Development of a Land Cover Characteristics Data Base for the Conterminous U.S.

Thomas R. Loveland

James W. Merchant
University of Nebraska-Lincoln

Donald O. Ohlen

Jesslyn F. Brown
University of Nebraska-Lincoln

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by

Thomas R. Loveland

U.S. Geological Survey

EROS Data Center

Sioux Falls, South Dakota 57198

James W. Merchant

Center for Advanced Land Management Information Technologies

Conservation and Survey Division

Institute of Agriculture and Natural Resources

University of Nebraska-Lincoln

Lincoln, Nebraska 68588-0517

Donald O. Ohlen

TGS Technology, Inc.

USGS/EROS Date Center

Sioux Falls, South Dakota 57198

Jesslyn F. Brown[1/]

Center for Advanced Land Management Information Technologies

Conservation and Survey Division

Institute of Agriculture and Natural Resources

University of Nebraska-Lincoln

Lincoln, Nebraska 68588-0517

[1/] Ms. Brown serves as a Visiting Scientist at the EROS Data Center.

ABSTRACT

Information about land cover characteristics and spatial distribution is critical to global environmental research. A prototype land cover data base for the continental United States was created for use in a variety of global modeling, monitoring, mapping, and analytical endeavors. Data base development has involved (1) a stratification of vegetated and nonvegetated land, (2) an unsupervised classification of multitemporal "greenness" data derived from AVHRR imagery collected within the period March-October 1990, and (3) post-classification stratification of classes into homogeneous land cover regions using ancillary data. Ancillary data sets included elevation, climate, ecoregions, and land resource areas. The resultant data base contains multiple layers, including the input AVHRR data, the ancillary data layers, the output land cover regions, and translation tables linking the regions to other land classification schema (i.e., UNESCO, USGS Anderson System). Future research plans include examination of impacts of interannual change, landscape/sensor interaction, development of improved analytical tools and methods, and appropriate modes for verification.

INTRODUCTION

Information regarding the characteristics and spatial distribution of the Earth's land cover is critical to global change research. Capabilities to inventory and map current land cover conditions and to monitor change are required for, among many other things, modeling the global carbon and hydrologic cycles, studying land surface-climate interactions and establishing rates of tropical deforestation (Risser, 1985; Dale, 1990; International Geosphere-Biosphere Programme, 1990; Pinker, 1990; Pielke and Avissar, 1990; and Dorman and Sellers, 1989). Global land process research has, to date, had to rely upon exceedingly simple interpretations of gross land cover and surface properties, such as biomass, albedo, surface roughness, and canopy resistance at low spatial resolution (Henderson-Sellers and others, 1986). The Matthews land cover and natural vegetation, (Matthews, 1983, 1984) and the Olson and Watts major world ecosystems (Olson and Watts, 1982) global data bases are the most common sources of land cover and surface parameter data. These data bases have, respectively, 1 degree by 1 degree and .5 degree by .5 degree spatial resolution. Higher resolution data having greater classificatory precision are clearly required (International Geosphere-Biosphere Programme, 1990).

During the last decade, substantial progress has been made in using National Oceanic and Atmospheric Administration (NOAA) Advanced Very High Resolution Radiometer (AVHRR) data for land cover characterization (e.g., Goward, Tucker and Dye, 1985; Tucker, Townshend, and Goff, 1985; Roller and Colwell, 1986; Townshend, Justice, and Kalb, 1987; and Lloyd, 1990).

AVHRR data has only moderate spatial resolution (1 km) when compared, for example, to Landsat 80 m for Multispectral Scanner (MSS) and 30 m for Thematic Mapper (TM) or SPOT (20 m for multispectral and 10 m for panchromatic) data. AVHRR data are, however, collected more frequently, with virtually the entire globe imaged twice each day. The high frequency of coverage enhances the likelihood that cloud-free observations can be obtained for specific temporal windows, and makes it possible to monitor change in land cover conditions over short time periods such as a growing season (e.g., Miller and others, 1988; Tappan and Moore, 1989; Justice and others, 1985; Goward, Tucker, and Dye, 1985). Moreover, the moderate resolution of the data makes it feasible to collect, store, and process continental or global data sets.

