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Medium resolution land cover mapping of Canada from SPOT 4/5 data

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Canada

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ABSTRACT

Medium resolution land cover is one of the most widely used geospatial datasets for environmental assessment in Canada. Canada's current coverage is from circa-2000 Landsat and is therefore out-of-date. With an update of the medium resolution orthoimage coverage of Canada from circa-2000 30 m Landsat to 2005 – 2010 20 m SPOT 4-5 imagery, an opportunity presented itself to update Canada's land cover with improved spatial resolution. Previous experience mapping the Northern Land Cover of Canada (NLCC) taught us to efficiently map at the national scale from Landsat, however the SPOT dataset required new approaches to deal with problems related to phenology and a smaller image footprint compared to Landsat. This paper presents solutions to the problems of radiometric normalization and classification extension with the objective of producing a consistent and accurate medium resolution national scale land cover. A 20 m SPOT land cover of Canada's forested regions at a 16 class thematic level is presented with full validation using nearly 1600 reference points across Canada. The overall accuracy of the product is 71% for strict assessment and 85% if relaxed to account for geolocation errors. An assessment of the product along the treeline ecotone suggests an improvement over existing land cover, while northward the product merges better with the existing circa-2000 Northern Land Cover of Canada from Landsat.

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1. INTRODUCTION

Land cover is required by a large number of academic, government and private stakeholders in Canada for research and planning in a variety of priority areas including wildlife and resource development. Existing land cover maps of Canada include the 250 m MODIS land cover time-series from 2000-2011 (Pouliot et al., 2014) generated using a change updating approach from a baseline 2005 land cover (Latifovic et al., 2012), as well as earlier products from year 2000, 1 km VGT (Latifovic et al., 2004) and 1995 AVHRR (Cihlar and Beaubien, 1998). While these data provide an accurate national overview and temporal dynamics of Canada’s land cover, they lack the spatial detail required by some users. For example, roads are not visible and features such as cut blocks and urban development may not be accurately delineated due to a minimum mapping unit greater than the size of these features.

To address the need for finer scale land cover in Canada, a 30 m circa-2000 medium resolution product from Landsat exists that was assembled from three separate maps including the Earth Observation for Sustainable Development (EOSD) map from the CFS representing Canada’s forested regions (Wulder et al., 2008), the National Land and Water Information System (NLWIS) map from AgCan representing agriculture regions (NLWIS, 2009), and the Northern Land Cover of Canada (NLCC) from the Canada Centre for Remote Sensing (CCRS) representing Canada north of treeline (Olthof et al., 2009). The CFS and AgCan collaborated to generate a common land cover legend and product where the two maps meet. The hard boundary that generally exists between agricultural fields and forest makes merging these two products relatively straight forward. However, the boundary between EOSD and NLCC along the northern limit of the treeline reveals many inconsistencies caused by different class definitions and the fact that the western subarctic treeline is not as well mapped as other forested parts of Canada. The discontinuity that results across treeline combined with an increasing interest in resource development in this ecotone makes a new consistent and reliable base map necessary. The need for improved base mapping is heightened when considering ongoing changes along treeline due to climate warming, permafrost melt and vegetation change and their impacts on infrastructure development and maintenance.

The circa-2000 Landsat data used to create existing land cover of Canada required a five year period to assemble the complete, nearly cloud-free medium resolution coverage representing mid-summer or peak-of-season vegetation conditions. Land cover change can be significant within this five year time-period due to disturbance such as fire and these changes affect the consistency and accuracy of derived land cover maps. Reducing this temporal window to fewer years offers the opportunity to improve consistency by lessening the amount of inter-annual change, but increases the need to use scenes acquired either early or late in the growing season to obtain a similar cloud-free coverage. Incorporating these off peak scenes into a land cover presents challenges due to the fact that radiometry cannot be normalized between peak-of-season and off-peak scenes. This is because vegetated surfaces are very different between these time-periods where peak-of-season represents green, fully leaf-out conditions while off-peak may represent emergent, senescent or leaf-off conditions.

The Centre for Topographic Information completed a second medium resolution image coverage of Canada from SPOT 4-5 data in 2011. The dataset contains four spectral bands in Green, Red, Near Infrared (NIR) and Shortwave Infrared (SWIR) at SPOT 4's 20 m native resolution that were orthorectified to within one pixel horizontal accuracy. As with Landsat, five years spanning 2005-2010 were necessary to acquire a full coverage of Canada from SPOT, while the seasonal window was wider than Landsat including scenes acquired both earlier in spring and later in fall to ensure the most cloud-free coverage possible. Updating land cover from these data was challenging due to several factors that required the development and application of new methods. Methods specific to SPOT were developed to balance radiometry, classify off peak-of-season images that are complicated by phenology, delineate new spectrally-based mapping zones and consistently interpret and classify images at the local, regional and national scales.

The objective of this work is to update existing circa-2000 medium resolution land cover of Canada. Initially, we will focus on the forested region of Canada where inter-annual change can be significant due to forest fire, defoliation and harvesting that are dominant disturbances in Canada (Pouliot et al., 2014). Northern Canada is also experiencing significant change due to climate warming that has led to an overall greening of the Arctic in recent decades (Myneni et al., 1997, Pouliot et al., 2009). However, these \ changes are progressive and tend to produce only minor land cover change confined to areas where initial land cover was either spectrally or thematically near a boundary between two land cover classes. For example, only areas that are classified as herb-shrub supporting the highest amount of shrub for this class would be expected to transition to erect shrub under warming conditions. In addition, inter-annual change due to disturbance such as fire and thaw slumps tend to be relatively rare in the Arctic, requiring less frequent land cover updating than in more southerly parts of Canada. Agriculture was also not updated due to complications caused by land use, crop rotation and phenology that can be better dealt with by Agriculture and Agri-Food Canada.

2. METHODS

2.1. Peak-of-season scene selection

Phenology plays an important role in interpreting land cover from satellite data. Consistent radiometry is required to reliably interpret and map vegetation and thus land cover types. Imagery acquired during spring or fall with leaf-off or senescent vegetation cannot be interpreted consistently alongside imagery acquired mid-summer when leaves are fully developed. Thus, separate procedures were needed to map peak-of-season and off-peak imagery, requiring a method to separate imagery into peak-of-season and off-peak depending on acquisition time, location and cover type.

Of the 5345 SPOT 4-5 scenes purchased to cover Canada, more than 3000 were acquired during the period considered peak-of-season in southern Canada either after mid-June or before September. However, the phenological peak-of-season window between June and September in southern Canada varies according to location and cover type. This temporal window narrows further north where summers are shorter, and lengthens over predominantly evergreen vegetation types due to the presence of needles year-round. 10-day composited 1 km Advanced Very High Resolution Radiometer (AVHRR) data from Canada's Long-Term Satellite Data Record (Latifovic et al., 2005) were used to identify annual location and cover-type specific peak-of-season windows across Canada. Annual 10-day data were lowess-smoothed and the annual maximum Normalized Difference Vegetation Index (NDVI) was determined. Based on knowledge of phenology in southern Canada and further north, the timing of the 95% of maximum NDVI before and 92% after maximum NDVI was determined to correspond to the beginning and end of the peak-of-season window, respectively (Figure 1).

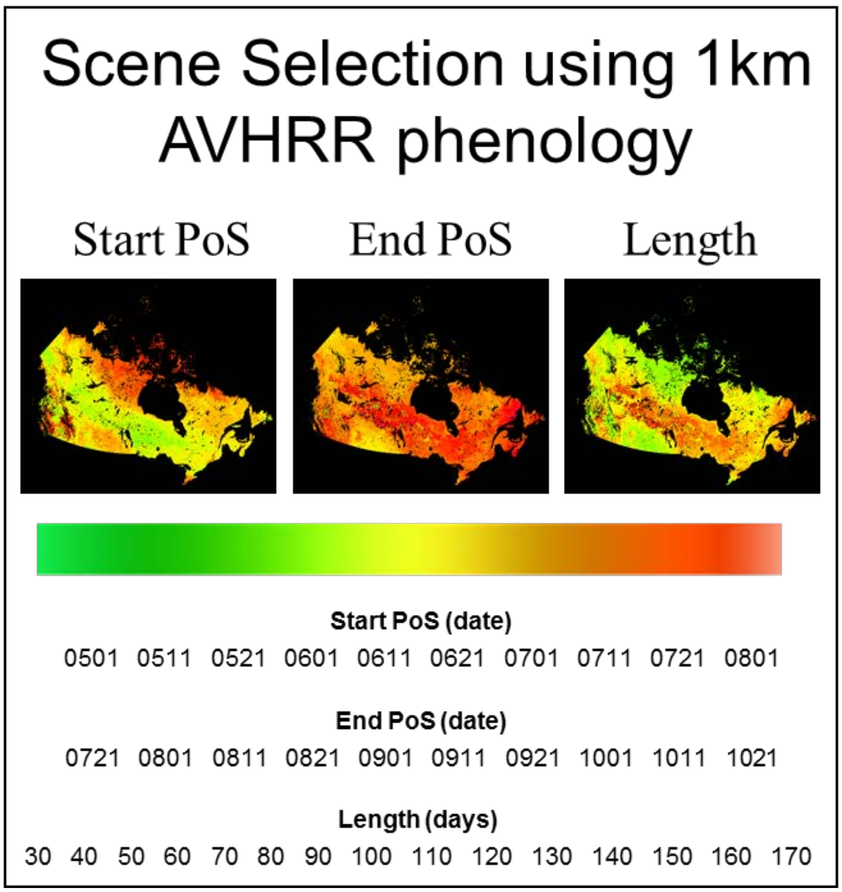


Figure 1. Peak-of-Season SPOT scene selection based on phenology from 10-day AVHRR

The timing of these thresholds was mapped at each 1 km location in Canada to correspond to beginning and end of peak-of season across Canada. SPOT scenes were evaluated against their corresponding phenology determined from AVHRR based on year and location to assess whether they were acquired during or outside of peak-of-season. Scenes acquired during peak-of-season were radiometrically balanced and classified in large area mosaics, while off-peak images were classified using decision trees and training data from adjacent overlap classifications.

