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FOREST AND RANGE EVALUATION PROGRAM

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Remote sensing opportunities for monitoring indicators of forest sustainability

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With contributions from Sam B. Coggins, Nicholas O. Soverel, Thoreau Rory Tooke, Steve N. Gillanders, Nicholas G. Goodwin, and Trevor G. Jones

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Sustainability of Forest and Range Resources Through Science and Stewardship

Management of forest and range resources is a complex process that often involves the balancing of ecological, social, and economic considerations. This evaluation report represents one facet of this process. Based on monitoring data and analysis, the author offers the following recommendations to those who develop and implement forest and range management policy, plans, and practices.

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MINISTRY OF FORESTS AND RANGE
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EXECUTIVE SUMMARY

Remote sensing offers the possibility to map and monitor a variety of indicators related to sustainable forest management over large areas, in a spatially explicit and cost effective manner. The wide array of available technologies and methods, however, can confound even those well versed in the area. Remote sensing is not a panacea, but it is also often underutilized by forest managers. It is also apparent that no single technology or sensor is universally suitable for monitoring all attribute values. Nonetheless, remote sensing technologies could be successfully incorporated into many areas related to sustainable forest management. Following interviews with Forest and Range Evaluation Program members, a number of subject areas were identified as having potential to benefit from remote sensing technology. In this report, applications related to archaeological sites, three dimensional visualization, fire mapping, fuel modelling, forest inventory, habitat mapping, invasive plant detection, land cover mapping, forest health assessment, terrain modelling, water body mapping, and reconnaissance mapping are discussed.

This report is divided into three sections:

1) A brief introduction to key remote sensing concepts.
2) Examples and discussions on the estimation of sustainable forest indicators using remote sensing technologies, concluding with recommendations for operational deployment and future research.
3) An appendix listing commonly employed sensors, and their specifications and data availability.

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INTRODUCTION

The establishment of multi-functional sustainable forestry goals and the associated development of resource values and indicators is occurring in a number of Canadian provinces, including British Columbia. While forestry's economic benefits are significant, extraction must be performed in a sustainable manner for future generations. In response to this need, the Province of British Columbia, under the auspices of the Forest and Range Practices Act (FRPA), has developed a suite of resource values to monitor forest health and sustainable management practices. The Forest and Range Evaluation Program (FREP) has been put in place as a multi-agency program to assess the effectiveness of the FRPA in achieving stewardship of the identified resource values. Each resource value is assessed by monitoring a number of indicators. To be useful, an indicator should:

- be easy to interpret;
- be correlated with changes in ecosystem processes;
- have regional applicability;
- show low temporal and spatial variability;
- be quantifiable using synoptic or automated monitoring;
- be responsive to change;
- be anticipatory and provide potential for early warning;
- have results that can be easily summarized and understood by non-experts; and
- be cost effective (Breckenridge et al. 1995; Stone et al. 2000).

Digital remote sensing systems are an evolving set of tools making available products that meet many of the criteria required of indicators: they provide data covering large areas, often at high spatial resolutions; they are capable of change detection through repeated observations; and they are becoming increasingly cost-effective. The past decade has seen a tremendous increase in the number of publicly-accessible imaging platforms designed to deliver data at ever-increasing spatial, spectral, radiometric, and temporal resolutions, which in turn allows for an impressive suite of forest-related attributes and indicators to be modelled, predicted, and monitored through time. The promise of remote sensing technologies lie in their ability to deliver high-quality, spatially-explicit observations over large areas with regular revisit intervals.

The goal of this report is to identify key areas of interest to the FREP, and then discuss the possibility of employing remotely sensed data for their estimation and observation through time. This report is divided into three broad sections. First, some fundamental concepts related to remote sensing are outlined; second, descriptions and examples of how indicators are typically examined using remotely sensed data are offered; finally, in Appendix A, remote sensing sensor characteristics and data availability are listed.

GENERAL CONCEPTS IN REMOTE SENSING

Remote sensing is "…the science, and art of obtaining information about an object, area or phenomenon through the analysis of data acquired by a device that is not in contact with the object, area or phenomenon under investigation" (Lillesand et al. 2007, p. 1). Fundamentally, this information is derived from data related to how an object reflects or emits electromagnetic energy.

Good introductions to remote sensing include Aranoff (2005), Jensen (2006), and Lillesand et al. (2007), while Frankilin (2001), and Wulder and Franklin (2003) focus on remote sensing of forest ecosystems in particular.

The electromagnetic spectrum

Visible light is the form of electromagnetic energy most people are familiar with. The electromagnetic spectrum, however, is made up of a range of radiation types with varying wavelengths (usually expressed in micrometres (µm)) and frequencies. As wavelengths increase, spectral regions shift from the ultraviolet to the visible (0.4-0.7 µm), then near infrared (0.7-1.3 µm), mid or shortwave infrared (1.3-3 µm), thermal infrared (3-14 µm), and microwave (1 mm to 1 m) portions of the electromagnetic spectrum. Radiation reflected or emitted within these regions may be used alone or in combination to obtain information about an object, area, or phenomenon of interest.

Critically, different objects have unique and distinguishable spectral response curves. For instance, vegetation species-specific reflectance curves are a result of the variable presence and absence of certain pigments, water and organic compounds, and internal leaf cell structure. These subtle differences can be measured, quantified, and then used to discriminate between vegetation and other objects.

Sensor type and resolution

Remote sensing systems vary widely in their specifications and design, but they may be thought of as either passive or active sensors which capture data at different spatial, spectral, radiometric, and temporal resolutions.

Passive sensors measure electromagnetic radiation reflected from the Sun or emitted by the Earth. These sensors typically detect visible, near infrared, or shortwave infrared energy reflected by a target, or thermal infrared radiation emitted by a feature. Active sensors, alternatively, provide their own illumination source. Radiation is emitted by the sensor towards a target of interest, and the reflected radiation is then measured. Advantages of active sensors include the ability to collect data at night, sometimes through cloud, and the ability to use portions of the electromagnetic spectrum that are difficult to detect using passive sensors, such as microwaves.

The concept of resolutions in remote sensing is a crucial factor in determining which technology will be most appropriate for achieving a given objective. Sensors, be they active or passive, are usually summarized by their spatial, spectral, radiometric, and temporal resolutions.

Spatial resolution

Spatial resolution defines the detail that is discernable on an image, and for passive sensors depends on the instantaneous field of view (IFOV; the cone angle within which incident radiation is focused on the detector) and the height of the sensor above ground. Depending on the size and spatial variability of features on the ground and the spatial resolution of the sensor, an image may be comprised of pure pixels, where a single pixel covers only one target (e.g. a part of a single tree crown), and mixed pixels comprised of numerous features within a single pixel (e.g. several tree crowns within a single pixel). Thus, the larger the number of pure pixels within an image, the greater the ability to discriminate spatial detail (Figure 1, Table 1). Spatial resolutions vary tremendously across sensor systems; the highest resolution aerial imagery may have a pixel sizes of only a few centimetres, while satellite systems may range in resolution from decimetres to kilometres. Critically, a tradeoff exists between spatial resolution and the size of an area that is covered by a single image. A single Landsat Thematic Mapper (TM) scene, for example, covers an area 185 by 185 km in size with a spatial resolution of 30 m, while the NOAA/AVHHR covers a far larger area of 2,394 by 2,394 km, but with a pixel size of 1.1 km at nadir (Appendix A).

Spectral resolution

Spectral resolution refers to the number and width of spectral bands a sensor has. Multispectral sensors, which have relatively low spectral resolution, tend to have several relatively “fat” bands, usually several tens of nanometres wide. Increasing the number of bands while reducing their width leads to an increase in spectral resolution. These sensors, referred to as hyperspectral sensors (or imaging spectrometers), typically have hundreds of very narrow continuous bands. These systems can identify targets that have specific reflectance and absorption characteristics over very narrow portions of the electromagnetic spectrum that are otherwise undetectable using multispectral sensors. So for instance, whilst a multispectral sensor may be used to discriminate between deciduous and coniferous forests, a hyperspectral sensor may be employed when it is necessary to isolate individual tree species. Contrast these to panchromatic sensors, which have a single band and record a very wide portion of the electromagnetic spectrum. Panchromatic bands sacrifice spectral resolution in favour of spatial resolution, as detecting very large amounts of incident energy allows for much smaller instantaneous fields of view.

Radiometric resolution

Radiometric resolution refers to the number of digital levels that a sensor employs to express the variability in brightness of a scene (or the ability of a sensor to detect shades of gray), and is summarized by the number of bits captured per pixel (Figure 2). An 8 bit pixel means that a sensor captures 28 or 256 shades of grey, so that the digital numbers of a given pixel would range from 0-255; an 11 bit sensor captures 211 or 2,048 shades of gray, so that its digital numbers will range from 0-2,047. The more levels detectable, the more detail captured. Radiometric resolution is an important concept, as it may place limits on a sensor’s ability to discriminate the variability in a phenomenon with enough detail to be useful to forest managers.

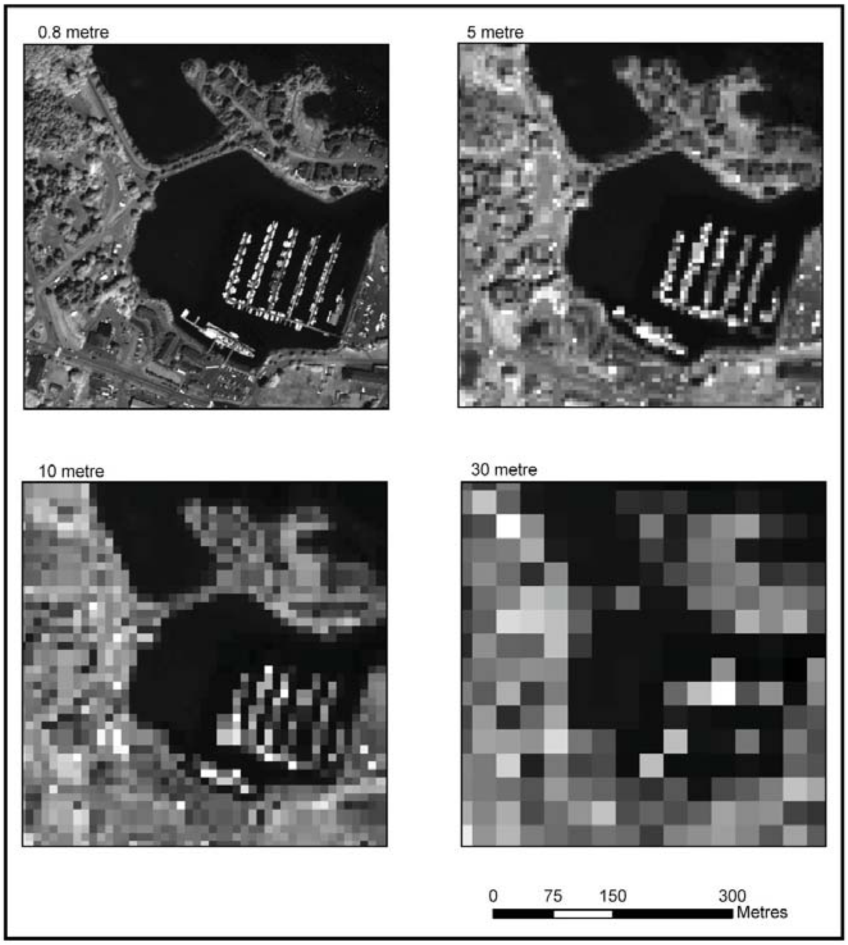

Figure 1 *The effects of pixel size on the ability to discriminate ground features. Here, a QuickBird panchromatic image of a harbour in Ucluelet, British Columbia, has been resampled from its original 0.80 m spatial resolution to 5 m (equivalent to SPOT 5 panchromatic), 10 m (equivalent to SPOT 5 multispectal) and 30 m (equivalent to Landsat TM and ETM+). Reducing spatial resolution results in a larger number of mixed pixels and a reduced ability to discriminate features.*

Table 1 *Typical use of aerial and satellite imagery based on spatial scale or resolution. The table is synthesis of information found in Wulder (1998) and Franklin and Wulder (2002). Sensors are described in Appendix A.*

Sensor type or photo scale	Approximate spatial resolution (m)	Appropriate use
1:500 to 1:2500	0.001 to 0.026	Identification of individual range plants and grassland types
1:2,500 to 1:10,000	0.026 to 0.12	Identification of individual tree and large shrubs
1:10,000 to 1:25,0000	0.12 to 0.31	Identification of major cover types and species in pure stands
1:25,000 to 100,000	0.31 to 1.24 Base on a standard aerial film camera with 150 mm lens	Recognition of large individual trees and broad vegetation types
Digital frame camera or airborne video	> 0.04	Identification of individual trees and large shrubs
Airborne multispectral scanners	> 0.3	Identification of large individual trees and stand-level characteristics
High resolution satellite imagery (examples include GeoEye, IKONOS, and QuickBird)	0.5 to 1 m panchromatic 2 to 4 m multispectral	Recognition of large individual trees and broad vegetation types. Large scale mapping applications.
Moderate resolution satellite imagery (examples include Landsat, SPOT, IRS, JERS, ERS, and Radarsat)	10 to 60 m	Separation of extensive masses of evergreen and deciduous forests and other stand level characteristics. Mapping phenomena that occur over tens or hundreds of metres. Moderate scale mapping applications.
Low resolution satellite imagery (examples include MODIS, GOES, NOAA AVHRR, SPOT VEGETATION)	250 m to 1 km	Mapping phenomena that occur over hundreds or thousands of metres. Ideal for small scale or province-wide mapping applications.