Research on applications of AVHRR data for land cover inventory and monitoring has focused on analysis of vegetation "greenness." Greenness is most often measured using a vegetation index, commonly the Normalized Difference Vegetation Index (NDVI) (e.g., Goward, Tucker, and Dye, 1985). A number of investigators have shown that changes in greenness during a growing season can be observed and often correlated with the spatial distribution of major biomes (e.g., Townshend, Justice, and Kalb, 1987; Tucker, Townshend, and Goff, 1985; and Lloyd, 1990). Because of limitations in AVHRR data availability, almost all regional, continental, and global-scale analyses have been conducted using data which has been resampled to either 4 or 16-km pixels (i.e., Global Area Coverage (GAC) or Global Vegetation Index (GVI) data). Only recently have spatially extensive data sets at the highest nominal resolution (1.1 km) started to become available on a continuing basis for major land areas. (Note: 1-km AVHRR data are referred to as High Resolution Picture Transmission (HRPT) for data collected directly by ground receiving stations, and as Local Area Coverage (LAC) for data gathered using on-board satellite tape recorders.)

The U.S. Geological Survey, National Mapping Division's (USGS/NMD) EROS Data Center (EDC) has a program to produce 1-km resolution AVHRR time series data sets for the conterminous U.S., Alaska, and Eurasia as products for applied research (Eidenshink and others, 1991; Kelly and Hood, 1991; Sadowski, 1990). EDC has direct reception capabilities for NOAA's TIROS series of polar-orbiting satellites (AVHRR HRPT data) covering most of the North American continent on a daily basis. EDC also operates a Domestic Communications Satellite System (DOMSAT) downlink that facilitates near-real-time access to virtually all of the AVHRR LAC data collected globally. AVHRR data reception activities are integrated with georegistration, product generation and archiving systems developed to insure that high quality data (e.g., greenness maps, land cover classifications) will be available to researchers and land managers.

Because spatially extensive 1-km data sets possessing high temporal resolution have heretofore been unavailable, capabilities to use such data for regional land cover characterization have not been well-explored. This paper presents the initial results of research being conducted by EDC with the Center for Advanced Land Management Information Technologies (CALMIT) of the University of Nebraska-Lincoln (UNL) focusing upon the design and evaluation of strategies for detailed land cover characterization over continental-size areas. A central premise of the research is the conviction that there is important synergism in the integration of data derived via remote sensing with earth science data acquired from other sources.

RESEARCH OBJECTIVES

The principal objective of the research is to define and evaluate the potential for using AVHRR 1-km digital imagery and multisource data (e.g., broad-scale climate, terrain, ecoregions), in concert, to characterize global land cover. The investigation includes a broad spectrum of questions involving methodological issues, data, and product requirements. The initial work has focussed upon development of a prototype 1 km-resolution land characteristics data base for the conterminous U.S. that is designed to meet the requirements of scientists dealing with global and mesoscale climate modelling, land surface change, and biosphere-atmosphere-hydrosphere interactions.

SCIENTIFIC HERITAGE OF THIS RESEARCH

Attempts to characterize land cover over large areas (i.e., subcontinental, continental, or global) using AVHRR data extend back at least 15 years. Most studies have focused upon GAC (4 km) or GVI (16 km) data rather than full resolution 1-km imagery. Typically, data are transformed to a vegetation index, such as the NDVI, for analysis. Tucker, Townshend, and Goff (1985), for example, used NDVI derived from GAC data to map major biomes and observe phenological change over the

African continent for a 19-month period in 1982 and 1983. Three-week maximum vegetation index composites and principal components analysis were used to define major ecosystems. The authors observed qualitative agreement between their results and published maps, but argued for further development of analytical techniques and examination of multiple years to determine effects of short-term climatic variations.

Townshend, Justice, and Kalb (1987) employed GAC data and GVI data in examining three different approaches to classification of land cover in South America. A principal components transformation of 13 dates, a multidate greenness curve-matching methodology, and a maximum likelihood classification approach were compared. The latter was determined to have the best outcome. The optimal result was achieved when 13 dates of coverage (rather than fewer) were used. Available ground reference material allowed only qualitative judgment that the outcome of classification appeared successful.

Goward, Tucker, and Dye (1985) examined GVI data for North America. Three-week composite maximum greenness (NDVI) images from April-November 1982 were analyzed to map regions of net primary productivity. They showed that seasonal NDVI patterns could be associated with major land cover regions, and that multidate greenness images could be used to observe patterns of vegetation growth and senecence. The authors recommends for research on interannual change and further technique development. In later work Goward and others (1987) compared the vegetation characteristics of North and South American biomes by analyzing GVI data using methods developed in Goward's 1985 research.

