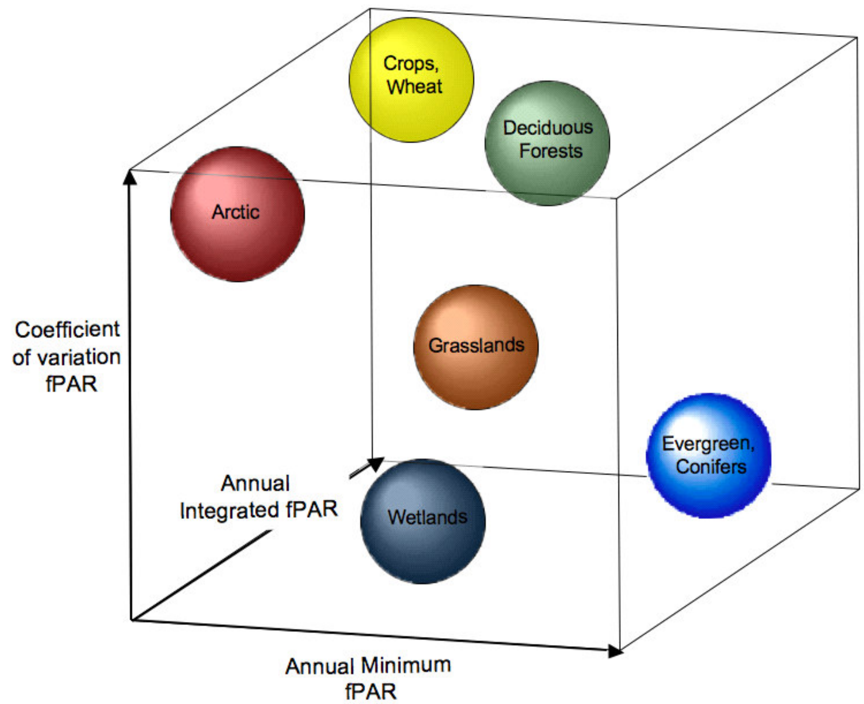

Northern Arctic
Arctic Cordillera
Taiga Cordillera
Boreal Cordillera
Taiga Plain
Southern Arctic
Taiga Shield
Pacific Maritime
Montane Cordillera
Boreal Plain
Hudson Plain
Prairie
Atlantic Maritime
Boreal Shield
MixedWood Plain
Legend
Terrestrial Ecozones
Species at Risk
per ecoregion
0 - 4
5 - 9
10 - 15
16 - 23
24 - 38
39 - 95
Source data provided by: Environment Canada (2005). Distribution Maps for Species at Risk in Canada, version December 2005. Canadian Wildlife Service, Environment Canada, Ottawa, Ontario.
0 250 500 1,000 Kilometers
Lambert Conformal Conic
NAD83

Figure 2:



Crops,
Wheat
Deciduous
Forests
Arctic
Coefficient
of variation
fPAR
Grasslands
Evergreen,
Conifers
Annual
Integrated fPAR
Wetlands
Annual Minimum
fPAR

Figure 3:

