REGIONAL LAND COVER CHARACTERIZATION USING LANDSAT THEMATIC MAPPER DATA AND ANCILLARY DATA SOURCES

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Abstract. As part of the activities of the Multi-Resolution Land Characteristics (MRLC) Interagency Consortium, an intermediate-scale land cover data set is being generated for the conterminous United States. This effort is being conducted on a region-by-region basis using U.S. Standard Federal Regions. To date, land cover data sets have been generated for Federal Regions 3 (Pennsylvania, West Virginia, Virginia, Maryland, and Delaware) and 2 (New York and New Jersey). Classification work is currently under way in Federal Region 4 (the southeastern United States), and land cover mapping activities have been started in Federal Regions 5 (the Great Lakes region) and 1 (New England). It is anticipated that a land cover data set for the conterminous United States will be completed by the end of 1999. A standard land cover classification legend is used, which is analogous to and compatible with other classification schemes. The primary MRLC regional classification scheme contains 23 land cover classes.

The primary source of data for the project is the Landsat thematic mapper (TM) sensor. For each region, TM scenes representing both leaf-on and leaf-off conditions are acquired, preprocessed, and georeferenced to MRLC specifications. Mosaicked data are clustered using unsupervised classification, and individual clusters are labeled using aerial photographs. Individual clusters that represent more than one land cover unit are split using spatial modeling with multiple ancillary spatial data layers (most notably, digital elevation model, population, land use and land cover, and wetlands information). This approach yields regional land cover information suitable for a wide array of applications, including landscape metric analyses, land management, land cover change studies, and nutrient and pesticide runoff modeling.

1. Introduction

Many organizations require accurate intermediate-scale land cover information for a variety of applications. As an example, the National Oceanic and Atmospheric Administration's (NOAA) Coastal Change Analysis Program (C-CAP; Dobson *et al.*, 1995) has strong requirements for such information for assessing changes in coastal areas. In this case, the effects of land cover changes are being investigated with special emphasis on determining long-term effects on estuarine systems. Similarly, the U.S. Geological Survey (USGS) Water Resources Division National Water-Quality Assessment Program (Leahy *et al.*, 1993; National Research Council, 1990) is using medium-scale land cover data as input for nutrient and pesticide runoff models. This is a concerted effort involving the major watershed drainage units within the United States. Additionally, the USGS Biological Resources Division's Gap Analysis Program (Scott *et al.*, 1996) uses intermediate-scale land cover data to generate detailed data sets mapping natural and semi-natural plant assemblages. This information is linked with modeled vertebrate habitat preference distribution data to map (and ultimately manage) biodiversity on a national scale. The field base 30-in resolution to facilitate maximum use. The MRLC national land cover data can then be incorporated with spatial data, such as the AVHRR, at other scales and resolutions to provide a true multi-resolution land characteristics data base. This data set will have the following specifications: (1) there will be a nationally consistent hierarchical legend; (2) final data will be maintained at a minimum spatial resolution of 30 meters; (3) the data set will be produced and stored in a generic raster data format; (4) the data set will include the classified and labeled land cover data, appropriate ancillary data, and metadata

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documentation; and (5) data will comply with Federal Geographic Data Committee standards. In addition to these characteristics, all MRLC data will be easily accessible to the user community. To this end, the MRLC is developing Internet access as well as conventional delivery routes, such as Compact Disc or tape media.

The MRLC elected to execute its national land cover initiative using a template of 10 Standard Federal Regions as defined by the April 4, 1974, Executive Order OMB Circular A-105. The first "pilot" regional data set was completed for Federal Region 3, which includes the states of Pennsylvania, West Virginia, Virginia, Maryland, and Delaware. Federal Region 2 (New York and New Jersey) has also been completed, and classification work is currently under way in Federal Region 4 (the southeastern United States). Initial land cover mapping activities are under way in Federal Regions 5 (the Great Lakes region) and 1 (New England), and it is projected that land cover generation for the eastern United States will be completed during 1998. It is anticipated that a land cover data set for the entire conterminous United States will be completed by the end of 1999.

3. Data Sources

The primary source of data for this effort is Landsat TM data acquired in 1991, 1992, and 1993 for the MRLC (Loveland and Shaw, 1996). As part of this effort, data sets have been destriped, terrain-corrected using the 3-arc-second digital terrain elevation data (DTED), and georegistered using ground control points, resulting in a root mean square registration error of less than 1 pixel (30 in). Both leaf-on and leaf-off TM data sets are being analyzed.

