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Boreal forest mapping at the BOREAS study area using seasonal optical indices sensitive to plant pigment content

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Abstract. In this study, forest vegetation classification was investigated based on seasonal variation of pigments as inferred from visible and near-infrared spectral bands. This analysis was carried out on data collected over the southern study area of the Boreal Ecosystem–Atmosphere Study (BOREAS) with the Compact Airborne Spectrographic Imager (*casi*) in May and July 1994 and with the medium-resolution imaging spectrometer (MERIS) in May and August 2003. Three modified normalized difference vegetation indices (mNDVIs), which are sensitive to relative proportions among pigments and pigment content, and a red-edge spectral parameter, the wavelength at the reflectance minimum (λ_0), were used. Accuracy assessments of the derived land cover maps were performed using a forest inventory map provided by the Saskatchewan Environment and Resource Management Forestry Branch Inventory Unit (SERM–FBIU). The forest vegetation classification using seasonal optical indices (mNDVIs and λ_0), as derived from the *casi* data in May and July, shows an overall accuracy of 84% for all cover types identified, namely dry conifer, wet conifer, mixed stands, aspen, fen, and the disturbed and regenerated area. The classification results also demonstrate that classification using reflectance parameters sensitive to pigment absorption features outperforms that using the reflectance itself. In addition, the classification using seasonal information is better than that using information obtained from a single date, and the spatial patterns were consistent with those achieved using multidate MERIS imagery. The forest vegetation classification using seasonal changes in optical indices (mNDVIs and λ_0) derived from the MERIS imagery in May and August revealed a reasonably high overall classification accuracy (72%) for all vegetation cover types identified, namely conifer, mixed stands, and fen.

Résumé. Dans cette étude, on traite de la classification de la végétation forestière basée sur la variation saisonnière des pigments dérivée des bandes spectrales du visible et du proche-infrarouge. Cette analyse a été réalisée à partir des données acquises au-dessus de la zone d'étude sud de BOREAS (« Boreal Ecosystem–Atmosphere Study ») par le capteur *casi* (« Compact Airborne Spectrographic Imager »), en mai et juillet 1994, et par le capteur MERIS (« medium-resolution imaging spectrometer »), en mai et août 2003. Trois indices NDVI modifiés (mNDVI, « modified normalized difference vegetation indices »), sensibles aux proportions relatives entre les pigments et le contenu en pigments, ainsi qu'un paramètre du point d'inflexion du rouge, la longueur d'onde au minimum de la réflectance (λ_0), ont été utilisés. Des évaluations de la précision des cartes de couvert dérivées ont été réalisées en utilisant une carte d'inventaire forestier fournie par la SERM–FBIU (« Saskatchewan Environment and Resource Management Forestry Branch Inventory Unit »). La classification de la végétation forestière utilisant les indices optiques saisonniers (mNDVIs et λ_0), tels que dérivés des données *casi* en mai et juillet, affiche une précision globale de 84 % pour tous les types de couvert identifiés : conifères secs, conifères humides, peuplements mixtes, tremble, tourbière basse et les zones perturbées et régénérées. Les résultats de classification démontrent également que la classification utilisant les paramètres de réflectance sensibles aux caractéristiques d'absorption des pigments performe mieux que celle utilisant la réflectance elle-même. De plus, la classification utilisant l'information saisonnière est meilleure que celle utilisant les informations obtenues à une seule date, qui étaient cohérentes avec celles des images multitemporelles de MERIS. La classification de la végétation forestière utilisant les changements saisonniers dans les indices optiques (mNDVIs et λ_0), dérivés des images de MERIS de mai et août, a révélé une précision globale de classification relativement élevée (72 %) pour tous les types de couvert de végétation identifiés : conifères, peuplements mixtes et les tourbières basses.
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Introduction

Distribution of forest vegetation types is one of the most important surface parameters from both scientific and management points of view. From the scientific perspective, forest cover characteristics influence the rates of exchange of water, energy, and carbon dioxide between the land surface and the atmosphere. As a result, they affect the climate. Forest cover classification is a starting point to parameterize land cover functioning. Forests also directly affect our daily life as an economic good or as an environmental regulator. Therefore, careful planning, management, and monitoring are needed by foresters and decision-makers to ensure that forest resources are being utilized efficiently and wisely. Gathering this type of information must be based on up-to-date forest cover information. Forest cover classification from remote sensing data has been one of the important topics since the beginning of remote sensing, and it has benefited from the evolution of remote sensing methodologies and technologies (Peddle et al., 1997; Beaubien et al., 1999; Cihlar et al., 2003; Hall et al., 1997). However, the accuracy of forest vegetation classification remains low. This is mainly due to the following two facts: (*i*) the surface reflectance values of forest canopies are affected by numerous spectral and spatial variables; and (*ii*) image sensors that are used to obtain remote sensing data have some constraints in their spectral and spatial characterizations. As a result of these two facts, scientists often face the following challenge. On the one hand, the reflectance spectra are quite similar, even from widely differing plants, since vegetation is dominated by the same pigment constituents; on the other hand, the reflectance spectra may be dramatically different from one pixel to another, even for the same forest species, because of the influence of such factors as crown coverage, view and illumination angles, and atmospheric absorption–scattering.

The development of hyperspectral remote sensing provides an opportunity to considerably improve the accuracy of forest vegetation classification because the fine spectral resolution of hyperspectral remote sensing data offers the potential to discriminate between species with subtle spectral signature differences. The high spectral resolution, on the other hand, makes the hyperspectral data highly redundant and poses great challenges in developing methodologies suited for forest vegetation identification. Without proper approaches to dealing with the high redundancy of hyperspectral data, important characteristics of a vegetation cover may be lost or submerged by other insignificant information that coexists in the hyperspectral data, and thus classification accuracy may even be deteriorated. It is well recognized that the use of a smaller number of spectral bands can probably produce better classification accuracies than the use of all bands. As a result, feature selection including band selection is very important for forest cover classification using hyperspectral data. Much effort is currently focused on statistical approaches to represent the data by a few basic components, and a number of methods have been developed (Bruce et al., 2003). The commonly used approaches include principal component analysis (PCA) and its variants and the minimum noise fraction (MNF) transformation (Green et al., 1988). The components obtained by the statistical approaches exhibit poor physical significance.

One of the early attempts to utilize features related to vegetation physical properties in the classification was the use of vegetation growth patterns by Badhwar et al. (1982) and Hall and Badhwar (1987). In their approach, the authors used the physically understandable vegetation-specific growth parameters, the seasonal leaf area duration, the characteristic time of "greenup," the characteristic "greenup" time of peak greenness, and the peak greenness. This algorithm was successful in classifying agriculture crops, since different crops tend to have unique temporal growth patterns or trends. Later, Hall et al. (1995; 1997) developed a physically based classification approach that employed geometric canopy reflectance models. In their approach, canopy reflectance models were used to define spectral reflectance trajectory for each land cover class. Positions along each trajectory corresponded to unique areal canopy cover fractions ranging from zero to unity. To classify any multispectral value, it was assigned to the nearest multispectral trajectory using the Euclidean distance metric. To form the spectral reflectance trajectory for each class, pixel-level reflectance was considered as a linear composition of end members, sunlit crown, sunlit background, and shadow. In this physically based approach, signature variations because of view and illumination angle, canopy cover, and other factors are inherently accounted for (Hall et al., 1995; 1997). Even though the classification accuracies were shown to be superior to those obtained with conventional statistically based algorithms, they remain generally low for fen (a major source of methane in the boreal region) and dry conifers in the Boreal Ecosystem–Atmosphere Study (BOREAS) area (Hall et al., 1997). Furthermore, the end-member reflectance values needed for this classification approach are not generally available except through field measurements.

