North American Landscape Characterization Dataset Development and Data Fusion Issues

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Abstract

With the launch of Landsat 1 on 23 July 1972, the United States initiated the capability for land resource monitoring from space. Over a 20-year period, the Landsat Multi-Spectral Scanner (MSS) sensor collected data documenting land-cover conditions over the majority of the globe. The global change research community has prioritized reducing the uncertainty associated with land cover-change as a major constituent of importance to balancing the global carbon cycle. The MSS archive currently represents the best available, continuous public source of relatively high resolution imagery for the monitoring of land cover over the 1972-1992 period. The North American Landscape Characterization project was designed to exploit this archive by providing standardized satellite data sets to support land-cover change analysis. Land-cover categorization products derived from MSS data alone provide only a general characterization of land-cover condition and change. A data fusion approach using a post-classification technique is presented as a cost-effective method for delineating land cover at appropriate thematic and spatial resolutions to support a quantitative inventory of forest carbon stocks. Issues related to assessing the accuracy of carbon inventory datasets is presented, and a two-step model is proposed for accuracy assessment.

Introduction

The North American Landscape Characterization (NALC) project is a component of the National Aeronautics and Space Administration's (NASA) Landsat Pathfinder program of experiments to study global change issues. The NALC project is one of three Landsat Pathfinder projects approved by the Landsat Pathfinder Science Working Group along with the Humid Tropical Forest Inventory Project and the Global Land Cover Test Site Project. The NALC project was sponsored by the U.S. Environmental Protection Agency's (EPA) Office of Research and Development (ORD), the U.S. Global Change Research Program (USGCRP), and the U.S. Geological Survey, EROS Data Center. In addition, substantial collaboration for NALC efforts in the Laurentian Great Lakes was performed by the Canada Centre for Remote Sensing (CCRS), Ottawa, Canada. Landsat Pathfinder coordination and technical review was provided by the NASA Ames Research Center at Moffett Field, California and the Goddard Space Flight Center at Greenbelt, Maryland.

This paper provides a descriptive overview of the NALC program, provides examples of NALC land-cover categorization products, presents provisional carbon inventory data fusion products, and describes a two-step model for accuracy assessment.

The primary goal of the NALC project was to assemble and distribute standard Landsat MSS image datasets to the scientific community, and to provisionally apply these data on a selective basis to study land cover and land-cover change in support of global change research issues. Land-cover data products at a 3.2-hectare spatial resolution have been produced for priority locations in the Mexican humid tropics (Lyon *et al.*, 1998). Other projects have been completed using NALC data, including a mosaic of the Canadian and United States Laurentian Great Lakes watershed (Guindon, 1995). The program was originally designed to provide source data for land-cover categorization and change-detection analysis across North America. Initially, these data have been used to supply information on the spatial distribution of forest cover types required for regional and national inventories of terrestrial carbon stocks and trace greenhouse gas (i.e., CH_4, N_2O) emissions, in support of the Intergovernmental Panel on Climate Change (IPCC) science objectives (Houghton *et al.*, 1992) and the climate-change action plan target of returning emissions of greenhouse gases in the United States to 1990 emission levels by the year 2000 (Clinton and Gore, 1993).

The main objective of the NALC project was to produce standardized remote sensing datasets, or "triplicates," that consisted of three or more registered Landsat MSS images corresponding to the 1990s, 1980s, and 1970s time periods. On average, a NALC triplicate consists of one scene from the 1990s and 1980s and two from the 1970s for each path/row.

Background

The principal clients of the NALC project were the USGCRP and, in particular, the EPA's GCRP. An important objective of the USGCRP was to document global change through an integrated, comprehensive, long-term program of observing and analyzing change on a global scale (CEES, 1993). The NALC project will provide documentation of land-cover change for large portions of North America, by establishing a database of Landsat MSS images acquired over a 20-year period. The principal science goal was to monitor forest land cover, including forest distributions across the North American continent, land-cover conversion (i.e., forests to alternate land-cover types), and forest regrowth. NALC data can support the

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creation of land-cover database products by exploiting the extensive Landsat MSS data archive.

Many researchers believe that, to conserve significant quantities of carbon (C), deforestation must be controlled and management strategies need to be implemented to improve forest system net primary productivity (NPP) (Houghton, 1992; Clinton and Gore, 1993; Haynes *et al.*, 1994). Current estimates indicate that the world's forests contain up to 80 percent of the above-ground and 40 percent of below-ground C stocks. Uncertainties in balancing the contribution of forest landscapes to the global C budget will continue until source data are available that can accurately characterize the spatial distribution and condition of forest resources (Dixon *et al.*, 1994).

