

Public Domain Mark 1.0 Universal

This work was written as part of one of the author's official duties as an Employee of the United States Government and is therefore a work of the United States Government. In accordance with 17 U.S.C. 105, no copyright protection is available for such works under U.S. Law.

Access to this work was provided by the University of Maryland, Baltimore County (UMBC) ScholarWorks@UMBC digital repository on the Maryland Shared Open Access (MD-SOAR) platform.

Please provide feedback

Please support the ScholarWorks@UMBC repository by emailing scholarworks-group@umbc.edu and telling us what having access to this work means to you and why it's important to you. Thank you.

Applications of the BIOPHYS Algorithm for Physically-Based Retrieval of Biophysical, Structural and Forest Disturbance Information

Derek R. Peddle, K. Fred Huemmrich, Forrest G. Hall, Jeffrey G. Masek, Scott A. Soenen, and Chris D. Jackson

Abstract—Canopy reflectance model inversion using look-up table approaches provides powerful and flexible options for deriving improved forest biophysical structural information (BSI) compared with traditional statistical empirical methods. The BIOPHYS algorithm is an improved, physically-based inversion approach for deriving BSI for independent use and validation and for monitoring, inventory and quantifying forest disturbance as well as input to ecosystem, climate and carbon models. Based on the multiple-forward mode (MFM) inversion approach, BIOPHYS results were summarised from different studies (Minnesota/NASA COVER; Virginia/LEDAPS; Saskatchewan/BOREAS), sensors (airborne MMR; Landsat; MODIS) and models (GeoSail; GOMS). Applications output included forest density, height, crown dimension, branch and green leaf area, canopy cover, disturbance estimates based on multi-temporal chronosequences, and structural change following recovery from forest fires over the last century. Good correspondences with validation field data were obtained. Integrated analyses of multiple solar and view angle imagery further improved retrievals compared with single pass data. Quantifying ecosystem dynamics such as the area and percent of forest disturbance, early regrowth and succession provide essential inputs to process-driven models of carbon flux. BIOPHYS is well suited for large-area, multi-temporal applications involving multiple image sets and mosaics for assessing vegetation disturbance and quantifying biophysical structural dynamics and change. It is also suitable for integration with forest inventory, monitoring, updating, and other programs.

Index Terms—Biophysical structure, BOREAS, canopy reflectance models, change, fire, forest disturbance, harvest, inversion, Landsat, LEDAPS, MODIS.

Manuscript received August 27, 2009; revised August 24, 2010; accepted December 13, 2010. Date of publication September 15, 2011; date of current version December 14, 2011. This work was supported by grants from the NASA MODIS Science Program, the Natural Sciences and Engineering Research Council of Canada (NSERC) and the Alberta Ingenuity Centre for Water Research (AICWR), and also supported by NASA/LEDAPS, the MODIS Science Team, and the Alberta Terrestrial Imaging Centre (ATIC).

D. R. Peddle is with the Department of Geography and Alberta Terrestrial Imaging Centre (ATIC), University of Lethbridge, Water and Environmental Science Building, Lethbridge, Alberta, T1K 3M4, Canada (corresponding author, e-mail: derek.peddle@uleth.ca; <http://people.uleth.ca/~derek.peddle>).

K. F. Huemmrich and F. G. Hall are with the NASA Goddard Space Flight Center, Biospheric Sciences Branch, Greenbelt, MD 20771 USA. They are also with the University of Maryland Baltimore County (UMBC), Joint Center for Earth Systems Technology (JCET).

J. G. Masek is with the NASA Goddard Space Flight Center, Biospheric Sciences Branch, Greenbelt, MD 20771 USA.

S. A. Soenen and C. D. Jackson are with the Department of Geography, University of Lethbridge, Lethbridge, Alberta, T1K 3M4, Canada.

Color versions of one or more of the figures in this paper are available online at <http://ieeexplore.ieee.org>.

Digital Object Identifier 10.1109/JSTARS.2011.2164899

I. INTRODUCTION

REMOTE sensing imagery provides unique, multi-temporal, spatially comprehensive data over local to regional/continental scales from which essential biophysical structural information (BSI) can be derived for ecosystem, climate and carbon models and for inventory, land management and ecological studies (e.g., [1]–[5]). Methods to extract BSI from airborne and satellite imagery have generally used either statistical or physically-based approaches [6]. Statistical approaches typically rely on empirical relationships (e.g., correlation, regression equations), while physically-based methods describe target and measurement properties and radiation interactions amongst land, atmosphere, energy sources and sensor attributes using quantitative models based on physical laws [6]. However, conventional statistical methods to extract BSI can be problematic and instead the use of canopy reflectance models (CRMs) has been shown to provide an improved theoretical and physical basis for deriving BSI [1], [7]–[13]. Model inversion provides BSI output, with the look-up table (LUT) approach providing an appropriate context for dealing with the complexity and computational demands associated with direct inversion algorithms [10], [11], [14]–[16]. This paper presents the BIOPHYS algorithm as an improved, physically-based CRM approach based on LUT inversion for deriving required vegetation continuous fields and vegetation state vectors for independent use and validation, and/or follow-on process model input. The algorithm exploits powerful canopy reflectance models and includes flexible approaches for model inversion. A key objective is to demonstrate the versatility of this type of approach across various study sites, applications and data sets to show the capability of general look-up table based canopy reflectance model inversion approaches.

In Sections II–IV, an overview of the BIOPHYS algorithm is first provided, and followed by a series of studies that demonstrate a variety of selected applications. Several of these include integrated analyses involving use of different models in BIOPHYS to achieve a synergy in algorithm outputs, as opposed to previous work that has focused on individual studies and singular applications only. The technical specifications of BIOPHYS and embedded MFM methodologies and experimental designs have been published elsewhere and are not repeated here. Instead, the applied nature of the algorithm is emphasized, with a focus on illustrating the diversity, flexibility and different types of integrated applications possible.

II. BIOPHYS ALGORITHM OVERVIEW

The BIOPHYS MFM-CRM approach has been extensively used and validated over a range of applications in collaboration with agencies in Canada and the USA over the past decade, such as the Canada Centre for Remote Sensing (CCRS), Canadian Forest Service (CFS), Canadian Model Forests, Alberta Ingenuity Centre for Water Research (AICWR), and in the USA by the NASA COVER, BOREAS and MODIS Science Teams, the Landsat Ecosystem Disturbance Adaptive Processing System (LEDAPS) and as part of NASA's contribution to the North American Carbon Program [2], [3]. In these and other projects, MFM has been used for land cover, biomass, stand and crown volume, stem density, height, crown closure, leaf area index (LAI) and branch area, crown dimension, productivity, topographic correction and validation, structural and partial harvest change detection, forest fire mapping and structural change, mountain pine beetle forest damage assessment, and water/hydrology applications in different locations and ecosystems in Canada (six provinces from Newfoundland to British Columbia) and USA (NASA COVER, MODIS and LEDAPS sites) using 7 different canopy reflectance models and a variety of airborne and satellite remote sensing systems (e.g., SPOT, Landsat TM/ETM, MODIS, IKONOS, airborne MSV, MMR,iasi, Probe-1, AISA), as described in [11], [17]–[26], with broader perspectives on MFM provided in [27] and [28].

BIOPHYS is based on innovative and flexible methods implemented for the inversion of canopy reflectance models, such as the multiple-forward mode (MFM) approach [11], [15]. Based on spectral, angular, temporal and scene geometry inputs that can either be provided or automatically derived, the approach generates look-up tables that comprise reflectance data, structural inputs over specified or computed ranges [17], [19] and the associated CRM output from forward mode runs. The approach includes 3D specification of physical objects and is compatible with radiative transfer inputs from land surface reflectances [e.g., [29]] although BIOPHYS can also be used with lower level and raw image data. Image pixel and model LUT spectral values are then matched and retrieved [11], [22], with the corresponding BSI associated with the matches output as the vegetation continuous fields result(s).

Fig. 1 illustrates the main algorithm components of BIOPHYS. A CRM is run multiple times in forward mode (i.e., MFM), varying the inputs incrementally over a range of values covering the possible ranges of the values found in nature or which can be derived automatically if no ground or other *a priori* information is available [17], [19]. The inputs and outputs of each model run are stored in a LUT. Once the database is populated, it can be used to determine biophysical characteristics from image pixel data. The LUT is searched for entries in which the given image pixel value matches the modeled (MFM) reflectance value [18]. The associated BSI entries with that record (i.e., the structural model inputs used to generate the modeled reflectance value that matches the image pixel) are then output. Typically, unique solutions are not always obtained and instead there can be multiple or no exact matches between the modeled and image reflectance. A full suite of solution set processing protocols are invoked [22] to derive final retrievals

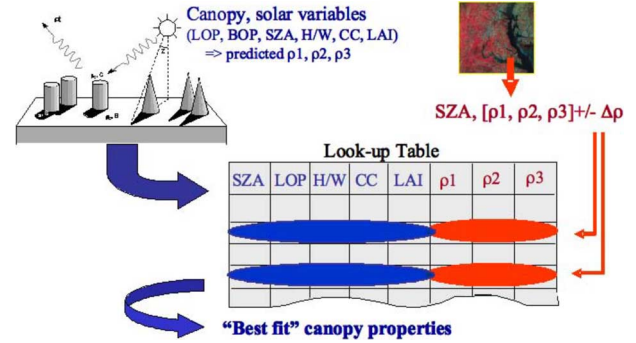


Fig. 1. Conceptual design and process flow of BIOPHYS for remotely sensed and modeled reflectance values (ρ). LOP/BOP = leaf/background optical properties; SZA = solar zenith angle; H/W = height/width ratio; CC = canopy cover; LAI = leaf area index.

from which statistical metrics as uncertainty estimates can also be provided.