Recently, a new paradigm for the land cover classification emerged, which exploited systematic differences by cover type or by species of the reflectance features sensitive to pigments, water, and foliar chemistry (Martin et al., 1998; Zarco-Tejada and Miller, 1999; Fuentes et al., 2001). The differences in the reflectance in the absorption bands sensitive to foliar chemistry were used and reported in Martin et al. (1998). Further, the red-edge parameters sensitive to chlorophyll content (Zarco-Tejada and Miller, 1999) and optical indices sensitive to pigments and water content (Fuentes et al., 2001) were used in recent studies to map land cover in the BOREAS southern study area (SSA). These three studies showed that the forest cover classification accuracies were improved using parameters sensitive to the absorption features instead of using the reflectance itself. By using such parameters, it is expected that the information needed to identify forest species is not masked by other information contained in the reflectance spectrum. However, these three studies show that there are still undesirable misclassifications such as between wet conifers and dry conifers and between stands of coniferous species and those of mixed conifers and deciduous forests. Even though different parameters were used in these three classification studies, they were similarly limited in one respect. All of the three classification studies were based on information obtained from a single date.

It is well known that forest canopies and the associated vegetated understory change seasonally. The plant pigments change across the growing season both in terms of the proportions among pigments and total pigment content. A separate study conducted recently clearly demonstrates that the chlorophyll content of jack pine increases significantly from spring to summer in new needles (Moorthy, 2004). The seasonal changes in plant pigments are different by species, due to the seasonality of pigments in either the overstory leaves or the understory vegetation. Therefore, for some species, if we cannot identify them based on the absorption features in one season, we may be able to identify them by looking at the change in the absorption features from one season to another. This inspires our research to exploit systematic differences by cover type of reflectance features sensitive to the seasonality of pigment concentrations in forest cover classification. This research was first carried out on data collected with the Compact Airborne Spectrographic Imager (*casi*) for the BOREAS SSA in May and July 1994. The algorithms developed with the *casi* data were then applied to the medium-resolution imaging spectrometer (MERIS) data.

Data description and data preprocessing

Three datasets from the BOREAS southern study area were used in the present study on forest vegetation cover classification: (*i*) forest cover data for detailed validation of the classification results, provided by Saskatchewan Environment and Resource Management, Forestry Branch Inventory Unit (SERM–FBIU) as derived from infrared aerial photography and field reconnaissance notes; (*ii*) surface reflectance derived from *casi* data collected in May and July 1994 at 2 m spatial resolution and in 15 narrow spectral bands; and (*iii*) MERIS full-resolution radiance data at a spatial resolution of 300 m obtained in May and August 2003.

SERM–FBIU forest cover dataset

A forest cover dataset covering the BOREAS SSA was prepared by the BOREAS science staff by processing the original vector data into raster images with a cell size of 30 m. It includes four images providing information on species association (cover type), crown closure, height class, and the year of origin or disturbance. The original maps were first produced using infrared aerial photography taken in 1988 and field reconnaissance notes but maintained and updated based on fires, cuttings, and other disturbances by SERM–FBIU until 1993 when they were acquired by the BOREAS Information System (BORIS) (www-eosdis.ornl.gov/BOREAS/bhs/BOREAS_Home.html). The SERM–FBIU classification included 20 cover types. BOREAS scientists grouped the 20 cover types into nine ecologically significant classes to meet the needs of modelling the boreal forest ecosystem (Steyaert et al., 1997; Hall et al., 1997). Based on the groupings and the existence status of these classes in our study area, the following six categories were used: (1) wet conifer (black spruce, spruce–pine, and tamarack), (2) dry conifer (white spruce and jack pine), (3) mixed conifer and deciduous (mixed spruce–fir – broadleaf, mixed jack pine – broadleaf, mixed broadleaf – spruce–fir, mixed broadleaf – jack pine; the broadleaf species are mainly aspen and birch), (4) deciduous (mainly aspen), and (5) fen (treed muskeg and clear muskeg), and (6) the disturbed areas (clearing, burned, disturbed–cut–burn, disturbed – jack pine regeneration, experimental area). The SERM–FBIU classification map, as shown in **Figure 1c**, was used to assess the classification accuracy.

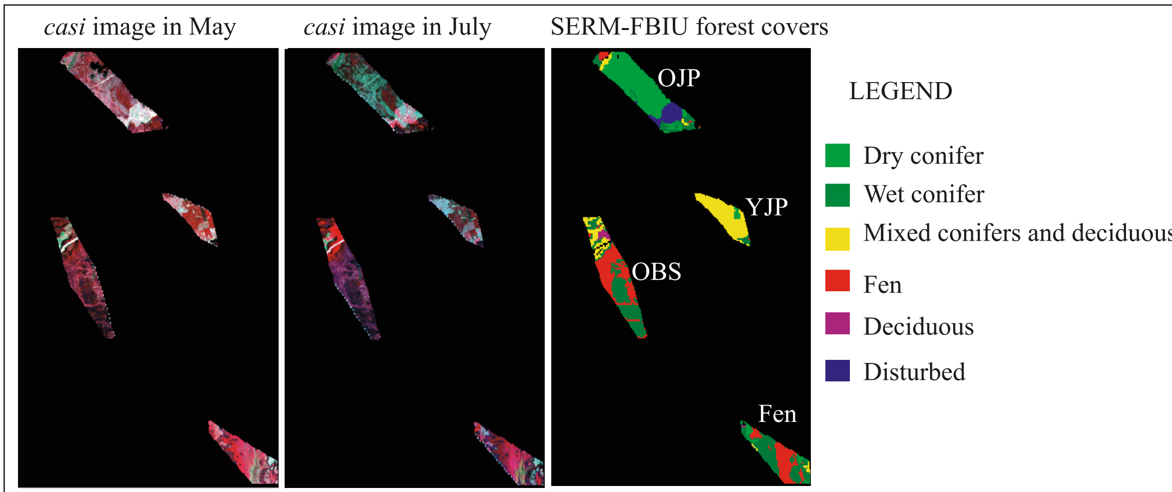


Figure 1. Colour composite *casi* images in (a) May 1994 and (b) July 1994, with band 13 (682 nm) printed as red, band 8 (665 nm) as green, band 5 (565 nm) as blue; and (c) the SERM–FBIU forest cover image (aggregated into six functionally dominant categories). Note that the actual location of the old black spruce (OBS) site is far from the old jack pine (OJP), young jack pine (YJP), and fen sites. It is located to the west but has been repositioned together with the other sites for display purposes only.

Table 1. Spectral characteristics of the *casi* sensor for this study.

Channel	Centre wavelength (nm)	Spectral bandwidth (nm)[a]
1	409.7	11.8
2	443.2	11.8
3	490.9	11.8
4	520.1	13.6
5	565.4	11.8
6	619.8	10.2
7	665.5	12.0
8	682.5	9.9
9	709.5	9.9
10	741.9	9.9
11	750.0	12.0
12	769.0	10.2
13	799.8	10.2
14	880.7	15.8
15	905.4	17.6

[a]Full width at half maximum (FWHM).

Table 2. Spectral characteristics of the MERIS sensor for this study.

Channel	Centre wavelength (nm)	Spectral bandwidth (nm)[a]
1	410	10.0
2	445	10.0
3	490	10.0
4	520	10.0
5	560	10.0
6	620	10.0
7	665	10.0
8	681	7.5
9	705	10.0
10	754	7.5
11	760	2.5
12	775	12.5
13	855	10.0
14	865	10.0
15	900	10.0

[a]Full width at half maximum (FWHM).

casi dataset

The *casi* dataset used in this study was collected over the BOREAS flux tower sites of old jack pine (OJP), young jack pine (YJP), fen, and old black spruce (OBS) in the BOREAS SSA, as part of the BOREAS project field deployments in 1994. Three acquisitions of *casi* were made in May, July, and September to capture the seasonal change of the forest canopies across the growing season of 1994. The geometric quality of the data obtained in September is very poor. As a result, only the *casi* data obtained in May and July were used. The spectral characteristics of the *casi* dataset used in this study are shown in **Table 1**. All of the data were collected at approximately 1800 m above ground level (AGL) and resampled to 2 m square pixels using onboard global positioning system (GPS) data. The *casi* data were processed to at-sensor radiance and then to at-canopy reflectance using the CAM5S radiative transfer model. CAM5S is the Canadian Advanced Modified 5S (O'Neill et al., 1997) based on H5S (Teillet and Santer, 1991), and it incorporates some of the advanced features of 6S