Other intermediate-scale spatial data are being used as ancillary information in the analysis, including DTED (U.S. Geological Survey, 1993) and derivative DTED products (slope, aspect, and shaded relief), population density data at the census block level (Bureau of the Census, 1991a and b; 1992), Land Use and Land Cover (LUDA) data, and National Wetlands Inventory (NWI; U.S. Fish and Wildlife Service, 1996) data. Additionally, available water capacity and organic carbon (0-40 cm depth) data from the State Soil Geographic (STATSGO) Data Base (U.S. Department of Agriculture, 1994) are being used. Land cover information from various state or national programs, such as the USGS Biological Resources Division Gap Analysis Program (Scott *et al.*, 1996), are being incorporated when appropriate.

4. Classification System

The MRLC classification system (Table I) provides a consistent hierarchical approach to defining 23 classes of land cover across the lower 48 United States. Because of landscape differences found among the ten federal regions, all classes may not appear in the legend of a particular regional data set. The land cover classification approach is a merging of the C-CAP classification protocol (Dobson *et al.*, 1995) and draft Federal Geographic Data Committee standards. The intent behind creating this hybrid classification approach is to provide a linkage between existing generalized land cover data sets, such as the C-CAP system, with the more detailed natural vegetation data, such as that provided by the USGS Gap Analysis Program. In addition, the C-CAP classification protocol is based on the Anderson system (Anderson, 1976), and thus land cover data generated by the MRLC system can be easily related to legacy data sets, such as the LUDA data set.

5. Classification Procedure

The general procedure for creating the national land cover data set includes (1) generating mosaics of leaf-on and leaf-off TM scenes and clustering each using an unsupervised classification algorithm, (2) interpreting and labeling clusters into MRLC classes using aerial photographs, (3) resolving confused clusters by constructing models that make use of the appropriate ancillary data sources, and (4) incorporating information from onscreen digitizing (e.g., quarries and transitional bare areas, such as clear cuts) and additional available land cover data sets to refine and augment the basic classification developed above. Depending on the region being analyzed, either leaf-on or leaf-off mosaics are used as the primary source of land cover information. The other mosaic is then used as an ancillary data layer to aid in class-splitting operations.

The smallest federal regions are analyzed as single units, whereas large federal regions are broken down into smaller areas for analyses. In general, current software and hardware limitations make it difficult to work with files that exceed 2 gigabytes. Assuming that a three-band composite is required at some stage of the analysis procedure (e.g., for onscreen digitizing steps, or for overlaying classifications onto imagery), then the upper limit of the land area that can be analyzed as a single unit using TM data is approximately 700,000 km^2. Once the individual units of a given federal region have been classified, the pieces are edge-matched with the goal of obtaining a consistent and seamless land cover product for the region. Land cover results from adjacent federal regions are similarly edge-matched, which will ultimately result in a consistent land cover data set for the conterminous United States.

Table I
Multi-Resolution Land Characterization regional land cover classification system.
Definitions of classes available by request.

- 1.0 Water
  - 1.1 Open Water
  - 1.2 Perennial Ice/Snow
- 2.0 Developed
  - 2.1 High Intensity
    - 2.11 Residential
    - 2.12 Commercial/Industrial/Transportation
  - 2.2 Low Intensity
    - 2.21 Residential
- 3.0 Bare
  - 3.1 Transitional
  - 3.2 Quarries/Strip Mines/Gravel Pits
  - 3.3 Bare Rock/Sand
- 4.0 Vegetated
  - 4.1 Woody Upland Vegetation
    - 4.11 Natural Forested
      - 4.111 Deciduous Forest
      - 4.112 Evergreen Forest
      - 4.113 Mixed Forest
    - 4.12 Natural Shrubland
      - 4.121 Deciduous Shrubland
      - 4.122 Evergreen Shrubland
      - 4.123 Mixed Shrubland
    - 4.13 Planted/Cultivated * (orchards, vineyards, groves)
  - 4.2 Herbaceous Upland Vegetation
    - 4.21 Natural/Semi-natural Herbaceous
      - 4.211 Grasslands
    - 4.22 Planted/Cultivated Herbaceous

4.221 Bare Soil
4.222 Small Grains
4.223 Row Crops
4.224 Grasses
4.2241 Pasture/Hay
4.2242 Other (parks, lawns, golf courses)
4.3 Wetlands
4.31 Woody Wetlands
4.32 Emergent Herbaceous Wetlands

* Classification of woody planted/cultivated vegetation subject to availability of sufficient ancillary data to differentiate from natural woody vegetation.