III. BIOPHYS APPLICATIONS

BIOPHYS results using a variety of study areas, sensors, models, and applications are demonstrated to provide a sense of the breadth of BIOPHYS capabilities and applications as well as synergies within given study area themes. The GeoSail model [30] and the Geometric-Optical Mutual Shadowing (GOMS) model [31] were used in BIOPHYS for airborne, Landsat and MODIS imagery over several study areas, dates, regions, and forest types and ecological applications. Different BIOPHYS capabilities as well as types of output have been selected to further illustrate algorithm capabilities. In several cases, this is demonstrated within a given study.

Where possible, these example applications include field validation, however, several do not, such as multi-temporal studies from various archival image data sets for which field and other validation data did not exist. In larger, regional scale and temporally dynamic studies this reality is not uncommon and is a context within which BIOPHYS necessarily must also operate. At some point after the acceptance of a method as being viable from a series of previous studies [11], [17]–[28], the applications domain must move forward to the next level to encompass broader studies and applications for which validation is not and cannot be expected to be available, but for which sufficient confidence exists from the maturity and extensive verification of the approach. This is particularly the case given the importance of quantifying (not just detecting) change from the wealth of multi-temporal and archival data sets that are crucial to delivering comprehensive information on surface dynamics over space and time. It is also consistent with the importance and investments being made in long-term remote sensing missions and future continuity for satellite programs such as Landsat, SPOT, AVHRR and MODIS (e.g., [32]–[34]).

IV. AIRBORNE MMR BSI: NASA COVER PROJECT

A. LUT Creation

BIOPHYS was applied at the Superior National Forest (SNF) in Minnesota USA as part of the NASA COVER project

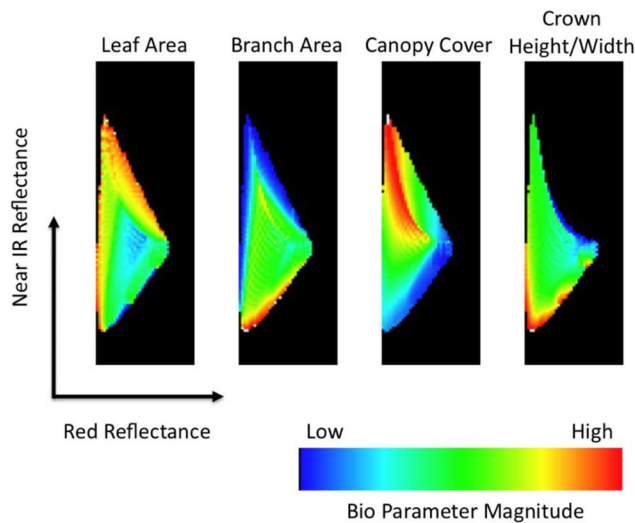


Fig. 2. Distribution of 4 BIOPHYS BSI variables, Superior National Forest, Minnesota USA. GeoSail model output for red (simulated MMR band 3) and near-infrared (NIR, simulated MMR band 4) reflectance shown in LUT spectral space with respect to BSI. Colours indicate the relative values of each biophysical parameter averaged for a 0.5% by 0.5% reflectance grid (black: no values for those reflectances).

[35]. Using the GeoSail model to populate the output LUTs, the model input variables were varied over a range of possible biophysical parameter values found at the SNF sites. The BIOPHYS LUTs contain modeled reflectance values that were gridded to 0.5% reflectance to be consistent with the data precision associated with sensor noise characteristics of the helicopter Multiband Modular Radiometer (MMR) sensor system. The LUTs contained BSI for crown green leaf area index, crown branch area index, fraction canopy cover and crown height to width ratios. The surface reflectance value for each pixel in an image was searched and located in these LUTs, from which the associated BSI parameter values were retrieved as the final output. A graphic representation of the LUTs (Fig. 2) shows how these parameters vary within spectral space.

B. Testing BIOPHYS

In the SNF NASA COVER study, biophysical measurements were collected at a number of forest plots in northern Minnesota [35]. Reflectance data were also obtained for the plots from a helicopter-mounted nadir-viewing MMR with 30 m spatial resolution [36]. We used the measurements from 16 black spruce plots to test BIOPHYS. The MMR band 3 (red: 630–690 nm) and band 4 (near-infrared: 750–880 nm) data were used to obtain leaf area index (LAI) from the BIOPHYS LUTs, with results compared with LAI field validation data derived from allometric relationships (Fig. 3). We found no significant difference between BIOPHYS and field-based LAI over a wide range of LAI. Some plots had higher standard deviations, with an overall moderate relationship between modeled and field-derived LAI. In terms of specific plot values, although not statistically significant, BIOPHYS overestimation of LAI was reduced at higher LAI. It was also found that by combining multiple observations collected at different solar zenith angles, MFM retrievals

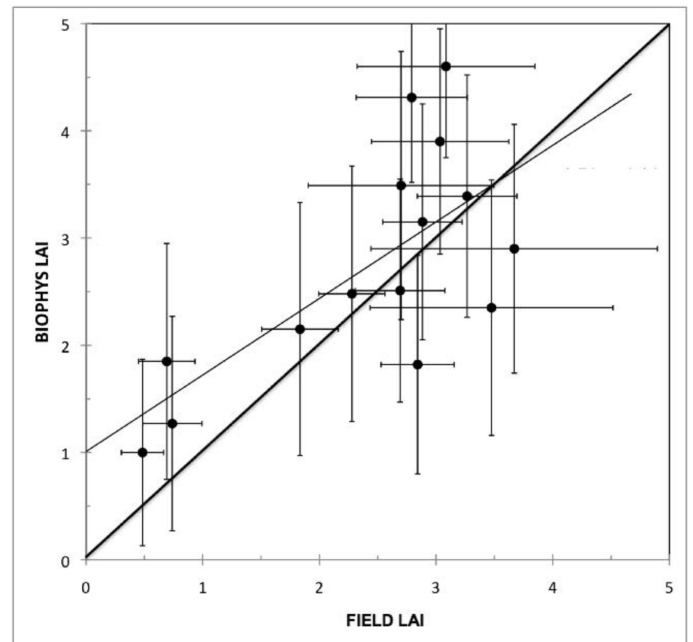


Fig. 3. Leaf area index based on BIOPHYS retrievals from helicopter reflectance data versus field validation LAI from allometric relationships for 16 black spruce stands in the Superior National Forest, northern Minnesota. Bars around each value indicate standard deviation of both field based and modeled LAI.

and BSI estimates were further improved due to the additional matching criteria.

V. BOREAS CHRONOSEQUENCE STUDY: FOREST FIRE DISTURBANCE, CHANGE AND RECOVERY USING LANDSAT

BIOPHYS was used to study structural change in boreal forests following recovery after fire. A Landsat-7 ETM+ image from August 12, 2001 of the Boreal Ecosystem Atmosphere Study (BOREAS) Southern Study Area (SSA) in Saskatchewan, Canada was atmospherically corrected prior to running BIOPHYS using Landsat band 3 (630–690 nm) and band 4 (770–900 nm). From the Saskatchewan fire history data set, study sites were located in a chronosequence following burns at 3, 12, 24, 34, 46, 56, and 120 years prior to the 2001 Landsat image acquisition (1998, 1989, 1977, 1967, 1955, 1945, 1881, respectively). While NDVI saturated 30 years following post-burn, BIOPHYS provided a comprehensive and complex change dynamic in forest structure for all time periods (Fig. 4), with LAI increasing in the first 25 years, then decreasing up to 60 years, and finally showing little change at 120 years.

VI. TEMPORAL CHANGE IN BOREAL FOREST BIOPHYSICAL STRUCTURE

BIOPHYS was run on two Landsat images for the BOREAS SSA acquired August 30, 1987 and August 12, 2001, producing maps of multiple canopy structural variables: LAI, fraction of canopy cover, and crown height to width ratio using MFM-GeoSail, and density, crown radius and height using MFM-GOMS. A key feature of BIOPHYS for assessing multi-temporal change is its explicit characterization (as opposed to “correction”) of