National C pools have traditionally been determined by multiplying the area (ha) for each major land cover type (e.g., forest, woodland/scrub, wetland, mangrove, etc.) by its respective C density (MgC/ha) and summing the resultant quantities (PgC) for entire countries. Ideally, all aspects of NPP, including changes in above- and below-ground phytpomass, should be measured. In practice, this rarely occurs due in large part to the lack of reliable land-cover and land-cover change datasets (Cairns *et al.*, 1997). Above-ground forest C content can be crudely estimated based on general forest type land-cover distributions or quantified with a higher degree of certainty by resolving individual forest community types and densities. The following relationship is proposed as a potential quantification approach:

$$\text{forest community C content} = \sum_{i=1}^{n} fc_i\,(s_i \cdot a_i \cdot d_i \cdot k_i)$$

where c is the carbon content (PgC), n is the number of forest community types, fc is the forest community type, s is the forest seral stage coefficient, a is the stand area (ha), d is the stand density (percent canopy cover), and k is the forest community specific carbon content density for late seral and 100 percent canopy cover (MgC/ha).

Also, the long-term monitoring of cleared forests is important to quantify the rate of C storage or sequestration (Dixon *et al.*, 1994), and the emissions of other radiative important trace gases (RITG). For example, forest-to-pasture conversions in the humid tropics of Costa Rica resulted in a three-fold increase of N_2O flux relative to the original forest soil. The rate of flux peaked during the first ten years of conversion, then dropped below original forest flux rates (Keller *et al.*, 1993). This example indicates the value of general land-cover and land-cover change data when used in combination with field sampling measurements to further our understanding of regional scale processes.

Numerous attempts have been made to use satellite data to monitor forest stand condition and change in the humid tropics of Brazil or the Pan-Amazon (Nelson and Holben, 1986; Nelson *et al.*, 1987; Skole and Tucker, 1993). Results indicate that Advanced Very High Resolution Radiometer (AVHRR)/Local Area Coverage (LAC) data can provide reconnaissance level data of forests at a regional to continental scale, when used in conjunction with higher resolution data (e.g., Landsat MSS) (Nelson and Horning, 1990). However, Landsat MSS and TM data provide the finer spatial resolution necessary to accurately characterize forest change (Nelson *et al.*, 1987). Landsat Thematic Mapper (TM) and SPOT multispectral (XS) data provide comparable estimates of forest extent and distribution (Skole and Tucker, 1993).

Approach

NALC triplicate data sets have been assembled for a large portion of the North American continent land mass. The NALC study area was defined as the area north of the Panama-Colombia border and including the Caribbean and the Hawaiian Islands. Due to funding restraints and insufficient Landsat data holdings in U.S. archives for Canada, the NALC project did not assemble triplicate datasets for all of Canada. Canadian archives contain an extensive collection of Landsat MSS data from the 1990s, 1980s, and 1970s that could be used in support of a NALC/Canada effort.

Satellite Data Acquisitions

Landsat MSS data were selected as the source data for the NALC triplicate development. This was for several reasons, including the extensive 20-year MSS data archive and the relatively low data acquisition and processing costs as compared to Landsat TM or SPOT XS data. Data used to assemble the NALC triplicates included MSS data for three epochs, 1990-92, 1985-87, and 1972-74. These epoch periods were selected to coincide with archival data maxima and provide roughly equal temporal spacing. The objective was to select high quality scenes for each epoch period; however, numerous deviations occurred due to the lack of available high quality archive data.

A total of 801 new (i.e., non-archival) Landsat MSS scenes were acquired for the time period of 1991 plus or minus one year. The acquisition of these 1990 scenes was a major program accomplishment. This purchase was significant because the existing archive contained insufficient data to provide complete coverage for the 1990s and additional acquisitions were not planned before the MSS sensor was scheduled to be decommissioned in 1992. New data purchases for the 1990s were made for Mexico (119 scenes), Central America (32 scenes), the Caribbean Islands (48 scenes), Alaska (180 scenes), the Continental United States (414 scenes), and the Hawaiian Islands (eight scenes).

New Data Acquisition and Archival Scene Selection

Vegetation Phenology

The first step in the process was the establishment of time "windows" for Landsat MSS data acquisitions. Time "windows" were defined using temporal variables based on plant phenology to provide temporal continuity essential for performing accurate land-cover change analysis. The goal was to minimize spectral differences associated with vegetation phenology in order to optimize accuracy.

AVHRR NDVI biweekly composite data sets, or "greenness" images (Eidenshink *et al.*, 1991), were used to establish suitable vegetation phenology time windows for each Landsat path/row location. The suitability of times was based on the onset, peak, and duration of "greenness." An optimal 90-day window was defined for use in scheduling of new data acquisitions and to search for suitable archival data.