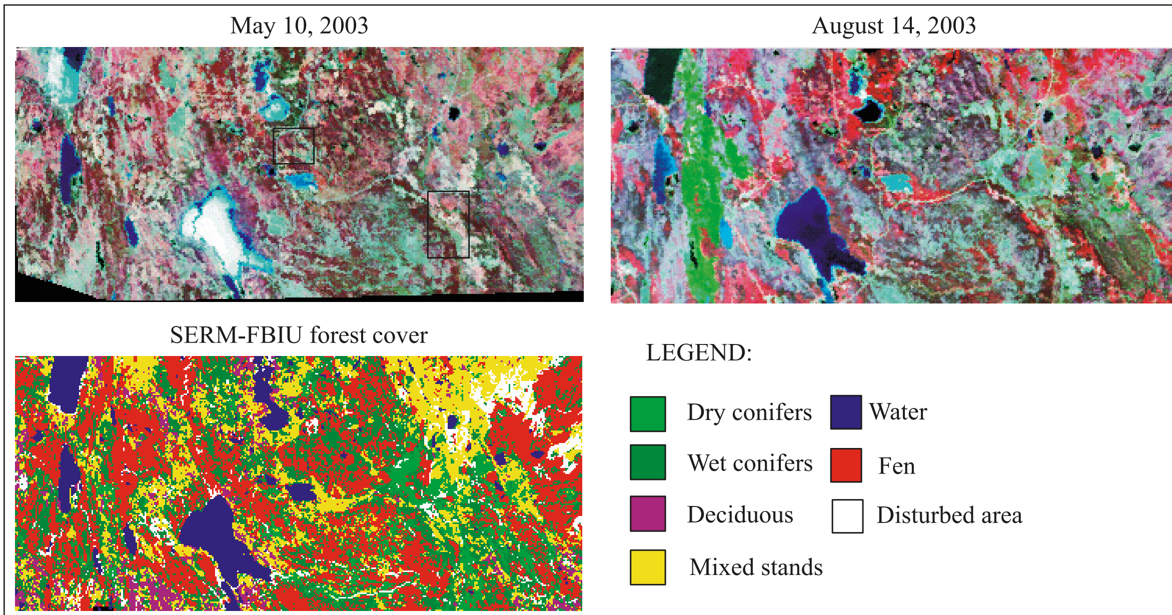


Figure 2. MERIS full-resolution colour composite images, with band 14 (865 nm) as red, band 8 (681 nm) as green, and band 5 (560 nm) as blue, and the SERM–FBIU forest cover image. The rectangular areas in the MERIS image in May include the BOREAS SSA and are covered by the *casi* images shown in **Figure 1**. The SERM–FBIU original forest cover classification was aggregated into seven functional classes.

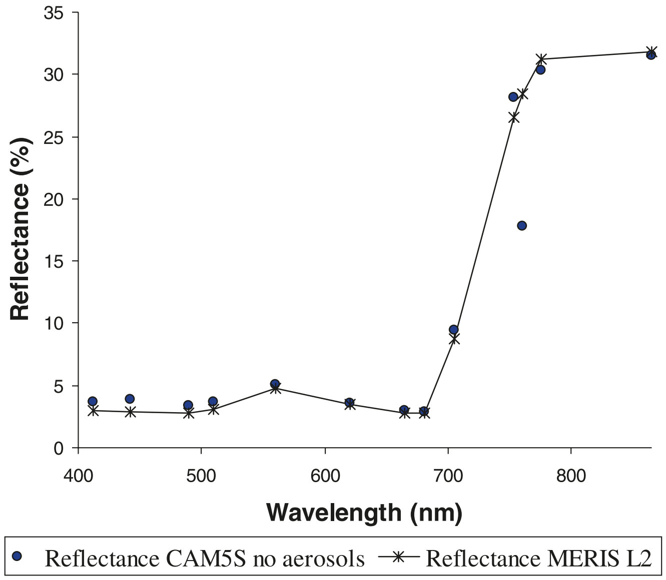


Figure 3. Comparison between the reflectance obtained by CAM5S without aerosols and MERIS ESA L2 reflectance.

(Vermote et al., 1994) without the substantial increase in time required to run the latter model. The reflectance retrieval accuracies reported in the validation experiments performed during similar *casi* deployments in 1994 were 0.005 and 0.008 absolute errors in the visible and 0.013 and 0.022 in the near-infrared for two forest targets, black spruce and tamarack, respectively (O'Neill et al., 1997). The reflectance images covering the four flux tower sites (OJP, YJP, fen, and OBS) were then georeferenced and mosaicked. The processed *casi* images at a spatial resolution of 2 m by 2 m were resampled to 30 m by 30 m (using the software PCI Geomatica version 8; PCI Geomatics, 2001). The 30 m by 30 m pixel was chosen to simulate data obtained by a hyperspectral satellite sensor, such as Hyperion (eo1.usgs.gov/hyperion.php). The *casi* colour composite images are shown in **Figures 1a** and **1b**.

MERIS dataset

MERIS, a pushbroom imaging spectrometer with an angular field of view of 68.5°, measures the solar radiation reflected by the Earth's surface in 15 spectral bands in the visible and near-infrared regions (**Table 2**). The MERIS full-resolution data have a spatial resolution of 300 m, whereas the spatial resolution is 4 km for the reduced-resolution data. In this study, the MERIS full-resolution radiance data (L1) acquired in May and August 2003 (**Figure 2**) were used. They were first converted to reflectance data and then georeferenced. The CAM5S radiative transfer model was used to correct the MERIS data to at-ground reflectance from at-sensor radiance. Used extensively at York University (Toronto, Ont.) to correct airborne *casi* imagery over the last 10 years, the CAM5S procedure was slightly modified to correct the MERIS data. Although unsuited to correct the full MERIS image without extensive changes, the methodology was considered appropriate for the small region of interest used here. As an initial validation, the model was run with no aerosol content