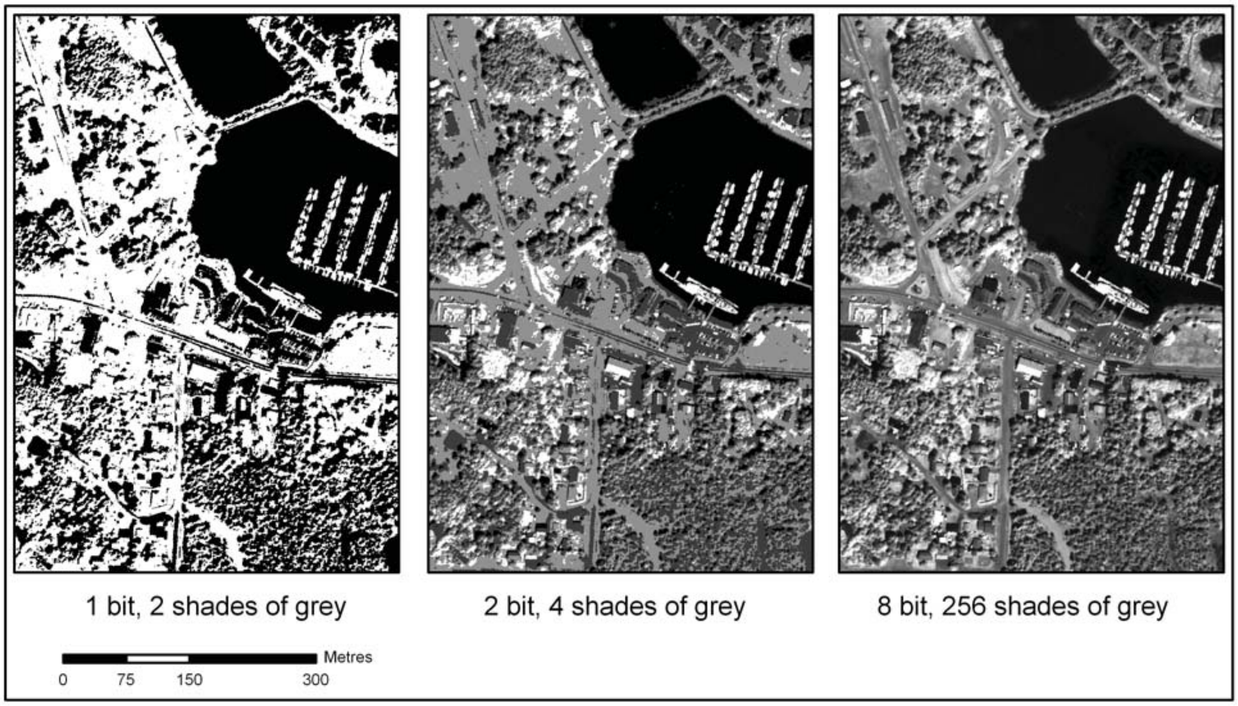

Figure 2 *Radiometric resolution refers to the number of digital levels that a sensor employs to express the variability in brightness of a scene. Here, a QuickBird panchromatic image of a harbour in Ucluelet, British Columbia, has been resampled from its original 11 bit pixel depth to 1, 2 and 8 bits.*

Temporal resolution

Finally, temporal resolution refers to the amount of time required for a remote sensing system to return to an area for data acquisition. Some space-borne sensors, such as the Landsat series of satellites, can only image targets at nadir (or directly below the sensor). Thus, they are limited by their orbital characteristics and the width of the swath they image, resulting in longer return periods (16 days for Landsat). Other space-born sensors such as Systeme Probatoire d'Observation de la Terre (SPOT) IKONOS, and QuickBird, are referred to as "agile" and have the ability to rotate and view targets off-nadir. As a result, though they may pass over an area relatively infrequently, they are able to capture images of areas not directly below the satellites by pointing their sensors toward them.

REMOTE SENSING APPLICATIONS FOR SUSTAINABLE FOREST MANAGEMENT

Interviews with FREP team members indicated that a large number of individual indicators are relevant to numerous resource values. The presence of roads, for instance, was of concern to virtually all of the FREP teams interviewed. Thus, rather than address each resource value individually, the following section is divided into a series of topics or themes that were identified as being of interest to one or more of the FREP teams. The themes include three dimensional visualization, archaeological sites and trails, fire mapping and fuel modelling, forest inventory and structure, animal habitat, invasive plants, land cover, mountain pine beetle and forest health, roads, terrain modelling, water bodies and streams, and reconnaissance mapping. Table 2 summarizes the themes discussed in this report, the operational status of associated applications, and makes recommendations on which technologies are most appropriate for their estimation. Note that specific sensors are described in Appendix A.

Table 2 *Summary of the themes and applications discussed in this report. Note that specific sensors are described in Appendix A.*

Theme	Application	Recommended remote sensing technology	Potential Platform (s)	Methodology	Status in British Columbia
Three dimensional visualization	Synoptic large area visualizations	Moderate to high resolution satellite imagery, moderate resolution terrain model	Landsat Thematic Mapper, Spot 5	Visual Interpretation	Can be operational with some research
	Small area, highly detailed visualizations	Aerial imagery, lidar	Existing Aerial Photography, Airborne LiDAR for DEM Derivation	Visual Interpretation Terrain Derivation from ground hits	Operational in some limited, select, areas. Broad scale application unlikely.
Archaeological sites and trails	Surface feature extraction	Aerial imagery, high resolution satellite imagery, lidar	Existing Aerial Photography, Airborne LiDAR for DEM Derivation	Visual Interpretation Terrain Derivation from ground hits	Needs research, unlikely to be operational
	Trail identification	Lidar	Airborne LiDAR for DEM Derivation	Terrain Derivation from ground hits	Needs research
	Subsurface feature extraction				Not possible
Fire mapping and fuel modelling	Fuels inventorying	High to moderate resolution satellite imagery, lidar	Landsat Thematic Mapper ASTER	Image Classification Spectral Moisture and Vegetation Indices	Operational in US, with some research can be operational in BC
	Predictive services	Moderate to low resolution satellite imagery	MODIS	Spectral Moisture Indices	Operational in US, with some research can be operational in BC
	Active fire mapping	Moderate to low resolution satellite imagery	MODIS	MODIS Rapid Response	Operational
	Post fire mapping	Moderate resolution satellite imagery	Landsat Thematic Mapper	Normalized Burn Ratio	Can be operational with some research

Theme	Application	Recommended remote sensing technology	Potential Platform (s)	Methodology	Status in British Columbia
Forest inventory and structure	Manual interpretation of basic inventory attributes	Aerial imagery	Existing Aerial Photography	Aerial Photographic Interpretation	Operational
	Automated classification	Optical satellite data, lidar, radar	QuickBird / Ikonos Hyperspectral Imagery RADARSAT LiDAR	Image Classification Spectral Un-mixing Structure Indices	Operational in some limited, select, areas. Can be operational with some research
Habitat Mapping	Broad scale habitat	Moderate resolution satellite data	Landsat Thematic Mapper SPOT XS SPOT 5	Image Classification Spectral Vegetation Indices	Can be operational with some research
	Land cover	Moderate resolution satellite data	MERIS (300m) Landsat Thematic Mapper (30m)	Image Classification Earth Observation for Sustainable Development (EOSD)	Operational
	Chemical/pigments constituents	Airborne hyperspectral data	Airborne Hyperspectral AISA, AVIRIS, CASI2	Spectral Image Classification	Requires significant research to be operational
	Vertical vegetation structure	Lidar	Airborne LiDAR	Structure Indices	Can be operational with some research
Invasive plants	Species identification	Airborne hyperspectral data	Airborne Hyperspectral AISA, AVIRIS, CASI2	Spectral Image Classification	Requires significant research to be operational
Land cover	Land cover classification	Moderate resolution satellite imagery	MERIS (300m) Landsat Thematic Mapper (30m)	Image Classification Earth Observation for Sustainable Development (EOSD)	Operational
Mountain pine beetle and forest health	Tree level mapping	High resolution satellite or airborne data	QuickBird / Ikonos Airborne Digital Camera (eg. Terrasaurus)	Object Based Image Classification	Can be operational with some research
	Stand level mapping	Moderate resolution satellite imagery	Landsat Thematic Mapper SPOT XS SPOT 5	Image Classification Spectral Vegetation Indices	Operational
Road mapping	Manual interpretation	High resolution optical data	Existing Aerial Photography QuickBird / Ikonos SPOT 5	Visual Interpretation	Operational
	Automatic extraction	High resolution optical data	QuickBird / Ikonos SPOT 5	Automated linear feature extraction	Requires significant research to be operational

Theme	Application	Recommended remote sensing technology	Potential Platform (s)	Methodology	Status in British Columbia
Terrain modelling	Photogrammetry	Aerial photography, satellite imagery	Existing Aerial Photography QuickBird / Ikonos	Standard Digital Photogrammetry Photogrammetry	Operational
	Radar	Airborne or spaceborne radar	IFSAR ERS – 2 Shuttle Radar Topography Mission (STRM)	Digital Photogrammetry	Operational with constraints
	Lidar	Airborne small footprint, discrete return lidar	Airborne LiDAR	Terrain Derivation from ground hits	Operational with constraints
Theme	Application	Recommended remote sensing technology	Potential Platform (s)	Methodology	Status in British Columbia
Water body and stream mapping	Water body delineation	Airborne or spaceborne optical infrared imagery	SPOT 5 Airborne Multispectral Imagery	Image Classification	Operational
	Bathymetry	Sonar, bathymetric lidar	SHOALS	Terrain Derivation from hits	Operational
	Temperature	Airborne thermal scanner	Airborne Thermal Scanners	Image Thresholding Temperature Indices	Can be operational with some research
Reconnaissance mapping		Typically optical data of various spatial resolutions	Existing Aerial Photography QuickBird / Ikonos Digital Camera Imaegry SPOT 5 Landsat Thematic Mapper	Visual Overlay and Interpretation	Operational

Three dimensional visualization

In most of British Columbia, landscape planning occurs over topographically varied mountainous areas, and, as a result, is a three-dimensional endeavor. Visual resource management, where scenic landscapes are identified and classified, is also a critical component of the FREP program. As a result, three dimensional visualization, where an image is draped over digital elevation data to provide a perspective view of a landscape, is an emerging tool with a number of forest management applications. Visualization techniques may also be used to help those not familiar with two dimensional maps recognize and locate familiar traditional-use sites (Sheppard et al. 2004), or to lend to a better understanding of the distributions of and relationships between terrain, geology, soils, and vegetation (Maune 2001).

From a remote sensing perspective, a variety of satellite image data may be used for 3D visualization, and their selection depends on the purpose and level of detail required in the visualization (Discoe 2005). Medium resolution sensors such as Landsat or SPOT may be appropriate for the examination of larger landscape units, whilst finer resolution data such as QuickBird, IKONOS, or large-scale aerial imagery may be used for smaller areas. It can, however, be difficult to translate accurate forest management/design information from a two dimensional image to a three dimensional landscape.
In particular, the use of widely available but coarse scale digital elevation models (DEMs; e.g. TRIM 20-30 m data) may not adequately capture fine terrain features, and may be difficult to combine with more accurate data such as those collected in the field using a global positioning system (GPS) (Bergen et al. 1998). Since bare-Earth DEMs contain only terrain elevation data, when image features such as trees are draped over them, vegetation may appear flattened and unrealistic (Discoe 2005). At large distances or coarse scales, however, individual trees are not discernable, only their pattern and

texture are detected. For example, general forest growth and large-scale changes due to fire and insect infestation may be modelled. At finer scales, closer viewpoints, or when more detail is required, individual plants may need to be represented and remotely sensed data may not convey this necessary realism. In this case, three dimensional modelling tools such as Visual Nature Studio (from World Construction Set) may be preferred for inserting higher quality three dimensional tree objects into virtual landscape models, thereby simulating accurate forest cover.[1] Thus, while imagery may convey much about the forest, the realism of individual trees is a challenge for even the highest spatial resolution remotely sensed data (Orland 2005).

Visual quality assessments in particular require very high spatial resolution data for 3D simulations of ground level vistas and fly-throughs, which are typically performed on a given landscape unit or catchment. The need for extremely high spatial resolution imagery has necessitated the use of ground-based 35mm film or digital cameras, which still provides more detail than is available from any high spatial resolution satellite and most airborne data.

Discussion

Within the context of British Columbia, visual quality assessments are becoming a critical indicator of forest management practices. At the land unit or catchment scale, these visualizations are required to be developed from a ground level perspective which limits standard applications such as Google Earth, which only provides a bird-eye view. The need for extremely high spatial resolution imagery has necessitated the use of ground-based 35mm film or digital cameras. In this respect, satellite remote sensing cannot be seen as a replacement technology at this stage.

A number of other researchers concerned with other indicators, in particular Culture, indicated landscape visualization as very useful for helping elders identify cultural use sites, as they provide a more realistic representation of the traditional areas. This use of visualizations, at this broader or synoptic scale, could be increased, and satellite remote sensing data and existing software (such as ESRI ArcScene) could be more extensively used for this purpose.