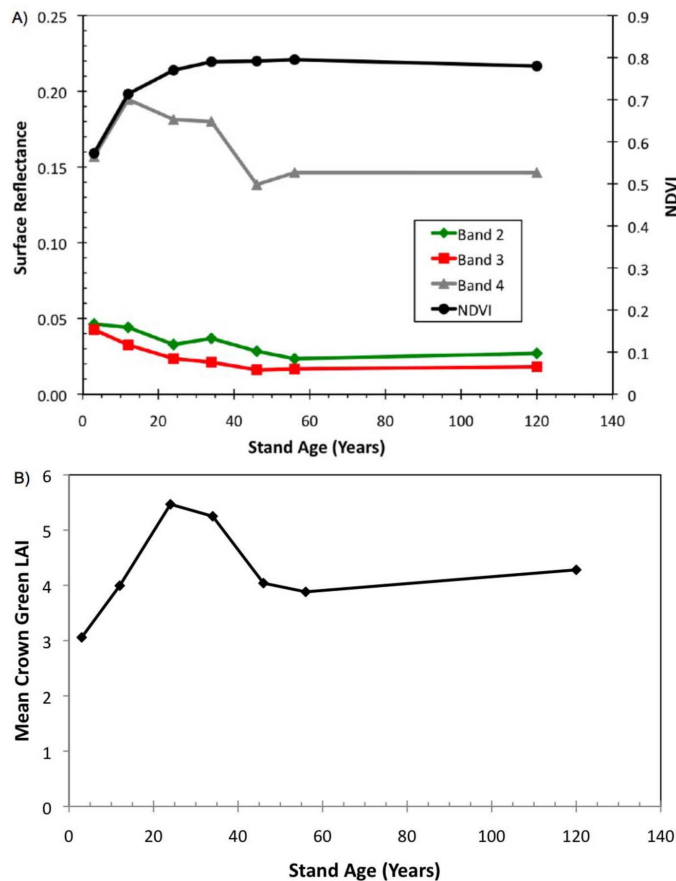


Fig. 4. (A) Reflectance changes for Landsat bands 2, 3, and 4, and NDVI for boreal stands of different ages following fires (1881–1998), BOREAS. (B) BIO-PHYS LAI values retrieved from Landsat bands 3 and 4 for corresponding fire stand ages.

scene-specific solar zenith angles (SZA) by providing angle-dependent signatures during LUT creation. BIOPHYS thus uses the angular dimension of image information to advantage, instead of trying to suppress it.

A. Change in LAI, Canopy Cover and Crown Height: Width Ratio

To graphically display how BIOPHYS can show vegetation structure changes over time, we generated colour images from MFM-GeoSail analyses of the two Landsat scenes (Fig. 5). The RGB images, in effect, colour-code values of crown green LAI, fraction of canopy cover, and crown height to width ratio. Thus, the colours in the images in Fig. 5 correspond to canopies with different structural characteristics. In these images there are clear spatial patterns shown as different coloured patches. The change in the colour patterns between images reflects the changes in forest canopy structure over time. For example, the blue patch right of center in 1987 has low LAI and canopy cover associated with forest disturbance. In 2001, higher canopy cover and LAI are evident in this area as a result of forest succession. Areas that are black had no forest structural returns, such as water.

Authorized licensed use limited to: University of Maryland Baltimore Cty. Downloaded on January 29, 2024 at 19:36:40 UTC from IEEE Xplore. Restrictions apply.

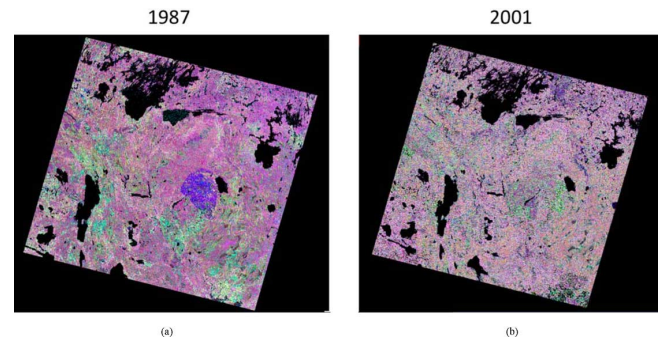


Fig. 5. BIOPHYS output from Landsat images acquired August 30, 1987 (left) and August 12, 2001 (right) over the BOREAS SSA. These RGB images show crown green LAI (red plane), canopy cover (green plane), and crown height to width ratio (blue plane).

TABLE I
MFM-GOMS VALIDATION FROM BOREAS 1987 AND 2001 LANDSAT IMAGERY. THE 1987 AND 2001 COLUMNS SHOW THE DIFFERENCES OF MFM OUTPUT VS VALIDATION DATA. THE MFM CHANGE COLUMN IS THE DIFFERENCE IN MFM OUTPUTS OVER THE TWO DATES

	1987 Diff(±): MFM vs. Field Val.	2001 Diff(±): MFM vs. Field Val.	MFM Change: 2001-1987
BSI			
Density (stems/ha)	625	602	125
Horizontal Crown Radius (m)	0.35	0.45	-0.26
Height (m)	1.51	1.53	0.28

B. Change in Density, Crown Radius and Height

Further analysis was conducted using MFM-GOMS. Validation (Table I) showed good correspondence with field data for the density, crown radius and height parameters tested. Stem density error ranged to ± 625 stems/ha, with horizontal crown radius error $< \pm 0.5$ m and height error slightly over ± 1.5 m. The BSI change magnitudes from MFM 1987 vs. 2001 outputs were within the error envelopes of each variable. BSI change indicated an increase in stem density consistent with earlier stage succession, a decrease in horizontal crown radius likely influenced by regeneration following two burns (1989, 1998) as well as other disturbance, and a slight increase in overall height corresponding to normal growth patterns over the 15 year period.

VII. VIRGINIA/LEDAPS: MULTI-TEMPORAL LANDSAT BSI

A multitemporal sequence of Landsat images of mixed deciduous and coniferous forest in Virginia state, eastern USA, was assessed as part of the Landsat Ecosystem Disturbance Adaptive Processing System (LEDAPS) project [37]. Forest BSI was extracted from 1985, 1988, 1989 and 1999 imagery and compared in several change detection applications using different dates and CR models to assess forest disturbance.

A. BIOPHYS GeoSail: Virginia 1988 to 1999

The GeoSail model was run in MFM-mode for both 1988 and 1999 Landsat images, and change maps and statistics produced. In Fig. 6, the 1988 and 1998 green leaf area is shown together with the 11-year difference. The majority of higher-magnitude change was due to disturbance (decreases shown in blue), with nominal increases (red) due to undisturbed growth.

Overall, there was a net reduction in average green leaf area of

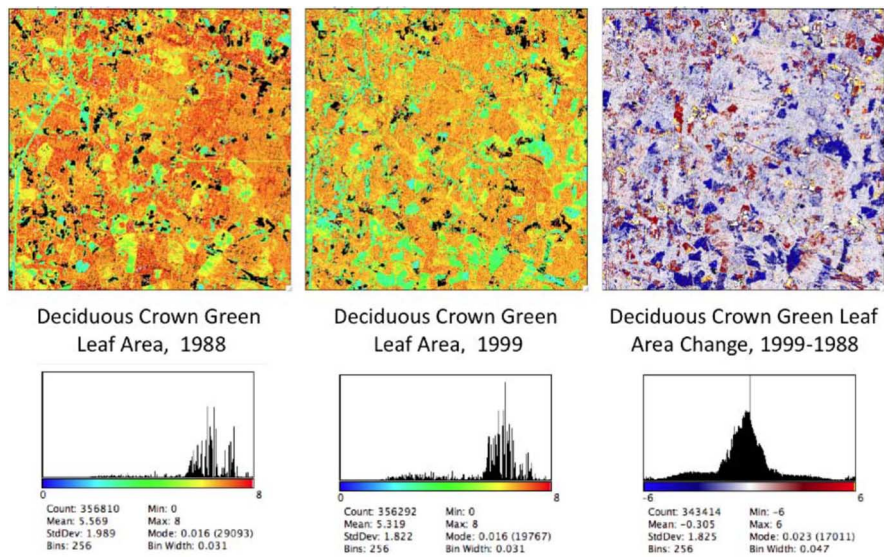


Fig. 6. BIOPHYS deciduous crown green leaf area, Virginia LEDAPS site: (L-R): 1988, 1999 and 11 year disturbance change (1999–1988). Colour scale and distribution of values shown below each map.

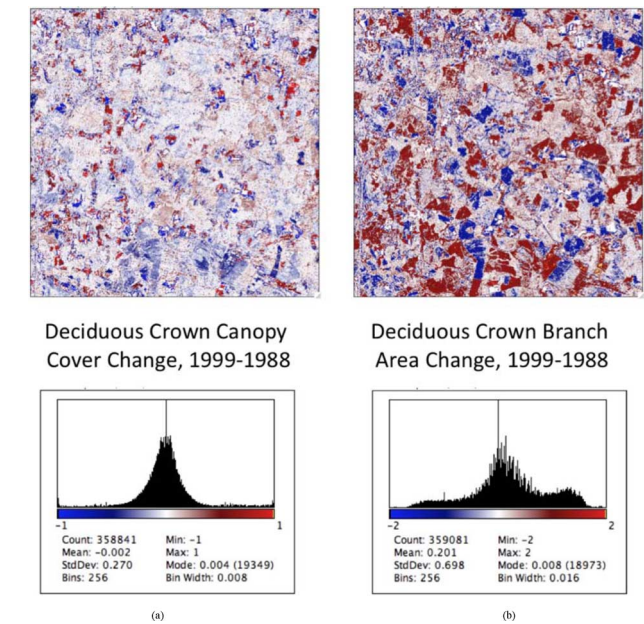


Fig. 7. BIOPHYS deciduous disturbance change (1999–1988) at the Virginia LEDAPS site: canopy cover (left) and branch area (right). Colour scale and distribution of values shown below each map.

0.25. In Fig. 7, changes in canopy cover and branch area are shown. Crown canopy cover showed a normal distribution of change, however for branch area change this was not the case owing to a noticeably larger amount of branch area increase over the 11 year period.