Temporal Continuity

The Landsat MSS archive was evaluated to determine the availability of existing high-quality and cloud-free MSS images for 1980s and 1970s that met established acquisition "windows." An EROS Data Center document that describes the historical cloud-cover conditions for each World Reference System 2 (WRS-2) path/row was used to further refine the phenology based acquisition windows to optimize for new data acquisitions. Subsequent to data acquisitions in 1991 and 1992, approximately 3,000 Landsat MSS NALC images were screened to obtain an initial list of scenes that fell within the established acquisition windows and exhibited a cloud cover of less than 30 percent. Microfiche of all candidate scenes were then viewed, and scene selections made for

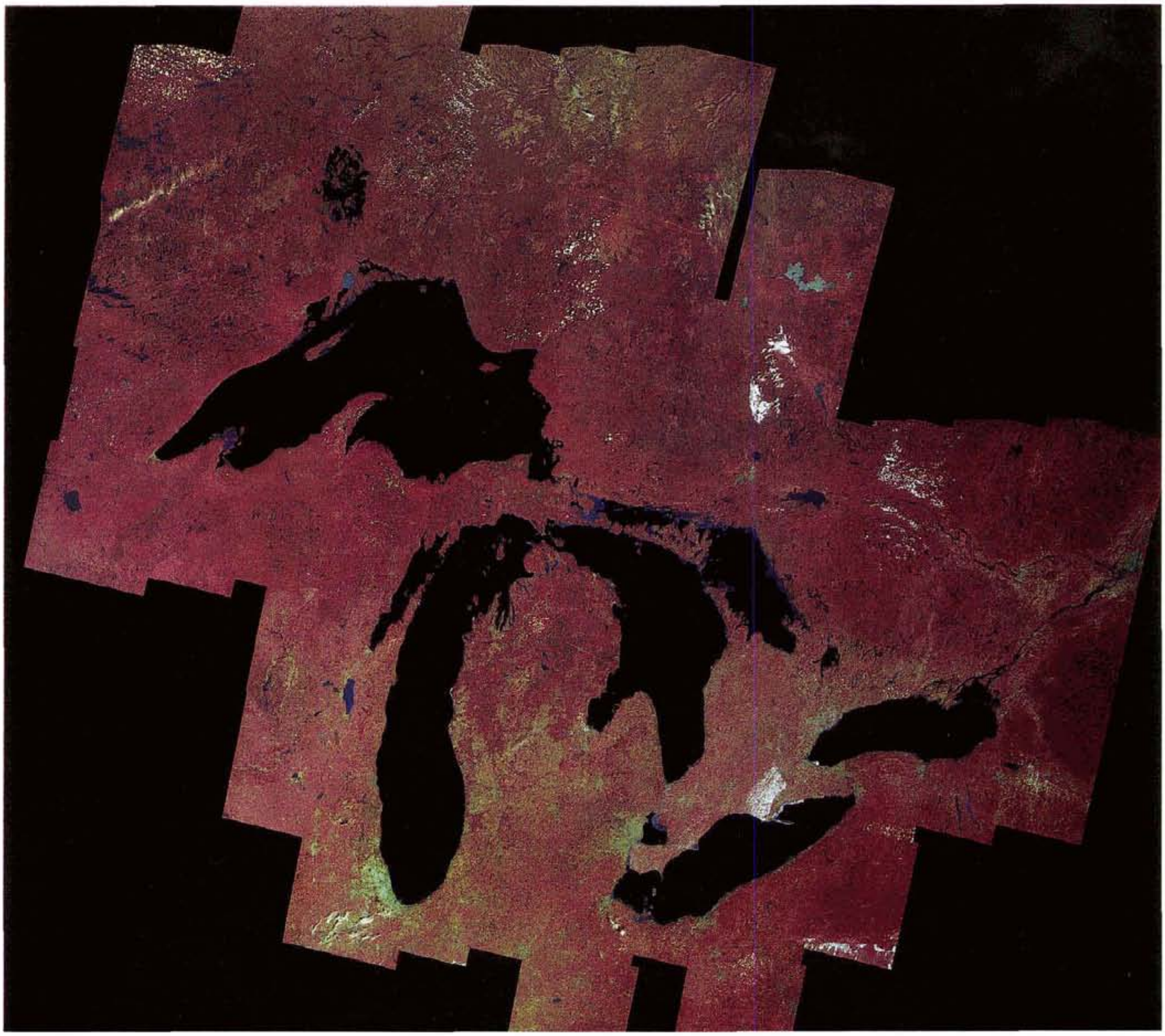


Plate 1. NALC mosaic image of the Canadian and United States Laurentian Great Lakes developed by the Canada Centre for Remote Sensing. A total of 82 Landsat MSS scenes, acquired over the 1985-1987 time window, were merged in order to cover the whole watershed. Note that the MSS data in the mosaic have been aggregated to a pixel resolution of 200 metres.

the three epoch periods. When an image was not available within a given three-year window that met the phenology and cloud-cover requirements, images were selected outside of the window to coincide with the established phenology windows. All triplicate scene selections have been published in the NALC Research Plan (Lunetta *et al.*, 1993).

Triplicate Data Sets

The standard data used in support of NALC featured Landsat MSS triplicates that have been georeferenced, coregistered, and registered to Earth coordinates (rectified). Standard triplicate datasets included coregistered digital elevation model (DEM) data in addition to the image data (Lunetta *et al.*, 1993). All datasets were clipped to the Landsat WRS-2 image sampling frame. In the case of the 1970s imagery, which conforms to the WRS-1 sampling frame, multiple scenes were acquired and clipped to the WRS-2 boundaries and processed as separate images in order to provide complete coverage for each scene in each decade.