Archaeological sites and trails

Archaeology has become an interdisciplinary field with branches in a variety of physical and social sciences such as forestry, botany, geography, anthropology and sociology.[2] As a result, modern archaeologists are interested in various features ranging from overgrown trails to buried cities, each requiring unique remote sensing systems and approaches. Although few examples exist within the province of British Columbia, numerous studies have demonstrated the successful application of remotely sensed data for archaeological applications (Table 3). The operational remote sensing techniques and technologies presented in this section are divided into two categories, specifically surface feature extraction and subsurface feature extraction.

Table 3 *Examples demonstrating the application of remotely sensed data for archaeological applications.*

Reference	Dataset	Objective	Study area
Lasaponara and Lanorte 2007	QuickBird-derived vegetation indices	Detection of archaeological crop marks	Italy
Crow et al. 2007	Lidar	Examined the ability of lidar to detect archaeological features, including circular and linear features, and charcoal platforms, beneath mixed woodland	England
Holcomb 2001	Radarsat-1 imagery	Employed imagery as a reconnaissance tool to indentify Palaeolithic subsurface features	Gobi Desert, Mongolia

1 World Construction Set's Visual Nature Studio: www.3dnature.com

2 Archaeological Remote Sensing: http://wwwghcc.msfc.nasa.gov/archeology/remote_sensing.html

Surface Feature Extraction

Surface feature extraction involves detecting archaeological features based on above-ground land cover observed from remotely sensed data. These techniques may involve either direct extraction of an exposed archaeological feature, or inferential extraction where land cover provides an indication of features underlying the surface substrate. Passive airborne and satellite imagery are most commonly used for these types of applications.

A common technique for archaeological remote sensing involves the analysis of landscape pattern using edge-detection algorithms. In a recent study, Lasaponara and Masini (2007) applied a Gaussian smoothing kernel to enhance the edges of a panchromatic QuickBird image fused with normalized difference vegetation index (NDVI) data derived from the red and near-infrared multispectral bands. Results from this analysis provided an image with exaggerated vegetation edges which were used to manually interpret selected features that resembled the linear patterns of archaeological sites buried beneath the soil. This technique has been applied in several European countries whose archaeological patterns tend to be characterized by linear features

Forested areas of British Columbia have presented many barriers to the remote sensing of archaeological sites since dense forest canopies inhibit the direct observation of ground and below ground features. However, emerging light detection and ranging (lidar)-derived data may reveal patterns on the forest floor indicative of archaeological sites or trails. Lee et al. (2005), for instance, investigated the detection of trails beneath dense forest canopies. This is an area of active research, however, and requires very sophisticated analytical techniques.

Subsurface Feature Extraction

Subsurface feature extraction applications of remote sensing in archaeology have received attention from both the public and the archaeological community in past decades. These remote sensing devices tend to include field based instruments operated in areas of known buried archaeological features; some studies, however, have demonstrated the ability of active synthetic aperture radar (SAR) shuttle and satellite mounted sensors for detecting buried archaeological features in areas with dry soils.

Field based instruments for archaeological geophysics employ active sensors that penetrate the ground to reveal anomalies which often represent archaeological features. Electromagnetic conductivity and resistivity instruments emit an electrical current and measure either the ease in which the energy passes through the soil or the local resistance. Ground penetrating radar, on the other hand, emits long wavelength electromagnetic radiation and measures the velocity at which this energy travels through the ground. These field instruments can detect features between 0.2 and 5 m below ground depending on soil mineralogy, clay content, ground moisture, surface topography, and vegetation.

Spaceborne radar sensors have been used to detect subsurface archaeological features such as buried cities. The long wavelength radiation that radar sensors emit can penetrate dry soils up to several metres, enabling successful archaeological application in arid environments (Holcomb 2001). Due to the moist soil conditions in many areas of British Columbia, such techniques would likely be constrained to drier areas in the province's interior. In addition, the spatial resolution of satellite mounted radar sensors requires that targets be relatively large and located close to ground surface for successful extraction.

Discussion

Within the context of British Columbia, the use remote sensing technology to help detect unknown archeological sites (e.g. old structures, grave sites, and cultural trails) is extremely limited. This is due to the small size and extent of these features, which cannot be readily detected using satellite based remote sensing technology. There may be potential to use airborne remote sensing datasets at very high spatial resolutions (e.g. <1m), these datasets, however, would need to be collected on a case by case basis, limiting their wide application. The second issue is the fact that within British Columbia, soils tend to be relatively moist and covering vegetation dense, making detection of subsurface features extremely unlikely, even using radar- or lidar-based technologies.

One area where potential does exist is the identification of culturally important vegetation types such as cedar, birch, grasslands, bogs and so on. The combined use of high spatial resolution imagery to infer species, and lidar to extract structural characteristics, may provide an approach for detection and monitoring. Similarly, monitoring vegetation buffer condition around culturally important sites is also feasible using satellite data such as SPOT-5.

Fire mapping and fuel modelling

Fire mapping and fuel modelling using remote sensing technology can involve fuel inventorying, seasonal fire planning and predictive services, active fire mapping, and post-fire mapping.

Fuels Inventorying

Wildland fuels inventorying is the quantification of the structure and composition of fuel accumulation and its predicted relationship to wildland fire. Many fire managers and researchers are particularly interested in the use of moderate to high spatial resolution multispectral imagery and lidar data to map forest fuel conditions. Fire growth models, such as Prometheus, that utilize the Canadian Forest Fire Behavior Prediction (FBP) System as their basis require many fuel data inputs.[3] Some components include:

- species composition,
- density of tree species,
- percent leafless of trees,
- percent dead and standing,
- crown base height (CBH) in metres, and
- crown fuel load (CFL) in kg/m².

Depending on the level of discrimination required, species composition and plant health can be estimated using multispectral sensors such as Landsat, MODIS (Moderate Resolution Imaging Spectroradiometer), ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer), and QuickBird (Table 4). Measurements of forest structure (height, canopy closure, density of trees, and surface fuels) is best suited to lidar. Multispectral imagery can also be used to map weakened, diseased, or dead stands that pose a significant fire hazard. The United States is currently funding the Landfire (Landscape Fire and Resource Management Planning Tools Project) project, which uses Landsat imagery to produce consistent and comprehensive maps and data describing vegetation, wildland fuel, and fire regimes across the entire United States.[4]

Predictive Services

Remote sensing technologies have also been applied in a predictive sense by producing daily or weekly broad-scale maps of current fuel conditions, using MODIS and AVHRR 1km data. MODIS imagery has been found to not only aide in fuel moisture mapping but also fuel heating, a critical variable for forest fire managers (Pinheiro et al. 2007). RADARSAT-1 has also been tested with some success in boreal regions to measure dead fuel moisture (Abbott et al. 2007).

Table 4 *Satellites with potential to map fuels, predict fire occurrence, map current and ongoing fires, and map post-fire damage. See also Appendix A.*

Satellite-Sensor Name	Description	Fire Mapping Use	Reference
Landsat	Moderate spatial resolution multispectral sensor, long historical archive	Fuels inventorying, predictive services, active fire mapping, post fire mapping	Eidenshink et al. 2007; Lentile et al. 2007
AVHRR	Low resolution sensor, long historical archive and rapid repeat time	Fuels inventorying, predictive services, active fire mapping	Fraser et al. 2000; Li et al. 2000; Pu et al. 2007
RADARSAT-1	C-Band RADAR backscatter linked to fuel moisture, day or night acquisition, irrespective of cloud cover	Predicative services	Abbott et al. 2007

3 Prometheus Wildland Fire Growth Model: www.firegrowthmodel.com

4 Fire and Resource Management Planning Tools Project: http://www.landfire.gov/index.php

Satellite-Sensor Name	Description	Fire Mapping Use	Reference
MODIS	250 to 1 km spatial resolution, 36 spectral bands available, data available since late 1999	Fuels inventorying, predictive services, active fire mapping, post fire mapping	Fraser et al. 2000; Justice et al. 2002; Giglio et al. 2003; Kaufman et al. 2003; Giglio 2005; Pinheiro et al. 2007
ASTER	Higher resolution than Landsat, Limited availability	Fuels inventorying, post fire mapping	Giglio et al. 2003; Csiszar et al. 2006; Csiszar et al. 2006
QuickBird	High spatial resolution multispectral sensor	Fuels inventorying, post fire mapping	Lasaponara and Lanorte 2007; Mutlu et al. 2008
Lidar	Airborne laser altimeter measures vegetation height and vertical structure	Fuels inventorying	(Mutlu et al. 2008); (Canfield et al. 2005)

Active Fire Mapping

Mapping of active fires, fire burned areas, and hotspot detection are the most advanced and operational of all the components described here. The most commonly used data for these applications in North America are the suite of MODIS products (specifically Products 2 and 3, and Rapid Response; Tables 5 and 6).[5 6] Hotspot detection is employed in Canada and the United States to detect fires in near real time. MODIS is the most common as it is available daily and burned area maps are available soon after fire start. Currently the Canadian Forest Service has implemented the interactive fire mapper.[7] This website utilizes MODIS, AVHRR (Advanced Very High Resolution Radiometer), and ATSR (Along Track Scanning Radiometer) sensors in combination to map hotspots or thermal anomalies. In conjunction with CCRS (Canadian Center for Remote Sensing) the interactive fire mapper website provides current hotspot information, estimated fire perimeters, and year-long burned area polygons. Burned area polygons are derived using MODIS 250 metre resolution grids along with hotspot detections for a given year using the HANDS (Hotspot and NDVI Differencing Synergy) method described in Fraser (2000). Another growing concern among local, provincial, and federal governments is wildland fire smoke. In a study conducted in North America using MODIS images, the rate of smoke emissions were estimated by mapping fire intensity and multiplying the total burned area by combustion efficiency to model total smoke dispersion (Kaufman et al. 2003).

Table 5 *MODIS Fire Products and general information (Justice et al. 2002; Giglio 2005))*

MODIS fire products	Resolution	Description	Repeat interval	Relative accuracy
Rapid Response	1 km	Active fire hotspot locations coupled with 250 m resolution background image	2-4 hours	Least accurate
Level 2	1 km	Identifies active fires and other hotspot anomalies	12 hours	Medium accuracy
Level 3	1 km	A 1-km gridded composite of fire pixels detected in each grid cell	8 days	Most accurate

Table 6 *A list of MODIS web addresses and product descriptions*

URL	Available Product
http://vulcan.geog.umd.edu/alerts/alerts.phtml	Subscribe for e-mail fire alerts
http://earthobservatory.nasa.gov/MissionControl/overpass.html	Satellite overpass predictor
http://rapidfire.sci.gsfc.nasa.gov/realtime/	Download current MODIS fire images
http://www.fs.fed.us/eng/rsac/index.html	Download active fire maps

5 MODIS Fire and Thermal Anomalies: http://modis-fire.umd.edu/MOD14.asp
6 Rapid Response: http://rapidfire.sci.gsfc.nasa.gov/
7 NRC Canadian Wildland Fire Information System: https://nofc1.cfsnet.nfis.org/mapserver/cwfis/index.phtml

Post Fire Mapping

Post fire mapping can be important in terms of understanding and measuring the post-fire impact on water quality, and ecosystem health and recovery. Remote sensing tools for post-fire mapping include MODIS 250 m resolution data providing initial maps of burned areas. Landsat-derived indices such as the differenced normalized burn ratio (dNBR) allows for 30m resolution mapping of burned perimeter and fire severity (Lentile et al. 2007; Eidenshink et al. 2007). Landsat burned area and severity maps have been used successfully worldwide and continue to be the most common form of burn severity products currently used in North America. Finally, ASTER imagery, with a 15 metre panchromatic and 30 metre multispectral sensor, has been found to be very useful in fire mapping and severity assessment (Csiszar et al. 2006).

Discussion

Information on fire location and the estimation of burn severity was recognized as important by a number of attribute value teams, including karst and wildlife habitat. The use of MODIS hotspots, which provides near real time mapping of fire hot spots across Canada at 1km spatial resolution, and the subsequent mapping of fire boundaries using MODIS were recognized as tools which the resource value teams could use more readily. The current impediment to operational use is simply access to and integration of this data into the province's existing data warehouse. Developing scripts to integrate this type of information could be an immediate project depending on overall interest.

Forest inventory and structure

Manual interpretation of aerial photographs

Remote sensing technologies have a long history in measuring forest structural attributes for forest inventory (Dralle and Rudemo 1996; Leckie et al. 1998; Zagalikis et al. 2005). Table 7 highlights a number of the critical attributes that have been successfully predicted using remote sensing technology. Aerial photography, for example, has been used extensively to map individual tree attributes such as height, crown area, species, basal area, wind throw, ground elevation, and forest types. The accuracy of estimates is influenced by user experience, complexity of the forested area, spatial resolution of the photographs, and the interpreter's knowledge of the surveyed forest (e.g. likely tree species). By deriving height and stand density it is also possible to estimate site index. The advantages with approaches based on aerial photography are that data acquisition is relatively inexpensive, it requires little post-acquisition processing, and the photographs can be captured at high spatial resolutions (e.g. 15 cm). The limitations relate primarily to the subjectivity of interpretations and the time consuming nature of interpretation work.