2.2. Radiometric normalization

Initially, radiometric balancing using TOA reflectance calculated from scaled radiance data and accompanying calibration coefficients was investigated as means to achieve data consistency among many individual SPOT scenes, as is done in the USGS's WELD program using Landsat (Roy et al., 2010). However, in addition to the known problem of band reversal of SPOT 4 data in DIMAP format that was corrected (Guo and He, 2008), there appears to be a problem with the calibration gains provided in the header file based on a consistency analysis between adjacent overlap scenes calibrated to TOA reflectance, the source of which is still unknown to us.

Peak-of-season images were radiometrically balanced using 250 m MODIS as a consistent national scale radiometric reference and methods developed for Landsat in Olthof et al. (2005). The MODIS reference image was derived using multi-year rank-based median compositing to eliminate outliers due to cloud and shadow and to generate robust radiometric measurements of TOA reflectance. Reference MODIS bands that were used (band 1: Red: 0.630-0.690 um, band 2: NIR: 0.775-0.900 um, band 6: SWIR: 1.550-1.750 um) corresponded roughly to SPOT bands 2 (Red: 0.61-0.68 um), 3 (NIR: 0.78-0.89 um) and 4 (SWIR: 1.58-1.75 um). MODIS band 6 was downscaled from 500 m to 250 m following methods in Tritchenko et al. (2006). These three bands have traditionally been used to interpret land cover at CCRS using a NIR, SWIR, Red displayed as R, G, B false-colour.

Because the areal footprint of SPOT is roughly one ninth of that of Landsat, radiometric normalization of single scenes to a coarse resolution reference image like MODIS produced sub-optimal results in many cases. This was due to a lower dynamic range used in the Thiel-Sen regression in instances where the majority of a SPOT scene imaged only a few land cover types that were either dark or bright such as predominantly dark conifer or bright sand. In order to minimize this problem, multiple SPOT scenes acquired along orbits were mosaiced and normalized together as one. Because of the north-south orientation of orbits and the larger footprint associated with the use of multiple scenes, this procedure had the effect of increasing the dynamic range of data input into the normalization regressions, thereby producing more stable results.

Normalized orbits served as seed data for subsequent normalization using robust regression between adjacent overlap regions. Fortunately, most normalized orbits were within one or two scenes of adjacent normalized orbits, which ensured minimal radiometric drift that can occur due to error propagation from one scene to the next. In the case of overlap normalization, a seven by seven average filter was applied to each band prior to regression to minimize the effects of image mis-registration. Normalization results were verified using statistics on a subset of overlapping image pairs to confirm visual quality assessment and control. Quick-look images in JPEG format were generated for each overlapping pair and checked to ensure a seamless normalization result between adjacent scenes (Figure 2).

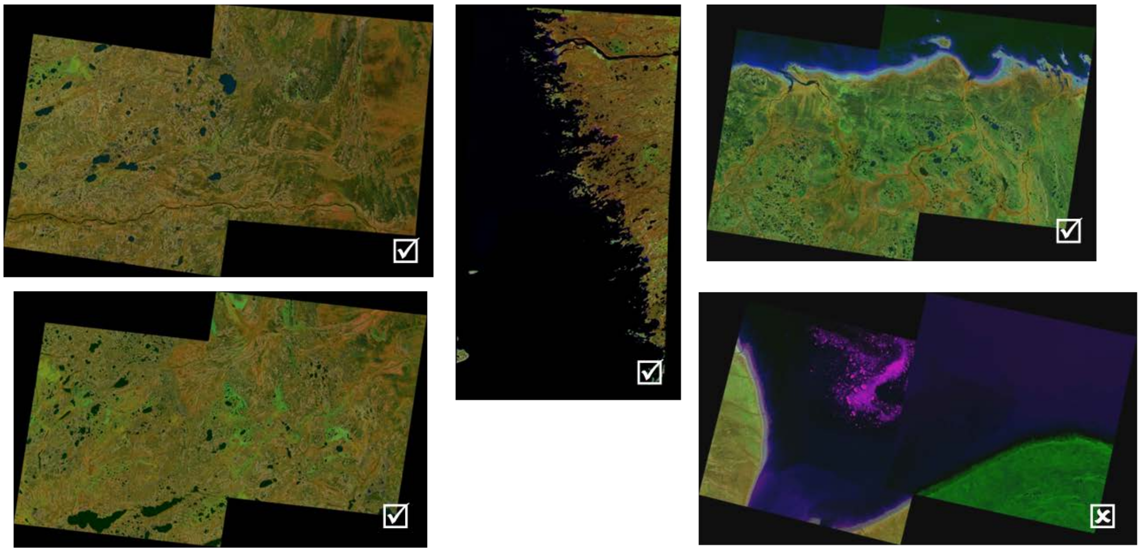


Figure 2. Example JPEG overviews used to evaluate overlap normalization

2.3. Mapping zone delineation

Initially, mapping zones were delineated using the ecozones of Canada. However, once classification of individual SPOT scenes was underway, it was realized that the same spectral signature on geographic ends of an ecozone could represent different land cover types. This was caused by the size of some ecozones, for example the boreal shield that extends a distance of nearly 4000 km from the Island of Newfoundland to the north eastern corner of Alberta. Spectrally similar zones could be visually seen in national scale coarse resolution imagery that correspond to known unique bioregions, for example the Hudson Bay Lowlands and surroundings. Thus, mapping zones were delineated in coarse resolution 1 km SPOT VGT using the same bands 2, 3, 4 as SPOT 4-5 and E-Cognition segmentation software. Two hundred sixty segments were initially generated and subsequently merged manually using visual interpretation of spectral and feature similarity, producing twenty mapping zones below treeline (Figure 3).

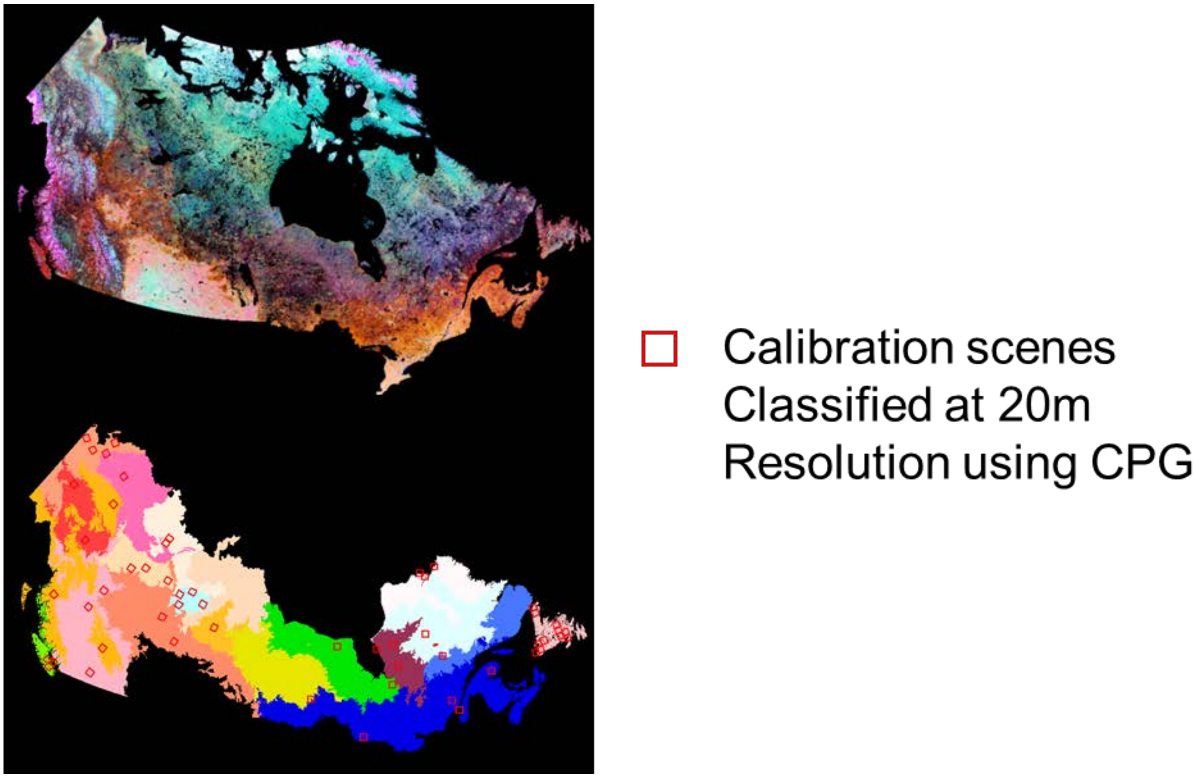


Figure 3. SPOT VGT used to delineate mapping zones (top) and mapping zones with calibration scenes used to map land cover for each zone (bottom)

2.4. Reference data

Reference data consisted of both visually interpreted high resolution remote sensing imagery and ground truth acquired during summer field campaigns between 2004 and 2011. These data were used only to develop the classification legend and for accuracy assessment.

Field campaigns were conducted in a different region of Canada each year to collect data that simultaneously served national scale and other project needs within the Government of Canada such as ParkSpace (Fraser et al., 2009) with Parks Canada and the Transportation Risks in the Arctic due to Climatic Sensitivity (TRACS) with the Geological Survey of Canada. A significant amount of ground truth was collected along the treeline and north due to a lack of otherwise suitable reference data in these regions. Within established field plots that were purposefully located based on satellite imagery, basic vegetation attribute data was collected in terms of functional type and composition along with field pictures taken in four cardinal directions, one downward looking and another upward looking beneath forest canopies. Because each campaign was designed to meet different objectives, attribute data varied slightly between campaigns due to the level of detail required. For example, ecosystem maps generated for Parks Canada from satellite imagery (Fraser et al., 2009) required indicator species level information in addition to soils and permafrost, whereas other campaigns focussed on the collection of a maximum amount of data in terms of spatial extent within a limited amount of time and thus less detail was collected. In order to make all data comparable, all field data representing different campaigns were interpreted simultaneously using available attribute data, field pictures and any existing ancillary data.