Database Development

For each triplicate set, the 1980s image was rectified and then used as a template to coregister 1970s and 1990s images. Image control points were selected from the 1980s images, and corresponding map control points were obtained from maps or a library of ground control points (GCP) for use in developing the model for geometric transformations (geocoding). A single-step cubic convolution algorithm was used to rectify and resample the image into a Universal Transverse Mercator (UTM) projection with a 60- by 60-metre pixel

TABLE 1. NALC PATHFINDER CATEGORIZATION SYSTEM

Level 0	Level 1	Level 2
Land	1.0 Barren or Developed Land	1.1 Exposed Land 1.2 Developed Land
	2.0 Woody	2.1 Forest 2.2 Scrub/Shrub
	3.0 Herbaceous	3.1 Herbaceous
	4.0 Arid	4.1 Arid Vegetation 4.2 Riparian
	5.0 Snow/Ice	5.1 Snow/Ice
Water	6.0 Water & Submerged Land	6.1 Ocean 6.2 Coastal 6.3 Near-Shore 6.4 Inland
Other	7.0 Other	7.1 Cloud 7.2 Shadow 7.3 Missing 7.4 Indeterminable

size. Quantitative assessment was undertaken to ensure that residual geometric corrections were within acceptable limits established for both within and outside the United States to correspond with available map scales.

Images were preprocessed to compensate for variations in the radiometric response of the individual detectors prior to geometric registration in order to correct scan-line dependent noise. An interim systematic correction was applied, using the satellite ephemeris data and platform navigation model, to generate a UTM image that was oriented with north at the top. Automated cross-correlation procedures were then implemented to extract control points from triplicate images to compute coefficients for image-to-image registration. When an accurate transformation was developed, the grid for the interim systematic correction was convolved with the image-to-image transformation grid to produce coefficients that facilitated a single-step registration of the 1970s and 1990s products with the previously map-registered 1980s image. The result was an image registration procedure that only involved one step of re-sampling (Lunetta *et al.*, 1993). The last step involved creation of a pixel identity image to accompany each of the 1970s images. Each pixel value in the identity image identifies the specific 1970s scene used to build the WRS-2 path/row equivalent.

The final database development task involved the mosaicking and projection transformation of the DEM data. The DEM data were derived from the Defense Mapping Agency (now National Image and Mapping Agency or NIMA) digital terrain and elevation data (DTED) which were digitized from standard 1:250,000-scale topographic maps. Complete coverage existed for the United States and Mexico. These data, often referred to as three-arc-second DTED, were provided as a gridded DEM corresponding to a 1- by 1-degree data block. For the NALC project, these blocks were mosaicked for the path/row of interest, and then reprojected and resampled to 60- by 60-metre pixels in the UTM projection.

Land-Cover Categorization

The NALC land-cover categorization system was designed to provide information for documenting land-cover change and for the calculation of standing carbon stocks (Table 1). The original NALC classification system was based primarily on vegetation structure and was hierarchical. This hierarchial system provided the capability to translate (convert) between other major land-cover categorization systems (e.g., Anderson *et al.*, 1976; Brown *et al.*, 1979; Cowardian *et al.*, 1979). This multiple layer approach to categorization system development was consistent with the ongoing effort by the United Nations Environmental Program to develop a Global Vegetation Categorization System (United Nations Workshop, 1993).

The initial effort to categorize NALC imagery involved a three step process. First, unsupervised spectral clustering and statistical analysis of the raw Landsat MSS data were performed to generate training sets. Second, a maximum-likelihood classifier was applied to individual MSS scenes to produce a spectrally categorized data set using the training sets developed from clustering and statistical analysis. Third, the image categorization step involved labeling the spectral categories as to land-cover types corresponding to the NALC land-cover categorization system. Labeling was accomplished through the use of National High Altitude Photography (NHAP) leaf-on photography and subsequent field identification of spectral clusters with a low interpretation confidence.

Accuracy Assessment

An integral component of the NALC project was the quality control of data and subsequent validation of land-cover change products. Data and products should be assessed in both spatial and thematic accuracies (Lunetta *et al.*, 1991). The data quality objectives were

- *Absolute Geometric Accuracy.* The data quality objective for image-to-map registration root-mean-square (RMS) error was better than $\pm$ 1.0 pixel RMS error within the United States (1:24,000-scale base maps) and $\pm$ 1.5 pixels outside the United States (1:50,000-scale base maps).
- *Relative Geometric Accuracy.* Image-to-image registration of better than $\pm$ 0.5 pixel was established as a data quality objective. A high level of importance was placed on the image-to-image registration so as to accommodate image differencing for change-detection analysis. This accuracy objective was established so as to provide an absolute registration accuracy of $\pm$ 1.0 pixel in the resultant change image product. This accuracy was calculated using the following formula:

$$e = 2k$$

  where e is the change image relative misregistration and k is the original image misregistration.
- *Thematic.* Categorized data products were designed to be 80 percent accurate by class at a 75 percent confidence interval. The target of 80 percent accuracy was established based on results reported in the literature (Jensen *et al.*, 1984; Ormsby and Lunetta, 1987; Hopkins *et al.*, 1988). Reporting procedures for thematic accuracies included an error matrix with the percent commission error by category, percent omission error by category, total percent correct, number of points sampled, thematic accuracy at 75 percent confidence interval, and Kappa statistic (Lunetta *et al.*, 1991).