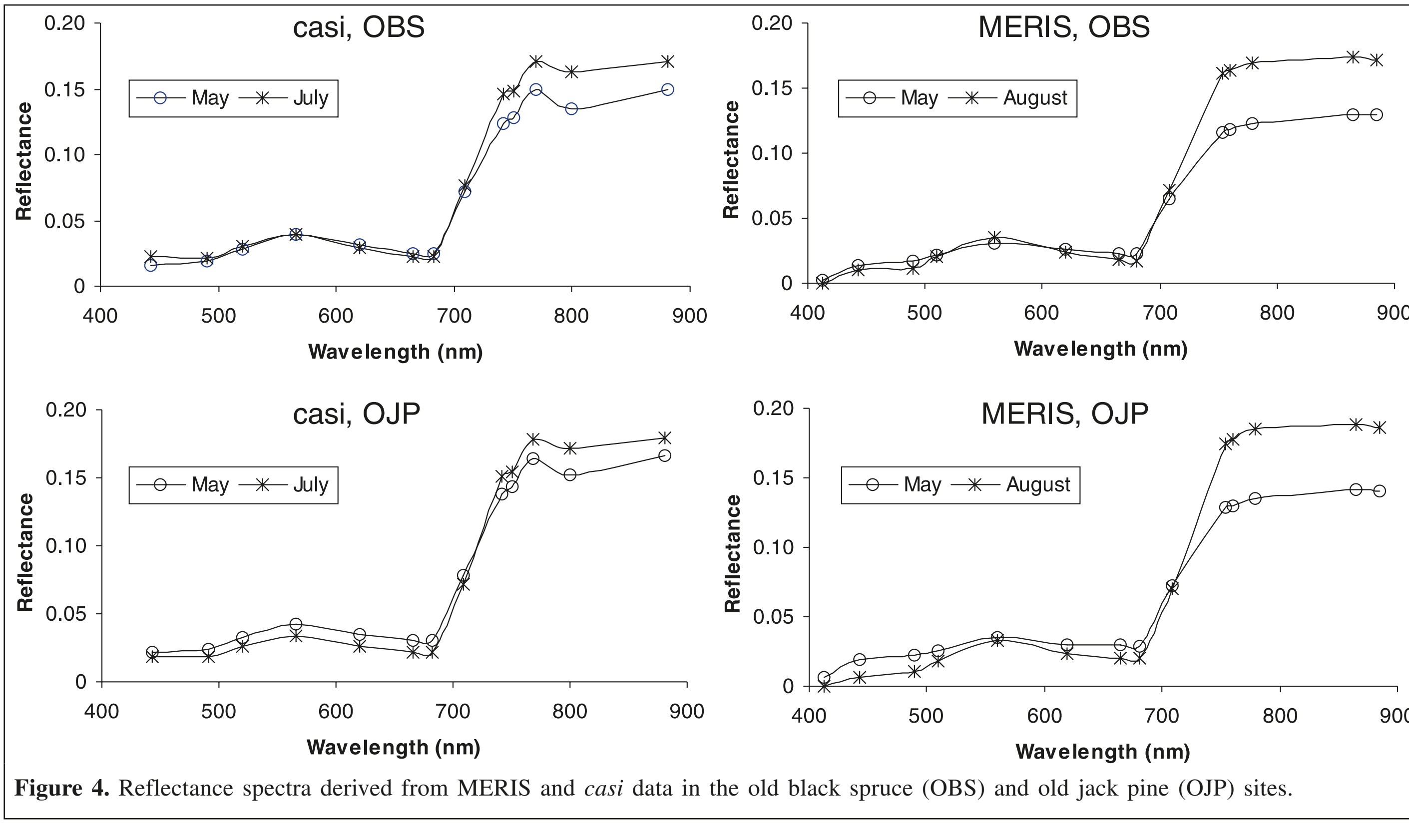


Figure 4. Reflectance spectra derived from MERIS and *casi* data in the old black spruce (OBS) and old jack pine (OJP) sites.

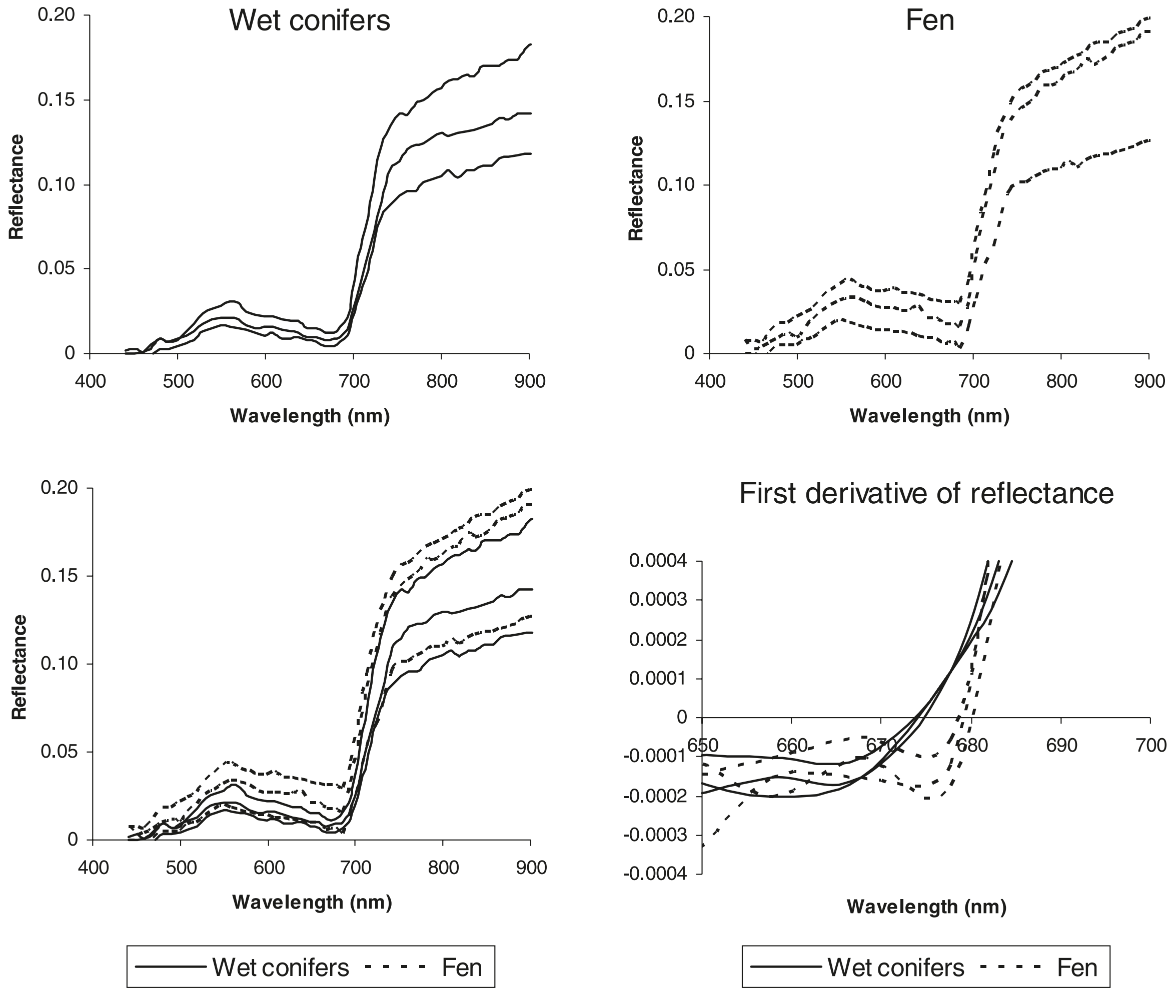
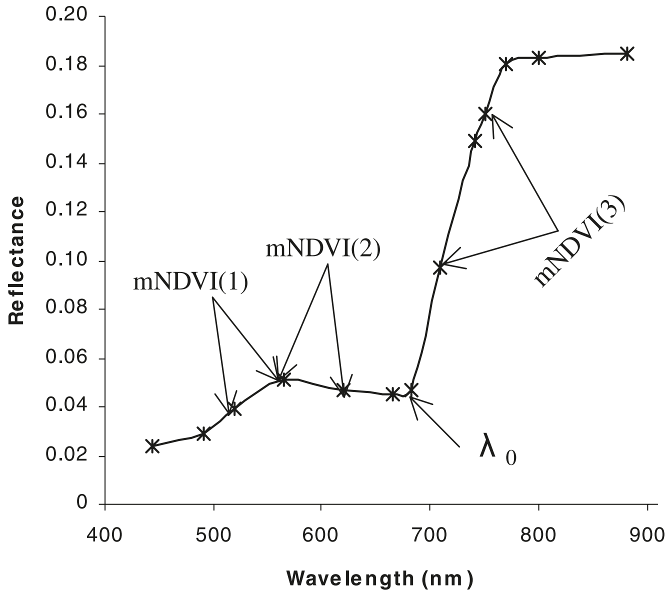


Figure 5. Reflectance spectra and first derivative of reflectance for the pixels derived from AVIRIS data over BOREAS southern study area for the forest cover types wet conifers and fen.

and compared to the level 2 "top of the aerosol layer" product provided by the European Space Agency (ESA). As an example, the comparison for a pixel is shown in **Figure 3**. The outlier lies in the oxygen absorption band, which was discarded in later processing. The reflectance in this band was interpolated using the reflectance values of its neighbouring bands.