Field data were interpreted using fields within the Land Cover Classification System (LCCS) by assigning attributes to each field data point. Attributes were generic and modeled after those used to map land cover for GlobCover (Defourny et al., 2006) to interpret reference data from Google Earth™. The LCCS scheme is hierarchical and allows rollup to a user defined classification legend based on the number of unique classes observed in the data. Up to three fractions of dominant, co-dominant and sub-dominant land cover were interpreted where applicable within an approximate 20 m x 20 m area centred on the field point to account for mixed pixels. Attribute fields including the perceived certainly of the interpretation are shown in Table 1.

1246 field points were interpreted in this manner. While these data are located across Canada, they tend to be clustered in regions where field data were collected on foot, in a vehicle by road or sometimes by helicopter. This sample was supplemented with data interpreted from Google Earth™ to ensure a more even coverage of Canada (Figure 4). All areas imaged in Google Earth™ at high resolution of approximately 1 m or better were delineated and a random sample of points was extracted for interpretation. A 20 m x 20 m pixel footprint was overlain on the high resolution Google Earth™ imagery in KML format in the same orientation as the SPOT imagery. This footprint was interpreted in same manner as above with the aid of Street View and other online content. A consistence analysis between field and Google Earth™ interpreted reference data was conducted using 24 random points, revealing an 83.3% agreement on the Dominant Land Cover class between the two sources of reference data. A total of 965 points were interpreted using Google Earth™, increasing the total number of reference points to more than 2000 across Canada. Additional data were consulted where available to assist interpretation specifically, including hundreds of oblique airphotos taken from helicopter north of Yellowknife across treeline, an oblique airphoto database over Quebec, other land cover datasets such as Boreas (Cihlar et al., 1997) and high resolution Google Earth™ imagery beyond sample point locations.

Table 1. Modified LCCS Classification Scheme

Dominant (Second, Third where applicable) LC Class	% area	Life Form	Closure	Height	Leaf Type	Leaf Phenology	Certainty
A11 - Cultivated & Managed Lands	0%	Herbaceous A2	Sparse (<25%)	0 - 0.5m	Broadleaved D1	Evergreen E1	certain
A12 - Nat. & Semi-Nat. Terrerstrial Veg.	10%	Trees A3	Open (25 - 40%)	0.5 - 2m	Needleleaved D2	Deciduous E2	reasonable
A24 - Nat. & Semi-Nat. Aquatic Veg.	20%	Shrubs A4	Medium (40 - 60%)	> 2m			doubtful
B15 - Artificial Surfaces & Ass. Areas	30%	Lichens/ Mosses A7	Closed (> 60%)				
B16 - Bare Areas - consolidated A1	40%						
B16 - Bare Areas - unconsolidated A2	50%						
B28 - Inland Waterbodies Snow & Ice - water A1	60%						
B28 - Inland Waterbodies Snow & Ice - snow and ice A2	70%						
	80%						
	90%						
	100%						

Figure 4. Location and source of reference data used to develop the classification legend and for land cover accuracy assessment

Attributes were hierarchically summarized to a 16 class legend (Table 2). The fist hierarchy separated reference data into forest and non-forest. For each reference point, tree crown closures were summed across dominant, co-dominant and sub-dominant fractions for needeleaved evergreen and broadleaved deciduous based on the product of crown closure and the percent area occupied. The average closure was used within the range of sparse (<25 %) : average cover 12.5 %, open (25-40 %) : average cover 32.5%, medium (40-60%) : average cover 50 % and closed (>60 %) : average cover 80 %. This product approximated the total tree cover within the 20 m pixel by tree functional type. All reference points with greater than 15 % tree cover were considered forest while those equal to or less than 15 % were considered non-forest. Thresholds applied to tree cover based on functional type in Table 2 were used to classify forest reference points into three needleleaved evergreen density classes of high, medium and low, one mixed and one deciduous class. For non-treed reference points, dominant fraction functional type was considered when it occupied 60 % or more of the pixel, while both the dominant and co-dominant were considered when the co-dominant equalled or exceeded 30 % of the pixel.

The third or sub-dominant fraction was not considered to classify non-forest reference points.

2.5. Classification of peak-of-season scenes

2.5.1. Enhancement and clustering

Classification of radiometrically normalized peak-of-season imagery was performed using the combined Enhancement Classification Method and Classification by Progressive Generalization methods developed and used at CCRS to generate numerous regional to national scale land cover products (Beaubien et al., 1999; Cihlar et al., 1998). The method requires image enhancement on each band to enable better visual discrimination and thus spectral separability of land cover classes by maximizing the dynamic range representing land cover while compressing cloud, cloud shadow and water on the high and low end of the spectral range. In order to adequately preserve the dynamic range representing multiple land cover classes, data were initially stratified into high and low Infrared Simple Ratio (ISR = NIR / SWIR) strata and enhancements were performed separately on each stratum. Previously in EOSD, the NDVI was used to stratify, however the red band used to calculate the NDVI is most affected by atmosphere of the three bands used here, producing a less stable index for stratification than the ISR. Further, the ISR is known to predict Leaf Area Index (LAI) and vegetation biomass better than other vegetation indices (Fernandes et al., 2004). Both the ISR threshold and enhancements were determined visually on all peak-of-season imagery at the national scale. A 250 m grid was generated and each radiometrically balanced peak-of-season image was mosaiced using nearest neighbour resampling to preserve original radiometric values (Figure 5). This national scale image provided a reduced sample image and overview of the entire country that was manageable in size to determine the ISR threshold, perform enhancements, generate spectral clusters and signatures and also to visually determine data consistency at regional to national scales.

Table 2. Classification Legend

	Tree Cover		Class	Density / comments	Functional type 1	Fractional cover 1	Functional type 2	Fractional cover 2	Range % Tree Cover*		Average % Tree Cover*		
		Code							Needleaved	Broadleaved	N	Needleaved	Broadleaved
Forest	> 15%	1	Evergreen conifer forest	high	Trees A3				>= 20 %	< 2.5 %	184	42.78	0.11
		2	Evergreen conifer forest	medium	Trees A3				>= 12.5 %, < 20 %	< 2.5 %	58	18.57	0
		4	Mixed forest		Trees A3				> 2.5 %	>= 2.5 %	106	14.68	19.18
		5	Deciduous forest		Trees A3				<= 2.5%	>= 7.5 %	73	0.44	38.27
Non-forest	<= 15%	3	Evergreen conifer	low	Trees A3				< 12.5%	< 2.5 %	34	5.66	0.11
		6	Young forest	Generally > 5 years	Shrubs A4	>= 40%	Trees A3	>= 30%					
		7	Recent disturbance	Generally < 5 years	Trees A3 - refer to comments field								
		8	Erect shrub		Shrubs A4	>= 60%							
		9	Herb - shrub		Herbaceous A2	>= 40%	Shrubs A4	>= 30%					
		10	Herbaceous		Herbaceous A2	>= 60%							
		11	Bryoid		Lichens/ Mosses A7	>= 60%							
		12	Barren		B16 - Bare Areas - unconsolidated A2	>= 60%							
		13	Sparse conifer lichen		Lichens/ Mosses A7	>= 40%	Trees A3	>= 30%					
		14	Herbaceous wetlands		A24 - Nat. & Semi-Nat. Aquatic Veg.	>= 60%							
		15	Ice		B28 - Inland Waterbodies Snow & Ice - snow and ice A2	>= 60%							
		16	Water		B28 - Inland Waterbodies Snow & Ice - water A1	>= 60%							