Database Availability and Distribution

An information management system (IMS) that consisted of a relational database and descriptive metadata was developed to facilitate the indexing, archiving, and distribution of data sets. The NALC and other Pathfinder data sets are managed by the Earth Observing System Data and Information System (EOSDIS) IMS. The EOSDIS IMS provides the data information and management system for all Landsat Pathfinder Project data, including source data and derivative products. Distribution is provided by the Distributed Active Archive Center (DAAC) at the USGS EROS Data Center.

The following elements are the capabilities provided by an IMS: graphic display of the extent of data coverage, geographic query, interrogation of metadata attributes, data richness or status tracking, overlays of basic cartographic elements (such as political boundaries and hydrography), viewing of selected browse products, linkages between value added products and their source data, and the ability to execute product orders.

The EDC DAAC is distributing the NALC triplicate products via file transfer protocol (ftp), on magnetic tape media, and CD-ROM. These contain the data descriptor record (DDR) files in ASCII format and the image data in band sequential format. The DDRs contain information describing the image projection parameters and UTM coordinates. The order in which files are written to tape is constant, except that the number of files depends on the number of scenes used for each of the 1970s and 1990s components. The image files, in turn, vary in size (number of lines, samples, and bands). A DDR file is written before each image file. All files (images and DTED) have the same dimensions; the MSS images are 8-bit data and the DTED are 16-bit data. Data are provided either at no cost or at the marginal cost of filling the user request.

NALC Project Results

Triplicate Images

Figure 1 contains a subset of the NALC data for path 21, row 49, located in the State of Chiapas, Mexico. Portions of three georegistered Landsat MSS "triplicate images" and the DEM data are shown. The DTED data used to construct the Mexico DEMs were acquired from the Instituto Nacional de Estadistica, Geografia e Informatica (INEGI), Aguascalientes, AGS, Mexico. As a collaborator in the NALC/Mexico effort, INEGI provided the Mexico DTED data as their contribution to the project. These data have been provided by INEGI for use in scientific investigations and projects conducted by government agencies, universities, and non-profit research institutions. For-profit organizational use of the Mexico DEM data requires prior approval from the INEGI Director General. Data may be acquired at the cost of duplication and distribution and can be queried and accessed through the EOSDIS/V.0 IMS.

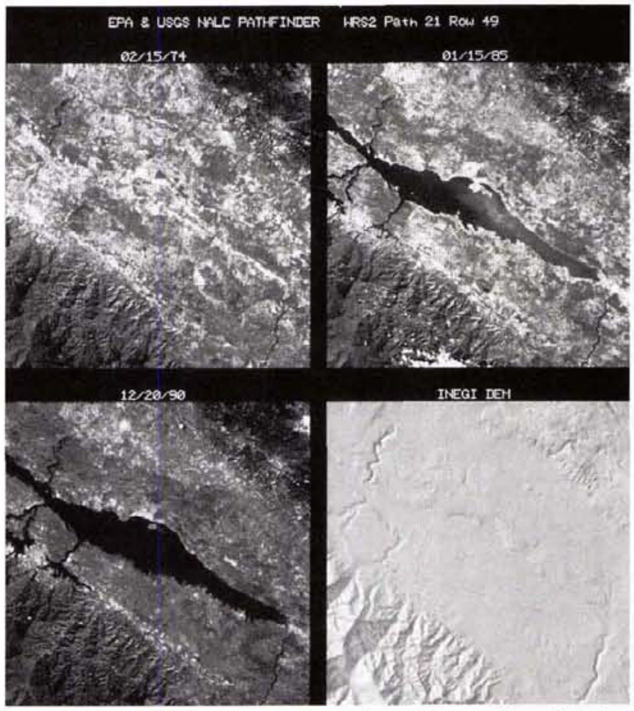


Figure 1. NALC Landsat MSS "triplicate images" and digital elevation model data (DEM) for WRS-2 path 21, row 29 in the State of Chiapas, Mexico.

An excellent example of a significant change in land cover between the 1970s data acquisitions is illustrated in the above path 21/row 29 1970s image. Although the reservoir was not present in the 15 February 1974 image, in a companion image collected on 12 May 1975 (not shown), the reservoir was present. This inconsistency in land cover between the 1970s dates necessitated that the images be held as separates in the triplicate image set.