Automated classification

By targeting particular reflection or absorption features across multiple wavelengths (typically between 0.4 and 2.5 µm), passive optical sensors have been used to quantify physiological stress events (e.g. insect attack), classify tree species or forest classes, and map wildfire disturbances (White et al. 1996; Coops et al. 2004a; Asner et al. 2008a). In addition, hyperspectral data has proven useful in the extraction of detailed forest attribute information (Niemann and Goodenough 2003); including vegetative species discrimination (Cochrane 2000; Goodwin et al. 2005; van Aardt and Wynne 2007). Research has also indicated that forest structural complexity can be inferred from spatial patterns of reflectance (Coops and Catling 1997; Lévesque and King 2003) .

Satellite based passive optical imagery is typically less expensive and better suited for regional applications than airborne data. Earlier imagery captured from sensors such as Landsat Thematic Mapper have been demonstrated to accurately quantify the extent, location, and timing of landscape disturbances such as clear fell harvesting or insect attack (Wulder et al. 2006c; Kennedy et al. 2007). Empirical relationships with field data have also been developed to derive leaf area index (LAI) and assess patterns of forest regeneration (Chen and Cihlar 1996; Schroeder et al. 2007). Due to the broad spectral bands and coarse spatial resolutions typical of moderate resolution satellite imagery, mapping of vegetation has generally targeted communities rather than individual tree species. Similarly, satellite based radar (e.g. RADARSAT-1 and -2) can be used for regional assessments of forest structure at considerable cost savings (Ticehurst et al. 2004).

Table 7: Examples of forest attributes estimated using remote sensing data.

Reference	Dataset	Variable(s)	Accuracy	Study area
Sandvoss et al. 2005	Aerial photography (typically 1:20,000)	Cover patter, crown closure, tree layers, vertical complexity, species composition, age, height, density, snag frequency	Variable	Example from vegetation resources inventory manual
Zagalikis et al. 2005	Aerial photography (1:10 000)	Tree height, basal area, volume, biomass, and density	+/- 10%	Rosarie Forest, northeast Scotland
Leckie et al. 2005	Multiband passive optical imagery (CASI)	Tree species	40 to 72%	Vancouver Island, British Columbia, Canada
Dobson et al. 1995	Radar (SIR-C/X-SAR)	Vegetation height Trunk biomass	2.4 m (RMSE) 1.1 kg/m2 (RMSE)	Racho Supersite, Michigan
Vepakomma et al. 2008	Multi-temporal lidar	Canopy Gaps (wind throw)	96.5%	Teaching and Research Forest, Canada
Hyyppä et al. 2000	Lidar	Stem volume Basal area	2m2/ha or 10.2% (Standard Error) 18.5m3/ha or 10.5% (Standard Error)	Kalkkinen, southern Finland

Small footprint lidar has received considerable attention over the last two decades and can provide an accurate means to quantify a range of forest structural attributes (Lefsky et al. 2002). Commonly extracted attributes include maximum tree height, height to green canopy, crown diameter, crown area, canopy height and canopy cover (Coops et al. 2004b; Goodwin et al. 2006). Using allometric equations, it is also sometimes possible to estimate secondary attributes such as stocking density, diameter at breast height (DBH), and stem volume per unit area (Hall et al. 2005). Lidar, through its ability to penetrate small gaps in the forest canopy, has been suggested to be sensitive to coarse woody debris and understorey structure (Riaño et al. 2003; Seielstad and Queen 2003); however, this requires further research and is likely to be affected by the structure of the overstorey canopy (Maltamo et al. 2005). Additionally, lidar technology can provide high resolution digital elevation models under forest canopies, which supplies valuable information for activities such as road planning, harvest planning and hydrological modeling.

Another active remote sensing technology is radar. This data has been used to estimate biomass, stem volume, and vegetation heights, as well as derive ground elevation and forest classes (Schuler et al. 1996; Hoekman and Quinones 2000; Hyyppä et al. 2000) . However, the ability to estimate biomass has been found to saturate at high levels (e.g. 150 Mg/ha; Waring et al. 1995) and its vertical accuracy theoretically cannot be below 1 m (Hill et al. 2000).

Discussion

The manual interpretation of aerial photography for the majority of indicators of interest is already operational. The automated classification of these indicators using satellite imagery may sometimes be possible, but a more likely scenario would be the adoption of proxy indicators for synoptic monitoring over large areas. For example, broad species classification from Landsat 30 m imagery, or data transformations related to vegetation amount and vigour may provide broad indices of canopy function or health.

For more localized studies, such as the mapping of riparian vegetation species and structure, high spatial resolution imagery can be utilized at the individual tree scale. These approaches commonly use an object based classification scheme combined with special classification techniques to provide species associations comparable to that developed by TEM. As listed above, there are a number of research studies which demonstrate the applicability of the method.

Lidar technology provides valuable information on forest structure and is already used operationally in Scandinavia, as it holds more promise than competing radar technologies. A number of ongoing studies are underway within MFR investigating the operational use of lidar technology for mapping both forest structure and terrain elevation. At the TFL scale, the use of lidar data to develop both terrain and forest height maps can be considered operational. Specifications exist as to the required density and footprint size suitable for the operational use of lidar technology in forestry, and a number of operational examples exist, including in the state of Delaware, USA, and in western Alberta.

A number of key indicators within the forest structure and inventory theme comprise areas of ongoing research using remote sensing technology. These key indicators include coarse woody debris, wind throw, and snag identification. The sampling of coarse woody debris after two to six years following forest operations remains a major indicator for the biodiversity assessment team. Two critical measures of course woody debris (length and diameter) are collected along transect surveys within cut blocks. Aerial photography is currently used to provide general plot layout information, and is also used to orient and gain familiarity with an area prior to field survey. Given these cut block locations are known in advance, the use of other remote sensing data could be investigated. For example, if high spatial resolution (e.g. < 2 m) satellite data or lidar data were available, the data could be processed to extract a variety of layers to use for base stratification and improve the efficiency of a sampling program, including information on forest health, exposed soil, terrain condition and accesss.

Habitat mapping

Habitat mapping is of interest to several FREP teams. Because each specific species has different indicators of habitat quality and home range sizes, the scale of analysis using remote sensing technologies may range from several to thousands of hectares. Common amongst the different species of interest, however, is the need to assess the quality of habitat both within and surrounding their home ranges.

Remote sensing can be an important data source for information on habitat quality and quantity. Principally, these attributes provide information on such factors as land cover physiognomy, vegetation structure and condition, forage characteristics, specific nutrient concentrations, overall productivity, and biomass. From these attributes, information on the distribution of shelter, shade, and nesting resources for wildlife, as well as the capacity to meet metabolic needs, can be assessed. Table 8 highlights a number of critical attributes that have been successfully predicted using remote sensing technologies and have high relevance for habitat studies.

Table 8 *Examples of habitat attributes that have been estimated using remote sensing technologies.*

Focal Species	Core Habitat Attributes	Methodology	Sensor Platform	Location	Resolution	Reference
Boreal Bird Populations	Land Cover	Supervised Classification	Landsat TM	Finland	30 m	Luoto et al. 2004
Mexican Spotted Owl	Land Cover	Supervised Classification	Landsat TM	Mexico	30 m	Peery et al. 1999
Kirtland's warbler	Land Cover	Supervised Classification	SPOT-2	Bahamas	20 m	Miller and Conroy 1990
Grizzly bear	Land Cover	Combined Classifications	Landsat TM	Alberta	30 m	Franklin et al. 2001
Amphibian richness	Biomass / Primary Production	GVI	NOAA AVHRR	Europe	1km	Rodríguez et al. 2005
Barren-ground caribou	Biomass / Primary Production	NDVI	NOAA AVHRR	Arctic Tundra	1km	Stow et al. 2004
Chinook salmon	Energy	Water Temperature	FLIR (Forward Looking Infra-red)	North-Eastern Oregon, US	20 – 60 cm	Torgersen et al. 1999

Broad scale habitat and biodiversity trends from remote sensing

There is strong evidence that contemporary climate drives broad-scale species richness gradients of both plants and animals (Hawkins et al. 2003). For plants, it is widely accepted that energy and water together drive diversity and form (Leathwick et al. 1998; Francis and Currie 2003). For animals, energy either alone or in combination with water has been linked to large-scale variation in diversity, depending largely on the location in the world the study is focused (Hawkins et al. 2003). The NDVI is the most common and widely-applied of these vegetation indices as an estimator of 'greenness' (Francis and Currie 2003; Stow et al. 2007), and acts as a surrogate for a large number of vegetation attributes, including biomass, leaf area index, phytomass, amount of green cover, productivity, photosynthetic activity, and leaf nitrogen content (Turner et al. 1992; Huete et al. 1994; Asner and Wessman 1997).

Stow et al. (2004), for example, used the annual median and rate of change of NDVI to estimate the quality and quantity of green forage that was available to the Porcupine caribou herd in Alaska and the Yukon. Similarly, Nilsen et al. (2005) linked satellite measured greenness with measures of faunal diversity by comparing variations in the mean and seasonal greenness over a two year period with the home ranges of 12 carnivore species in the northern hemisphere. Results indicated that the accuracy of prediction for eight of the 12 species' home range sizes was improved through the inclusion of satellite estimated greenness.

Land cover as indicators of habitat

Issues of habitat suitability require information on contemporary land cover condition. In most cases, remote sensing technology is used to predict land cover, which is then used to infer spatially-explicit habitat suitability for a wide range of wildlife species. One of the most common approaches to predicting land cover information from remotely sensed data is through the use of image classification, which involves the categorization of pixels to generate a number of land cover classes, based on their similar spectral and/or spatial properties (Peery et al. 1999). For British Columbia, remote sensing-based land cover maps such as the Earth Observation for the Sustainable Development of Forests (EOSD) have been generated over extensive areas and are publicly available.[8]

Remote sensing technology has also been used to map land cover in support of a wide array of species, including birds (Gottschalk et al. 2005), large carnivores (Waller and Mace 1997) and ungulates (Huber and Casler 1990). It should be noted that using an inappropriately large number of detailed forest classes can result in significant misclassification of key classes critical for habitat mapping. Caution should be exercised when attempting to classify highly-detailed land cover types, which may not appear spectrally distinct from other classes in satellite data (Huber and Casler 1990).

Chemical/pigment constituents and their impact on habitat

An important application for remote sensing technologies, in addition to the classification of land cover and habitat, is the detection of different vegetation characteristics based on underlying pigment and chemical constituents. These differences in the composition of vegetation are often difficult to detect, since the changes are often subtle and gradual, with species having many similar spectral characteristics. These surveys, however, can be successfully undertaken using hyperspectral data, which have a very fine spectral resolution (Norris et al. 1976; Mollot and Bilby 2007; Asner et al. 2008a; Asner et al. 2008b). Hyperspectral data are primarily available from airborne sensors, such as the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS), the Compact Airborne Spectrographic Imager (CASI) or the Airborne Imaging Spectroradiometer for Applications (AISA), one of which is owned by the University of Victoria.

Vertical vegetation structure

Information on vertical vegetation structure is difficult to quantify from passive remote sensing technology, and yet is a key mechanism underlying many wildlife–habitat models. Manual survey of vegetation structure becomes prohibitive in terms of time and cost if sampling needs to be of sufficient density to characterize fine-grained heterogeneity at a landscape extent (Bradbury et al. 2005). The derivation of vegetation structure data from airborne lidar has several clear advantages over field surveys in the construction of habitat models. First, the vertical resolution and sampling density

8 Earth Observation for Sustainable Development of Forests: http://eosd.cfs.nrcan.gc.ca/

of the data is equivalent to or better than that which can be achieved by field measurement; second, the vertical and horizontal resolution available from lidar is scalable to landscape levels; and finally, the predicted attributes from these data allow heterogeneity in vegetation structure to be expressed at a variety of spatial scales, ranging from a small foraging patch or territory to a landscape (Bradbury et al. 2005; Vierling et al. 2008).

Kasischke et al. (1997) undertook a detailed review of the application of radar in ecological studies and highlighted a wide range of applications, including land cover classification, measurement of above ground woody biomass, and delineation of wetland inundation. Beaudoin et al. (1994) utilized multi-polarized P-band data to document significant correlations with forest biomass, and found backscatter amount to be sensitive to a variety of ground surface attributes such as plant undergrowth, relief, and soil conditions. Despite this success, a number of other studies have found radar to be unresponsive to biomass when a certain threshold has been reached. For example, Rauste et al. (1994) found that L-band radar reached saturation at 70 mg/ha. The recent launch of advanced satellite-based platforms, such as the Canadian Radarsat-2 instrument, promises future advances on this front.

Despite the overriding evidence that active remote sensing instruments may be better-suited for extracting vegetation structural information, a number of authors have reported considerable success using passive high-spatial-resolution optical imagery from either satellite or airborne systems (Wulder et al. 2004). These include estimation of individual crown closure, prediction of stem density and stand height, and classification of relative stand age or stage of development. Employing high-spatial-resolution imagery to extract structural attributes also lends itself to the use of textural attributes, which can provide information on stand crown gaps (Blackburn and Milton 1997) and foliage estimation (Wulder et al. 1998). Additionally, the derivation of image variance and semivariance to provide measures of stand structure, and the fitting of spatial statistical models such as semivariograms to represent forest structure, has also been successful (Lévesque and King 2003). In this latter approach, the semivariogram range, sill, and nugget are fitted to image objects and subsequently interpreted.