*Tree Cover = tree crown closure X fractional cover

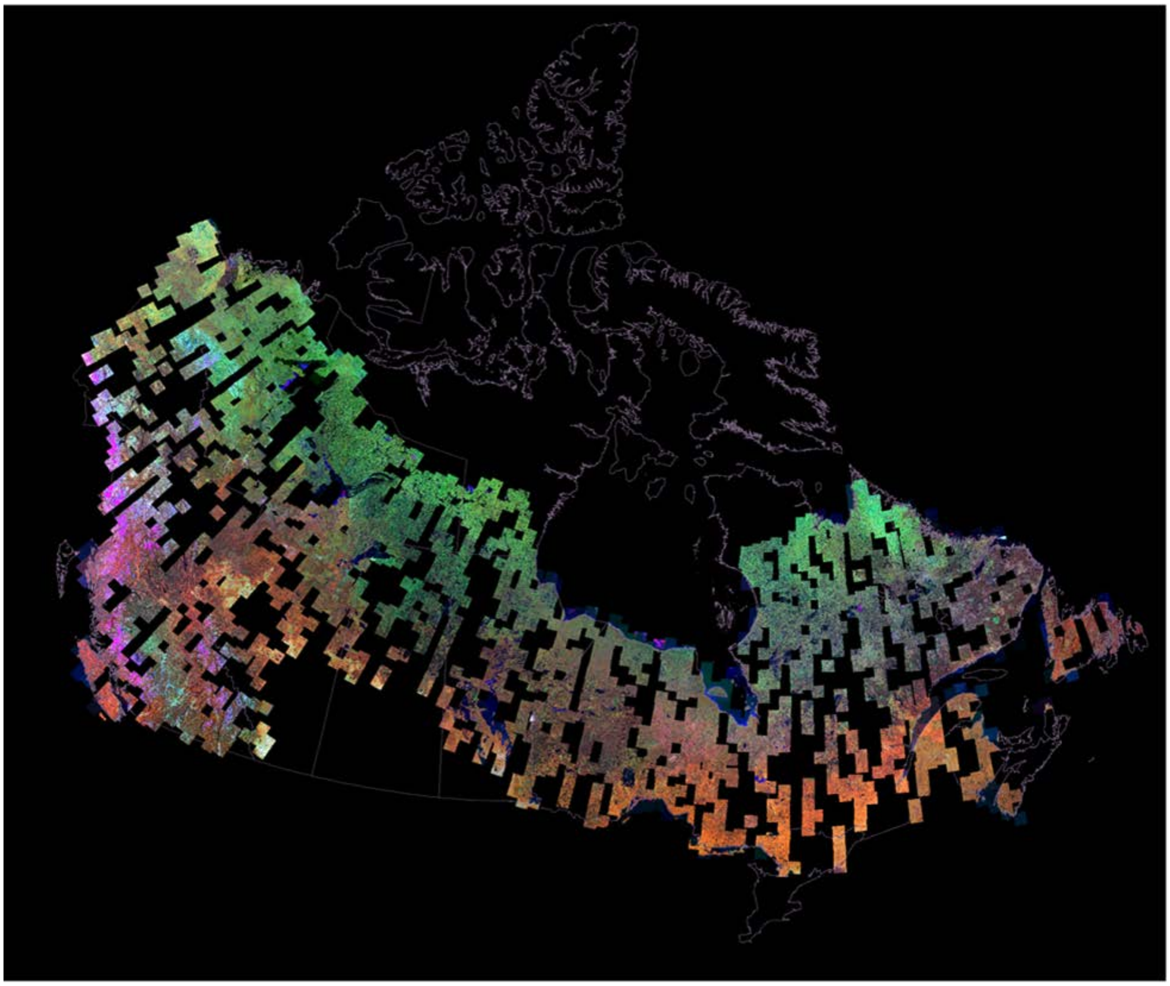


Figure 5. Radiometrically balanced peak-of-season SPOT mosaic resampled to 250 m

The ISR threshold was set to broadly in the 250 m resampled image to discriminate fire and barren to low biomass vegetation including sparsely treed areas from medium to densely vegetated areas further south. This threshold roughly separates the taiga treeline ecotone from the boreal forest. Visual enhancements were determined next for each stratum and applied. 200 spectral clusters were generated from the enhanced imagery with corresponding spectral signatures from each stratum using the fuzzy k-means clustering algorithm and pseudo-colour tables representing enhanced false colour were produced. The ISR threshold value, lookup tables for linear enhancements, spectral signatures and pseudo-colour tables were transferred to each normalized peak-of-season scene to generate minimum-distance cluster images at 20 m resolution. Most peak-of-season scenes contained both ISR strata and therefore a maximum of 400 spectral clusters were available for merging and labelling.

2.5.2. Water body extraction

Water bodies have been mapped nationally at 1:50k scale in the CanVec National Topographic Database (NTDB). Previously for the land cover of northern Canada, we mapped water from Landsat and accepted only those water pixels that intersected CanVec water bodies buffered to one pixel. This method allowed slight differences to exist between the land cover product and CanVec water, but not large differences due to change. A different approach was used in the current effort since the average CanVec mapsheet start date is 1970 and therefore many are out of date, while significant differences in water bodies exist mainly in northern Quebec caused by recent hydro electric developments.

Water can be spectrally variable in such a large number of satellite images acquired at different times, stemming from suspended sediment, ice, aquatic vegetation and atmosphere. An adaptive classification method to account for variability among scenes was developed that tunes water body extraction to each scene and uses the CanVec water bodies as a source of training data. For each peak-of-season scene, training data were derived from lakes gridded at 20 m resolution from the 1:50k CanVec hydrography polygon layer. Cluster images were intersected with the gridded CanVec water layer and clusters whose majority area intersected with permanent water in CanVec were assigned to water. The 1:50k CDED elevation later was used to generate a topographic slope image and water was removed on slopes greater than five percent. The shadow mask described in a subsequent section was used to refine water further.

2.5.3. Land cover classification

A set of 20 m land cover calibration scenes were used to determine cluster merging and labelling, similar to Satellite Information for Land Cover (SILC, 2000) data generated from Landsat. Because separate enhancements were applied to each stratum, enhanced colours and pseudo colours were not easily interpretable on their own. Therefore, calibration scenes were chosen based on the availability of high resolution Google Earth imagery in corresponding locations. Interpretation was done by consulting the false colour SPOT image, the cluster image and Google Earth simultaneously. Along with high resolution imagery in Google Earth, online content including geolocated images, Street View and field data were consulted to guide cluster merging and labelling. To assist in determining object boundaries in the classification, adaptive enhancements were applied to false colour imagery to improve visual separability and to facilitate the selection of clusters belonging to a known object. Through visual interpretation and merging of cluster images to land cover, two lookup tables were generated for each mapping zone for high and low ISR strata that relate input spectral clusters to output land cover classes (Figure 6).

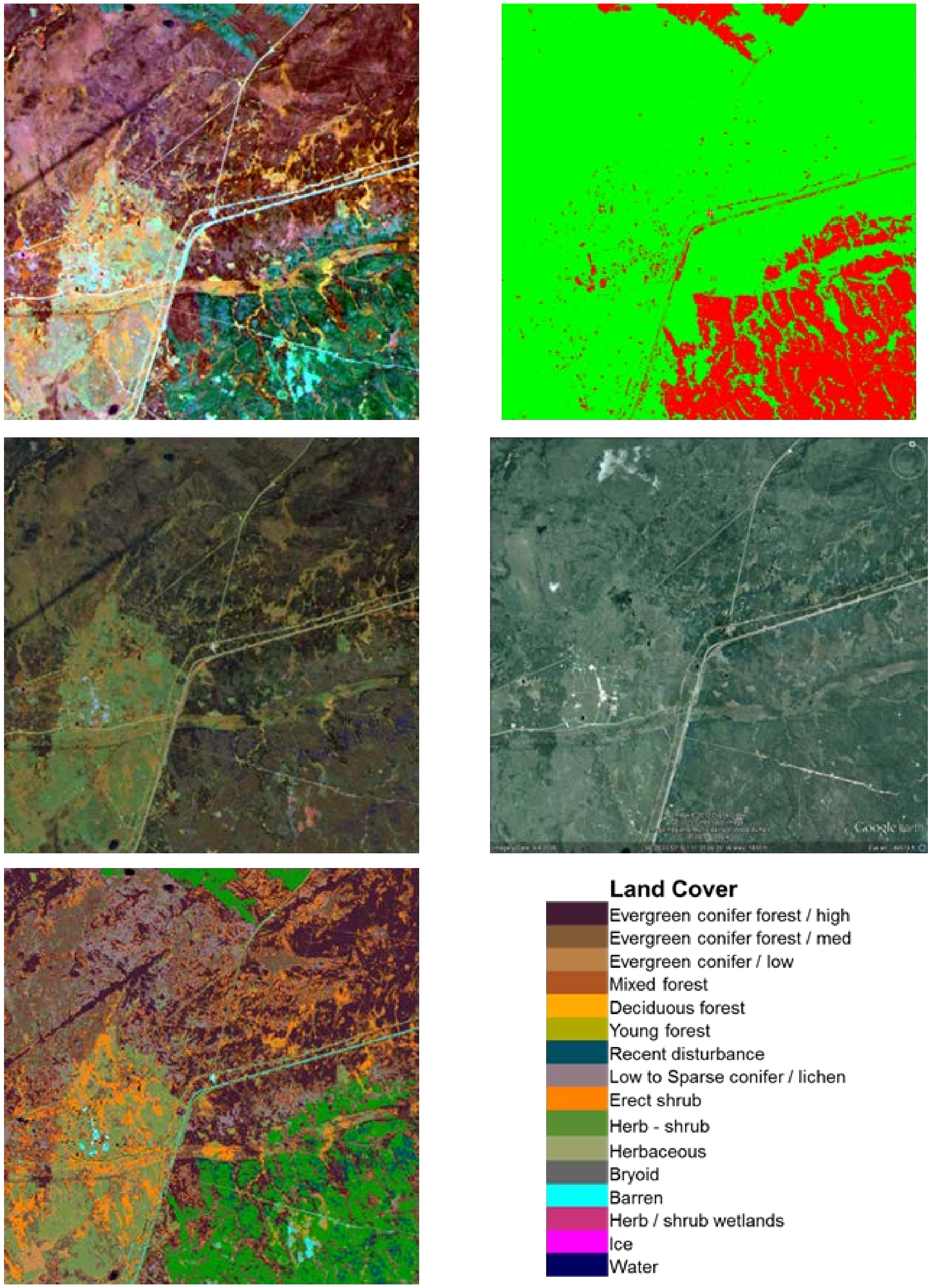


Figure 6. Enhanced SPOT NIR, SWIR and Red as R, G, B (top left), ISR stratification (top right), cluster image with pseudo-colour tables applied (middle left), high resolution Google Earth™ image of the same region (middle right) and classification (bottom left) with 16 class legend (bottom right)

The mapping legend was determined based on previous experience mapping Canada at the national scale using the modified Federal Geographic Data Committee (FGDC) legend in Cihlar et al. (1997) and Latifovic et al. (2004). These classes were kept in mind when interpreting land cover, however, certain classes were added, modified or omitted based on unique attributes that could be reliably seen and mapped at 20 m resolution national scale. The development and application of this legend to map Canada at the national scale had been done at a coarse resolution (250 m – 1 km) previously and therefore certain classes were less appropriate at describing land cover at the medium resolution (20-30 m) scale, while additional classes were necessary to describe unique features that were visible at medium resolution. A detailed product was created initially at a 34 class legend that was subsequently generalized to16 classes for validation. The 34 class legend describes classes that may be specific to certain mapping zones, for example sparse conifer on sand / lichen is dominated by Jack Pine and exists largely in western Canada including the mapping zone south of Lake Athabasca, while sparse conifer with a vascular understory exists across Canada. Both sparse conifer classes are merged to the low density conifer class in the 16 class legend that depicts generalized land cover based on functional type.