They found that the differential timing and longer duration of the South American growing season was well-captured. Biome distributions appeared, qualitatively, well-associated with published maps. Lloyd (1990) used a supervised binary decision tree classification approach to map world biomes with multidate GVI data. Although the spatial distributions appeared reasonable, no quantitative verification was possible. Gallo and Brown (1990) used biweekly composited GVI data to examine global phytoclimatological conditions. They concluded that biweekly histograms of greenness change could be used to indicate general climatic conditions and associated vegetation distributions.

One-kilometer AVHRR data have been used less often than GAC or GVI data because they have not generally been available. Tucker, Gatlin, and Schneider (1984), however, employed 1-km data to monitor vegetation conditions in the Nile delta. No attempt was made to classify land cover, but changes in greenness conditions over the period May-October 1981 were observed to correspond to known phenological circumstances and agricultural practices. Gervin and other (1985) compared 1-km data acquired over the Washington, D.C. area to Landsat MSS data. They performed unsupervised classification of single date images collected in July 1981 to identify Anderson Level I land cover/land use. The first four channels of the AVHRR were used rather than a vegetation index. Accuracies of classification were similar for predominant land use/cover classes, but the MSS classification had higher accuracy on classes that were spatially heterogeneous or of limited spatial extent.

Overall accuracy was 71.9 percent for the AVHRR and 76.8 percent for the MSS. The authors concluded that additional work on AVHRR data classification was warranted.

DESIGN CONSIDERATIONS

Discussions of land cover mapping inevitably lead to debate over classification schemes (i.e., assignment of class descriptors/labels) and accuracy specifications. Most classification schemes are designed to be useful for a rather narrow range of applications; conversely, no single classification scheme can satisfy all, or even most, applications. The International Geosphere-Biosphere Programme (IGBP), following a year-long discussion of appropriate land cover products for global change applications, concluded that "...the varied requirements for the IGBP cannot be satisfied by a single map of one set of attributes..." (International Geosphere-Biosphere Programme, 1990).

A number of studies have indicated that, with appropriate methodological design, it is possible to produce data bases of land characteristics that can satisfy a wide range of applications (Loveland, 1984; Fitzpatrick-Lins and others, 1987). This study has been directed to this end.

Five major principles guide the land characterization research (Loveland and Ohlen, 1991). Data analysis strategies and methods developed must be:

1. Applicable and repeatable over large (i.e., continental, global) areas;

2. Capable of discerning significant seasonal, ecological and cultural variations in land cover;
3. Applicable to very large data sets;
4. Able to deal with data varying in quality; and,
5. Capable of producing flexible results that are not application-specific.

In keeping with these principles, an initial conceptual strategy was developed that, via use of geographic information system (GIS)-based tools, allows examination of interrelationships between spatial data sets to characterize land cover, yet relies upon relatively simple methods for image segmentation (Figure 1). Very large data sets present unique image analysis problems. Continental areas typically exhibit greater variations in climate, terrain, and vegetation, than are encountered in analyses of single scenes.

Such problems can be dealt with in one of two ways. First, the study area can be partioned into separate, smaller data sets based on, for example, climatic or ecological regions. This would serve to minimize environmental diversity, but, would likely create significant post-classification mosaicking and interregional class correlation problems. Therefore, this research treated the U.S. data set as a single unit.

Lessons from previous studies suggest that multitemporal, multisource image classification techniques are required for large-area land cover characterization. Single-date analyses, especially using AVHRR data, are frequently found inadequate for discriminating land cover types since disparate cover types can share significant similar spectral reflectance characteristics. The problems are compounded when one deals with large areas exhibiting great climatic, topographic, and ecological diversity. Classification of multitemporal AVHRR-NDVI data should have advantages over single-date observations, though some cover parameters required for global analyses will likely be imperfectly characterized. Ancillary data (e.g., elevation, climate variables, ecological regions) are, therefore, incorporated in land cover descriptions.