The inputs required for the CAM5S correction procedure are aerosol optical depth, date, solar and sensor geometry, and atmospheric model (mid-latitude summer, continental aerosols). Values for aerosol optical depth were considered constant across the BOREAS SSA and were taken from the AEROCAN sun photometer at Bratt's Lake, Saskatchewan (ccrs.nrcan.gc.ca/ccrs/rd/ana/aerocan/aerocan_e.html). AEROCAN is a subnet of the larger AERONET network of sun photometers (Holben et al., 1998). If sun–photometer measurements were not available on the day of image acquisition, a historical monthly average value was used. For the MERIS data, the historical monthly average value was used. The MERIS reflectance spectra were compared with *casi* reflectance spectra. In the MERIS data, the flux tower sites in the BOREAS SSA, namely OBS, OJP, YJP, and fen, were identified and the reflectance spectra of a pixel were derived for each site; the areas in the *casi* image corresponding to the selected pixel in the MERIS image were then determined and the average reflectance spectra were calculated. The comparison of results, as shown in **Figure 4**, indicates the shapes of the reflectance spectra and the seasonal change trends are similar, although there are differences in the absolute values. The uncertainties in the atmospheric correction of MERIS data may cause a discrepancy in the absolute value. However, this is not expected to significantly affect the classification results, since reflectance ratios were used in this study. Moreover, any attention to spectral differences between *casi* and MERIS needs to be tempered by the fact that a 9 year time interval exists between the image acquisitions. Even though no evident changes were observed by visually examining *casi* data (1994) and Landsat enhanced thematic mapper plus (ETM+; with a spatial resolution of 30 m × 30 m) data (2003) over the same area, subtle changes in forest properties are expected. These changes may lead to changes in spectral magnitude.



Optical indices	Formulation	Functions
mNDVI (1)	$\frac{R_{565} - R_{520}}{R_{565} + R_{520}}$	Relative proportion among pigments and pigment content
mNDVI (2)	$\frac{R_{565} - R_{619}}{R_{565} + R_{619}}$	Relative proportion among pigments and pigment content
mNDVI (3)	$\frac{R_{750} - R_{710}}{R_{750} + R_{710}}$	Chlorophyll content
λ_0	Inverted Gaussian	Chlorophyll content

Figure 6. Locations of the optical indices used (in the graph) and their formulation and functions (in the table). λ_0 was calculated using the inverted-Gaussian model in Miller et al. (1990).

Feature selection

The spectral signatures of plants in the visible and near-infrared regions are dominated by the absorption of blue and red light by pigments for photosynthesis and high reflection of the near-infrared radiation (Gates et al., 1965). Since vegetation is dominated by the same pigment constituents, the reflectance spectra from widely differing plants will look similar. To make things worse, due to the influence of others factors such as crown coverage, view and illumination angles, and atmospheric absorption and scattering, the reflectance spectra are different from one pixel to another, even for the same forest species. As a result, it is very important to select features that are sensitive to diagnostic absorptions of forest species and use these features explicitly in the classification. As an example, the reflectance spectra of wet conifers and fen derived from the airborne visible/infrared imaging spectrometry (AVIRIS) over the BOREAS study areas are shown in **Figure 5**. It is clear from **Figures 5a** and **5b** that there are variations in the reflectance spectra even for the same forest cover type (wet conifers or fens). Due to the variations in the reflectance values, there is an overlap between the reflectance range of wet conifers and that of fens. As a result, it is difficult to correctly identify these pixels based only on the reflectance values, as shown in **Figure 5c**. However, observing **Figure 5d** where the reflectance first derivative is shown, all of the wet conifers and fen pixels are grouped together at the pigment absorption band (around 680 nm). Therefore, we can distinguish the wet conifers pixels from the fen pixels when focusing on the pigment absorption features.

Extensive research has been carried out at the leaf and canopy levels to identify optical indices as indicators of vegetation functioning, and a number of valuable optical indices have been developed. Zarco-Tejada et al. (2001) grouped these indices into the following four categories: (1) visible ratios, such as the photochemical reflectance index (PRI) calculated as $(R_{531} - R_{570})/(R_{531} + R_{570})$ (Gamon and Surfus, 1999) and the red to green ratio (R_{554}/R_{677}) (Gamon and Surfus, 1999); (2) visible to near-infrared (NIR) ratios, such as the normalized difference vegetation indices (NDVIs) and the simple ratio (SR); (3) red edge reflectance-ratio indices, such as R_{740}/R_{720} (Vogelmann et al., 1993) and R_{750}/R_{710} (Zarco-Tejada et al., 2001); and (4) spectral and derivative red edge indices, such as the red edge inflection and chlorophyll-well wavelengths, λ_p and λ_0, respectively, from red-edge inverted-Gaussian curving fitting (Miller et al., 1990), and spectral indices calculated from derivative analysis (D_{715}/D_{705}).

Zarco-Tejada and Miller (1999) used λ_p and λ_0 (the indices in group 4) to perform unsupervised classification on data collected with *casi* for a 16 km by 12 km image mosaic over the BOREAS SSA. Their results show that land cover mapping, based solely on red edge spectral parameters, appears to be feasible and robust and for some cover classes outperforms the classification based on reflectance itself. The overall classification accuracy is 61%. Fuentes et al. (2001) explored the ability of AVIRIS to map vegetation type based on pigment and water absorption features for the BOREAS SSA. They used seven indices (the indices in groups 1 and 2) of vegetation structure and physiological function calculated from AVIRIS. The overall classification accuracy is 69%. In this study, the indices from groups 1, 3, and 4 were selected based on the research results reported in Zarco-Tejada and Miller (1999), Fuentes et al. (2001), and Zarco-Tejada et al. (2001). Three modified normalized difference vegetation indices (mNDVIs) and the spectral position of the reflectance minimum at the red edge (λ_0) were used. They are all called optical indices for convenience in this paper. Their formulation and functions are listed in **Figure 6**. The first two mNDVIs were used here to characterize the absorption features by calculating the slope of the reflectance change from the blue absorption to the green peak and from the green peak to the red absorption, respectively. Note that the first mNDVI is the same as PRI, and the term PRI was not used to maintain consistency in this paper with the other indices. The third mNDVI and λ_0 have been demonstrated to be sensitive to chlorophyll content (Zarco-

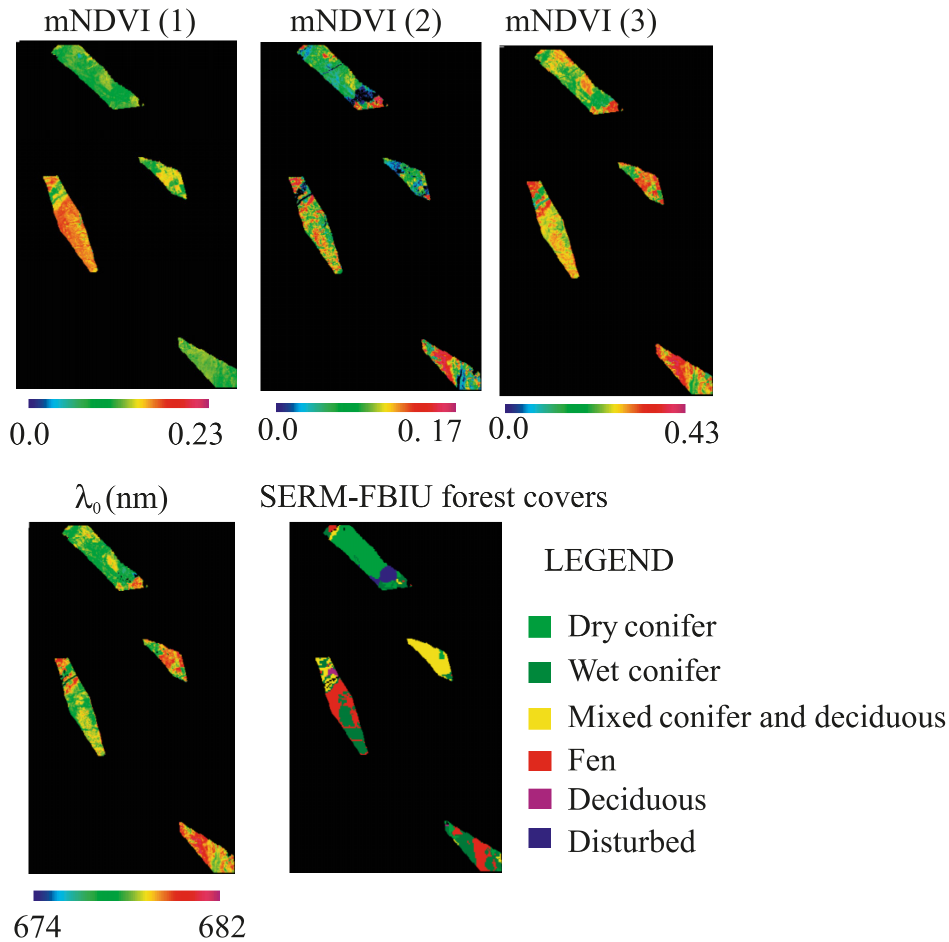


Figure 7. Images of the optical indices derived from the *casi* reflectance data in May 1994 compared to the SERM–FBIU forest cover map updated in 1993.