Each mapping zone had a maximum of 400 clusters from 200 high ISR and 200 low ISR clusters. Multiplied by twenty mapping zones, 8000 clusters needed to be assigned to land cover classes at the national scale. The process of labelling such a large number of clusters was made more efficient in two ways. First, spectrally similar and spatially adjacent clusters are often assigned to the same class and this tendency was exploited within ISR strata as is commonly done in CPG. As well, spatially adjacent clusters between ISR strata representing the same land cover object were assigned to the same class by default. Secondly, in adjacent mapping zones the high likelihood of the same spectral cluster representing the same land cover class was exploited by assigning clusters in adjacent zones to the same class by default. The largest mapping zone located within central Canada was mapped first and generated lookup tables from this zone were extended and applied to calibration scenes and 250 m overview data in adjacent zones. Visual quality checking of the resulting classification of calibration scenes and of the 250 m overview in adjacent zones was required to ensure that all default cluster assignments to land cover classes were appropriate or needed to be changed as necessary. Lookup tables were adjusted when needed and the process was repeated for adjacent mapping zones in all directions until all zones were mapped.

The region south of the St. Lawrence River and east of Quebec City including the Gaspe Peninsula, New Brunswick and Nova Scotia was mapped separately using 150 unique spectral clusters. This was done to avoid saturation in the NIR band that was caused by the national image enhancement that was too bright in the NIR due to the significant presence of broadleaved forest in the region. Scenes that were common to this region and its adjacent mapping zone were classified together to ensure consistent land cover interpretation. The Island of Newfoundland was also mapped separately using 150 unique spectral clusters due to its uniqueness in terms of land cover compared to the mainland

and because a separate product was requested by Newfoundland's Department of Environment and Conservation for wildlife biology studies.

2.6. Classification of off peak-of-season scenes

Off peak-of-season scenes were classified using RuleQuest's See5 decision trees (Quinlan, 1993) trained on adjacent images' overlap regions (Figure 7). This decision tree software is also used by the USGS for NLCD land cover mapping. A sample of up to 1 million pixels was used to relate off peak-of-season radiometry and mapping zones to corresponding land cover from adjacent overlapping classified scenes. Trees were boosted with a 25% sample used for cross-validation. Off-peak scenes adjacent to classified peak-of-season scenes were classified first based on the maximum amount of overlap in the longitude and latitude directions. Selecting off-peak scenes with overlapping classifications in both directions ensured the most complete sample for training in order to minimize attempts to predict classes outside the range trained on by the classifier. Once the first set of off-peak scenes were classified, they were used along with available adjacent peak-of-season classifications to train and classify remaining off-peak scenes.

Growing the classification in this manner produced reasonable results. Of the 993 scenes that were classified using decision trees, 602 produced errors that were sufficiently low to proceed with boosting (31.02% error at a 34 land cover class level on ten cross validation trials), while the remaining 391 were abandoned, thereby producing only one classifier. As with radiometric normalization, error propagation from one scene to the next can occur when relying on this method to extend a classification across several scenes. The distribution of scene acquisition dates in the available Geobase SPOT coverage was such that classification extension across multiple scenes was necessary in few cases.

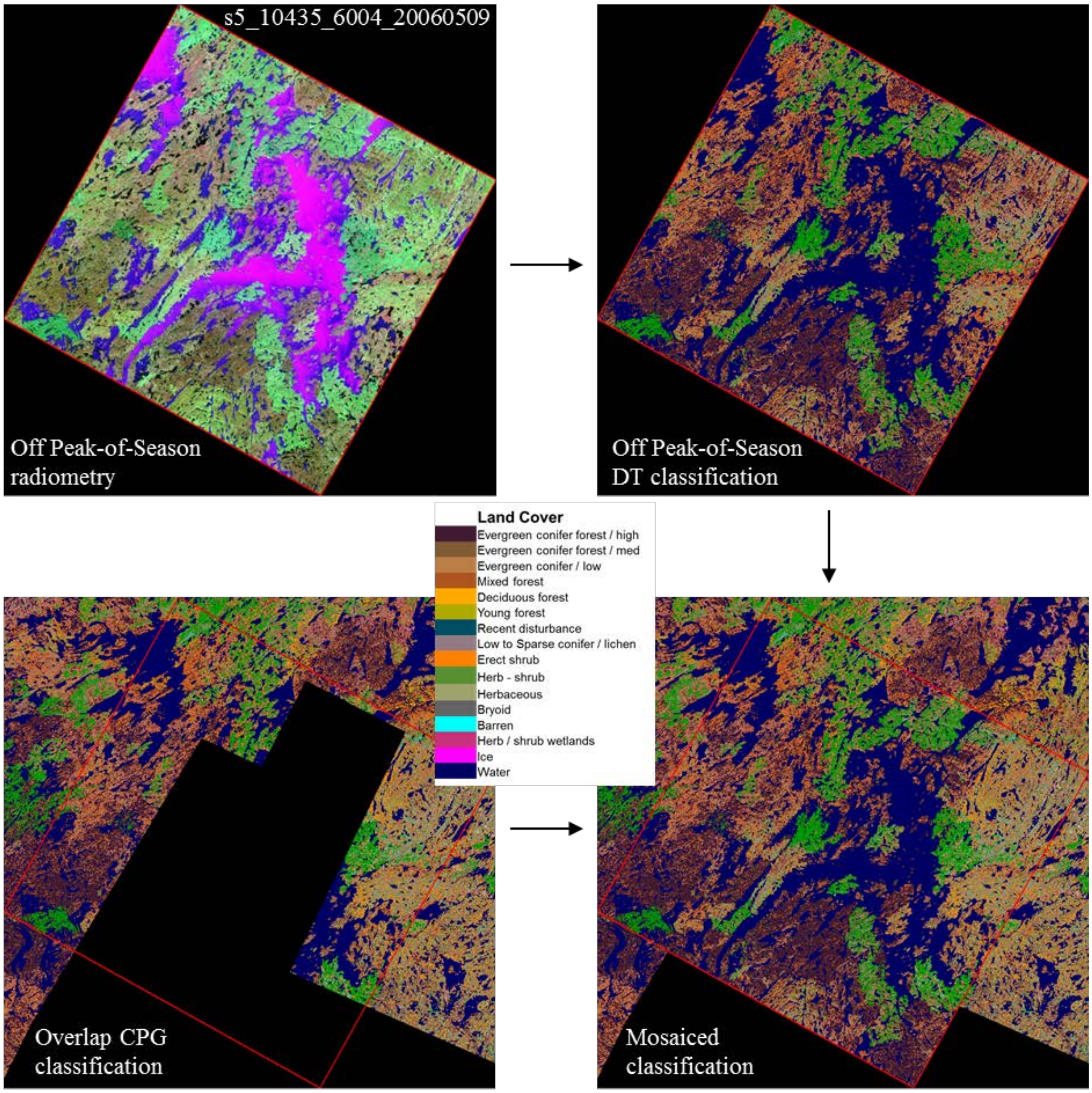


Figure 7. See 5.0 decision tree classification of off peak-of-season imagery trained on overlapping peak-of-season classification

2.7. Shadow mask

Shadow masks were generated for each scene using solar geometry read from the metadata and slope and aspect images from the 1:50k DEM. Based on experimentation on a range of scenes in different mapping zones with corresponding topography and land cover, thresholds on aspect with respect to solar azimuth and slope with respect to solar elevation were determined. Aspects within +/-25 degrees of the solar azimuth with slopes having a solar incident angle less than 26 degrees were assigned as shadow. Because these values depend on the bi-directional reflectance of the surface, they should be land cover specific. However, global values were used that were conservative based generally on dark land cover types with high bi-directional reflectance such as conifer. The resulting shadow mask was mode filtered using a 3 x 3 square kernel. The shadow mask along with a peak-of-season versus off-peak scenes map was used to generate the quality flag layer.

3. RESULTS

A 250m nearest neighbour resampled version of the SPOT land cover is shown in Figure 8. Broad land cover features and ecotone transitions are well represented. Southern Canada in Eastern Ontario, Western Quebec and Maritime Provinces are dominated by broadleaf that transitions to mixed and then conifer into the boreal forest northward. Going westward and north, the Hudson Bay Lowlands are dominated by wetlands and low density conifer with lichen in more upland areas. The boreal forest is largely comprised of medium to high density conifer forest with fire and cut block disturbances of various regeneration ages throughout. The Aspen Parkland north of the Prairies is seen as deciduous forest transitioning towards low to medium conifer on the Athabasca Plain. Further north, the treeline transition goes from low density conifer to herb / shrub with large areas of erect shrub towards the western shore of Hudson’s Bay. In western Canada, the Rocky Mountains are clearly visible as barren with conifer and mixed forest and a large region of recent disturbance in central to northern British Colombia that is Mountain Pine Beetle defoliation. Northern Quebec contains a significant amount of bryoid and sparse conifer with lichen understory that transitions to barren further north and along the Labrador Peninsula.