B. BIOPHYS MFM-GOMS: Virginia 1985 to 1989

BIOPHYS MFM-GOMS was used to assess disturbance and change from the Landsat TM 1985 and 1989 images (Fig. 8). Part of this analysis included first creating a forest/non-forest mask based on a multi-temporal structural boolean logic decision rule in which non-forest was determined per-pixel as

TABLE II
 AGGREGATED BSI AND CHANGE FROM THE LEDAPS VIRGINIA STUDY SITE FOR DENSITY, HORIZONTAL CROWN RADIUS AND HEIGHT FROM BOTH 1985 AND 1989 IMAGE DATES

BSI	1985	1989	1989-1985
Density (stems/ha)	1760	1734	-26
Horizontal Crown Radius (m)	1.48	1.49	0.01
Height (m)	8.34	8.40	0.06

having both horizontal and vertical crown radii < 1.0 m on both image dates (Fig. 8).

MFM-GOMS was run for both 1985 and 1989 Landsat images, and change maps and statistics produced. A key advantage to BIOPHYS in multi-temporal studies is that for a given ecosystem and region, the same set of LUTs can be used for all dates provided the images have the same units (e.g., reflectance, or raw DN), otherwise independent LUTs are generated which thus provides a capability to assess imagery from different sources and levels of radiometric processing. Regardless, the LUTs contain the full range of variability from which change is detected based on the actual (different) matches obtained from the image pixel values that vary by date. This provides consistency to the quantitative change analysis and reduces computation time. In Figs. 9–11, the 5-year differences are shown with distribution of change for density, horizontal crown radius (HCR) and height. Most changes were < 1000 stems/ha, and < 1 m HCR and height. Overall change for the full area (Table II), a function of both disturbance and normal growth, showed a slight reduction in density and small increases in both radius and height, indicating a net loss of primarily younger (higher density) forest, and nominal growth in the remaining undisturbed areas.

From these BIOPHYS results, a number of follow-on statistics and products are possible. For example, in this study based on the various temporal change and disturbance products generated, the area and percent of forest disturbance (burned, logged) was determined as 1.03 Mha corresponding to 5.8% of the full

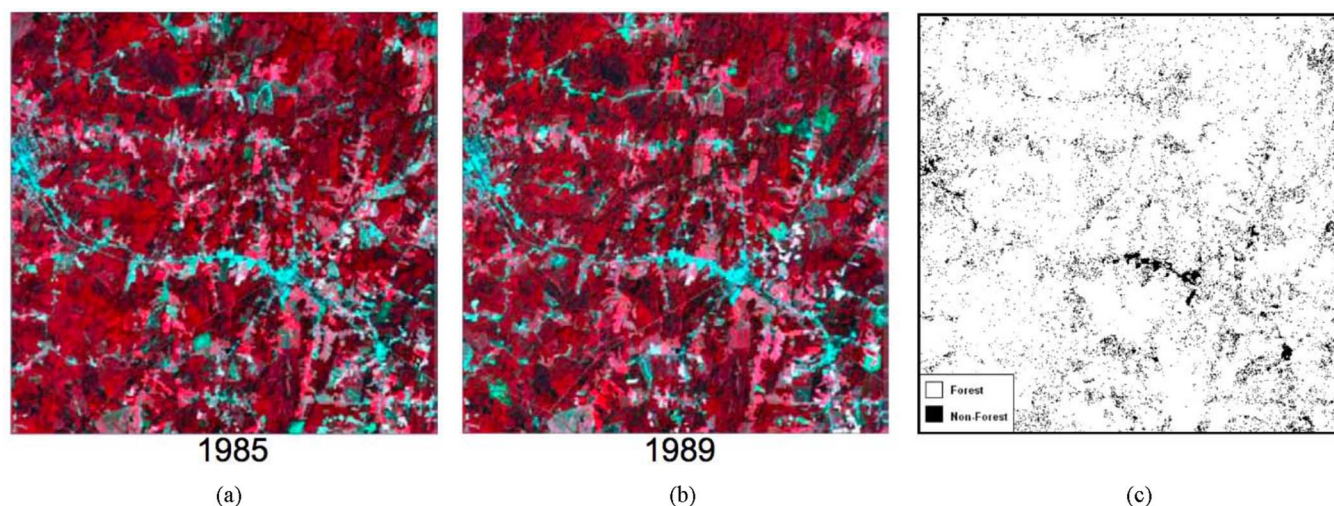


Fig. 8. Landsat TM imagery (RGB bands 4, 3, 2 respectively) at the Virginia LEDAPS site from September 15, 1985 (left); September 10, 1989 (middle); and the forest/non-forest mask (right) derived from a multi-temporal structural decision rule.

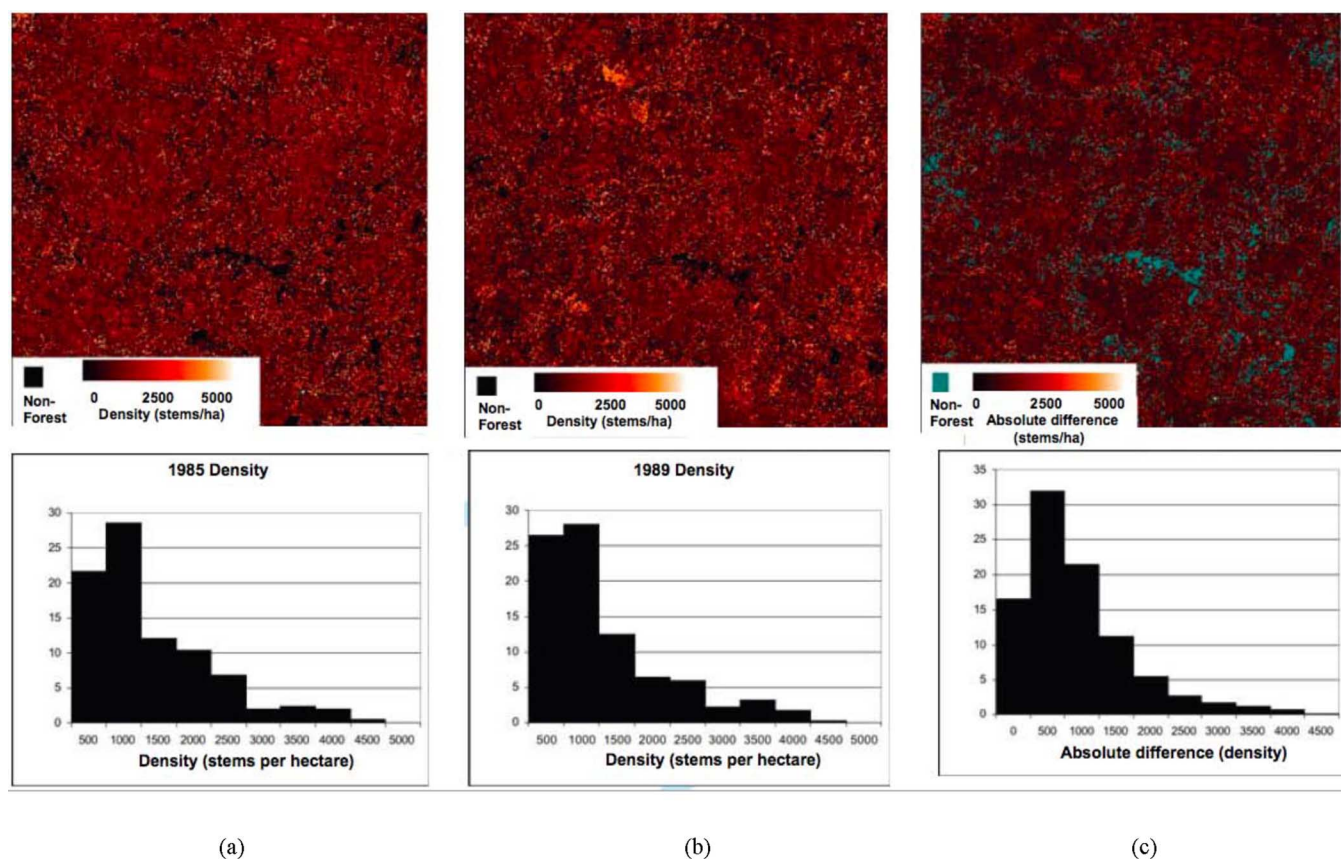


Fig. 9. BIOPHYS MFM-GOMS density from Landsat TM imagery, Virginia LEDAPS site showing 1985 (left), 1989 (middle) and change map (right), with associated colour scale and distribution histograms below.

region, while areas of early regrowth and succession were assessed to be 0.89 Mha (4.9% of area). Derivations such as this as well as their spatial characteristics through map outputs represent useful inputs to process-driven ecological, climate and carbon models [4], especially for those operating at increasingly finer spatial scales that require surface variability accounting for proper parameterisation and use.