Discussion

In many respects, assessment of habitat and biodiversity using remotes sensing technologies is a proven application. However, because observations are necessarily species specific and cover a broad range of spatial scales, the development of universal indicators of habitat suitability may not be an achievable goal. In conducting this survey, it is apparent that there are a number of species of interest, including amphibians, marbled murelettes, goshawks, badgers, moose, and caribou, and they are found in a in a wide variety of locations, including Fort St. James, Cascades, South Island, and Haida Gwaii. Currently, models are generated using existing TEM and VRI data. Various studies in BC have demonstrated that state of the art remote sensing data can complement TEM structural data, for example, by using lidar and/or QuickBird high resolution imagery. Similarly, Landsat is a proven technology for determining land cover, which is often used to stratify areas for investigation. Furthermore, time series of Landsat images can be used to predict disturbance history and stand age.
In addition to using remote sensing attributes themselves to predict habitat, remote sensing can also play a role in threat assessments; for example, monitoring forest health, mountain pine beetle impacts, road density, forest encroachment, and land use changes are all well established applications. Habitat assessments are currently performed by consultants and their methods are poorly understood. One way to overcome this problem may be to develop specific collaborative projects with universities with a technology transfer component using funding sources such as the Forest Science Program.

Invasive plants

Most broadband medium resolution sensors have limited ability to distinguish between vegetation species as is necessary when identifying invasive plants. When utilizing medium spatial resolution broadband data (e.g. Landsat or SPOT) for species mapping, different vegetative types often times do not reflect discernibly unique spectral properties (Franklin et al. 2003). Furthermore, medium spatial resolution pixels, such as the 30 x 30 m pixels associated with Landsat data, result often in mixed pixels containing more than one target species type of interest.

Recently, the advent of high spatial resolution hyperspectral systems has been shown to significantly improve vegetation discrimination. Hyperspectral data, which consists of a large number of very narrow spectral bands, often makes the discernment of an area's species composition through spectral response discrimination more effective than is possible with multispectral sensors. To date, numerous studies have employed hyperspectral data to remotely sense invasive plants (Table 9).

Table 9 *Examples of invasive plant surveys undertaken using hyperspectral data.*

Reference	Dataset	Emphasis	Accuracy	Study area
Morisette et al. 2006	MODIS data; field plots	Saltcedar (Tamarix spp) habitat suitability map	90%	Continental United States
Glenn et al. 2005	HyMap hyperspectral data	Leafy spurge (Euphorbia esula L.) detection	84-94% (overall)	Swan Valley, Idaho
Miao et al. 2006	CASI-2 hyperspectral data	Yellow starthistle (Centaurea solstitialis) abundance	$r^2 = 0.88$	Central Valley Grasslands, California
Mundt et al. 2005	HyMap hyperspectral data	Hoary cress (Cardaria draba) discrimination	86% (overall)	Ada County, Idaho
Williams and Hunt 2004	AVIRIS hyperspectral data	Leafy spurge (Euphorbia esula L.) detection	75-97% (overall)	Crook County, Wyoming
Underwood et al. 2003	AVIRIS hyperspectral data	Iceplant (Carpobrotus edulis) and jubata grass (Cortaderia jubata) detection	98-99% iceplant; jubata grass not quantified	Vandenberg Air Force Base, California

Although the spectral and spatial resolution inherent to hyperspectral data allows for detailed, species-level discrimination, these data are often geographically restricted to the extents of the airborne transects in which they are typically collected. Certain invasive species mapping endeavors require broader geographic predictions of distribution, and therefore, sometimes necessitate the use of coarser spatial resolution data. However, the ability to actually predict the distribution of an invasive species on broad geographic scales is dependent on the spectral and spatial characteristics of the target in question and whether or not these characteristics are predictable or can be statistically related to coarser spatial resolution data. Table 9 provides an example of a successful nationally implemented invasive species range prediction initiative conducted with medium spatial resolution data used in conjunction with tens of thousands of field plots (Morisette et al. 2006).

Discussion

For a number of reasons, remote sensing of invasive plants is a much promised but so far undelivered application. First, the local nature of invasive plant mapping necessitates high spatial resolution data and small study areas, which increases cost. Critically, in most cases, the invasive species identified in British Columbia occur on verges and road sides, which should facilitate their detection. However, the key problem is the capacity of remote sensing to distinguish invasive species from surrounding vegetation, which is difficult using broad spectral band sensors. One potential way forward is to target detection to flowering events or other phenological behavior. In summary, broad maps of invasive species produced using remotely sensed data are unlikely to appear in the near future. Highly focused, location specific studies using hyperspectral imagery are more likely to be successful. These studies, however, carry with them significant operating costs.

Land cover

The demand for timely information representing the distribution, composition, and status of land-cover at both regional and national levels is increasingly growing (Wulder et al. 2003). Accurate, detailed and up to date depictions of land-cover are essential for a variety of applications. Digital remotely sensed data can be utilized to provide information on past and current land-cover distributions. The type of land-cover information obtainable from remotely sensed data is dependent on spatial scale. The selection of an appropriate spatial resolution represented by particular remotely sensed data is dependent on informational goals and needs. For analysis involving general land-cover characteristics, medium spatial resolution (e.g. 30 m) multispectral data are most appropriate and most typically employed. These data are readily available, allow for long-term continuity, and can provide synoptic coverage of targeted study areas (Cohen and Goward 2004). Although there are numerous sensors which can provide medium spatial resolution remotely sensed data, the most commonly utilized are those carried aboard the Landsat series of satellites. The Landsat program has been at the core in the development of operational remote sensing applications (Cohen and Goward 2004). The archival legacy of Landsat (> 30 years) offers the longest running time series of systematically collected remotely sensed data and has been specifically designed to facilitate mapping and monitoring of land-cover at a spatial resolution appropriate for general land cover mapping. With the recent announcement by the United States Geological Survey (USGS) that the entire Landsat archive will be freely available to the public, applications using Landsat are expected to proliferate (Woodcock et al. 2008).

Over the last decade, medium spatial resolution remotely sensed data have increased in affordability and availability. Simultaneously, major technological and methodological advances have occurred, allowing for the acquisition and analysis of large data volumes as never before (Rogan and Chen 2004). The potential variety of applications for these data has never been richer. To date, common vegetation related applications have included the abstraction of general cover, landscape connectivity and fragmentation, invasive species, timber volume, successional stage, biodiversity, wildlife habitat and rare and endangered plant species (Woodcock et al. 2001; Cohen and Goward 2004). Although all applications of these data are important, the mapping and subsequent monitoring of land-cover has proved to be one of the most successful and important. Hierarchical multi-level mapping schemes have laid the foundations for comparability between different mapping endeavours through the use of compatible multi-scale classification schemes (Anderson et al. 1976). Despite differences inherent to classification schemes, they all share a commonality in that the variety and detail of classes obtainable is entirely dependent on factors such as the characteristics of the remotely sensed data utilized (e.g. spatial resolution), as well as the land-cover distribution occurring within the targeted landscape. Regardless of the particular scheme utilized, when employing moderate spatial resolution remotely sensed data to predict land-cover distribution, some classes are bound to remain coarse in their representation (e.g., water bodies), whereas others can be appropriately broken down into their finer detailed constituents (e.g., forested land being comprised of coniferous vs. broadleaf and further broken down based on canopy/crown closure criteria).

An example of a successfully implemented land-cover mapping endeavor is the Earth Observation for Sustainable Development of Forests (EOSD) program. Through a collaborative effort of federal, provincial, and territorial governments, universities, and industry, a circa 2000 land-cover map representing the forested area of Canada was produced using primarily Landsat data (Wulder et al. 2003). Another example of an operational land cover mapping initiative is the US National Gap Analysis Program (GAP). The goal of GAP is to identify 'gaps' in conservation areas by producing maps depicting the distribution of dominant vegetation types and using these maps to predict the distribution of vertebrate species (Jennings 2000). Relying on Landsat data combined with a suite of finer detail reference information, this cooperative effort among regional, state, and federal agencies, as well as private groups, has produced state level products readily available for public use. For more examples of currently implemented land-cover mapping initiatives, refer to Table 10.

Table 10: *Examples of large area land cover classification programs in North America.*

Program	Reference	Dataset	Emphasis	Study area location
EOSD		Landsat imagery	Forested area condition	Forested areas of Canada
GAP		Landsat scenes supplemented by digital environmental data, field data, and expert knowledge	Dominant vegetation type and distribution	State level products for the United States
NLCD 1992		Landsat imagery	Categorical land cover distribution	State level products for the United States
NLCD 2001		Landsat imagery	Categorical land cover distribution	State level products for the United States

Although current medium spatial resolution sensors, such as those carried aboard Landsat 5 and 7 are facing difficulties in continuing to supply data, the Earth Observing-1 (EO-1) Advanced Land Imager (ALI), launched in 2000, will ensure excellent data continuity for temporal studies of natural resources focused on general land-cover characteristics (Bryant et al. 2003). Specifically, the EO-1 ALI will pave the way for specifications related to sensors carried aboard the Landsat 8 platform, tentatively scheduled for launch in 2011 (Woodcock et al. 2008; Wulder et al. 2008). This will enable the long-term continuity of land-cover products derived from medium spatial resolution remotely sensed data.

Although proven to be operationally useful for the abstraction of general land-cover characteristics, including programs implemented at ecosystem, watershed, and wildlife specific habitat scales, the spatial and spectral resolutions of Landsat-like data limit, and in many cases prohibit, the feasibility of operationally monitoring finer scale attributes. For example, although the categorization and quantification of broad vegetative ecosystems may be accurately determined using these data, due to the spatial and spectral resolution of Landsat imagery, species-specific mapping of species specific is generally an unrealistic goal. However, larger constituents found within landscape mosaics can be accurately abstracted and categorized, such as wetlands, and in many cases, riparian zones.

Discussion

Land cover mapping based on moderate resolution satellite imagery can be considered an operational application. The EOSD, for example, was developed with input from MFR and includes numerous classes which are mapped across the forested regions of Canada. Although land cover categories are typically broad and not species specific, they nonetheless provide information which may be useful for stratification purposes, change detection, landscape fragmentation assessments, and so on.

Mountain pine beetle and other forest health impacts

A variety of remotely sensed data can be utilized to assess the impacts of mountain pine beetle infestations. Data sources include aerial photography, high-spatial resolution digital aerial and satellite imagery, and moderate-spatial resolution satellite. Used individually, these data sources have potential to provide accurate spatial information about the severity and extent of infestations, albeit at different scales (Wulder et al. 2006c). The information obtained from remotely sensed data is dependent on the type of information required and the spatial resolution of the image. According to the type of imagery used, remotely sensed data can guide a range of planning levels from strategic to operational, by providing very precise spatial information to guide salvage logging of small infestations, or guide cut block layout to address large infestations (Wulder et al. 2006b). When deciding which source of remotely sensed data to use it is important to first define the variable of interest. If tree-level variables for operational planning are required, high-spatial resolution imagery should be utilized as it provides the ability to detect individual tree crowns. However, if forest stand level information for strategic planning is required, then moderate spatial resolution imagery may provide sufficient information (Wulder et al. 2006c).

Aerial photography has been the most commonly used data to map a number of damaging agents at various scales (Wulder et al. 2006c). When acquired at a suitable scale, aerial photographs are able to resolve individual tree crowns, which is of importance when attempting to discern the subtle changes in crown foliage colour indicative of poor tree health (Ciesla 2000). More recently high-spatial resolution digital aerial imagery has become available which are able of discerning objects as small as 0.05 m.

Recent research indicates that if trees captured by digital imagery can be visited in the field, measurements from each tree may be linked directly to the same trees in the imagery. For example, if diameter at breast height and crown area is measured on each tree, it is possible to build a relationship between the two variables and then generate such measurements for every tree within an image. If diameter can be generated, individual tree volumes can be acquired across the imagery. Therefore, estimates of stand volume or biomass affected by mountain pine beetle infestation can be generated using digital aerial imagery. Research at UBC is currently being conducted to determine how the proportion of pine trees greater than 0.15 m diameter at breast height, tree age (measured during ground surveys), and stand density can be combined with location and elevation data to provide estimates of susceptibility of stands to infestation according to a stand susceptibility index (Shore and Safranyik 1992).

High-spatial resolution digital aerial imagery and aerial photography provide highly accurate spatial data, but only over relatively limited geographic extents. Satellite imagery such as QuickBird and IKONOS, however, is used to define the severity and extent of mountain pine beetle infestations over larger areas at resolutions as low as 0.66 m (Table 11).

Table 11. *Examples of red attack detection using remote sensing technologies.*

Reference	Dataset	Variable	Accuracy	Study area size and location
Franklin et al. 2003	Landsat TM	Red-attack detection (single-date)	73%	Fort St. James Forest District
Smith 2006	Landsat TM	Red-attack detection (multi-date)	67% - 78%	Prince George Forest Region
White et al. 2005	IKONOS	Red-attack detection	71% (low attack) 92% (high attack)	Central interior of British Columbia (near Prince George)
Wulder et al. 2006a	Landsat ETM+	Red-attack detection	86%	Western Montana, Lolo National Forest

High-spatial resolution satellite imagery provides the ability to detect small groups of trees infested by mountain pine beetle, and may be used to detect individual trees before infestations expand. A study completed in lightly and moderately infested trees near Prince George, British Columbia indicated that the IKONOS satellite sensor had the ability to detect red-attack stands. Attacked stands were categorized into light and moderate infestation classes. When compared to independent validation data collected from aerial photography, the accuracy of red-attack detection from IKONOS imagery was shown to be 71% for lightly infested stands and 93% for moderately infested stands (White et al. 2005).