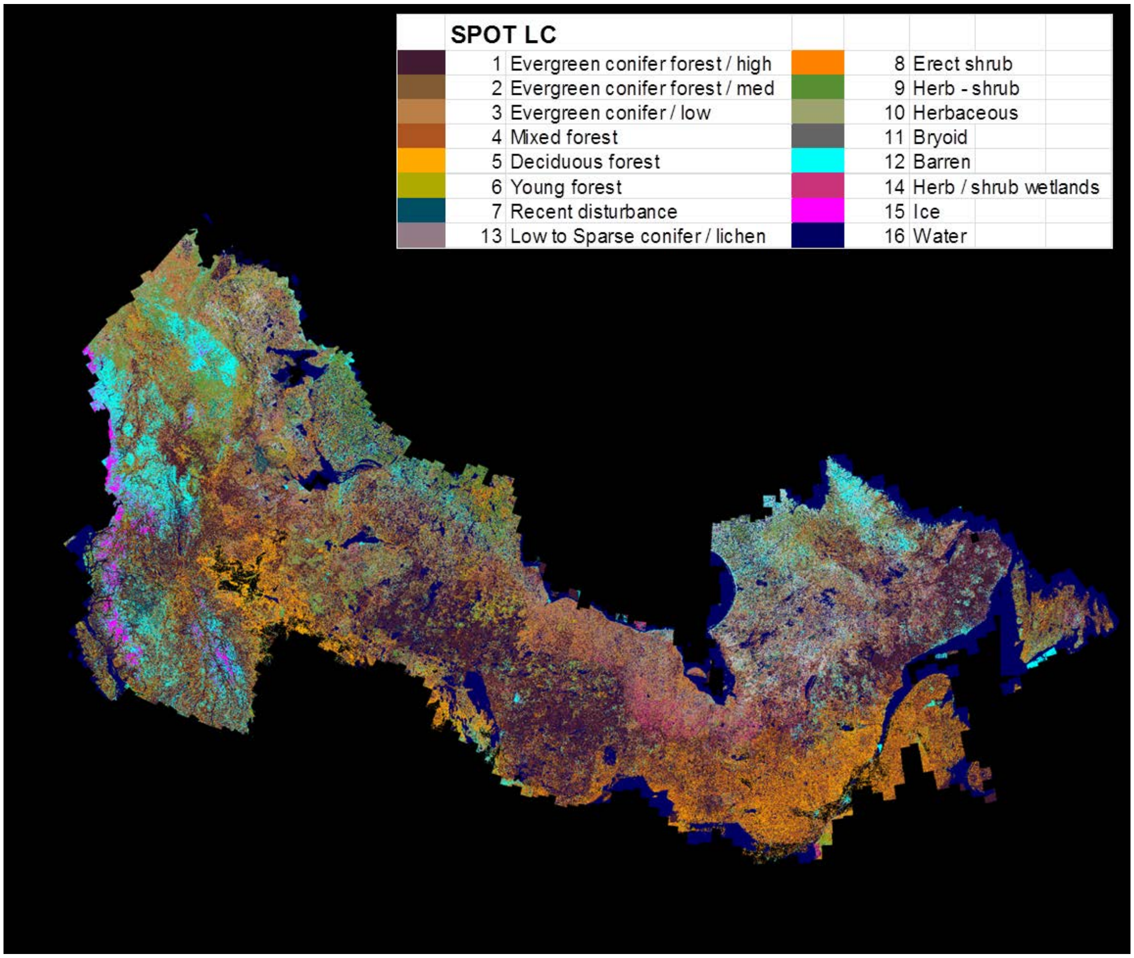


Figure 8. Combined peak-of-season and off-peak classifications of forested regions of Canada

3.1. Accuracy assessment

An overall accuracy of 71 % and kappa of 68 % was achieved at the 16 land cover class level against 1566 reference points consisting of both field and Google Earth™ interpreted data. An examination of the error matrix (Table 3) reveals reasonable user accuracy for all classes except for four treed classes, barren and wetlands that have user accuracies less than 60 %. Of the 22 pixels classified as medium density evergreen conifer, only nine are correct while 11 of the remaining 13 are other forest classes or sparse conifer with lichen understory. Only 63 low density evergreen conifer of 143 pixels classified as such are correct, while 37 of the remaining 80 are forest classes and six are sparse conifer with lichen understory. The other 35 pixels are non-treed classes which may be due to extreme low tree cover that is not detected by SPOT in these cases.

All 63 low density evergreen conifer reference points are classified correctly with 100 % producer accuracy and therefore 0 % omission error. The mixed forest class has the lowest user accuracy at less than 40 %. Significant confusion exists with other forest

Table 3. Classification error matrix

REFERENCE DATA

MAP DATA		1 Evergreen conifer high	2 Evergreen conifer med	3 Evergreen conifer low	4 Mixed forest	5 Deciduous forest	6 Young forest	7 Recent disturbance	13 Low conifer lichen	8 Erect shrub	9 Herb - shrub	10 Herbace-ous	11 Bryoid	12 Barren	14 Herb shrub wetlands	15 Ice	16 Water	Total	User's :
1	Evergreen conifer high	145	2		7	15			5		10		2	2			2	190	76.3%
2	Evergreen conifer med	5	9		3	1			2		1			1				22	40.9%
3	Evergreen conifer low	22	3	63	6	6			6		20	2	4	11				143	44.1%
4	Mixed forest	18	2		41	34			3	1	4			1				104	39.4%
5	Deciduous forest	5	1		8	92			7	1	5		1	3			2	125	73.6%
6	Young forest	1	1				10				2		2				1	17	58.8%
7	Recent disturbance	3						10	1				1					15	66.7%
13	Low conifer lichen				1	6			32		2							41	78.0%
8	Erect shrub	3	1		2	4			1	196		3	6	8				224	87.5%
9	Herb - shrub	6				4	1		5		90	10	2	21				139	64.7%
10	Herbaceous								12	1	20	102		2				137	74.5%
11	Bryoid	6				1			7		17	4	192	9	1		1	238	80.7%
12	Barren	2							1		7		11	27				48	56.3%
14	Herb shrub wetlands	4			2	2			5		2		1	2	11			29	37.9%
15	Ice	1							1							4		6	66.7%
16	Water																88	88	100.0%
Total		221	19	63	70	165	11	10	88	199	180	121	222	87	12	4	94	1112	
Producer's :		65.6%	47.4%	100.0%	58.6%	55.8%	90.9%	100.0%	36.4%	98.5%	50.0%	84.3%	86.5%	31.0%	91.7%	100.0%	93.6%		

1566

Overall Accuracy : 71.0%

Kappa : 67.9%

classes especially deciduous. This error is likely caused as much by error in the reference data as error in the classification, since accurate interpretations in both field and Google Earth are difficult for this class. Sub-pixel geolocation errors in reference data may lead to different interpretations in heterogeneous mixed landscapes. Difficulties also arise in precisely assessing reference data forest composition as well as the contribution of understory versus overstory to the signal measured by the SPOT sensor.

The young forest class is incorrectly mapped seven of 17 times, with four of those seven instances being low vegetation, non-forest classes. Mapped barren is either herb-shrub or bryoid in 18 of 48 cases, while 27 of 48 are correct. This confusion is understandable given the nature of barren surfaces especially northward where they are often mixed with grasses or are either mixed or lie beneath crustose lichen adherent to most rock surfaces. The lowest user accuracy is for the herb / shrub wetland class, which is somewhat expected given the known difficulties mapping wetlands with optical data (Sader et al., 1995). Four pixels mapped as wetland are high density evergreen conifer, likely due to the presence of some standing water that darkens the signal within a mixed pixel. Five additional pixels are mapped as sparse to low density conifer on a lichen understory. Part of this confusion is due to the fact that this class includes spruce lichen bog in addition to more xeric land cover such as jackpine lichen woodland.

From the above, it is clear that some confusion exists among forest classes, but relatively little confusion exists between forest and non-forest classes suggesting that this map is reliable for forest, non-forest mapping. When the error matrix is collapsed by merging all classes with greater than 15 % tree cover and assigning them to forest and all remaining classes with less than 15 % tree cover to non-forest, overall classification accuracy is 87 %. At the original 16 class thematic level, overall accuracy is 85 % when considering only 349 of 1566 reference points that are mapped homogeneous within 3 x 3 pixels or 60 x 60 m, however this sample is biased towards easily mapped classes such as water and herbaceous. For comparison purposes, the 2006 National Land Cover Dataset (NLCD) of the USGS from Landsat reports 78 % accuracy against a primary or secondary reference label at Level II that includes 16 land cover classes (Wickham et al., 2013).

3.2. Comparison with EOSD along treeline

A visual comparison of the SPOT land cover and EOSD was conducted at the national scale by generating 250 m land cover fraction maps. These were created by calculating the dominant, co-dominant and sub-dominant land cover type and frequencies within 250 m cells that align with national-scale 250 m data and products from MODIS. Visual inspection of these fraction maps provides an overview that allows an evaluation of the spatial consistency of the maps since anomalies, artefacts and discontinuities are easily seen (Figure 9). From this assessment, SPOT land cover appears to form a relatively continuous surface in all three dominant land cover types across most of Canada. Within EOSD, provincial boundaries can be seen in the dominant type and become more apparent in co-dominant and sub-dominant types. These discontinuities are due to the fact that provincial partners, interpreters and datasets were heavily relied upon when classifying EOSD.