As an example NALC product, a Great Lakes watershed pilot study was conducted by the CCRS. The CCRS Pilot differs from non-Canadian NALC project activities in that the Great Lakes watershed pilot developed a seamless 200-metre MSS data product (Plate 1) (Guindon, 1995; Guindon, 1996) in order to demonstrate the feasibility of (a) integrating NALC and Canadian operational MSS scene products and (b) creating value-added image products from the NALC archive.

Categorization Products

Provisional NALC Level II land-cover products are presented in Plates 2 and 3. The images are a subset of path 15 and row 33 and include the Washington, D.C., and Baltimore, Maryland, metropolitan areas. General trends in land-cover change associated with the process of urbanization are apparent. Over the short time period of 1987-90, there has been a significant increase in developed and herbaceous lands at the expense of forested land cover. The high degree of image-to-image coregistration between these datasets yielded land-cover products ideal for post-categorization change-detection analysis using a raster-based geographic information system (GIS). Note that the land-cover categorization depicted in these products is slightly different from that presented in Table 1.

Carbon Inventory Products

Land-cover products developed from NALC data alone are insufficient for global change research because the measurement of forest canopy density is a important variable required for C content calculations (Lunetta *et al.*, 1993). However, land-cover data derived from NALC triplicates can be combined with other raster data sets to produce interpolated data products that provide superior thematic and spatial resolution for GIS-based calculation of standing C stocks. In support of this effort, prototype carbon inventory products were developed. Plate 4a presents a product created by integrating a high spatial resolution NALC land-cover categorization product with the coarse resolution Forest Type Group data set for the continental United States. Plate 4b illustrates the integration of a NALC categorized product with the U.S. Forest Service (USFS) Forest Type Group and Forest Density data. These coarse resolution datasets were derived from AVHRR data by the USFS (Zhu and Evans, 1994).

Discussion

The "higher order" interpolation products presented here integrate the strengths associated with each data type; the relatively high spatial resolution and categorical accuracy associated with the NALC forest land cover complements the forestry attributes contained in the USFS data. This is consistent with the successful use of other types of ancillary data (e.g, DEMs, city lights, census block, etc.) to improve categorization accuracies (Bara and Shaw, 1995). The "higher order" NALC product provides information detailing the specific forest community type and density data required for calculation of forest C content. A working hypothesis is that this product provides a data set of superior quality and accuracy for the calculation of standing C stocks throughout the North American continent. The USFS is currently working on expanding the Forest Type Group and Density data to include Mexico. Once completed, this product will be available to complement the high spatial resolution NALC-based land-cover data products currently under development in the continental United States and Mexico.

The propagation of error associated with these "higher

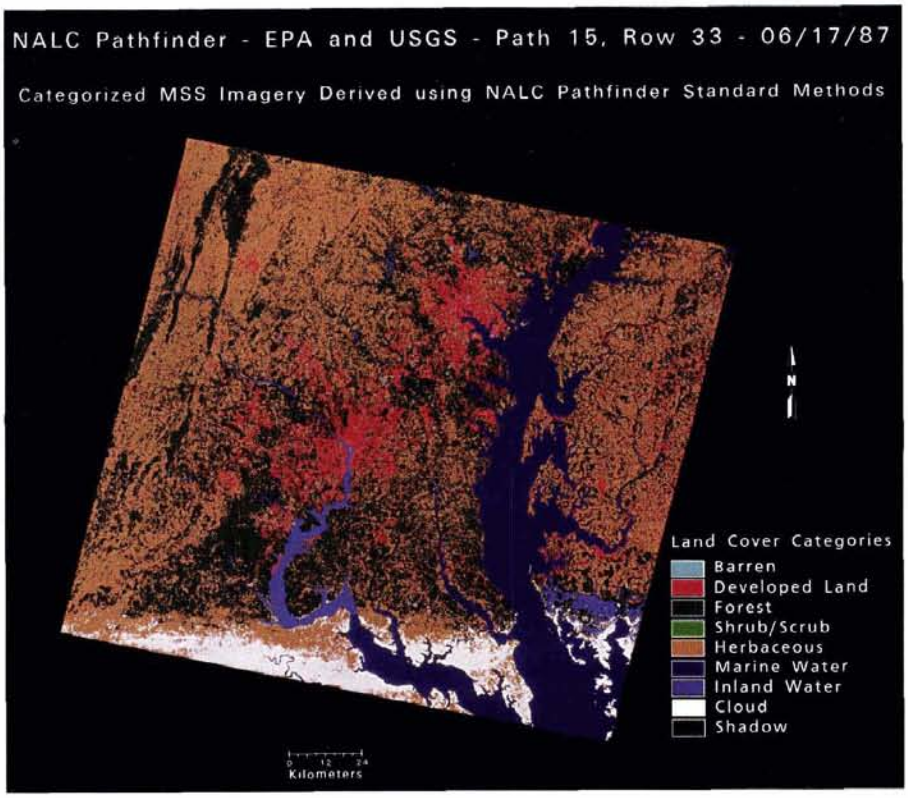


Plate 2. Categorized 17 June 1987 NALC data from WRS-2 path 15, row 33.