Moderate-spatial resolution data can be used to detect the severity and extent of infestations over broad geographic areas. Data such as that provided by the Landsat TM and ETM+ sensors provides the opportunity to conduct landscape-scale monitoring of mountain pine beetle red-attack and has been successfully utilized for a number of applications (Franklin et al. 2003; Skakun et al. 2003; Wulder et al. 2006c). In the Fort St. James Forest District, for example, single-date Landsat imagery was used to generate an estimates of red-attack detection with an accuracy of 73.3% (± 6.7%) (Franklin et al. 2003). Wulder et al. (2006a) used a single Landsat image in conjunction with slope and elevation surfaces to detect mountain pine beetle infestation. These data were analyzed using a logistic regression approach to map red attack damage in the Lolo National Forest in Montana, USA. With this method, red-attack was mapped with accuracy of 86% (± 7%).

Furthermore, time-series analysis based on the use of Landsat data to monitor the spread of mountain pine beetle infestation has been applied to a range of studies. For instance, Skakun et al. (2003) employed tasseled cap wetness indices (Crist and Cicone 1984; Jensen 2006) to detect beetle-related changes in vegetation moisture. Using this approach, Skakun et al. (2003) reported red attack detection accuracies of 76% (± 12%) for groups of 10 to 29 infested trees, and 81% (± 11%) for groups of 30 to 50 infested trees.

Because a Landsat pixel measures 30 m by 30 m, it may contain an amalgamation of several forest elements typical of a pine stand, i.e. trees, shadowing, and understorey. This amalgamation of elements may dilute the appearance of red-attack tree crowns in each pixel and make detailed mapping difficult, because patches of infestation will become clear only when the majority of trees within a pixel become infested. Thus, while Landsat imagery cannot define individual trees, it is inexpensive and can provide accurate, synoptic spatial information at the grain and extent appropriate for strategic land management.

Discussion

As stated, a large amount of research has been undertaken in British Columbia on the assessment of mountain pine beetle infestation extent and severity. When necessary to conduct surveys at the individual tree scale, high resolution multispectral satellite imagery may be employed. Stand level mapping, including change detection, may be conducted using moderate resolution imagery and standard image derivatives related to forest health. Research is currently being conducted to ascertain whether data of various spatial and spectral resolutions can be used in combination to derive infestation estimates over larger areas with greater efficiency. Much of this work is being undertaken by MFR's remote sensing group, and their results should be actively incorporated into indicator methodologies.

Road mapping

The presence of roads have implications for fish passage, stream sedimentation, slope stability, and habitat fragmentation (e.g. Lunetta et al. 1997; Lugo and Gucinski 2000; Borga et al. 2005; Mena and Malpica 2005; Coffin 2007). Road networks are typically stored as vector lines in a GIS database. However, the information may not be updated with sufficient regularity to be useful for applications such as environmental impact assessments, particularly in remote areas. Remote sensing offers the possibility to derive information related to road networks in a timely manner in areas that may be difficult to access. While many roads are evident on moderate scale satellite imagery, those commonly used in harvest operations likely necessitate the use of high spatial resolution optical data.

As an example of a very detailed road network survey, the state of Florida has developed the Roadway Characteristics Inventory (RCI), which is a GIS database containing information associated with signs, pavement condition, bridges, and drainage structures along highways.[9] The dataset was derived from 10 cm resolution digital orthophotos and field surveys (Wolf and Dewitt 2000).

Yagoub (2003) describes methods used to update road networks using Landsat TM, SPOT HRV, IKONOS , and scanned aerial photographs. While the medium spatial resolution imagery was used for regional monitoring of land use patterns, the high spatial resolution imagery was employed to manually digitize road networks. Visual interpretation indicators included colour, size, shape and texture. Attempts to classify roads using the lower spatial resolution data, however, were confounded by the presence of mixed pixels.

While roads may be manually digitized from imagery (e.g.Yagoub 2003), there is ongoing research into their automated or semi-automated extraction (Jin and Davis 2005). Mena and Malpica (2005), for example, used 2-3 m resolution optical imagery and preexisting road vector data to extract image objects, classify them, and then update a GIS database. While Mena and Malpica (2005) report an accuracy of approximately 70%, they also note that fully automated road extraction is still an active area of research and not ready for operational implementation.

Discussion

Knowledge about the placement, use, and condition of forest road networks is one of the most crucial information layers required by the FREP teams. Many indicators, including fish passage, soils, biodiversity, and habitat require frequently updated information on roads. In some cases, however, the MFR information is up to two decades out of date, making the contemporary use of strategic, road-related indicators very difficult. For example, in the case of Fish Passage, the establishment of roads is a critical concern for aquatic habitat, and information on the length of roads versus the length of streams and the number of culverts is a key strategic indicator. Another example is that of Soils, where roads are related to indicators of soil and hydrological health. As a result, any methods which allow regular updating of the forestry road network across the province should be keenly investigated. A number of potential data sources exist. The provincial access to SPOT-5 imagery will allow most roads within forests to be located and delineated. Similarly, high resolution aerial imagery allow finer scale attributes such as culverts and road condition to be mapped.

The current issue for the FREP working groups is to develop or adopt a methodology which will allow the extraction of road attributes annually in a cost effective manner. This could be done manually using on-screen digitization, or semi-automatically using advanced classification techniques. It is unlikely that any method will be fully automatic; however, some degree of automation is likely to increase cost effectiveness. To move forward on the issue, a large management area (such as a TFL or TSA) which has had significant road construction and which is of interest should be used to test methodologies which extract road networks from available SPOT-5 imagery. The derived networks should then be compared

9 Roadway Characteristics Inventory: http://www.dot.state.fl.us/planning/statistics/rci/

to local forestry records, field based data, or aerial imagery. Whilst the extraction of road networks from remotely sensed data may not be viewed as interesting or innovative, the survey clearly highlighted this data gap as a major issue for a number of resource values.

Terrain modelling

Terrain elevation models are useful for forest engineering, landslide detection (Catani et al. 2005; Dewitte et al. 2008), flood inundation mapping and hydrologic modelling (Townsend and Walsh 1998; Ludwig and Schneider 2006 ;Sanders 2007), predicting plant and animal species distributions (Lassueur et al. 2006; Sesnie et al. 2008), and as an input for three dimensional visualizations (Discoe 2005).

Traditionally conveyed using contour maps, elevation information is increasingly being stored in electronic formats, including vector-based triangulated irregular networks (TINs) consisting of Delaunay triangles, and raster formats consisting of an array of digital numbers relating to heights. Maune (2001) provides an excellent review of the technologies and applications of digital elevation models, including both terrestrial and bathymetric examples, and discussions on vertical datums and accuracy standards.

Three remote sensing technologies which may be used to map terrain include photogrammetry, radar, and lidar data. Both optical imagery and radar data may be collected using airborne or spaceborne platforms, while lidar is collected using aerial platforms. Table 12 provides examples of accuracy assessments conducted on DEMs derived from the three technologies.

Table 12 *Examples of accuracy assessments performed on photogrammetry-, IFSAR-, and lidar-derived digital elevation models.*

Reference	Objective	Vertical accuracy	Study area size or location
Hodgson et al. 2003	Compare vertical accuracies between lidar and IFSAR data collected during leaf on conditions	Varied by land cover type and terrain slope. Lidar RMSE varied from 0.33-1.53; IFSAR varied from 1.73-15.03 m.	Watershed in North Carolina, USA
Shortridge 2006	Asses accuracy of three arc second SRTM data	Overall RMSE of 6.53 m, and 90% absolute accuracy of 10.73 m,; large positive bias in elevation errors	Michigan, USA
Hodgson and Bresnahan 2004	Assess lidar error and develop error budget	Varied by land cover type and terrain slope. RMSE ranged from 0.17-0.26 m	2,000 km2 area comprising Richland County, South Caroline, USA
Adams and Chandler 2002	Compare lidar and 1:7,500 scale aerial photography for detecting short-term coastal change	RMSE were 0.26m for the lidar-derived DEM and 0.43 m for photogrammetry	Black Ven mudslide, Dorset, UK

Photogrammetry

Photogrammetric DEMs may be derived from three sources of image data (Maune 2001):

1) traditional aerial film cameras;
2) digital airborne cameras, which are rapidly replacing traditional film systems; and
3) optical satellite systems such as IKONOS, QuickBird, SPOT, and ASTER.

Regardless of the data source, DEM derivation employs stereo image pairs to extract terrain heights using either manual or automated techniques.

Airborne imagery may be used to create large scale terrain models (e.g. >1:10,000), but because of the lower spatial resolution of satellite imagery, spaceborne systems are limited to mapping at smaller cartographic scales, often at provincial or national levels.

Accurate bare-Earth DEM development may be hampered in areas of dense vegetation where the ground is not visible. The imagery can, however, be used for various other purposes, and when compared to lidar, photogrammetry is less data-intensive, sometimes requires less manual editing, and often generates more pleasing cartographic contours.

Radar

Digital elevation models may be created using radar, which is an active remote sensing system operating in the microwave portion of the electromagnetic spectrum (e.g. 3-5 cm; Jensen 2006). Terrain height estimates are made using synthetic aperture radars (SAR). A SAR simulates a very long antennae by using the forward movement of the platform. Interferometric synthetic aperture radar (IFSAR) is a type of SAR which uses two antennas on the same platform to collect three-dimensional information relating to terrain (Maune 2001). Essentially, an IFSAR determines the location of a point by solving the unknown third component of a triangle; the first two components being related to the sensor's antennae geometry.

Generally, radar data overestimates true terrain heights in forested areas, as short wavelength radio waves tend to interact with leaves, while longer wavelengths will interact with larger forest components such as trunks and limbs. However, IFSAR may offer a cost-effective mapping solution for large area, rapid mapping applications (Maune 2001; Jensen 2006).

Spaceborne platforms include the Canadian Radarsat series, ERS-2 (European Space Agency), and Envisat (European Space Agency), which are C-band radars, and ALOS (Japan) which is an L-band system. Of note is the Shuttle Radar Topography Mission, which mapped 80% of the Earth's land surface in 2000. Fully processed digital elevation data is freely available for all of British Columbia, and has a spatial resolution of three arc seconds (approximately 90 m).[10] The dataset has been shown to be have a vertical accuracy of approximately 10 m or less (Gorokhovich and Voustianiouk 2006; Shortridge 2006), which may be considered very high given the near global extent of the mission.

Lidar

Lidar systems estimate distances between a sensor and a target based on half the elapsed time between a laser pulse emission and the detection of a reflected return. Lidar systems can be separated into two basic types: discrete return and waveform-recording (Lefsky et al. 2002; Lim et al. 2003). Discrete return sensors record single or multiple returns from a given laser pulse. As the laser signal is reflected back to the sensor, large peaks are interpreted to represent discrete objects in the path of the beam (e.g. the forest canopy, understorey, and ground). The sensor then records these peaks as discrete points in three-dimensional space. Alternatively, full waveform instruments have a higher sampling rate and record the full height distribution of the surfaces illuminated by the laser. Thus, within a forest canopy, discrete return instruments produce clouds of points representing intercepted surfaces, while full waveform sensors record the entire reflected signal for analysis (Lefsky et al. 2002). Generally, discrete return sensors use a small footprint (e.g. the laser's circle of illumination on the ground) several decimetres in diameter, while waveform recording sensors employ a large footprint typically greater than 10 m in diameter. Airborne small footprint, discrete return sensors are employed for operational mapping purposes. Regardless of the type of system employed, lidar is capable of simultaneously mapping both vegetation height and vertical structure, and the underlying terrain's morphology, with high accuracy.

The most critical step in deriving a DEM from a lidar point cloud is the separation of ground and non-ground returns (Xiaoye Liu 2008). This process, however, is typically performed by the data vendor. Nonetheless, lidar may be the best choice for terrain modelling in forest environments where the ground cannot be seen for photogrammetric derivation, and the canopy intercepts radar waves (Hodgson et al. 2003; Sanders 2007; Xiaoye Liu 2008). In fact, under certain conditions, a lidar derived DEM generated under forest canopy may approach the accuracy of photogrammetrically derived models in open areas (Kraus and Pfeifer 1998). Broadly speaking, lidar point clouds tend to be dense, often with more than 1 return/m2 in unvegetated areas. A typical lidar-derived DEM may range in spatial resolution from 0.5-5.0 m and have sub-metre vertical accuracy.

10 SRTM homepage: http://www2.jpl.nasa.gov/srtm/

Discussion

The development of terrain models, be they derived from photogrammetry, radar, or lidar, is an operational remote sensing application. The issues relate to tradeoffs between vertical accuracy, spatial resolution, aerial coverage, and cost. Large area mapping is best suited to satellite image pairs or radar, while the most detailed mapping initiatives will require higher resolution imagery or lidar. The finest scale land surface processes of interest to FREP teams, however, such as small landslide events ranging from 5-10 m3 in volume, may not be reliably detected by any of the technologies discussed here.