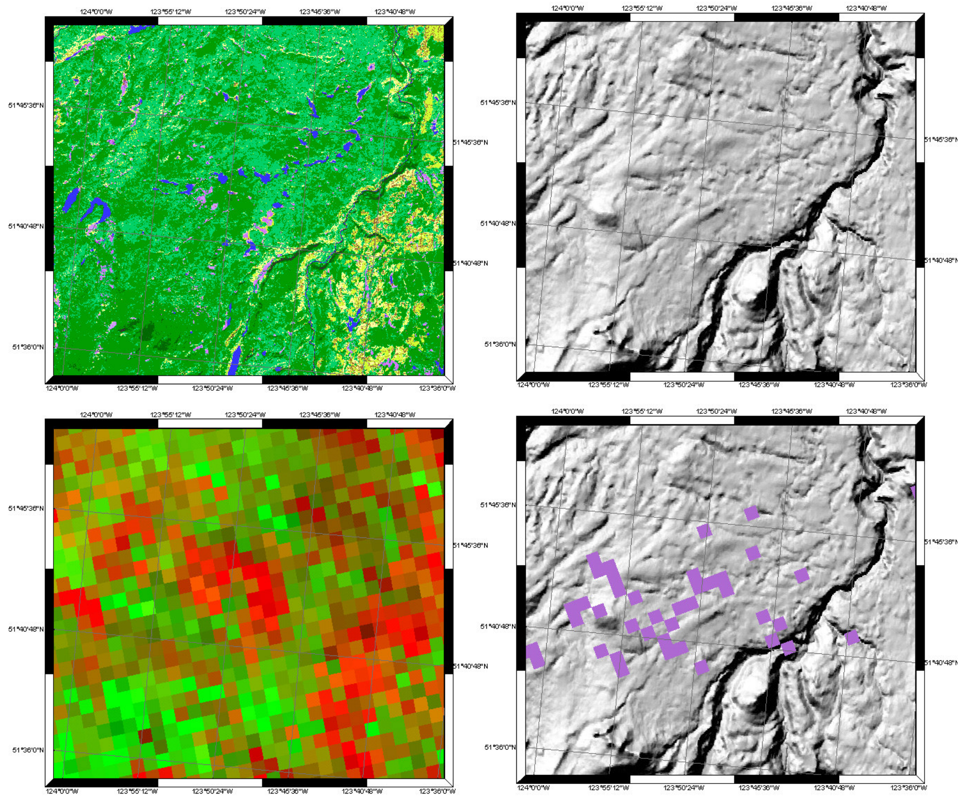
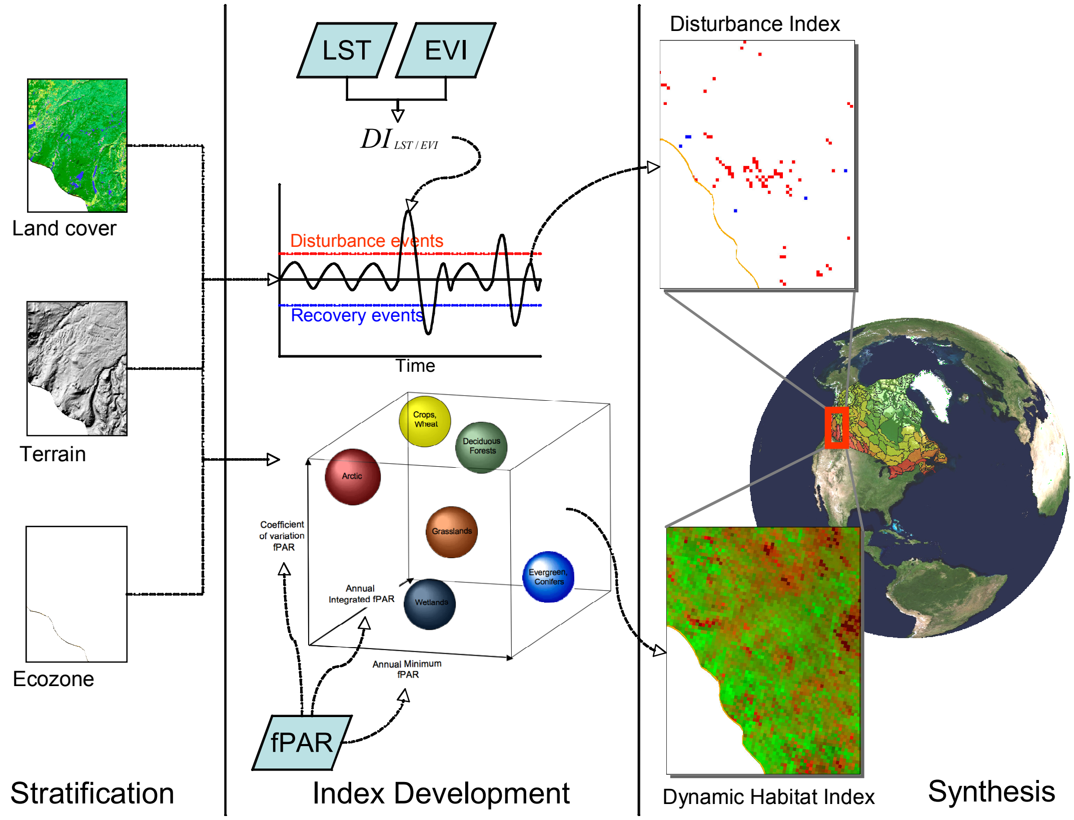


Figure 4:


LST
EVI
$DI_{LST/EVI}$
Disturbance Index
Land cover
Disturbance events
Recovery events
Time
Terrain
Crops, Wheat
Deciduous Forests
Arctic
Coefficient of variation fPAR
Grasslands
Evergreen Conifers
Annual Integrated fPAR
Wetlands
Ecozone
Annual Minimum fPAR
fPAR
Dynamic Habitat Index
Stratification
Index Development
Synthesis