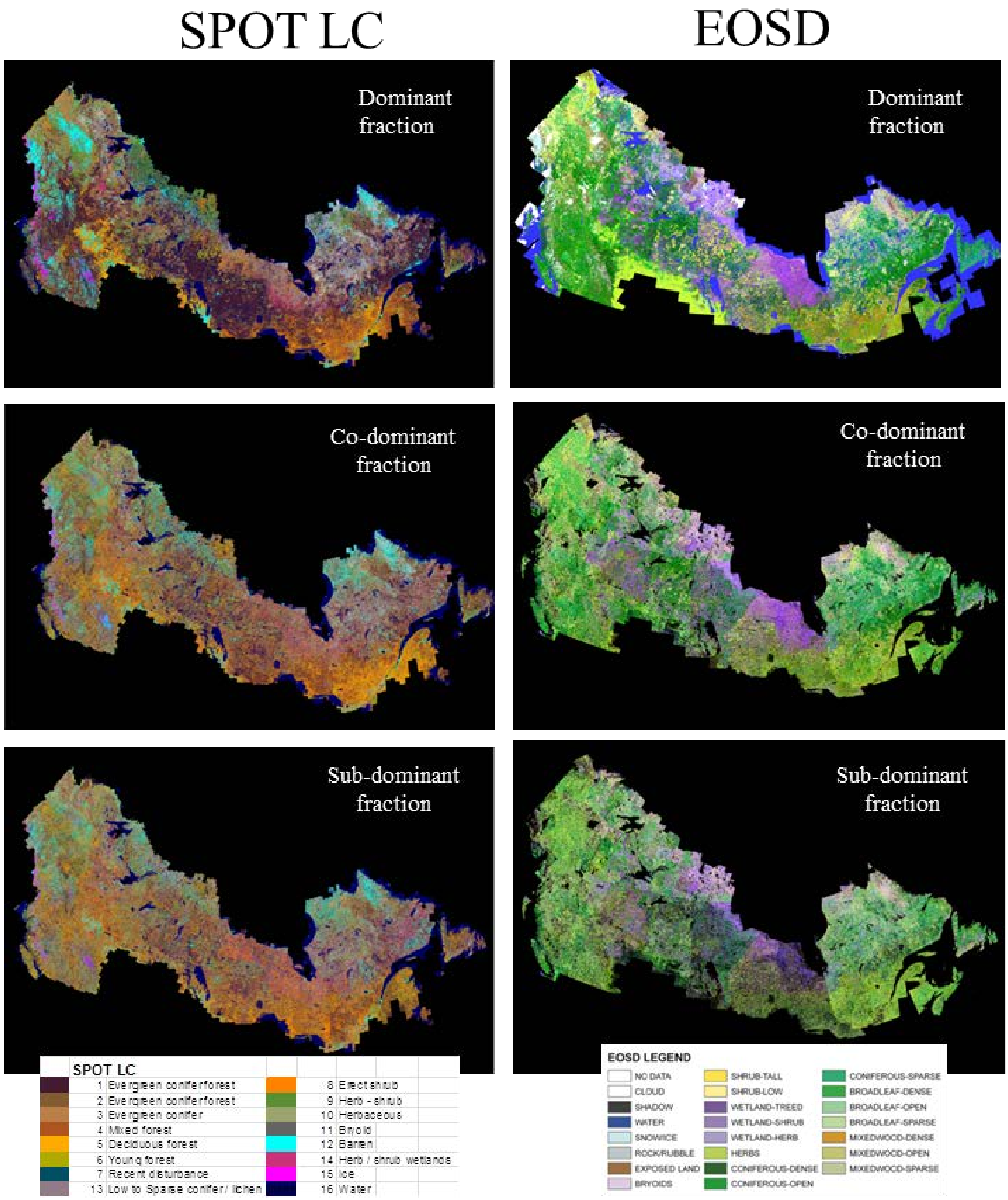


Figure 9. Dominant, co-dominant and sub-dominant land cover types within 250 m resolution pixels for SPOT land cover (left) and EOSD (right)

From the above land cover fraction maps, 250 m tree cover maps were generated for both SPOT land cover and EOSD by multiplying land cover class tree closure by its corresponding land cover fraction summed across all treed land cover types. For the

SPOT land cover, crown closure was based upon average closure from reference data within each treed land cover class (Table 2). For EOSD, crown closure was calculated as the average closure based on class definition. For example, EOSD coniferous dense with greater than 60 % crown closure was assigned an average closure of 80 % (Figure 10).

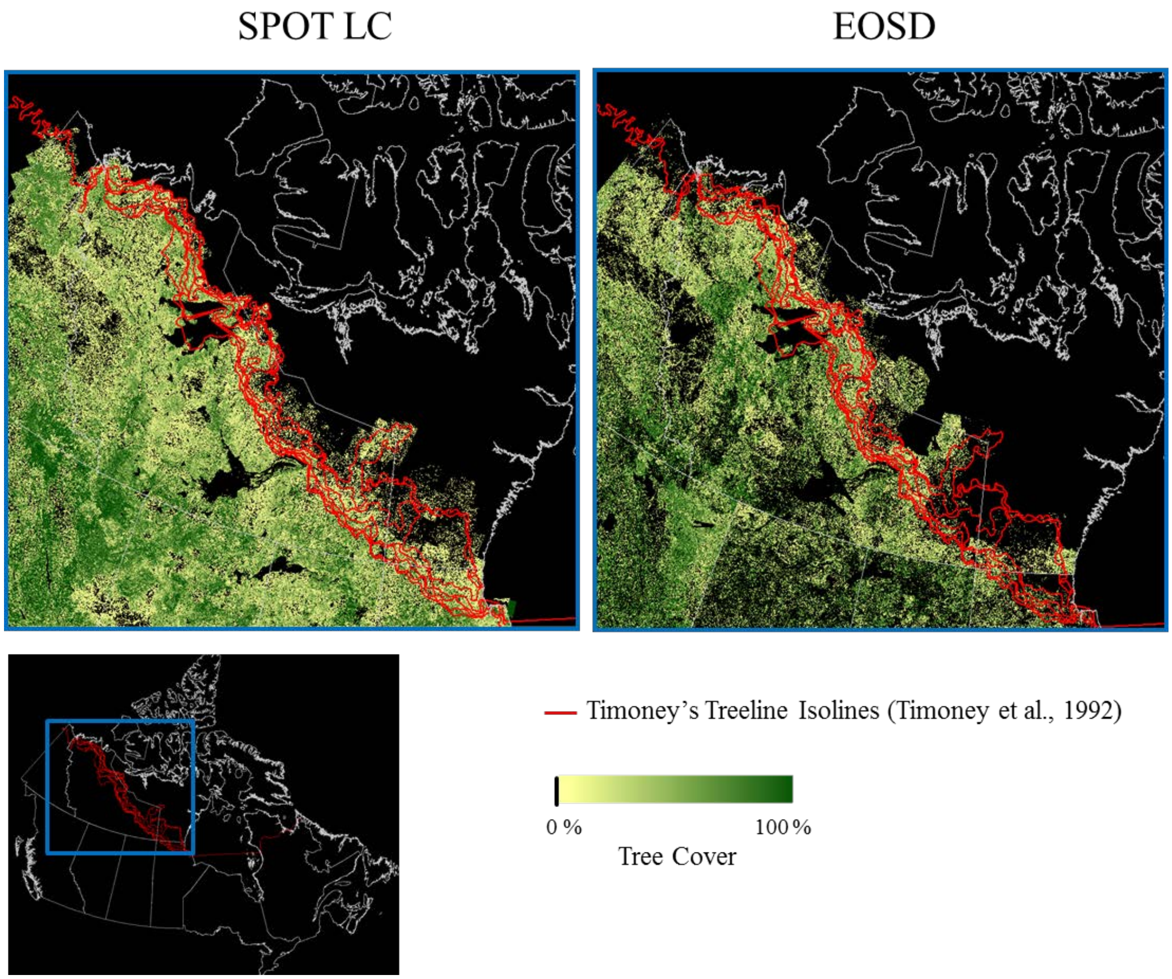


Figure 10. Tree cover in 250 m pixels in Canada's western subarctic with Timoney's treeline isolines overlain for SPOT land cover (left) and EOSD (right)

Timoney's six treeline isolines representing ratios of tree to tundra cover in the western subarctic that were generated from extensive field reconnaissance and airphoto interpretation (Timoney et al., 1992) were digitized (see Olthof and Pouliot, 2010 for details) and rasterized at 250 m resolution. SPOT land cover and EOSD tree cover were calculated beneath each of the six zones after the removal of water, and plotted north to south. EOSD overestimates closure in a zone 50 km wide above the northern limit of Timoney's treeline consisting of tundra only. EOSD predicts slightly more than 2 % closure in this zone while SPOT land cover estimates less than one percent. EOSD tree cover continues to increase towards the southern limit of treeline while SPOT land cover plateaus, exhibiting the characteristic sigmoidal tree density gradient across treeline described in Timoney et al. (1993) (Figure 11).

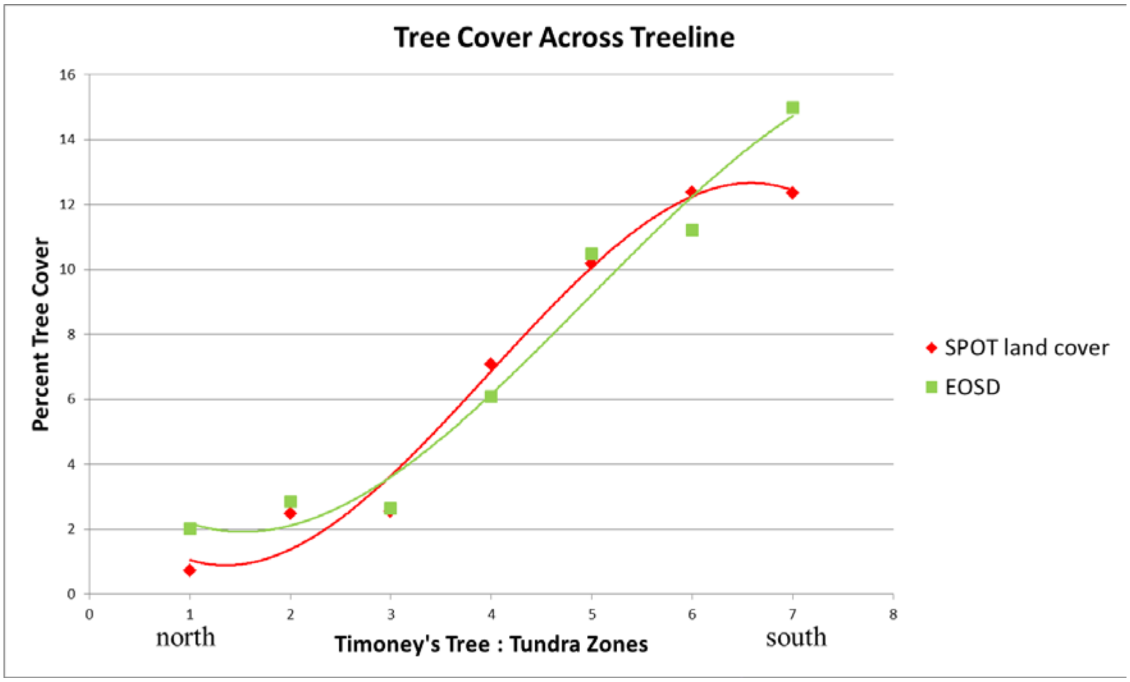


Figure 11. Percent tree cover as a function of Timoney's treeline zones from north to south showing characteristic sigmoidal shape in SPOT land cover

3.3. Merging with the circa-2000 Northern Land Cover of Canada from Landsat

A complete coverage of Canada exists in Geobase from SPOT 4-5, however land cover mapping was conducted only south of treeline from these data for a few reasons. First, phenology becomes more of an issue northward due to a shorter growing season and thus faster phenological change. Experiments revealed that the decision tree classification extension method employed in the south did not perform as well in the north. We suspect that the timing of northern phenological events such as flowering and senescence may be too short and variable within land cover types to match images acquired at significantly different times of year. Radiometry did not normalize as well in the north for similar reasons, and this issue was compounded by the relatively small SPOT footprint that requires nine scenes to cover the area imaged by one Landsat scene.