Water body and stream mapping

While most water-related or hydrological parameters are estimated using in situ point measurements, remote sensing technologies offer a detailed, repeatable synoptic view for many associated applications. (Table 13).

Table 13 *Examples of stream and water body mapping using remote sensing technologies.*

Reference	Objective	Technology	Results
James et al. 2007	Identify headwater streams and gullies below forest canopy.	Lidar	Identified gullies down to 3 m wide and provided approximate measures of cross-sectional morphology
Legleiter et al. 2004	Monitoring fluvial systems, including channel morphology and in-stream habitat.	Multispectral and hyperspectral imagery	Proposed a series of operational guidelines for remote sensing based stream studies. Suggested high radiometric resolution (e.g. 12 bit or greater) is desirable for bathymetric mapping, and high spectral resolution for classification of in-stream habitat.
Lafon et al. 2002	Develop bathymetric maps for a shallow tidal inlet.	SPOT multispectral data	Mean difference between estimated and measured depths was 20%.
Orgersen et al. 1999	Relate distribution of chinook salmon to stream temperature.	Airborne forward looking infrared (FLIR) sensor	Mapped stream temperature to within 1°C

Water body delineation

The near and mid infrared are the best regions of the electromagnetic sprectrum for discriminating between water and ground. Water absorbs virtually all incident infrared radiation (Bukata et al. 1995), so that in an optical image it will appear to be very dark or black. Vegetation and exposed soil, however, reflect large amounts of infrared radiation and appear bright in comparison. Conversely, the least amount of absorption takes place in the blue portion of the electromagnetic spectrum (0.4-0.5 µm), so that these wavelengths have the greatest penetration through a water column (Bukata et al. 1995). As a result, visible light may be reflected by the bottom or by suspended sediment, which can make the interface between land and water difficult to identify. Thus, infrared imagery is preferred for the accurate delineation of water and land.

Bathymetry

Bathymetry, or the bottom morphology of water bodies, may be mapped using optical imagery, sonar, and lidar data. Most mapping involving optical imagery utilizes data with wavelengths of 0.44-0.54 µm. To be effective, however, the water column must be almost free of suspended sediment and organic constituents (Jensen 2006). Legleiter et al. (2004) showed a ratio of two hyperspectral bands was well correlated with depth for a range of stream conditions.

Sound navigation and ranging (sonar) may refer to four types of sensors: single beam, multiple beam, interferometric, and side-scan sonars (Maune 2001). Unlike other technologies which rely on electromagnetic radiation to collect data, sonar relies on acoustic energy which is emitted in short pulses to collect water depths.

Lidar may be used to map shallow near-near shore areas. A common lidar bathymeter is the Scanning Hydrographic Operational Airborne Laser Scanner (SHOALS), which employs a blue-green laser to detect the bottom, and an infrared laser to detect the water surface.[11] The maximum water penetration depth is two to three times the Secchi depth, to a maximum of >50 m in very clear water. In extremely turbid conditions, however, a lidar survey may not be possible. Lidar is often used to map areas too shallow to be efficiently surveyed using sonar, and then later combined with sonar data to create a complete bathymetric map that includes both near-and off-shore information (Maune 2001) (Jensen 2006).

Temperature

While spaceborne thermal products are available, the generation of accurate stream temperature maps requires high spatial resolution data (Handcock et al. 2006). Typically sensing in the 8-14 µm portion of the electromagnetic spectrum (Jensen 2006), state of the art sensors are capable of discriminating temperature differences of ±0.1o.[12] An important consideration is the effect of the atmosphere on temperature estimates, which may be biased by as much as 2oC at flying altitudes of 300m (Lillesand et al. 2007). Several strategies exist to correct for atmospheric effects, and they are often based on regressing field-based temperature measurements with image digital numbers.

Discussion

Mapping water bodies essentially falls under the category of land cover mapping, and thus may be considered an operational remote sensing technology. In fact, water is usually one of the more accurately classified categories in land cover mapping initiatives. So too, bathymetric mapping is routinely performed by both government and industry.

Mapping stream temperature to assess fish habitat, which is a key indicator for the Watershed Monitoring group, is one area of possible application. Any survey would likely have to be coordinated with ground-based measurements of stream temperature for calibration purposes and to correct for atmospheric effects.

Of particular interest to many FREP teams is the mapping of vernal water bodies underneath forest canopies. This is an area in need of research, and the answer may lie in radar or nighttime thermal surveys. One ongoing initiative is the Canadian Wetland Inventory, which has been put in place to map wetlands consistently across forested areas of Canada. The initiative principally employs a combination of Landsat and Radarsat data. While this initiative is focused primarily in the east, it will eventually be expanded to western Canada. Obviously, whilst small water bodies may not qualify as wetlands, the tools developed may have relevance for detecting these vernal pools. A full issue of the Canadian Journal of Remote Sensing is dedicated to this topic.

Reconnaissance mapping

Remote sensing has been used extensively for reconnaissance mapping to stratify an area in support of field activities (Ahern and Leckie 1987). For example, the identification of acceptable samples for Karst, riparian areas, streams, wildlife tree and coarse woody debris patches is essential to the planning of resource stewardship monitoring. The ability to apply remote sensing information to confirm the presence of related features can improve the assessment procedure and save considerable time in the field.

The choice of data to be employed depends on the feature(s) of interest. Moderate scale satellite imagery have been shown to be useful for generating basic land cover maps delineating feature such as forest types and water bodies. More detailed information requirements, however, necessitate the use of high resolution imagery (Table 1). A very useful source of data that has recently emerged in the public domain is Google Earth.[13] Google Earth contains a variety of optical and terrain elevation data at varying spatial resolutions. It may be a useful tool for initial reconnaissance mapping, and the professional version allows GIS and GPS data to be imported for more sophisticate applications.

Discussion

Given the range of indicators of interest to the various FREP groups, it is difficult to make broad statements about reconnaissance mapping other than to say that it has been performed for virtually as long as remote sensing has existed.

11 Optech Inc. http://www.optech.ca

12 Itres TABI-320: http://www.itres.com/TABI_320

13 Google Earth: http://earth.google.com/index.html

Some teams may only require general land cover information prior to conducting field surveys, while others may require extremely detailed information on stand structure or terrain condition in order to improve the efficiency of their field programs. The indicators of interest will ultimately decide the nature and scale of the remotely sensed data necessary for reconnaissance mapping.

Future research

To assess the areas where future research should be focused in the remote sensing of sustainable forest indicators, a three level category system was developed and applied below:

Category 1: Indicators which can be measured operationally, or near operationally, from remote sensing technology. These indicators would only require small demonstration projects to transfer the potential of the technology to the MFR / FREP users. This research could be undertaken as small consultancies to private consulting firms, universities, or in consultation with federal agencies and NGO's.

Category 2: Indicators which require further research before operational implementation of the methods can occur. These indicators are ones which would require additional research and development to be undertaken prior to the indicator being operationally applied using digital remote sensing technology. This may involve developing projects for submission to the BC Forest Science Program, provide support and assistance to MSC and PhD programs at Universities, or extended consultative projects up to 5 years in length.

Category 3: Indicators where significant new research is required to ensure practical, sensitive, and cost-effective implementation. These would be indicators where either a significant investment in research and development is required to make the indicator operationally effective (in excess of 5 years) or indicators, which in our view, are unable to be predicted using remote sensing unless there is a significant development (or availability) of new remote sensing technologies.

Category 1 Indicators:

- **Incorporation of fire-related products into the province's data warehouse.**
  As discussed, a number of remotely sensed datasets related to near real time fire locations, short term fire boundary definition, and operational monitoring of fuel hazard and post fire burn severity are currently available. In some cases these datasets simply need to be incorporated into the MFR image databases. In other cases, currently operational techniques such as those used in the Unites States could be relatively easily transferred to Canadian conditions.
- **Ongoing development and monitoring of a province wide, broad scale biodiversity hierarchy.**
  One area where digital remote sensing and modeling is relatively complementary to ongoing efforts is in the development of a broad scale biodiversity hierarchy for the Province. Currently the Province has just completed a broad assessment using three criteria, based on site index, age class, and landscape fragmentation. Both site index and landscape fragmentation can be readily predicted and monitored through time using remote sensing technology. Similarly imagery can be used as part of a time sequence to help in the prediction of disturbance and age class distributions. As a result, remote sensing could play a major role in the ongoing estimation of this index through time, using the recently produced dataset as critical ground truthing and validation of the approach.
- **The identification of semi-automated or fully automated road extraction techniques.**
  As discussed in this report, many FREP attribute values, including fish passage, soils, biodiversity, and wildlife habitat, require frequently updated information on roads; however, in many cases, road information is inadequate and does not provide information on the most recent road activity. As a result, any methods which allow regular updating of the forestry road networks across the province should be keenly investigated. In our view, ongoing research should be undertaken to quickly establish if the extraction of road attributes can be accomplished in a cost effective manner using the existing high spatial resolution data available to the Ministry. A research project could be commenced and a large management area (such as a TFL or TSA) which has had significant road construction be highlighted and used to test methodologies which extract road networks from available SPOT-5 imagery. The derived networks should then be compared to local forestry records, field based data, or aerial imagery. Whilst the extraction of road networks from remotely sensed data may not be viewed as interesting or

innovative, the survey clearly highlighted this data gap as a major issue for a number of resource values.

- **Incorporation of remotely sensed data into habitat suitability models and risk assessments.**
  In many cases, remote sensing technology can provide indicators of habitat quality and suitability. However, in most cases these datasets have been developed for specific applications and over small areas, making the applications often user specific. As discussed in this report, this is unlikely to change because most species and species groups have specific habitat requirements, necessitating specialized remote sensing solutions. Critical are issues related to technology transfer, and informing the relevant MFR staff and FREP indicator teams of the potential of remote sensing technologies. Through our interviews, key species and species groups have been indentified, as well as key areas of focus across the province. An ongoing dialog should continue to keep these FREP teams informed on the capacity of current remote sensing technologies and their relevance to the indicators. The tables produced in this report may help the FREP teams in this understanding.

Category 2 Indicators:

- **Estimation of coarse woody debris, wildlife trees, and wind throw amounts.**
  The prediction of key forest inventory indicators from digital remote sensing technology is an active area of research for both the remote sensing community and agencies such as MFR. Three areas which hold promise and could be potentially rapidly moved forward, following a number of small targeted research programs, is the prediction of wildlife tree class, wind throw, and coarse woody debris. In the case of wildlife tree class, methods using lidar technology have been developed and tested in the coastal forests of Vancouver Island. The application of these results could be expanded into other forest types across the province. The use of imagery to help predict and detect wind throw is another area which is currently the focus of ongoing research. Coarse woody debris detection and classification remains a non-operational application of remote sensing imagery, however, potential exists. Lidar data is capable of detecting woody debris on the forest floor, and the more common use of full waveform, small footprint lidar will help remove some of the current technological issues associated with its accurate detection. In addition, exploratory projects which link FREP indicator staff concerned with coarse woody debris and remote sensing scientists would be beneficial to help identify the most critical aspects of coarse woody debris which require accurate detection.

- **Stream temperature mapping for fish habitat.**
  One area where the technology exists yet applications are hard to find is the use of fine spatial resolution thermal imagery to routinely assess stream habitat. The use of this type of data is common in other applications including mine site rehabilitation, mining, and urban studies, and many of the tools and techniques could be used in the assessment of stream condition in forest environments. Whilst any developed technique would not be suitable to be applied operationally across the province, it would be suitable for high value stream habitat or for the monitoring of habitat for high value fish species.

Category 3 Indicators:

- **Archaeological applications, including traditional use sites and trail identification.**
  The application of remote sensing technology to detect archaeological features, for example trails and areas of traditional use, is problematic, especially in the wetter forests of coastal British Columbia. In the interior, where the areas are drier and forests less dense, it may be possible in select locations, however, the routine use of digital remote sensing technology for this purpose in the near future is unlikely.

- **Invasive plant mapping.**
  Similarly, the development of operational tools to utilize remote sensing data to predict invasive species is very difficult given phenological, technological, and financial constraints. The detection of key species in small localized areas is potentially possible, but in most cases significant research will be needed to ensure that invasives can be accurately and routinely separated from their surroundings.

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APPENDIX A: SENSOR SPECIFICATIONS AND DATA AVAILABILITY

The following section briefly describes the remote sensing systems discussed in this report (Table 14). Archived data, including aerial orthophotography, and Landsat 5, Landsat 7, SPOT 5, IKONOS, QuickBird, and IRS satellite images are available online at GeoBC, the Province of British Columbia Crown Registry and Geographic Base's online gateway.[14] These data are either free or provided at reduced cost to Government of British Columbia employees who have an IDIR account (Simons, S., Pers. Comm., 12 June 2008).

A very useful source of data that has recently emerged in the public domain is Google Earth.[15] Google Earth contains a variety of optical and terrain elevation data at varying spatial resolutions. It may be a useful tool for initial reconnaissance mapping, and the professional version allows GIS and GPS data to be imported for more sophisticated applications.