The prototype land characteristics data base has two components:

1. "Seasonally-distinct" land cover regions defined via analysis of AVHRR and ancillary data. These regions exhibit unique phenological characteristics (i.e., time of onset, magnitude of peak, and seasonal duration of greenness) and possess relatively homogeneous vegetative associations;
2. Attributes or characterize spreadsheets that describe the characteristics of the landscape regions. Attributes currently contained in the U.S. prototype are: 1. Descriptions of vegetation composition and physiognomy; 2. Quantitative seasonal characteristics including mean monthly NDVI (March-October 1990) and seasonal parameters (time of onset, magnitude of peak, duration of greenness, and total greenness); 3. Site characteristics including, for every pixel, elevation, climate, and ecoregion and MLRA membership; 4. Translation tables linking the regions to common land cover classification schemes such as UNESCO, USGS Anderson System, and the vegetation types used in the Simple Biosphere Model and the

Biosphere Atmospheric Transfer Scheme (Dickinson and others, 1986); and, 5. Summary data on climate, terrain, land use and land cover derived from publications describing U.S. ecoregions, MLRAs and from sampled digital USGS land use/land cover data. The strategy driving this approach is to provide researchers a capability to compute new parameters, derive new classifications and aggregations of the data to suit specific needs, and develop custom-tailored products. This provides the flexibility that may allow the land characteristics data base to be used in many models without extensive modification of inputs.

As research evolves, other attributes will be added to the land characteristics data base. For example, measurements of surface albedo, primary production estimates, and other surface properties associated with canopy resistance could be added to the region attributed when consensus methods are reached for their calculation. For example, measurements of surface albedo, primary production estimates, and other surface properties contributing to canopy conductance and evapotranspiration could be appended to the regions when consensus methods are reached for their calculation.

DATA REQUIREMENTS

AVHRR Data: Daily observations of NOAA-11 data were calibrated to percent reflectance, scaled to byte data, and georegistered to a Lambert Azimuthal Equal Area map projection (Kelly and Hood, 1991; Holben, 1986) Seventeen biweekly maximum NDVI composites were generated for the period

March - October 1990. This process involves the creation of a composite image in which the pixel having the maximum NDVI for each composite period is retained (Eidenshink and others, 1991). By selecting for maximum NDVI, nearly cloud-free data sets usually result. An image to image registration process is used to insure accuracy within a root mean square error of 1 pixel (Kelly and Hood, 1991).

Initial experiments using 1989 biweekly NDVI composites of the western U.S. suggested that the use of monthly composites would both minimize data volume problems and minimize computer resource needs without unduly affecting results. Consequently, the seventeen 1990 biweekly composites were reduced to eight monthly composites of maximum NDVI and were input to classification. The original biweekly data were, however, retained for region characterization. Data quality was improved by the monthly compositing through the elimination of much of the remnant atmospheric, cloud, and off-nadir contamination that remained in the biweekly composites. While previous studies with GAC or GVI data have documented improved classification results as more frequent observations are used (Townshend, J.R.G., Justice, C.O., and Kalb, V.T., 1987), that practical considerations argue for dimensionality reduction in continental studies using 1-km data.

Terrain Data: Digital elevation data incorporated in the data base were originally derived by the Defense Mapping Agency from 1 x 2 degree topographic maps, and were later refined by the National Telecommunications and Information Administration. These data are now distributed by the NOAA National Geophysical Data Center in Boulder, Colorado. The elevation values are rounded estimates to the nearest 20 feet for every 30 seconds of latitude and longitude.

Climate data : Climate data layers, including length-of-frost-free-period, average annual precipitation, average monthly precipitation, and monthly mean temperature, were digitized from climate atlas maps (NOAA/EDS, 1979). All of the maps were based on thirty-year means of temperature and precipitation (i.e., monthly precipitation from 1931 to 1960). The scales of these maps varied from approximately 1:7,000,000 to 1:18,000,000. Digitized isoline data were subsequently interpolated to a gridded surface. Because of the generalized nature of the source maps, these data relate to continental climate partions and do not represent local or microclimate conditions.

Ecoregions: Ecoregion maps from the U.S. Environmental Protection Agency (Omernik, 1987; Omernik and Gallant, 1990) were digitized and attributes of the regions (land surface form, major soils, land use and potential natural vegetation) were summarized.

Major Land Resource Areas: Major Land Resource Area (MLRA) regional boundaries were digitized from a 1:7,500,000 map published by the USDA/Soil Conservation Service (USDA/SCS, 1981). MLRA region attributes include soils, terrain, climate, potential natural vegetation, and land use).

Land Use/Land Cover Data: Land use and land cover () data were sampled from digital Land Use and Land Cover files obtained from the USGS (Feagas, 1983). These data, classified at Anderson Level II (Anderson and others, 1976), have been developed by the USGS over the past 20 years from visual analyses of aerial photography. The data are keyed to 1:250,000 USGS 1 x 2 degree quadrangles. Fifty-one quadrangle-based data sets were converted to a 1-km grid for use in the research. The quads, selected to sample major ecosystems, cover approximately 12% of the U.S.