Tejada, 2000). To capture the seasonality of plant pigment, the four optical indices were calculated for each pixel across the growing season (May and July for *casi* data and May and August for MERIS data). Evident spatial patterns corresponding to different forest cover types were observed in the images of optical indices derived from *casi* data in both May and July. The changes of these optical indices from May to July are different for different cover types. As examples, the optical indices in May and their changes from May to July are shown in **Figures 7** and **8**, respectively. The high mNDVI(1) values in the OBS site in May may be associated with the properties of understory vegetation. The field-measured understory reflectance in the OBS site exhibited a steeper reflectance increase from 520 to 565 nm than in other flux tower sites in May (Miller et al., 1997). In the OBS site, the understory vegetation is dominated by mosses that exhibit a "green" peak extending farther into the yellow and orange portions of the visible spectrum (Bubier et al., 1997). This feature is unique compared to the understory vegetation dominating other boreal forest sites. Similarly, evident spatial patterns are exhibited in all of the images (**Figure 9**) derived from MERIS data, and the spatial patterns are consistent with those shown in the cover type map in **Figure 2**. It can also be noticed that the temporal changes of these optical indices from May to August vary with cover type.

Classification and results

Classification using *casi* data

Isodata unsupervised classification (PCI Geomatica, version 8) was performed on the optical indices derived from the *casi* reflectance data in May and July. The spatial distribution of the cover type obtained from the classification can be observed in **Figure 10** to be similar to that exhibited in the SERM–FBIU forest cover image. The classification accuracy has also been assessed quantitatively. From the SERM–FBIU cover type image, a number of pixels for each class have been randomly selected. The classification accuracy was tested using these pixels. The confusion matrix is shown in **Table 3**. For this study, the overall classification accuracy is 84%. The Kappa coefficient (Jensen, 2003) is 0.78, which means the classification result is 78% better than that obtained by randomly assigning the pixels into class categories. The producer's accuracy and user's accuracy were also calculated for each forest cover (Jensen, 2003). The producer's accuracy

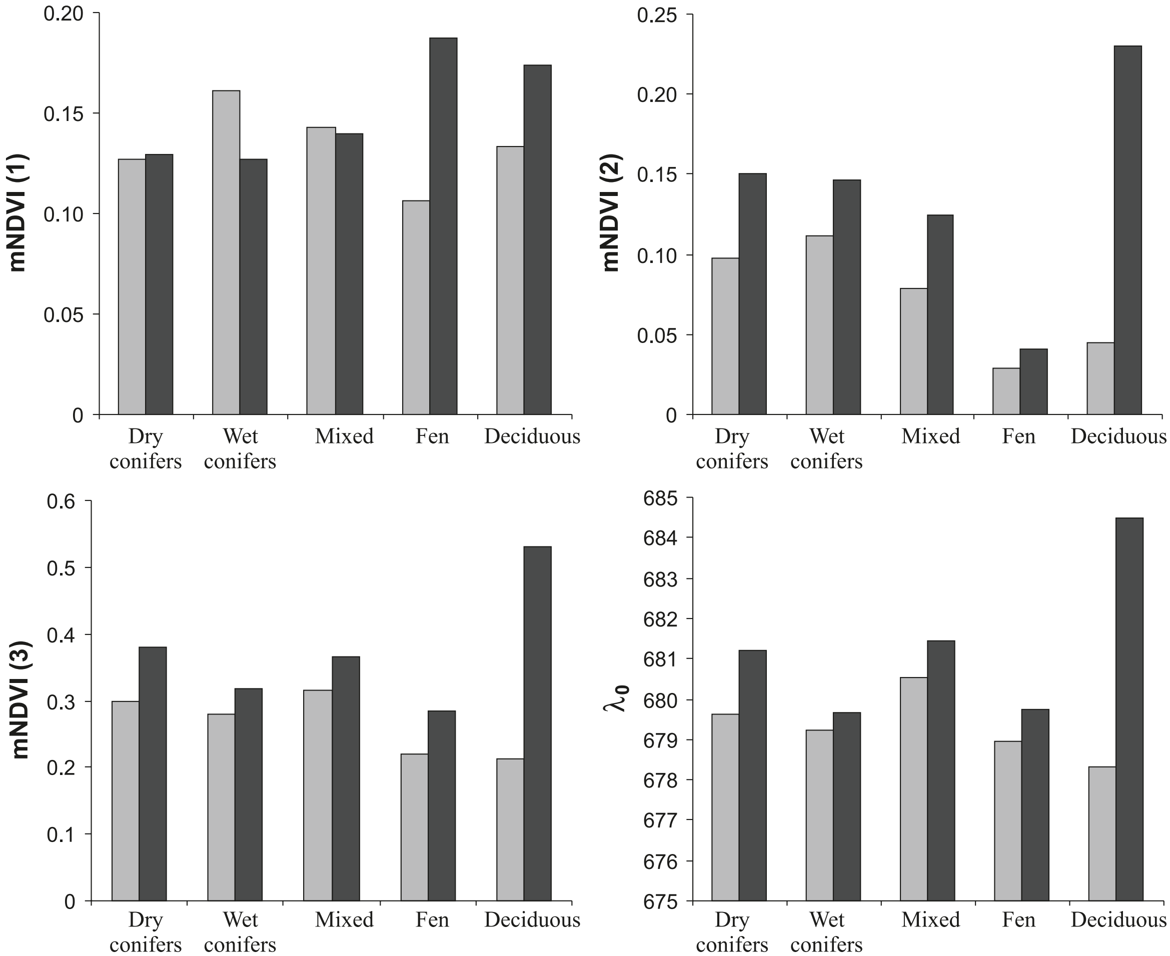


Figure 8. Changes of the optical indices from May (grey) to July (black) for different cover types.

indicates the probability of a reference pixel being correctly classified and is a measure of omission error. The user's accuracy is the probability that a pixel classified on the map actually represents that class on the ground, and it measures commission error. For each forest cover, the producer's accuracy is good, i.e., over 72%. The user's accuracy is very high for all of the forest cover types except the disturbed area. Some dry conifer pixels were classified in the disturbed area (such as the blue area in the YJP site in **Figure 10**). There are least two possible reasons for the low user's accuracy of the disturbed area: (*i*) the disturbance occurred between the last update of the SERM–FBIU forest cover image and the acquisition of the *casi* data, or (*ii*) the crown coverage is very low in the misclassified area.

The following three additional classification approaches were also tested with the *casi* data: (*i*) unsupervised classification (Isodata) using the reflectance data (bands 1–15) obtained in May, (*ii*) unsupervised classification using the reflectance data obtained in May and July, and (*iii*) unsupervised classification using the optical indices derived from the *casi* reflectance data in May. Accuracy assessments were performed for all of the classification approaches. The results summarized in **Figure 11** show that adding seasonal information to the classification can improve classification accuracy. If reflectance image data are used, seasonal information can also improve overall classification accuracy from 55% to 65% and increase the Kappa coefficient from 0.40 to 0.54. If the optical indices are used, seasonal information can improve classification accuracy from 78% to 84% and increase the Kappa coefficient from 0.71 to 0.78. These results also show that the classification approaches using the parameters sensitive to pigment absorption features are better than the classification approach using the reflectance itself. If only the data obtained in May are used, the classification accuracy using optical indices is 78%, and the classification accuracy using the reflectance itself is only 55%. If the data obtained in both May and July are used, the classification accuracy using optical indices is 84%, and the classification accuracy using the reflectance itself is 78%. The Kappa coefficient is increased significantly using the optical indices instead of the reflectance in the classification using either the May data (from 0.40 to 0.71) or the combined May and July data (from 0.54 to 0.78). This means that the classification with optical indices is much better than that with the reflectance itself.