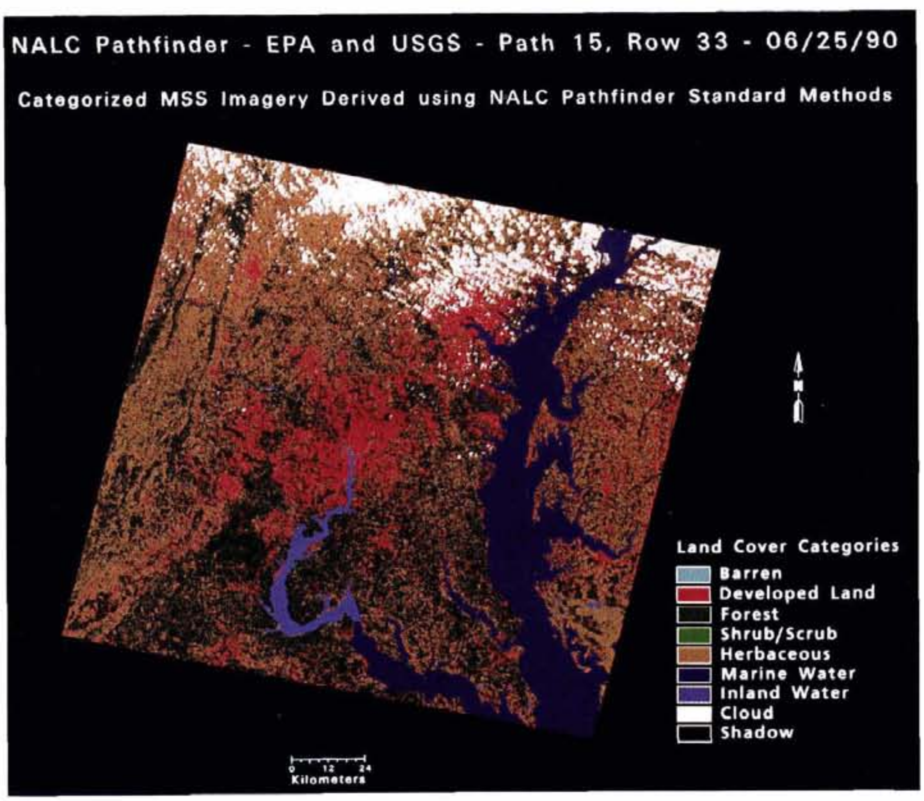
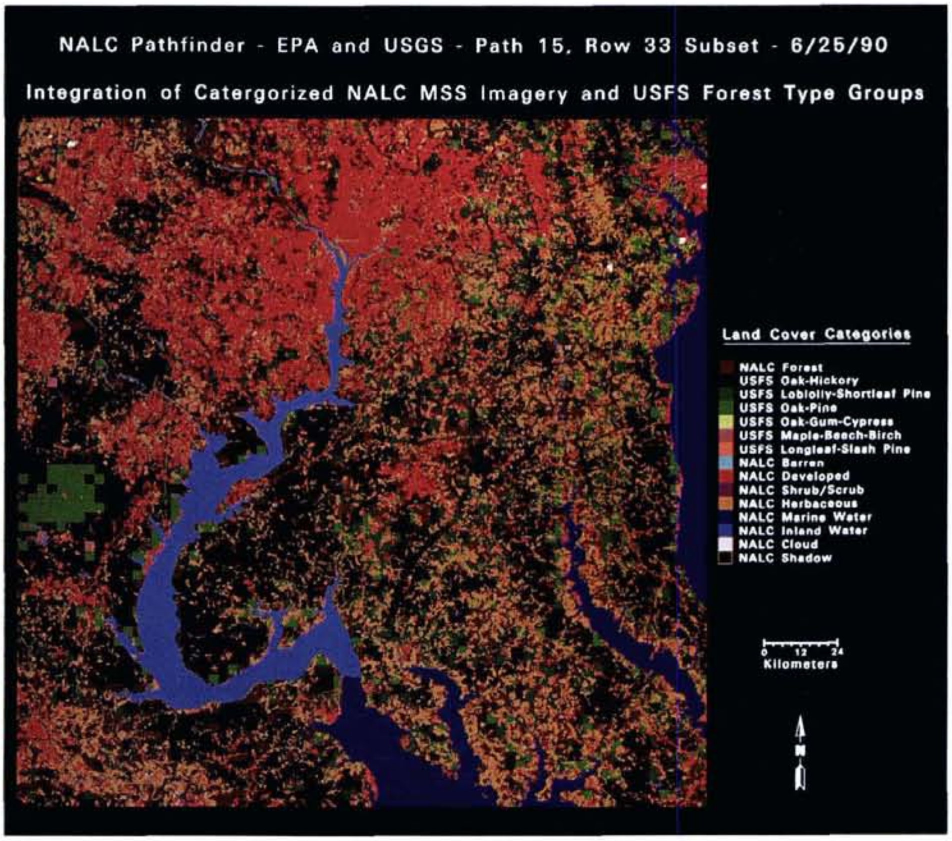
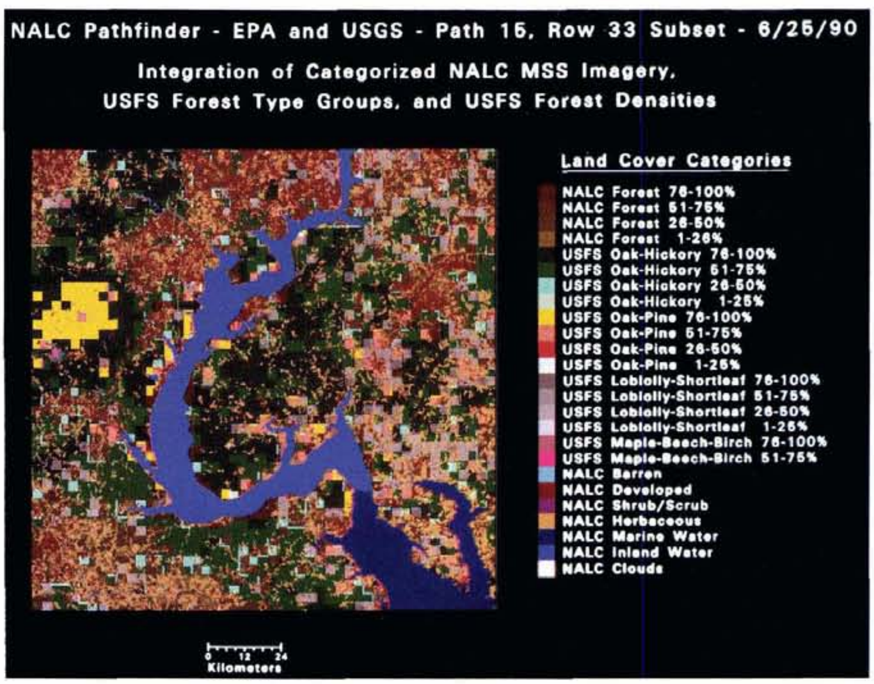