Political boundaries: State and county political boundaries from the USGS 1:2,000,000-scale digital line graph national data base were used as reference during the investigation (Domoratz and others, 1983).

Water Mask: Surface water bodies were separated using Channel 2 data from daily georeferenced AVHRR scenes. Cloud-free scenes were selected through a visual quality assessment of film facsimilies. After a threshold between land and water values was identified, a binary mask was computed and the water bodies data set was added to a land characteristics data base. Approximately 50 AVHRR scenes were used to create the mask.

Other Data: Many other supporting materials including state, regional and national land use and land cover maps, vegetation maps, atlases, agricultural statistics, and crop calendars were used. All data layers have 1-km resolution, and an array of 4587 x 2889 pixels. A Lambert Equal Area Projection was used for all data layers.

ANALYSIS METHODS

The strategy developed to characterize U.S. land cover employed both AVHRR data and ancillary data in a carefully structured manner (Figure 2). Analysis procedures involved overlaying, exploring, and interrelating the disparate spatial data and attributes.

Preliminary experiments: The image analysis methodology used in the development of the 1990 conterminous U.S. land characteristics data base evolved from a series of classification experiments conducted using 1989 AVHRR NDVI data covering the western U.S. These tests indicated that (1) an initial vegetated/non-vegetated land stratification would be required, (2) a minimum of 50 spectral-temporal classes would be required to define important land cover types, (3) unsupervised classification was suitable, and (4) the use of monthly rather than biweekly NDVI composites would be adequate in the classification of the conterminous U.S.

The vegetated/non-vegetated land stratification was developed because classes exhibiting high intraclass variance (e.g., water, bare soil, clouds, and snow/ice) tend to dominate the clustering process. Masking of these classes optimizes the spectral discrimination of the classes directly associated with vegetation. Separation and characterization of such cover can not, in any case, be reliably accomplished with NDVI data due to insensitivity of this transformation to low-biomass conditions. Plans call for the characterization of non-vegetated areas using a brightness measure (channel 1 plus 2).

Image classification: Initial stratification of vegetated and non-vegetated land was accomplished by analysis of a single maximum NDVI composite spanning the March-November 1990 period. Through interactive visual interpretation of the composite, an NDVI threshold of 0.09 was selected to separate vegetated and non-vegetated lands. The selected threshold was based upon comparison of the strata to available maps and imagery, and published data NDVI-land cover relationships.

An unsupervised clustering algorithm (ISOCLASS) and minimum-distance-to-mean classification methodology was used to define 70 spectral-temporal ("seasonally distinct") classes within the vegetated stratum (Figure 3). A 20% systematic sample of the 8 monthly composites was used to derive statistics to be used in the cluster analysis.

Land Cover Characterization: Initial evaluation, labeling, and characterization of the 70 classes was based on a combination of graphical, statistical and visual tools and techniques. For example, graphs portraying the variation of mean NDVI over the 8 month analysis period provided a profile of the phenology of each class (Figure 4). The NDVI multitemporal curves often proved to be diagnostic of land cover, and comparisons between curves helped in identifying related classes when analyzed in concert with a display of the spatial distribution of each class. Maps, atlases, agricultural statistics and Landsat image maps were used in interpretation of classification results.

Graphical summaries of elevation and frost-free period statistics for each cluster (Figure 5) enabled the association of the spatial distribution of each class with site characteristics. Ecoregion and MLRA boundaries were overlaid on the 70 class data set, and spatial interrelationships between the two data sets were computed, and tables depicting the associations were constructed (Tables 1 and 2). Similar summaries were developed showing the association between the 70 classes and sampled USGS data (Table 3).

The tables show the percentage of each of the 70 "seasonally distinct" AVHRR-derived classes falling within MLRA and ecoregion classes, and associated with data. The attributes of the ecoregion, MLRA and data were not considered "ground truth," but were used as aids in understanding complex land cover mosaics, identifying instances of "confusion" in the classification, and enabling the evaluation of alternative, independently-derived methods of landscape regionalization and characterization.