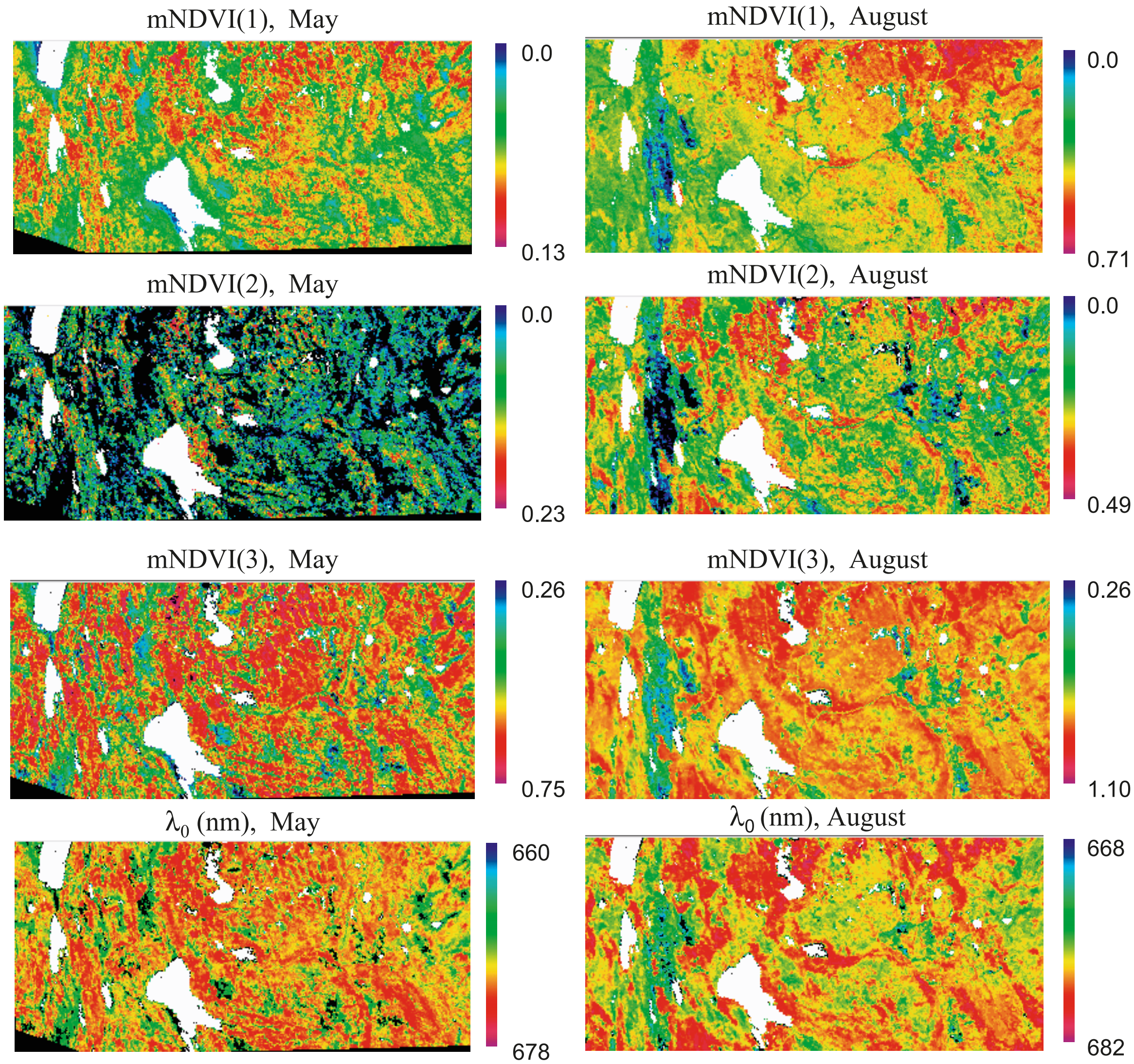


Figure 9. Images of optical indices calculated from MERIS reflectance data in May and August 2003, where the white areas are water bodies. Note that the scale varies between indices.

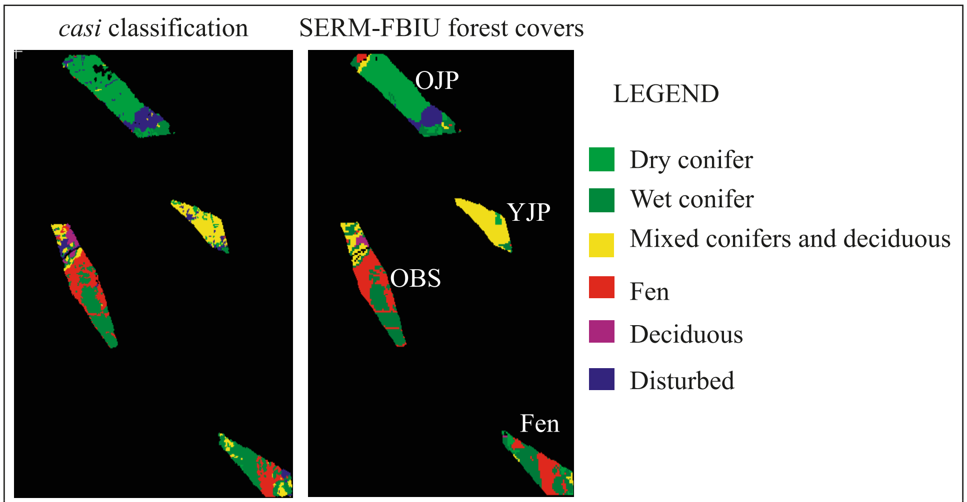


Figure 10. Classification result using the optical indices derived from *casi* reflectance data in May and July 1994 compared to the SERM–FBIU forest cover map updated in 1993.

Table 3. Forest cover classification assessment: unsupervised classification using the optical indices derived from the *casi* reflectance data in May and July 1994.

	Unsupervised classification (921 pixels)							
SERM–FBIU	Dry conifer	Disturbed	Mixed	Wet conifer	Fen	Deciduous	Total	Producer's accuracy (%)
Dry conifer	309	20	9	1	1	0	340	91
Disturbed	1	55	2	0	0	0	58	95
Mixed	24	9	88	0	1	0	122	72
Wet conifer	7	4	7	174	13	0	205	85
Fen	3	4	1	37	141	0	186	76
Deciduous	0	1	1	0	0	8	10	80
Total	344	93	108	212	156	8	921	
User's accuracy (%)	90	59	81	82	90	100		

Note: Overall accuracy = 84%; Kappa coefficient = 0.78.

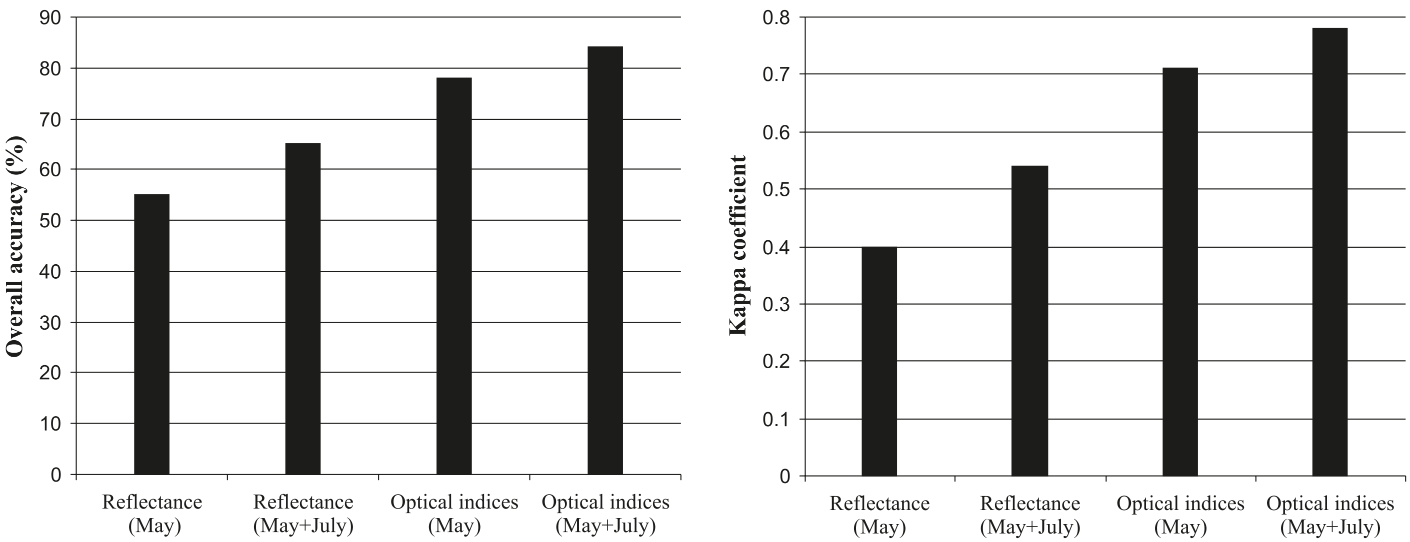


Figure 11. Comparison of classification accuracies among different classification approaches with different features (reflectance and optical indices).