Plate 3. Categorized 25 June 1990 NALC data from WRS-2 path 15, row 33.



(a)



(b)

Plate 4. Examples of "higher order" land-cover products for potential application in the calculation of standing carbon stocks. Developed by integrating a NALC categorization product with the U.S. Forest Service forest type data (a) and forest type and forest density data sets (b).

order" C inventory products must be quantified to evaluate their full potential application for global change C studies. What is the accuracy of these integration products? Initial comparisons between Landsat MSS and TM to AVHRR-derived land-cover products have demonstrated a poor one-to-one correspondence (Stoms and Davis, 1994). However, data accuracy cannot be determined by directly comparing land cover derived from higher resolution Landsat TM and MSS sensors to that from coarse resolution AVHRR data. The large differences in positional accuracy and spatial resolution render a direct comparison meaningless. Instead, the goal is to determine how to apply these two data sets in a complementary approach to optimize both spatial resolution and categorical accuracy.

What is the best approach for assessing the error associated with the fused or "higher order" products that integrate source data with disparate resolutions? One possible approach is to apply the following two step model. First, apply the higher spatial resolution categorical data (i.e., forest polygons derived from Landsat MSS or TM) to establish the spatial distribution and effectively reduce the minimum mapping unit of the coarser resolution data set. By sub-setting the coarser resolution data into the general land-cover category(s) of interest (i.e., forested land cover) the errors of omission and commission are effectively established to coincide with the accuracy and precision of the higher resolution data. Second, subsequent to the labeling of forest polygons by forest community types and densities using the coarser spatial resolution data, polygons can then be selected on a random or stratified random basis for ground data collection to determine the predominate forest association and average densities for the construction of standard error matrices to perform an accuracy assessment of the "higher order" land-cover products. The first model step has been illustrated in this paper.

By first performing a general characterization of land-cover types using remote sensor data at the appropriate spatial resolution required to delineate land-cover types of interest (e.g., using Landsat MSS or TM data), the spatial distribution of forests can be determined at a known level of accuracy and precision. Subsequent to the assessment of categorical accuracy of the "higher order" data fusion products, their application can be evaluated for global change research applications in support of terrestrial C inventory and carbon flux studies. Future studies will address the application of these products for national and regional scale forest C inventories.

Summary

Landsat MSS data sets provide a one-of-a-kind record of land-cover change over a two-decade period from 1972 to 1992. Previous limitations to the use of Landsat MSS archive for large-area studies have included inconsistencies in data quality, changes in Landsat satellite orbital configurations, differing data formats, and the high cost of data acquisitions. The NALC project Landsat MSS "triplicate images" represent a substantial contribution to a wide variety of users that will extend well into the twenty-first century. The low cost, consistent data processing, and multi-temporal data coverage for major portions of North America will potentially benefit global change research, natural resource managers, and land-use planners.

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