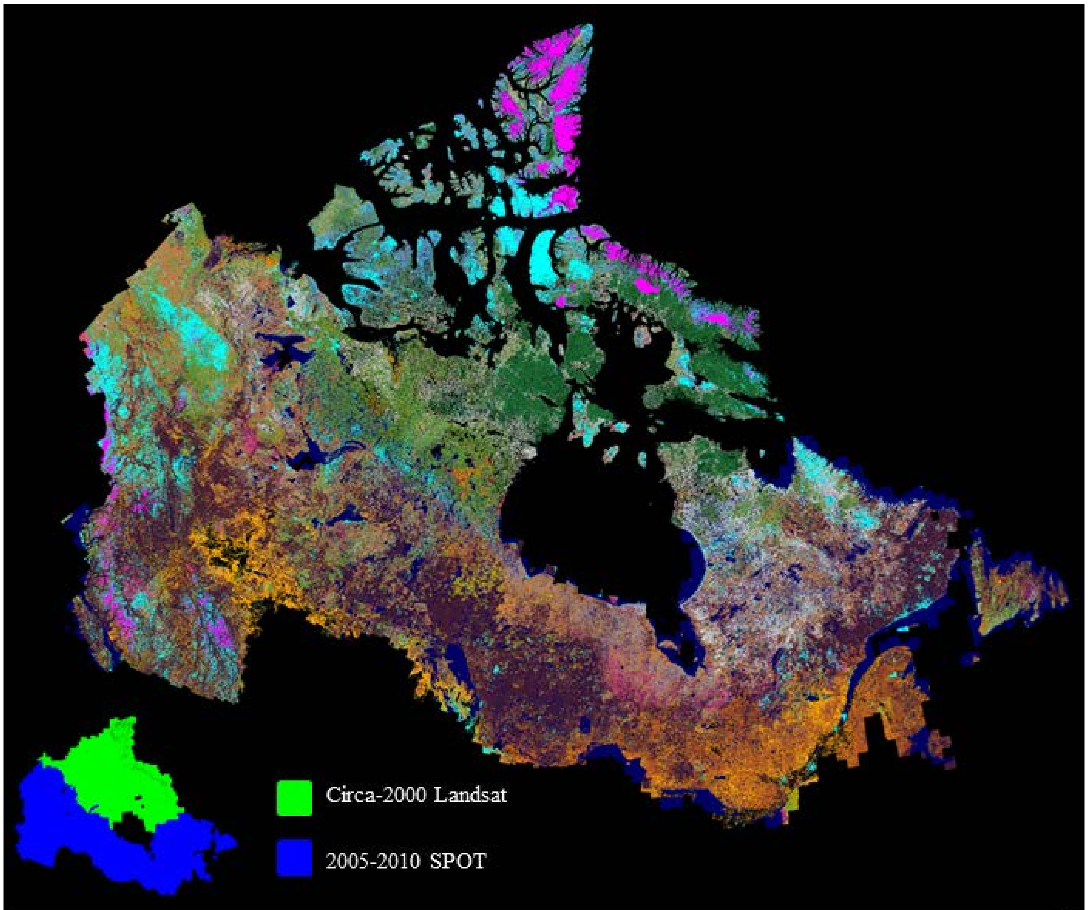
In addition to technical issues that are compounded in the north, a circa-2000 land cover of Northern Canada had recently been completed (Olthof et al., 2009) from Landsat. Abrupt change in the north due to disturbance and land use are relatively rare compared to the south, while progressive and subtle change due to climate warming may take decades to produce wholesale changes in land cover. For these reasons, updates to northern land cover are not required as frequently as in the south.

The SPOT land cover purposely included data above the northernmost treeline isoline from Timoney (1992) that formed the southern boundary of the circa-2000 northern land cover. Consideration was taken during classification to ensure that the two land cover products would be compatible so that the entire treeline ecotone from forest to tundra would be continuous. In doing so, CCRS has demonstrated the capacity to generate a complete national scale land cover of Canada at medium resolution excluding agriculture.

A national legend that contains 20 classes including a no data class was generated by combining the 16 class SPOT land cover and 15 class northern land cover legends (Table 4). Treed classes are unique to the SPOT land cover and were directly transcribed to the national legend. Eleven northern classes were assigned to eight equivalent SPOT land cover classes and labelled using the SPOT land cover naming convention. Three northern classes are unique to the north and were transcribed directly to the national legend. The northern land cover also contained a shadow class that is simply a no data class with a value of zero in the SPOT land cover. Shadow was assigned to this no data class in the national product. The SPOT land cover dominant type and modified northern land cover dominant type are merged to form the national land cover in Figure 12.

Table 4. Merging classification legends from the 2005-2010 SPOT land cover and the circa-2000 Northern Land Cover of Canada

	2005 - 2010 SPOT land cover			Circa-2000 Landsat land cover of Northern Canada (Olthof et al., 2009)		SPOT / Landsat land cover of Canada	
treed	1	Evergreen conifer high				1	Evergreen conifer high
	2	Evergreen conifer med				2	Evergreen conifer med
	3	Evergreen conifer low				3	Evergreen conifer low
	13	Low conifer lichen				13	Low conifer lichen
	4	Mixed forest				4	Mixed forest
	5	Deciduous forest				5	Deciduous forest
	6	Young forest				6	Young forest
	7	Recent disturbance				7	Recent disturbance
non-treed	8	Erect shrub		6	Tall shrub	8	Erect shrub
	9	Herb - shrub		1	Tussock graminoid tundra	9	Herb - shrub
				5	Low shrub		
	10	Herbaceous		2	Wet sedge	10	Herbaceous
				3	Moist to dry non-tussock graminoid / dwarf shrub tundra		
				4	Dry graminoid prostrate dwarf shrub tundra		
	11	Bryoid		7	Prostrate dwarf shrub	11	Bryoid
	12	Barren		12	Barren	12	Barren
	14	Herb shrub wetlands		11	Wetlands	14	Herb shrub wetlands
	15	Ice		13	Ice / snow	15	Ice
	16	Water		15	Water	16	Water
				8	Sparsely vegetated bedrock	18	Sparsely vegetated bedrock
				9	Sparsely vegetated till-colluvium	19	Sparsely vegetated till-colluvium
				10	Bare soil with cryptogam crust - frost boils	20	Bare soil with cryptogam crust - frost boils
				14	Shadow	0	no data



SPOT / Landsat Land Cover

	treed		non-treed
1	Evergreen conifer forest / high	8	Erect shrub
2	Evergreen conifer forest / med	9	Herb - shrub
3	Evergreen conifer / low	10	Herbaceous
4	Mixed forest	11	Bryoid
5	Deciduous forest	12	Barren
6	Young forest	14	Herb / shrub wetlands
7	Recent disturbance	15	Ice
13	Low to Sparse conifer / lichen	16	Water
		18	Sparsely vegetated bedrock
	Forest classes	19	Sparsely vegetated till-colluvium
		20	cryptogam crust

Figure 12. Merged SPOT and Circa-2000 Northern Land Cover of Canada from Landsat

4. CONCLUSIONS

An updated medium resolution land cover of Canada’s forested regions was generated from an orthorectified 20 m SPOT 4-5 coverage acquired between 2005 and 2010. This dataset presented three major challenges for land cover mapping compared to Landsat used to produce the previous land cover of Canada. First, a significant number of scenes in the dataset were acquired either too early or too late during the snow-free period to radiometrically balance and classify. Thus, solutions were developed to separate scenes acquired during peak-of-season from those acquired off-peak using phenology from 10-day AVHRR maintained in Canada's Long-Term Satellite Data Record. Second, the application of methods developed for Landsat to radiometrically balance numerous scenes produced suboptimal results for SPOT due to its smaller image footprint. Multiple SPOT scenes acquired in the same orbit were normalized together as one virtual scene to stabilize the dynamic range of the normalization regressions, while overlap normalization was used to extend the balanced peak-of-season coverage to include single scenes. The resulting balanced peak-of-season coverage was classified by an image interpreter using methods developed and used at CCRS to produce other national scale land cover products. The third major challenge was to classify scenes acquired during off peak-of-season. The solution to this problem was to train decision tree classifiers on overlap regions between the peak-of-season classification and off-peak scenes. The result of these efforts is a new land cover of Canada's forested regions that includes 16 classes and an overall accuracy of 71 %. When compared to previous medium resolution land cover, the new product provides more realistic tree cover gradients across treeline and merges better with the circa-2000 Northern Land Cover of Canada to the north.

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