VIII. MODIS: BOREAS

A. Simulated MODIS Imagery

BIOPHYS was tested at BOREAS for both simulated and real MODIS imagery. In the first example, Landsat TM 30 m imagery was scaled to MODIS 250 m pixels (Fig. 12) using a

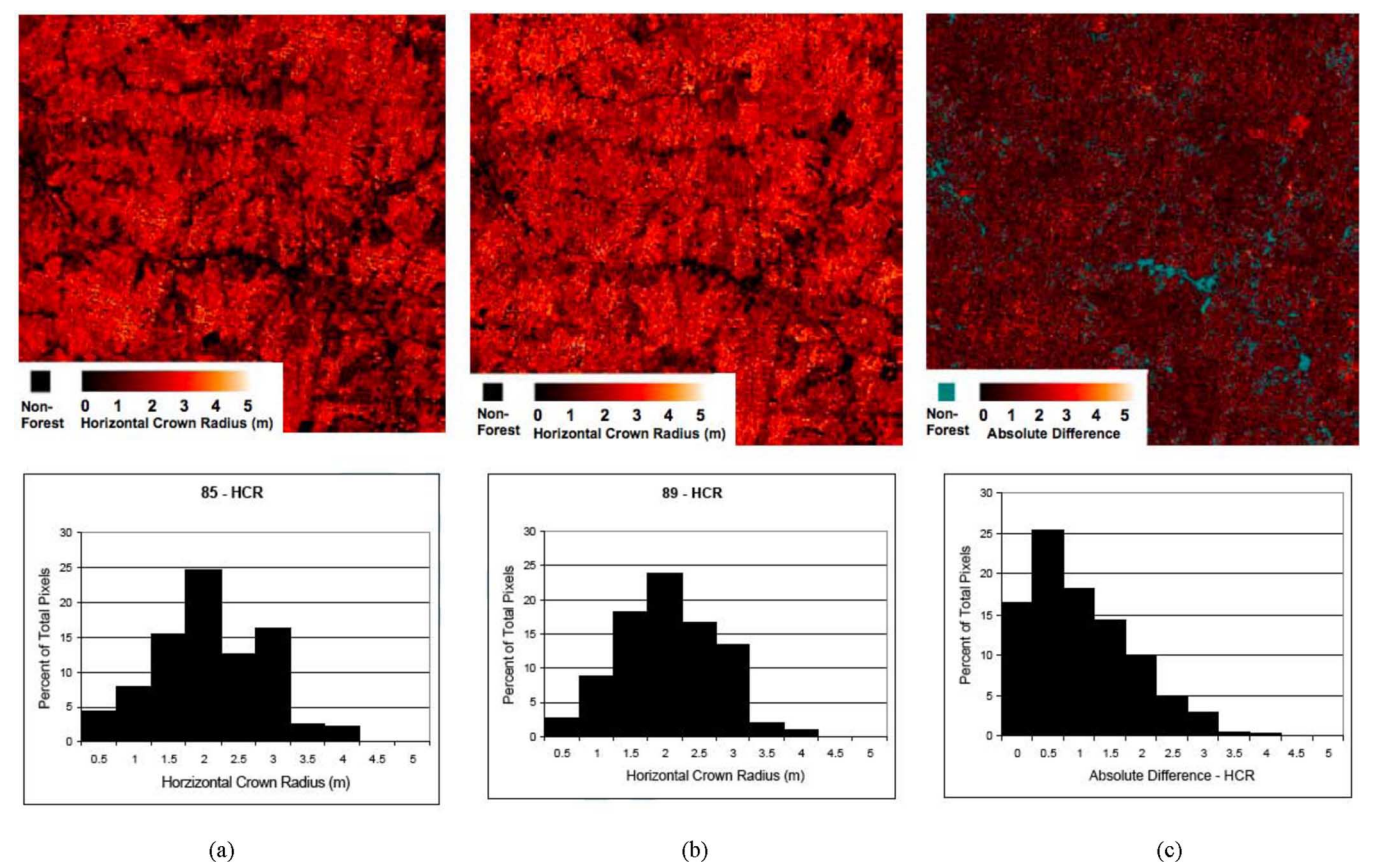


Fig. 10. BIOPHYS MFM-GOMS horizontal crown radius (HCR) from Landsat TM imagery, Virginia LEDAPS site showing 1985 (left), 1989 (middle) and change map (right), with associated colour scale and distribution histograms below.

TABLE III
 VALIDATION OF BIOPHYS MFM-GOMS STRUCTURE FROM SIMULATED MODIS 250 M IMAGE DATA AGAINST BOREAS OLD BLACK SPRUCE (OBS) FIELD VALIDATION DATA

BSI	Field Validation	2001 MFM (MODIS Sim.)	abs(Diff): MFM vs. Field Val.
Density (stems/ha)	2416	2500	84
Horizontal Crown Radius (m)	1.0	0.5	0.5
Vertical Crown Radius (m)	4.1	4.5	0.4
Height (m)	13.2	12.5	0.7

TABLE IV
 MODIS IMAGE ACQUISITIONS FOR BOREAS SSA OBS AREA SHOWING DAY OF YEAR (DOY), DATE (IN 2001), AND VIEW ZENITH ANGLE (VZA) OF EACH IMAGE

DOY	215	217	229	233	245	247
Date	Aug 3	Aug 5	Aug 17	Aug 21	Sep 2	Sep 4
VZA (°)	10	8	25	8	25	9

TABLE V
 VALIDATION OF BIOPHYS MFM-GOMS STRUCTURE FROM MULTI-VZA MODIS IMAGES AGAINST BOREAS OBS FIELD VALIDATION DATA

BSI	Field Validation	2001 MFM (Multi-VZA MODIS)	abs(Diff): MFM vs. Field Val.
Density (stems/ha)	2416	2333	83
Horizontal Crown Radius (m)	1.0	0.7	0.3
Vertical Crown Radius (m)	4.1	5.0	0.9
Height (m)	13.2	15.0	1.8

simple spatial averaging filter and tested at the Old Black Spruce (OBS) area and plot sites in the SSA.

Using the MFM-GOMS option in the BIOPHYS algorithm, good results were obtained from the simulated MODIS data against validation OBS field measurements (Table III). Density was 84 stems/ha different than field measurements, with horizontal and vertical crown radii both ≤ 0.5 m error and tree height 0.7 m different. Four BSI maps were produced (Fig. 13) for these outputs, with results grouped into classes for mapping purposes with intervals as shown in each legend.

B. Single-Date MODIS Imagery

BIOPHYS MFM-GOMS was applied to a MODIS image acquired August 3, 2001 (day of year: DOY 215) over the BOREAS SSA region with a nominal view zenith angle (VZA) of 10°. Validation was achieved at the OBS as well as Old Jack Pine (OJP) and Old Aspen (OA) sites.

Good results were obtained for most structural parameters and sites (Fig. 14). However, the level of correspondence was not as strong as in the previous section that used simulated MODIS data. For stem density, OBS and OJP were within 400 stems/ha, however OA was overestimated considerably. For crown radii, good correspondence was obtained for all three species (horizontal) and for OBS and OA (vertical), however the OJP VCR result had higher error. The error from this single date image test was attributed primarily to the more highly variable view angles and resulting variable pixel sizes that exist

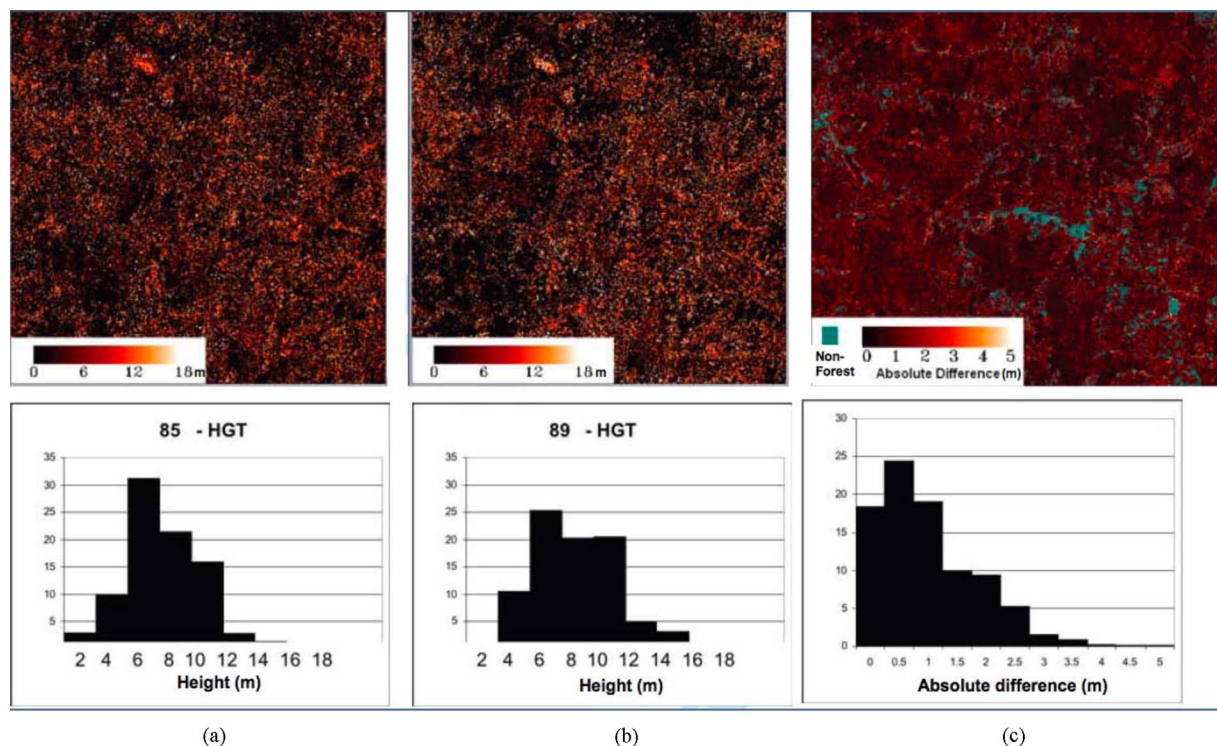


Fig. 11. BIOPHYS MFM-GOMS height (HGT) from Landsat TM imagery, Virginia LEDAPS site showing 1985 (left), 1989 (middle) and change map (right), with associated colour scale and distribution histograms below.