Classification using MERIS data

The Isodata unsupervised classification (PCI Geomatica version 9; PCI Geomatics, 2004) was performed on the optical indices derived from MERIS reflectance data in May and August. The MERIS pixels were classified into three classes, namely conifers, mixed coniferous and deciduous stands, and fen. The result is shown in **Figure 12**. The spatial distribution of the cover type obtained from the classification is similar to that exhibited in the SERM–FBIU forest cover image. The classification accuracy was also quantitatively analyzed. A number of pixels for each class were randomly selected from the SERM–FBIU cover type image, and the classification accuracy was tested using these pixels. The confusion matrix is shown in **Table 4**. The overall classification is 72%, the producer's accuracies for all of the classes are greater than 65%, and the user's accuracies for the mixed stands and fen are greater than 80%.

With the MERIS data, unsupervised classification using reflectance (bands 1–15) in August and optical indices in August for comparison was also examined. The results including the producer's accuracies are shown in **Figure 13**. A comparison with the results in **Figure 12** shows that the classification using the parameters sensitive to pigment absorption features are better than the classification accuracy using the reflectance itself, and adding seasonal information to classification can improve classification accuracy.

Conclusions

Parameters sensitive to the diagnostic absorption of forest cover types were exploited in this study in forest cover classification using both Compact Airborne Spectrographic Imager (*casi*) data and medium-resolution imaging spectrometer (MERIS) data. The classification results demonstrated that feature selection is very important in forest species classification. The classification using four optical

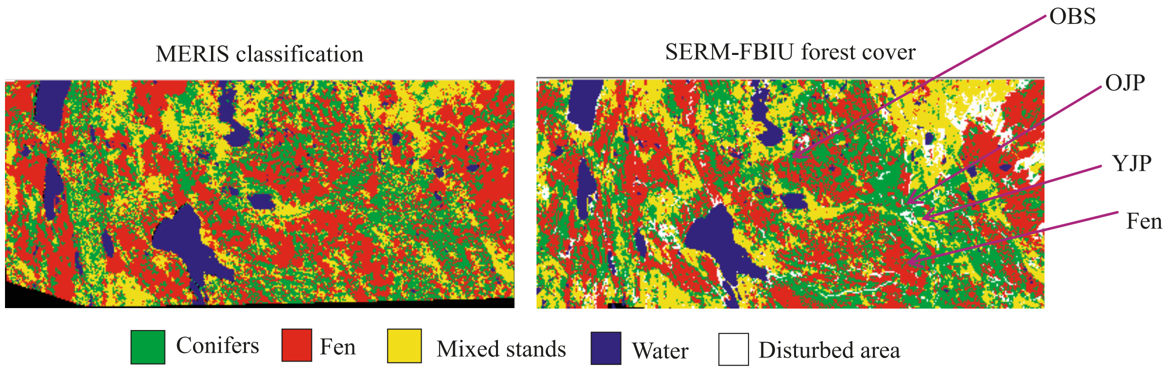


Figure 12. Classification result using the optical indices derived from MERIS reflectance data in May and August 2003 compared to the SERM–FBIU forest cover map updated in 1993.

Table 4. Contingency matrix of the unsupervised classification using the optical indices derived from MERIS data in May and August 2003.

	Unsupervised classification (6093 pixels)				
SERM–FBIU	Conifers	Mixed	Fen	Total	Producer's accuracy (%)
Conifers	871	152	314	1337	65.1
Mixed	335	1191	271	1797	66.3
Fen	585	121	2550	3256	78.3
Total	1791	1464	3135	6093	
User's accuracy (%)	48.6	81.4	81.3		

Note: Overall accuracy = 72.2%.

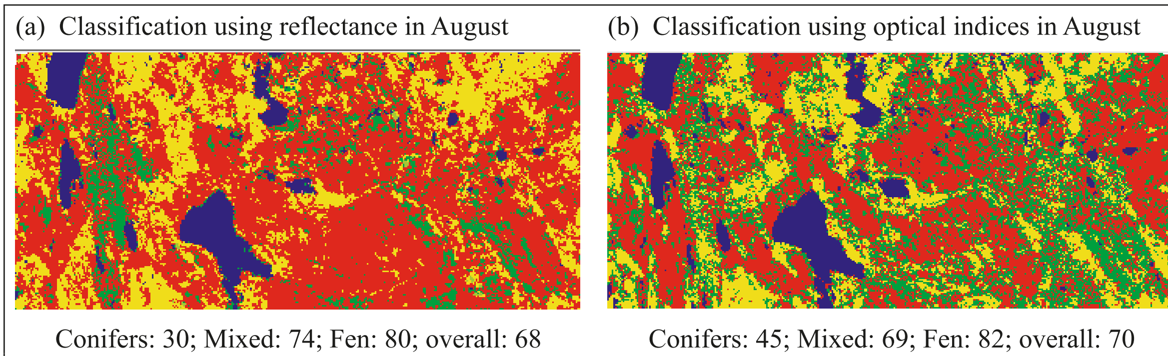


Figure 13. Classification images using (a) reflectance and (b) optical indices derived from MERIS data in August 2003. The producer accuracies for the different classes and the overall accuracies in percentage are listed at the bottom of the images.

indices sensitive to relative proportions among plant pigments and pigment content is better than that using the reflectance data themselves. For example, the classification accuracy improved from 55% to 78% using four optical indices instead of the reflectance, based on *casi* May data. The classification results also demonstrated that adding seasonal information improves forest cover classification. For example, seasonal information can improve overall classification accuracy for the *casi* data from 55% to 65% if reflectance values are used and from 78% to 84% if the optical indices are used. The classification accuracy using *casi* data is higher than that obtained using current algorithms for the same area (Hall et al., 1997; Zarco-Tejada and Miller, 1999; Fuentes et al., 2001).

The classification accuracy using two-date MERIS data is reasonably good, with an overall accuracy of 72%. The higher classification accuracy obtained using *casi* imagery compared with that using MERIS imagery may be due to the following factors: (*i*) the spatial resolution of the *casi* images is 30 m by 30 m (after resampled from 2 m × 2 m), and as a result the pixels are likely less mixed than the MERIS pixels with a spatial resolution of 300 m by 300 m; (*ii*) the *casi* images are primarily comprised of relatively homogeneous cover flux tower areas; and (*iii*) the MERIS data were obtained one decade after the *casi* data and nearly 15 years since the acquisition of the forest cover reference data used for accuracy assessment. In a future study, the fuzzy logic classification and spectral unmixing approaches will be exploited to deal with the highly mixed MERIS pixels.

In the present study, with both *casi* and MERIS data, the optical indices in spring and summer were simply used to carry out the classification. Although the classification result is very promising, the classification accuracy can be further improved if more detailed information about the seasonal changes of plant pigments were used. Further studies are also needed to develop optimum parameters for more accurate description of the absorption features of plant pigments, water content, and foliar chemistry and to select an improved set of optical indices for forest cover classification.

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