Finally, interpretive maps portraying, respectively, (1) the month in which the NDVI first rose above a threshold value (onset of greenness), (2) the month in which maximum NDVI occurred (peak of greenness), (3) the number of months when the NDVI reached or exceeded a threshold value (duration of greenness), and (4) the cumulative value of the NDVI (total NDVI) for the period of March-October were developed (Figure 6). These maps were derived through analysis of individual class NDVI statistics produced from 17 biweekly NDVI composites. Interpretation of temporal NDVI means led to the identification of the four seasonal parameters (figure 7). These four values are strongly related to the phenologic cycle of vegetation. The month in which the NDVI increases dramatically corresponds with the time of emergence of green vegetation at the beginning of the growing season. The month of maximum NDVI reflects the time of maximum photosynthetic activity (Lloyd, 1990). The time that the

NDVI exceeds a certain value is similar to the length of the growing season (Hoyd, 1990; Brown, 1990). The cumulative NDVI throughout the growing season is a general reflector of total photosynthetic activity on net primary productivity (Goward, 1987; Brown, 1990).

Postclassification refinement: As expected, a number of instances of classification "confusion" were observed (i.e., instances where the 70 classes were not uniquely associated with a single cover type). Thus provided considerable insight about phenological patterns of the U.S. through the process of observing the types and distributions of confusion. Such information will be useful in future attempts to refine and improve the classification strategy.

Examples of confused land cover are warm season desert grasslands and alpine meadows. The late "greenup," moderate peak greenness and short duration of greenness exhibited by desert grasslands in arid regions receiving limited mid-summer precipitation, for example, might be expected to correlate to the phenology of alpine meadows occurring at high elevations. In these instances, both elevation and frost-free period data were used for stratification.

In another instance, classes were observed to occur both in areas of the southern Great Plains dominated by cropland (winter wheat), and in coastal California where they were associated with cool season grasslands. Consideration of regional variables led to explanation of this confusion. In the southern Plains, winter wheat fields "green-up" quickly in April and May, senesce, and are harvested in June. On the west coast, the unique temporal distribution of precipitation (i.e., winter maximum) influences a similar phenologic pattern in grasslands, a type of vegetation not unlike wheat in physiognomy and biomass. In this case, the unique, but different ecological characteristics of the two cover types led to the use of ecoregions for stratification.

The postclassification stratification criteria were developed using interactive spatial/statistical comparison techniques. The techniques involved spatial display of each of the 70 classes with histograms of class relationships to ancillary spatial variables (i.e., elevation, ecosystems frost-free period). Through interactive selection of minimum and maximum threshold values of the ancillary data, the affected pixels within each class display would be alarmed. Thus, the pixels displayed in specific classes were highlighted in real-time reflecting the effects of selecting a particular threshold value.

Through analytical processes such as those set forth above, 75 percent of the original 70 preliminary vegetation greenness classes were stratified into 157 seasonally distinct land cover regions. The final characterization of the 157 classes was then completed, with the development of the descriptive and quantitative attributes of each region.

Verification: The determination of classification accuracy is a complex issue. The coarse resolution of AVHRR data leads to the development of classes based commonly on land cover mosaics rather than on homogenous landscape regions. The accessibility of consistent site data for verification is also a limitation. An additional complication is caused by the fact that the land characteristics data base is not based on well-defined categories. As a result, verification is limited to comparisons with other relevant data sets such as ecoregions, and MLRA's.

Linkages to Other Classification Systems: The final step in the prototype effort was to link the AVHRR-based classification and data to other commonly-used classification systems (Table 4). Efforts are underway to develop relationships with the UNESCO vegetation classification system, and the vegetation types used in the Simple Biosphere Model (SiB) and the Biosphere Atmosphere Transfer Scheme (BATS).

RESULTS AND DISCUSSION

In general, homogenous land cover regions were well identified if they were comprised of relatively large, regular landscape patches. In areas such as the eastern U.S., it was difficult to separate pure seasonally distinct land cover regions. In these cases, regions must be described according to the complexes of land cover that comprise the mosaic.

Rangeland classes, including some semiarid desert vegetation types, appear to be distributed over approximately 20 percent of the land surface, primarily in the western half of the U.S., with probably another 5 to 10 percent as a mosaic component of mixed landscapes. These are regions where the potential natural vegetation is predominantly herbaceous (i.e., grasses, forbs, and low growing shrubs) and trees may be scarace or nonexistent (Anderson and others, 1976).

Range is generally not improved or irrigated, although some areas may be seeded. It is used for grazing by domestic livestock and ruminant wildlife. Chief limiting factors include precipitation and grazing practices (Walter, 1979). Rangeland also tends to be part of mosaic landscapes, for example interspersed with agricultural fields in the western plains states. Range classes tended to have seasonal minimum NDVI values of approximately .10, and seasonal maxima near .30, usually not exceeding .40. These regions have low percentage cover and low standing biomass.