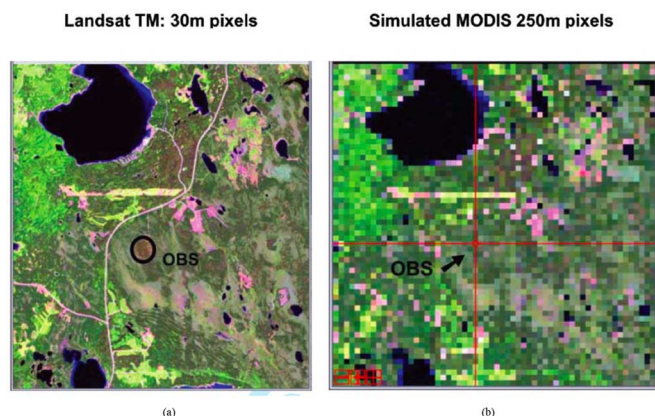


Fig. 12. Landsat TM 30 m image acquired August 12, 2001 (left), and simulated MODIS 250 m image (right). Location of BOREAS SSA Old Black Spruce (OBS) validation site shown.

across a scene. To address this for a given date would require more sophisticated within-scene modeling and geometric corrections that were not performed in this example.

C. Multi-Date, Variable View Angle MODIS Image Inversion

MODIS imagery acquired on different dates can provide different view angles for a given location. A set of 6 MODIS images of the BOREAS SSA acquired on different dates and view angles were assessed (Table IV) to test an integrated BIOPHYS MODIS BSI retrieval capability. The images were from 6 looks from DOY 215 to 247 (August 3 to September 4, 2001) with VZA ranging from 8° to 25° . All images encompassed the OBS

validation site with a nominal pixel resolution 2.5 km to resolve the multi-VZA field of view differential.

Using this approach improved the overall retrievals based on the expected convergence of results from the intermediate results shown and the final integrated VZA results from BIOPHYS (Fig. 15, Table V). For example, a considerable improvement was found for density against OBS validation (Table V) from the multi-date (multi-VZA) data set compared with the single-date (Fig. 14) MODIS image results (83 vs 416 stems/ha), with horizontal crown radius improved from a difference of 0.5 m to 0.3 m. A small increase in difference error was found for multi-VZA vertical crown radius, however in both cases (single-date and multi-date), the results were within 1 m of validation.

The multi-VZA convergent results were also more similar to estimation accuracies obtained using simulated MODIS imagery (Table III), which was interesting from both BSI retrieval and image scaling perspectives.

IX. CONCLUSIONS

Canopy reflectance modeling provides powerful and flexible capabilities for deriving biophysical, structural, and forest disturbance and change information compared with empirical approaches. Inversion of these models provides this type of information however, to overcome associated complexities with direct inversion, look-up table (LUT) based approaches have been recommended. One such LUT-based model inversion approach—the BIOPHYS algorithm—was used in a series of studies for a variety of different ecosystems, sensors, models, and applications to demonstrate the versatility of this type of information retrieval approach... The BIOPHYS algorithm's

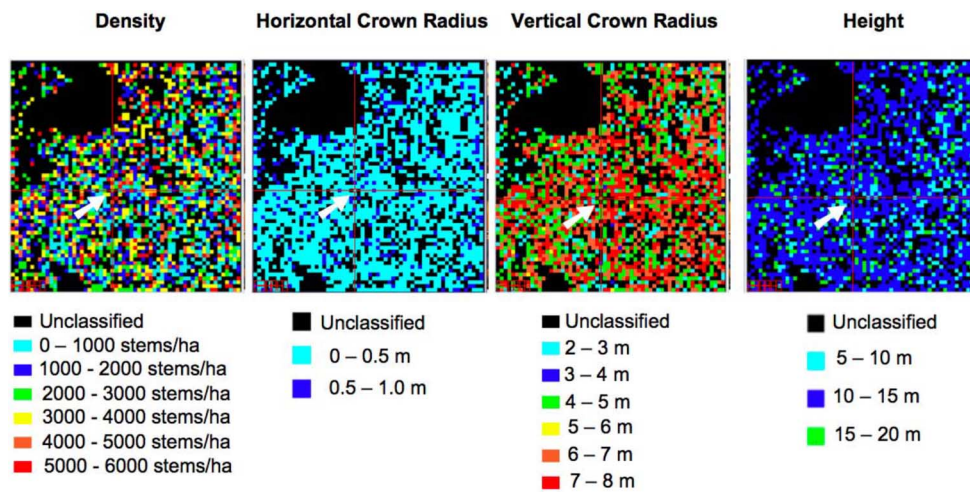


Fig. 13. BIOPHYS MFM-GOMS structure from MODIS 250 m simulated imagery. Location of BOREAS OBS site shown in each map at intersection of red lines (see white arrow).

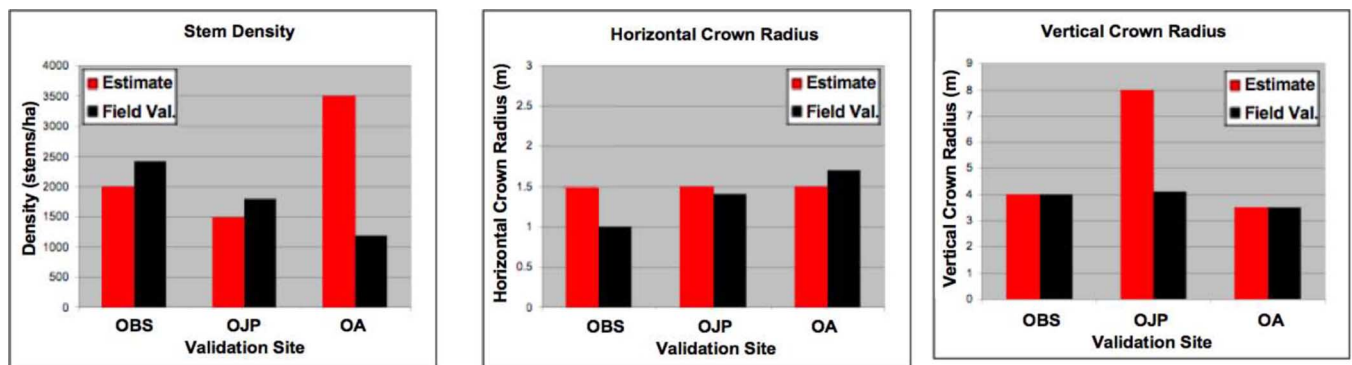


Fig. 14. BIOPHYS MFM-GOMS density and crown radii from single-date MODIS imagery (Aug. 3, 2001). MFM results (red) at BOREAS Old Black Spruce (OBS), Old Jack Pine (OJP) and Old Aspen (OA) validation sites shown in comparison with field validation values (black).

explicit characterization of illumination and view conditions, and the robustness of canopy reflectance prediction with change of geographic region permits BIOPHYS to quantify key ecosystem structural dynamics such as LAI, fraction of canopy cover, density, crown dimension and height, as well as providing estimates of uncertainty of retrievals. In multi-temporal studies, because BIOPHYS is a physically-based algorithm it was able to use the same LUT over space and time (e.g., 10 year difference in acquisitions) to retrieve biophysical parameters, thus providing consistency within a quantitative structural change analysis as well as computational savings. Comparisons with field observations indicate that BIOPHYS provides good estimates of BSI with errors similar to those tolerated from ground validation data. BIOPHYS retrievals in the forest fire chronosequence study showed variations in canopy characteristics that were not detected by NDVI, which saturated. BIOPHYS is able to account for varying solar zenith and view angles between images and can show spatial patterns of vegetation structure. Overall results also showed that BSI retrievals were sensitive to sun-surface-sensor geometry that is captured in the BIOPHYS algorithm, and that integrated analyses of imagery acquired at multiple solar angles and view

angles improved retrieval precision, with solution set processing validated against BSI site data. BIOPHYS assessment of simulated as well as single-date and multi-date MODIS imagery showed a flexible capability to ingest and take advantage of multi-VZA imagery based on improvements found through convergence of solution sets against validation field data. For a temporal chronosequence, results over a decade period in Virginia provided outcomes such as the area and percent of forest disturbance (burned, logged) and early regrowth and succession that represents quantitative, structural change information regarding disturbance and growth, as well as useful inputs to process-driven carbon, ecosystem and climate models. As one example of LUT-based canopy reflectance model inversion, the BIOPHYS approach provides a quantitative basis and a variety of comprehensive spatial and temporal capabilities that are also compatible for use with forest inventories and updates as well as other major land cover monitoring and ecosystem accounting programs.