Table 14 *Selected satellite sensors, their spatial resolutions and their availability.*

Sensor	Spatial Resolution	Availability
GeoEye-1	0.41 m panchromatic, 1.65 m multispectral	Sold by GeoEye
IKONOS	0.82 m panchromatic, 3.2 m multispectral at nadir	Satellite Imaging Corp and online from GeoBC
QuickBird	panchromatic, 2.44m multispectral at nadir	MDA Corporation and online from GeoBC
SPOT 2 and SPOT 4	10 m panchromatic, 20m multispectral	Iunctus Geomatics Corp.
SPOT 5	Two 5 m panchromatic sensors combine for 2.5 m, 10-20 m multispectral	Iunctus Geomatics Corp. and online from GeoBC
LISS-III	23.5 m multispectral	ASRC Management Services
Landsat-5 Thematic Mapper	30 m multispectral, 120m thermal	MDA Geospatial services ,and online from GeoBC and USGS
Landsat-7 Enhanced Thematic Mapper Plus	15 m panchromatic , 30 m multispectral, 60 m thermal	MDA Geospatial services ,and online from GeoBC and USGS
Advanced Land Imager	10 m panchromatic, 30 m multispectral	United States Geological Survey
MODIS	250m - 1000m	Free from NASA
Radarsat-1	8-100m	MDA Geospatial services
Radarsat-2	3-100m	MDA Geospatial Services

GeoEye-1

Specifications

- Spatial Resolution
  - 0.41 m panchromatic at nadir
  - 1.65 m multispectral at nadir
- Spectral resolution
  - Panchromatic, 0.45-0.9 µm
  - Blue, 0.45-0.52 µm
  - Green, 0.52-0.60 µm
  - Red, 0.625-0.695 µm
  - Near infrared, 0.76-0.90 µm

14 GeoBC: http://www.ilmb.gov.bc.ca/bmgs/products/

15 Google Earth: http://earth.google.com/index.html

- Radiometric resolution
  - 11 bits
- Temporal resolution
  - 8.3 days when 10° off nadir
  - 2.8 days when 28° off nadir
  - 2.1 days when 35° off nadir

Availability

GeoEye-1 will be the highest spatial resolution spaceborne optical data commercially available. The satellite is slated for launch on 22 August 2008, and data will become available approximate two months later. The data will be sold by GeoEye.[16]

IKONOS

Specifications

- Spatial resolution
  - 1 m panchromatic when 26° off nadir
  - 4 m multispectral when 26° off nadir
  - 0.82 m panchromatic when at nadir
  - 3.2 m multispectral when at nadir
- Spectral resolution
  - Panchromatic, 0.45-0.90 µm
  - Blue, 0.445-0.516 µm
  - Green , 0.506-0.595 µm
  - Red, 0.632-0.698 µm
  - Near infrared, 0.757-0.853 µm
- Radiometric resolution
  - 11 bits per pixel
- Temporal resolution
  - 3-5 days off-nadir
  - 144 days true nadir

Availability

Available from the Satellite Imaging Corporation,[17] Geoeye,[18] and online at GeoBC

QuickBird

Specifications

- Spatial resolution
  - 0.72 m panchromatic when 25° off nadir
  - 2.88 m multispectral when 25° off nadir
  - 0.61 m panchromatic when at nadir
  - 2.44 m multispectral when at nadir

16 GeoEye: http://www.geoeye.com/CorpSite/
17 Satellite Imaging Corporation IKONOS page: http://www.satimagingcorp.com/gallery-ikonos.html
18 GeoEye: http://www.geoeye.com/CorpSite/

- Spectral resolution
  - Panchromatic, 0.45-0.90 µm
  - Blue, 0.45-0.52 µm
  - Green , 0.52-0.60 µm
  - Red, 0.63-0.69 µm
  - Near infrared, 0.76-0.90 µm
- Radiometric resolution
  - 11 bits per pixel
- Temporal resolution
  - 7 days at 0o-15° off nadir at a latitude of 50°
  - 4 days at 0o-25° off nadir at a latitude of 50°
  - 2 day at 0o-45° off nadir at a latitude of 50°

Availability

Available from MDA corporation[19] and online from GeoBC.

SPOT 2 High Resolution Visible (HRV) and SPOT 4 High Resolution Visible Infrared (HRVIR)

Specifications

- Spatial resolution
  - 10 m panchromatic
  - 20 m multispectral
- Spectral resolution
  - Green, 0.50-0.59 µm
  - Red, 0.61-0.68 µm
  - Near infrared, 0.78-0.89 µm
  - Shortwave infrared, 1.58-1.75 µm (SPOT 4 only)
- Radiometric resolution
  - 8 bits per pixel
- Temporal resolution
  - 1 and 4 days alternatively when viewing off-nadir
  - 26 days at nadir

Availability

Available from Iunctus Geomatics Corporation.[20]

SPOT 5 High Geometric Resolution (HGR)

Specifications

- Spatial resolution
  - Two 5 m panchromatic sensors, can be combined to generate a 2.5 m product
  - 10 m multispectral
  - 20 m shortwave infrared

19 MDA Geospatial services: http://gs.mdacorporation.com/
20 Iunctus Geomatics Corporation: http://www.terraengine.com/

- Spectral resolution
  - > Panchromatic, 0.48-0.71 µm
  - > Green, 0.50-0.59 µm
  - > Red, 0.61-0.68 µm
  - > Near infrared, 0.78-0.89 µm
  - > Shortwave infrared, 1.58-1.75 µm
- Radiometric resolution
  - > 8 bits per pixel
- Temporal resolution
  - > 1 and 4 days alternatively when viewing off-nadir
  - > 26 days at nadir

Availability

Available from Iunctus Geomatics Corporation[21] and online at GeoBC.

ResourceSat-1 Linear Imaging Self Scanning Sensor (LISS-III)

Specifications

- Spatial resolution
  - > 23.5 m multispectral
- Spectral resolution
  - > Green, 0.52-0.59 µm
  - > Red, 0.62-0.68 µm
  - > Near infrared, 0.77-0.86 µm
  - > Shortwave infrared, 1.55-1.70 µm
- Radiometric resolution:
  - > 7 bits per pixel
- Return Period:
  - > Approximately two weeks

Availability

AWiFS data is available from **ASRC** Management Services.[22]

Landsat-5 Thematic Mapper (TM)

Landsat 5 was launched in 1984 and had a life expectancy of only three years. Nonetheless, at the time of this writing, the system continues to acquire data. The satellite's fuel levels are low, and it is unknown how much longer the system will continue to operate.

Specifications

- Spatial resolution
  - > 30 m multispectral
  - > 120 m thermal
- Spectral resolution

21 Iunctus Geomatics Corporation: http://www.terraengine.com/
22 ASRC Management Services: www.asrcms.com

    - Blue, 0.45-0.52 µm
    - Green, 0.52-0.60 µm
    - Red, 0.63-0.69 µm
    - Near infrared, 0.76-0.90 µm
    - Shortwave infrared, 1.55-1.75 µm
    - Shortwave infrared, 2.08-2.35 µm
    - Thermal infrared, 10.4-12.5 µm
- Radiometric resolution
    - 8 bits per pixel
- Temporal resolution
    - 16 days

Availability

Data is available from MDA Geospatial Services[23] and online at GeoBC. Much of the Landsat archive is now freely available from the USGS[24]

Landsat-7 Enhanced Thematic Mapper Plus (ETM+)

Landsat 7 was launched in 1999 and operated properly until 2003, when it suffered a scan line corrector (SLC) failure. The system continues to collect data; however, scenes must be heavily processed prior to being used for analysis.

Specifications

- Spatial resolution
    - 15 m panchromatic
    - 30 m multispectral
    - 60 m thermal
- Spectral resolution: 7 bands in the visible and near, shortwave and thermal infrared
    - Panchromatic, 0.50-0.90 µm
    - Blue, 0.450-0.515 µm
    - Green, 0.525-0.605 µm
    - Red, 0.630-0.690 µm
    - Near infrared, 0.750-0.900 µm
    - Shortwave infrared, 1.55-1.75 µm
    - Shortwave infrared, 2.09-2.35 µm
    - Thermal, 10.40-12.50 µm
- Radiometric resolution:
    - 8 bits per pixel
- Return Period:
    - 16 days

Availability

Data is available from MDA Geospatial Services[25] and online at GeoBC. Much of the Landsat archive is now freely available from the USGS[26]

23 MDA Geospatial services: http://gs.mdacorporation.com/
24 USGS Global Visualization Viewer: http://glovis.usgs.gov/
25 MDA Geospatial services: http://gs.mdacorporation.com/
26 USGS Global Visualization Viewer: http://glovis.usgs.gov/

Advance Land Imager (ALI)

The ALI is aboard the Earth Observing 1 (EO-1)[27] satellite, and is part of NASA's New Millennium Program (NMP) which was initiated to develop and validate several new spaceborne sensor technologies. The ALI was intended to be the precursor to Landsat 8. Originally planned to be a one year mission, data acquisition continues at present and may continue until 2011.

Specifications

- Spatial resolution
  - 10 m panchromatic
  - 30 m multispectral
- Spectral resolution
  - Panchromatic, 0.480-0.690 µm
  - 0.433-0.453 µm
  - 0.450-0.510 µm
  - 0.525-0.605 µm
  - 0.630-0.690 µm
  - 0.775-0.805 µm
  - 0.845-0.890 µm
  - 1.20-1.30 µm
  - 1.55-1.75 µm
  - 2.08-2.35 µm
- Radiometric resolution:
  - 12 bits per pixel
- Return Period:
  - 16 days

Availability

Image data acquired by EO-1 are archived and distributed by the United States Geological Survey's Center for Earth Resources Observation and Science (EROS).[28] The data are not freely available.

ResourceSat-1 Advanced Wide Field Sensor (AWiFS)

Specifications

- Spatial resolution
  - 56 m multispectral
- Spectral resolution
  - Green, 0.52-0.59 µm
  - Red, 0.62-0.68 µm
  - Near infrared, 0.77-0.86 µm
  - Shortwave infrared, 1.55-1.70 µm
- Radiometric resolution:
  - 10 bits per pixel
- Return Period:
  - Approximately two weeks

27 Earth Observing 1: http://eo1.usgs.gov/index.php
28 USGS: http://edc.usgs.gov/

Availability

AWiFS data is available from **ASRC** Management Services.[29]

Advanced Very High Resolution Radiometer (AVHRR/3)

The AVHRR is onboard the National Oceanic and Atmospheric Association's (NOAA) series of Polar-Orbiting Environment Satellites (POES), and is currently in its third generation.

Specifications

- Spatial resolution
  - 1.1 km at nadir
- Spectral resolution
  - Red, 0.58-0.68 µm
  - Near infrared, 0.725-1.00 µm
  - Mid infrared 1.58-1.64 µm
  - Thermal 3.55-3.93 µm
  - Thermal 10.30-11.30 µm
  - Thermal 11.5-12.50 µm
- Radiometric resolution
  - 10 bit
- Return Period
  - Twice daily

Availability

AVHRR data is available from NOAA's Comprehensive Large Array-data Stewardship System (CLASS), and small datasets are freely available.[30]

Moderate Resolution Imaging Sprectroradiometer (MODIS)

Specifications

MODIS is comprised of two identical sensors onboard the Aqua and Terra satellites. Each sensor has 36 spectral bands; only the first seven, however, are used for land applications.

- Spatial resolution:
  - 250 m (bands 1-2)
  - 500 m (bands 3-7)
  - 1000 m (bands 8-36)
- Spectral resolution
  - Band 1 – 0.62-0.67 µm
  - Band 2 – 0.841-0.876 µm
  - Band 3 – 0.459-0.479 µm
  - Band 4 – 0.545-0.565 µm
  - Band 5 – 1.230-1.250 µm
  - Band 6 – 1.628-1.652 µm

29 ASRC Management Services : www.asrcms.com

30 Comprehensive Large Array-data Stewardship System: http://www.class.ngdc.noaa.gov/saa/products/welcome

  - Band 7 – 2.105-2.155 µm
- Radiometric resolution
  - 12 bit
- Return Period
  - Twice daily

Availability

MODIS data are freely available online from NASA.[31] The MODIS program is product driven, and a wide variety relating to terrestrial investigations are provided on a daily, weekly, monthly, or annual basis. Products derived from MODIS data include surface reflectance, land surface temperature, land cover and land change, vegetation indices (NDVI and EVI), thermal anomalies/fire, bidirectional reflectance distribution function/albedo, vegetation cover change and conversion, and burned areas.

Radarsat-1

Specifications

- Spatial resolution
  - 8-100 m
  - Wavelength
  - C-band, 5.6 cm
  - Polarization modes
  - Single, dual, quad
  - Polarization
  - HH
- Temporal resolution
  - 1 day at high arctic
  - 3 day at mid-latitudes
  - 24 days to return to a given orbit path

Availability

Radarsat-1 data are available from MDA Geospatial Services.[32]

Radarsat-2

Specifications

- Spatial resolution
  - 3-100 m
  - Wavelength
  - C-band radar, 5.55 cm
  - Polarization modes
  - Single, dual, quad
  - Polarization
  - HH, VV, HV, VH

31 MODIS: http://modis.gsfc.nasa.gov/
32 MDA Geospatial services: http://gs.mdacorporation.com/

- Temporal resolution
  - > 24 days to return to a given orbit path

Availability

Radarsat-2 data are available from MDA Geospatial Services31

Aerial imagery, radar and lidar data

Specifications

Data acquired using aerial platforms do not have fixed specifications, as surveys are designed to suit the objectives of a given project.

Availability

Aerial data is collected on demand. Costs vary widely and are based on the size and location of the survey, and the amount of manual processing required.