Rangeland or grassland classes displayed a dispersed non-contiguous pattern in locations adjacent to and interspersed with forest land cover (i.e., alpine meadows) or agricultural classes. For example, Class 4 has extensive coverage west of the Rocky Mountains including some contiguous regions, especially in southwestern Wyoming and northeastern Arizona. But there are also widespread areas of scattered small pixel groups throughout Nevada corresponding to sagebrush steppe cover in basins between tree covered ridges.

This biome tends to be confused with eastern urban areas and coastal mixed pixels. In the southwest, some confusion occurs with mid-elevation evergreen forests where the interaction of widely spaced pinyon/juniper vegetation with the understory has a similar phenology to other range types. Two differing grassland phenologies, cool season and warm season, contribute to some confusion. For example, Class 14 encompasses both cool season grasses in California and winter wheat in both Oklahoma and Oregon (figure 8). Alpine meadows tend to be grouped with other warm season rangeland.

Regionally distinct patterns representing forest lands were well identified in the classification. Data identified by class 54, for example, illustrates an ability of these data to regionally represent mixed forest land cover (maple/birch/beech with spruce/fir species) of the northeastern mountains and foothills. Class 53 also illustrates northern forests, but in this case, corresponds to Great Lakes deciduous hardwoods (maple/birch). Class 61 regionally represents a deciduous forest cover of oak/hickory located within the Ozark-Boston Mountains and southern Appalachians. The unique hemlock/Douglas fir evergreen forests lands of the northwest U.S. is represented by class 70. Figure 9 provides monthly NDVI characteristics for these 4 classes.

Major agricultural regions are clearly identifiable, and NDVI profiles for agricultural classes reveal much information concerning phenology and crop types (figure 10). For example, winter wheat regions (class 35) in the southern Great Plains are clearly distinguished from spring wheat (class 30) in the northern Great Plains by the different period of greenness onset. Class 44 corresponds to the corn and soybeans regions of the midwest (Iowa, Illinois, Indiana). Class 43 also is distributed throughout the midwest, but represents a more mixed landscape with oats, woodlands, and pasture land cover interspersed with corn and soybeans. The NDVI curves for these two classes differ slightly with class 43 displaying a lower peak green level. It also displays a less rapid greenup rate, which is likely caused by the earlier green-up of the non-corn/soybean elements of the landscape.

The preliminary evaluation indicates that the procedures used perform, for the most part, in an acceptable manner. However, the research conducted to-date has illuminated many issues that remain to be addressed. For example, the outcome of the NDVI-based classification was clearly influenced by the specific meteorological conditions occurring during 1990. The preliminary work carried out using the 1989 western U.S. data set resulted in classes corresponding to drought conditions in the Great Plains during that year. California experienced similar drought conditions during 1990, which undoubtedly has impacted the 1990 classification. The specific effects of climatic anomalies on classification of land cover are, however, uncertain and remain to be investigated.

It is also likely that the classification was affected by the availability of AVHRR data for 1990. The fact that there were no seasonal observation during winter (i.e., late-November-March) very likely impacted the ability to discern some important cover types in the southeastern U.S. The addition of winter composites must be part of future work. Conversely, it is not clear whether eight monthly observations are required to characterize land cover. Similar results may be derived via analysis of fewer composites selected at phenologically "critical" points-in-time.

Some cover types cannot be adequately identified using NDVI data. Barren lands, snow and ice, and water bodies have similar NDVI characteristics due the absence of photosynthetically active plant material. Wetlands, for example, were difficult to accurately identify because of the coarse resolution of AVHRR data in relationship to the typically small landscape patches that comprise U.S. wetlands. As expected, urban areas could not be uniquely identified because of the complex mixtures of surface conditions within 1-km urban pixels.

The strategy to employ ancillary data in postclassification stratification of the 70 preliminary vegetation greenness classes served to identify some important problems in working with data sets covering large areas. One such problem is exemplified by the case warm season desert grassland/alpine cover confusion discussed earlier. Although the initial supposition was that stratification was possible using elevation thresholds, in practice this only worked in local circumstances. Because of the related effects of altitude and latitude on vegetation phenology, the elevation threshold needed to split these classes had to be continually lowered moving north to south in order to achieve acceptable results. In other words, the elevation threshold actually proved to be very difficult to apply in any effectual way. Instead, it was more appropriate to use climate variables such as length frost-free period, to which elevation is inversely related.