ACKNOWLEDGMENT

Qingyuan Zhang (UMBC), David Landis (SSAI), and Casey Vandenberg (University of Lethbridge) are thanked for image

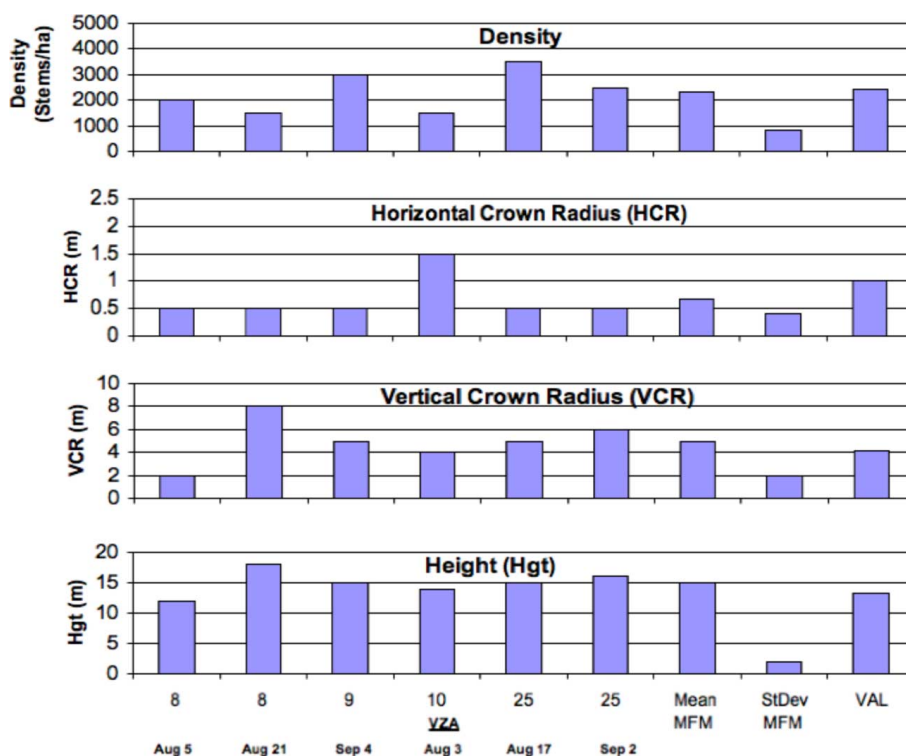


Fig. 15. BIOPHYS MFM-GOMS BSI from MODIS multi-VZA (8° to 25°), multi-date (August 3–September 4, 2001) imagery showing individual results and overall convergence statistics (mean, standard deviation MFM) against BOREAS Old Black Spruce (OBS) field validation (VAL) data.

preprocessing and data analysis support. The comments and suggestions from the anonymous reviewers are appreciated and helped improve this paper.

REFERENCES

- [1] R. B. Myneni, R. R. Nemani, and S. W. Running, "Algorithm for the estimation of global land cover, LAI and FPAR based on radiative transfer models," *IEEE Trans. Geosci. Remote Sens.*, vol. 35, pp. 1380–1393, 1997.
- [2] J. Cihlar, S. Denning, F. Ahern, O. Anno, A. Belward, F. Bretherton, W. Cramer, G. Dedieu, C. Field, R. Francey, R. Gommès, J. Gosz, K. Hibbard, T. Igarashi, P. Kabat, D. Olsen, S. Plummer, I. Rasool, M. Raupach, R. Scholes, J. Townshend, R. Valentini, and D. Wickland, "Initiative to quantify terrestrial carbon sources and sinks," *EOS Trans.*, vol. 83, no. 1, pp. 1–7, 2002.
- [3] North American Carbon Program Science Implementation Strategy. Prepared for the U.S. Carbon Cycle Scientific Steering Group (CCSSG) and Interagency Working Group (CCIWG). NACP, 2005 [Online]. Available: <http://www.nacarbon.org/nacp/>
- [4] J. G. Masek and G. J. Collatz, "Estimating forest carbon fluxes in a disturbed southeastern landscape: Integration of remote sensing, forest inventory, and biogeochemical modeling," *J. Geophys. Res.*, vol. 111, no. G01006, 2006.
- [5] M. A. Wulder, J. C. White, M. Cranny, R. J. Hall, J. E. Luther, A. Beaudoin, D. G. Goodenough, and J. A. Dechka, "Monitoring Canada's forests. Part 1: Completion of the EOSD land cover project," *Can. J. Remote Sens.*, vol. 34, no. 6, pp. 549–562.
- [6] S. Liang, "Recent developments in estimating land surface biogeophysical variables from optical remote sensing," *Progr. Phys. Geography*, vol. 31, no. 5, pp. 501–516, 2007.
- [7] A. H. Strahler, "Vegetation canopy reflectance modeling—Recent developments and remote sensing perspectives," *Remote Sens. Rev.*, vol. 15, pp. 179–194, 1997.
- [8] F. G. Hall, D. E. Knapp, and K. F. Huemmrich, "Physically based classification and satellite mapping of biophysical characteristics in the southern boreal forest," *J. Geophys. Res., BOREAS Special Issue*, vol. 102, no. D24, pp. 29567–29580, 1997.
- [9] J. M. Chen, X. Li, T. Nilson, and A. Strahler, "Recent advances in geometrical optical modelling and its applications," *Remote Sens. Rev.*, vol. 18, pp. 227–262, 2000.
- [10] D. S. Kimes, Y. Knyazikhin, J. L. Privette, A. A. Abuelgasim, and F. Gao, "Inversion methods for physically-based models," *Remote Sens. Rev.*, vol. 18, pp. 381–439, 2000.
- [11] D. R. Peddle, S. E. Franklin, R. L. Johnson, M. A. Lavigne, and M. A. Wulder, "Structural change detection in a disturbed conifer forest using a geometric optical reflectance model in multiple-forward mode," *IEEE Trans. Geosci. Remote Sens.*, vol. 41, no. 1, pp. 163–166.
- [12] S. Liang, Ed., *Advances in Land Remote Sensing: System, Modeling, Inversion and Application*. New York: Springer Press, 2008, pp. 498–498.
- [13] I. Moorthy, J. R. Miller, J. A. Jimenez-Berni, P. J. Zarco-Tejada, and B. Hu, "Characterization of olive (*Olea europaea* L.) tree crowns using terrestrial laser scanning and 3D radiative transfer modeling," in *Proc. 30th Can. Symp. Remote Sens.*, Lethbridge, Alberta, Canada, Jun. 22–25, 2009.
- [14] M. Weiss, F. Baret, R. B. Myneni, A. Pragnere, and Y. Knyazikhin, "Investigation of a model inversion technique to estimate canopy biophysical variables from spectral and directional reflectance data," *Agronomie*, vol. 20, pp. 3–22, 2000.
- [15] D. R. Peddle, R. L. Johnson, J. Cihlar, S. G. Leblanc, and J. M. Chen, "MFM-5-Scale: A physically-based inversion modeling approach for unsupervised cluster labeling and classification," in *Proc. 22nd Can. Symp. Remote Sens.*, Victoria, BC, Canada, Aug. 21–25, 2000, pp. 477–486.
- [16] B. Combal, F. Baret, M. Weiss, A. Tubuil, D. Mace, A. Pragnere, R. Myeni, Y. Knyazikhin, and L. Wang, "Retrieval of canopy biophysical variables from bidirectional reflectance using prior information to solve the ill-posed inverse problem," *Remote Sens. Environ.*, vol. 84, pp. 1–15, 2002.
- [17] D. R. Peddle, S. Boon, A. P. Glover, and F. G. Hall, "Forest structure without ground data: Adaptive full-blind multiple forward-mode canopy reflectance model inversion in a mountain pine beetle damaged forest," *Int. J. Remote Sens.*, vol. 31, no. 8, pp. 2123–2128, 2010.
- [18] D. R. Peddle, R. L. Johnson, J. Cihlar, S. G. Leblanc, J. M. Chen, and F. G. Hall, "Physically-based inversion modeling for unsupervised cluster labeling, independent forest classification and LAI estimation using MFM-5-Scale," *Can. J. Remote Sens.*, vol. 33, no. 3, pp. 214–225, 2007.

- [19] D. R. Peddle, R. L. Johnson, J. Cihlar, and R. Latifovic, "Large area forest classification and biophysical parameter estimation using the 5-Scale canopy reflectance model in multiple-forward mode," *Remote Sens. Environ., BOREAS Special Issue*, vol. 89, no. 2, pp. 252–263, 2004.
- [20] D. R. Peddle, P. M. Teillet, and M. A. Wulder, "Radiometric image processing," in *Remote Sensing of Forest Environments: Concepts and Case Studies*, M. A. Wulder and S. E. Franklin, Eds. London/Dordrecht/Boston: Kluwer Academic Press, ch. 7, pp. 181–208.
- [21] S. A. Soenen, D. R. Peddle, R. J. Hall, C. A. Coburn, and F. G. Hall, "Estimating aboveground forest biomass from canopy reflectance model inversion in mountainous terrain," *Remote Sens. Environ.*, vol. 114, no. 7, pp. 1325–1337, 2010.
- [22] S. A. Soenen, D. R. Peddle, C. A. Coburn, R. J. Hall, and F. G. Hall, "Canopy reflectance model inversion in multiple forward mode: Forest structural information retrieval from solution set distributions," *Photogramm. Eng. Remote Sens.*, vol. 75, no. 4, pp. 361–374, 2009.
- [23] S. A. Soenen, D. R. Peddle, C. A. Coburn, R. J. Hall, and F. G. Hall, "Improved topographic correction of forest image data using a 3-D canopy reflectance model in multiple forward mode," *Int. J. Remote Sens.*, vol. 29, no. 4, pp. 1007–1027, 2008.
- [24] S. A. Soenen, D. R. Peddle, and C. A. Coburn, "SCS+C: A modified sun-canopy-sensor topographic correction in forested terrain," *IEEE Trans. Geosci. Remote Sens.*, vol. 43, no. 9, pp. 2149–2160, 2005.
- [25] N. Pilger, D. R. Peddle, and R. J. Hall, "Forest volume estimation using a canopy reflectance model in multiple-forward-mode," in *Proc. 25th Can. Symp. Remote Sens.*, Montreal, QC, Canada, Oct. 14–17, 2003.
- [26] N. Pilger, D. R. Peddle, and J. E. Luther, "Estimation of forest cover type and structure from Landsat TM imagery using a canopy reflectance model for biomass mapping in western newfoundland," in *Proc. IEEE Int. Geosci. Remote Sens. Symp. (IGARSS'02)/24th Can. Symp. Remote Sens.*, Toronto, ON, Canada, Jun. 24–28, 2002, (CD-ROM).
- [27] J. Cihlar, B. Guindon, J. Beaubien, R. Latifovic, D. Peddle, M. Wulder, R. Fernandes, and J. Kerr, "From need to product: A methodology for completing a land cover map of Canada using Landsat imagery," *Can. J. Remote Sens.*, vol. 29, no. 2, pp. 171–186, 2003.
- [28] J. A. Gamon, K. F. Huemmrich, D. R. Peddle, J. Chen, D. Fuentes, F. G. Hall, J. S. Kimball, S. Goetz, J. Gu, K. C. McDonald, J. R. Miller, M. Moghaddam, A. F. Rahman, J.-L. Roujean, E. A. Smith, C. L. Walthall, P. Zarco-Tejada, B. Hu, R. Fernandes, and J. Cihlar, "Remote sensing in BOREAS: Lessons learned," *Remote Sens. Environ., BOREAS Special Issue*, vol. 89, no. 2, pp. 139–162, 2004.
- [29] A. Lyapustin and Y. Knyazikhin, "Green's function method for the radiative transfer problem. 2. Spatially heterogeneous anisotropic surface," *Appl. Opt.*, vol. 41, no. 27, pp. 5600–5606, 2002.
- [30] K. F. Huemmrich, "The GeoSail model: A simple addition to the SAIL model to describe discontinuous canopy reflectance," *Remote Sens. Environ.*, vol. 75, no. 3, pp. 423–431, 2001.
- [31] X. Li and A. H. Strahler, "Geometric-optical bidirectional reflectance modeling of the discrete crown vegetation canopy: Effect of crown shape and mutual shadowing," *IEEE Trans. Geosci. Remote Sens.*, vol. 30, pp. 276–292, 1992.
- [32] P. M. Teillet, N. E. Saleous, M. C. Hansen, J. C. Eidenshink, C. O. Justice, and J. R. G. Townshend, "An evaluation of the global 1-km AVHRR land dataset," *Int. J. Remote Sens.*, vol. 21, no. 10, pp. 1987–2021, 2000.
- [33] C. O. Justice and J. R. G. Townshend, "Special issue on the moderate resolution imaging spectroradiometer (MODIS): A new generation of land surface monitoring," *Remote Sens. Environ.*, vol. 83, pp. 1–2, 2002.
- [34] M. A. Wulder, J. C. White, S. N. Goward, J. G. Masek, J. R. Irons, M. Herold, W. B. Cohen, T. R. Loveland, and C. E. Woodcock, "Landsat continuity: Issues and opportunities for land cover monitoring," *Remote Sens. Environ.*, vol. 112, no. 3, pp. 955–969.
- [35] F. G. Hall, K. F. Huemmrich, D. E. Strebel, S. J. Goetz, J. E. Nickeson, and K. D. Woods, *Biophysical, Morphological, Canopy Optical Property, and Productivity Data From the Superior National Forest*. Washington, DC: NASA, Technical Memorandum TM-104568, 1992.
- [36] F. G. Hall, Y. E. Shimabukuro, and K. F. Huemmrich, "Remote sensing of forest biophysical structure using mixture decomposition and geometric reflectance models," *Ecol. Applicat.*, vol. 5, no. 4, pp. 993–1013, 1995.
- [37] J. G. Masek, C. Huang, R. Wolfe, W. Cohen, F. Hall, J. Kutler, and P. Nelson, "North American forest disturbance mapped from a decadal Landsat record," *Remote Sens. Environ.*, vol. 112, no. 6, pp. 2914–2926, 2008.



Derek R. Peddle received B.Sc. degrees in computer science and geography (Honours) from the Memorial University of Newfoundland, the M.Sc. degree in geography from the University of Calgary, and the Ph.D. degree in geography from the University of Waterloo.

He is Professor of geography at the University of Lethbridge and Associate Director of the Alberta Terrestrial Imaging Centre (ATIC). He has worked at C-CORE, NORDCO, ISTS, WLU and NASA.

In 2000 he was International Fulbright Scholar at NASA Goddard Space Flight Center and University of Maryland, USA. He received the NASA Visiting Scientist Award (USRA 1994), National Best Ph.D. Thesis Award (CRSS 1997), Alberta Centennial Medal (2005) and was awarded the 2006 Canada-U.S. Fulbright Distinguished Visiting Research Chair, University of California Santa Barbara, USA. His NSERC-funded research programme involves remote sensing and software development for environmental change, forestry, agriculture, water and mountain terrain applications.

Dr. Peddle is an Associate Editor of the *Canadian Journal of Remote Sensing*, was National Chair of the Canadian Remote Sensing Society (2007–2009), and was 2009 General Conference Chair of the 30th Canadian Symposium on Remote Sensing in Lethbridge. His website is <http://people.uleth.ca/~derek.peddle>



K. Fred Huemmrich received the B.S. degree in physics from Carnegie-Mellon University and the Ph.D. degree in geography from the University of Maryland.

He is a Research Associate Professor in the Joint Center for Earth Systems Technology at the University of Maryland Baltimore County and works in the Biospheric Sciences Branch of NASA's Goddard Space Flight Center. His current research interests include development of remote sensing techniques to describe ecosystem processes through

both modeling and field work.



Forrest G. Hall received the B.S. degree in mechanical engineering from the University of Texas, and the M.S. and Ph.D. degrees in physics from the University of Houston.

He is a physicist, currently with the University of Maryland Baltimore County, located at the NASA Goddard Space Flight Center in the GSFC/UMBC Joint Center for Earth Systems Technology (JCET). He has been active since 1980 in global change research using earth-observing satellites to monitor human-induced and natural changes to the earth's

land ecosystems and the effects those changes have had on the earth's climate. He has authored more than 50 scientific papers on satellite monitoring, the global carbon cycle and climate change. He is a regular lecturer, both nationally and internationally. He has addressed a broad range of audiences, including middle and high schools, universities, women's groups, state and national congressional representatives, religious organizations, and scientific meetings.

In 2009, Dr. Hall received the William T. Pecora Award with the citation for exceptional contributions to remote sensing of terrestrial ecosystems.



Jeffrey G. Masek received the B.A. degree in geology from Haverford College in 1989, and the Ph.D. degree in geological sciences from Cornell University in 1994.

He is a Research Scientist in the Biospheric Sciences Branch at the NASA Goddard Space Flight Center. His research interests include mapping land-cover change in temperate environments, application of advanced computing to remote sensing, and satellite remote sensing techniques. Dr. Masek has held previous positions at the University of

Maryland, Hughes Information Systems, and Cornell University. At the University of Maryland, he acted as project manager for the REALM Image

Database system, which pioneered automated, large-area land-cover analyses through parallel processing of Landsat data, and was also Deputy Team Leader for the Landsat Science Team. At Hughes Information System, he managed the collaborative prototyping program for the EOSDIS Core System (ECS) project, which sought out and funded innovative earth science information prototypes from the academic community.



Scott A. Soenen received the B.Sc. (Honours) degree in geography with a concentration in geographical information sciences (2003) and the M.Sc. degree in geography (2006) from the University of Lethbridge, Canada, for which he received the Canadian Remote Sensing Society 2006 Best Master's Thesis Award. From 2006 to 2008, he was a Research Associate supported by NSERC, the Alberta Ingenuity Centre for Water Research and the Prairie Adaptation Research Collaborative at the University of Lethbridge. In 2008–2009, he was an Alberta Ingenuity Industry

Associate. He is currently Chief Technology Officer with Iunctus Geomatics

Corp., Lethbridge. His research interests are in canopy reflectance modeling and remote sensing with applications in forestry and climate change.



Chris D. Jackson received the B.Sc. degree (with Distinction) in geography with a concentration in the geographical information sciences from the University of Lethbridge in 2006. He received the University of Lethbridge Scholarship in 2004, the Jason Lang Scholarship in 2004 and 2005, and the Geographic Information Science Scholarship in 2005.

From 2006 to 2008, he worked as a Research Assistant in Remote Sensing at the University of Lethbridge and then at the Northern Forestry Centre of the Canadian Forest Service, Edmonton Alberta (2008–2009). He is currently a GIS Specialist at Stantec Inc. in Calgary, Alberta. His research interests include hyperspectral and high-resolution imaging sensors and their applications in resource management.