Verification of classification results has also presented problems, though these are not unique to this research. In fact, little has been reported on quantitative accuracy assessment of land cover products derived from analysis of AVHRR data. Tucker, Gatlin, and Schneider (1985) note that such work is hampered by the dearth of suitable "ground truth" and lack of agreement between the few extant land cover maps covering the continents. Townshend, Justice, and Kalb (1987) assert that because existing maps of land cover and land use have been developed differently than AVHRR land cover data bases, they may not even be acceptable standards of reference where available.

Data bases containing land characteristics derived via classification of AVHRR data may produce unconventional regionalizations that do not match classifications used in existing maps, but may yet have great utility. Experience from this study suggests that often the spatial resolution, and probably also the classification precision, of the AVHRR-derived data are higher than existing state and regional maps. Adequate methods to verify land cover classification conducted at 1-km over continental-sized areas do not exist. Standards of reference, when they exist at appropriate resolution, are frequently old, have incompatible classifications, or exhibit other problems (Matthews, 1983). Research to re-examine conventional image classification accuracy assessment in the context of difficulties in conducting such assessments over very large areas is required. In order to employ methods such as those reported, attention needs to be given to the establishment of accuracy requirements for global land cover inventory and monitoring, and to definition of innovative procedures for gauging the quality of land cover data extracted from coarse resolution satellite data.

FUTURE RESEARCH DIRECTIONS

The research results reported here should be viewed as preliminary. Although these findings represent milestones, there is need for focused investigations of key problems that limit current efforts to characterize continental land cover using multitemporal AVHRR LAC imagery and ancillary data. Some of the important areas in which research is needed include:

1. Assessment of the impacts of seasonal and annual variations on identification and characterization of land cover regions; inter-annual effects of weather and climate on the development of seasonally-distinct land cover regions, and intra-annual variation of vegetation and its impacts on determination of the appropriate sample period (e.g., biweekly, monthly, and seasonal) for temporally-based classification;

2. Identification of influences of landscape/sensor interaction on the definition and characterization of land cover regions;

3. Refinement of data analysis methods and strategies including integration of data from other sensors, use of brightness measures in characterizing unvegetated areas, and potential use of AVHRR thermal channels in land cover classification; and

4. Development of verification strategies appropriate for continental-scale land cover data.

Current research suggests that 1 km-resolution multitemporal AVHRR/NDVI data employed in concert with ancillary data can be effectively used to characterize land cover over very large areas. Successful land cover characterization and data base development alone, however, are insufficient. The data bases developed must be useful to the global change community and others. Therefore, an important component of future work must be to address specific needs for products.

ACKNOWLEDGEMENTS

Most financial support of the participation of Dr. Merchant and Ms. Brown in this research has been provided by the Conservation and Survey Division (CSD), University of Nebraska-Lincoln. Special thanks are extended to Dr. Perry B. Wigley, CSD Director, for his support.

A portion of Dr. Merchant's and Ms. Brown's participation was supported by a U.S. Environmental Protection Agency (EPA) grant # ______.

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Figure 1. Conceptual strategy for large-area land characterization includes use of remote sensing/multisource data to create a spatial data base that includes seasonally-distinct land cover regions and associated attributes that can be tailored to a number of disparate applications.

Figure 2. Processing flow for the development of the prototype land characteristics data base. Note that the analysis of brightness data is planned but not yet completed.

Figure 3. Preliminary 1990 vegetation greenness classes derived from unsupervised classification of March-October monthly AVHRR NDVI composites.

Figure 4. Example of cluster class NDVI mean values for selected classes.

Figure 5. Statistical relationships between vegetation greenness classes and (a) elevation and (b) frost-free period.

Figure 6. Seasonal parameters calculated for preliminary vegetation greenness classes include: (a) onset of greenness; (b) period of peak greenness; (c) duration of green period; and (d) total NDVI.

Figure 7. Example of relationship between NDVI class temporal means (class 53) and selected seasonal parameters.

Figure 8. Monthly NDVI means for selected rangeland categories.

Figure 9. Monthly NDVI means for selected forest categories.

Figure 10. Monthly NDVI means for selected agricultural categories.

Table 1. Ecological regions and their characteristics that correspond to class 44.

Table 2. Major Land Resource Areas and their characteristics that correspond to class 44.

Table 3. USGS Land Use/Land Cover categories and proportions found in class 44.

Table 4. Relationship between selected seasonally distinct land cover regions and other classification legends.