For mosaicking purposes, an attempt is made during the scene selection process to minimize the unwanted effects of interscene phenological variability by choosing scenes acquired at approximately the same time of year. Alter scenes have been selected, a "master" scene (Homer *et al.*, 1997) is selected, and regions of spatial overlap with adjacent "slave" scenes are used to normalize digital data. From these zones of overlap, histograms of digital values from the slave scenes are adjusted to match the histogram brightness values of the master image on a band by band basis. Prior to normalization, areas with clouds and water are masked out so that normalization is performed using only digital data from areas dominated by land cover. Once a slave image is radiometrically matched to the master, it, in turn, becomes a master for its adjacent scenes.

Mosaicked scenes are clustered into 100 spectrally distinct classes using the CLUSTER algorithm developed at Los Alamos National Laboratory (Kelly and White, 1993; Benjamin *et al.*, 1996). Classification is accomplished using TM bands 3 (0.63-0.69 micrometers), 4 (0.76-0.90 micrometers), 5 (1.55-1.75 micrometers), and 7 (2.08-2.35 micrometers). Previous work has indicated that relatively little unique land cover information is derived by using greater numbers of clusters (Vogelmann *et al.*, 1997a), and it was decided that 100 clusters capture most of the regional land cover variability that could be derived from the TM data. Clusters are assigned into MRLC classes (Table I) using National High Altitude Photography (NHAP) Program aerial photographs as reference information.

Almost invariably, the individual spectral clusters derived from classification represent two or more of the targeted land cover classes. These clusters (hereafter designated "multi-class clusters") are split into more meaningful land cover units using ancillary raster data that have the same pixel size (30 m) and the same projection parameters as the imagery. Slope, aspect, and shaded-relief data sets are derived from the DTED data using standard raster-based image processing software, whereas the NWI, LUDA, STATSGO, and population census block group data layers are obtained by rasterizing and combining available vector-based coverages.

Briefly, for each multi-class cluster, digital ancillary values are obtained for a sample of individual pixels representing the suite of land cover classes represented by that cluster. The digital values of the various ancillary data layers are then compared to (1) determine which data layers are the most effective for splitting the multi-class clusters into the appropriate land cover units, and (2) derive the appropriate thresholds for splitting the clusters. Models are developed using one to several ancillary data sets to split each multi-class cluster into the desired land cover categories.

Each model consists of a series of conditional statements that split the cluster in question into two or more classes. The statements that are the most effective in splitting the clusters into the appropriate land cover classes are placed in the beginning of the models, whereas those that are less effective (but are still useful) are placed towards the end of the models. As an example, consider a multi-class cluster that includes both deciduous forest and low intensity developed land cover classes. Logically, regions of especially high elevation are not likely to be urbanized, and thus the first step of a model for this hypothetical cluster might be to assign pixels of the cluster that occur at relatively high elevations (e.g., 700 meters or greater) into the deciduous forest class. Those pixels from that cluster located in regions of high population density will most likely be low-intensity developed rather than deciduous pixels, and thus the next statement of the model might be to assign all pixels of the cluster that are located in areas with population densities greater than a particular threshold into the low intensity developed class. The last statement in the model might be to use LUDA data to assign the classes for the remaining pixels. The model development procedure is very empirical, and it generally takes several trials and modifications of model parameters using the subset of the mosaicked data set before the class-splitting models are considered refined enough to apply to the entire region (determined by visual inspection of model runs).

Most spectral clusters require development of class-splitting models. After all of these models are run, data are recombined into first-order classification products. It should be noted that there are advantages to conducting separate analyses of clustered leaf-on and leaf-off data sets rather than clustering and analyzing leaf-on and leaf-off data sets together. The analyst can make effective use of seasonally specific phenological information during the labeling process when data sets represent distinct time periods (e.g., leaf-on versus leaf-off). Such information is more difficult to use when the two dates are clustered as a single unit. It should also be noted that previous work (Vogelmann *et al.,* 1997a) has indicated that minimal gain in class discrimination is achieved after multi-temporal clustering of two TM data sets as opposed to clustering of the two data sets separately. However, it should also be noted that other investigators (Slaymaker *et al.,* 1996) have achieved excellent results after multi-temporal clustering of two seasonally distinct TM data sets.

Many bare areas (especially clearcuts and quarries) and the "other grass" category (i.e., parks, golf courses, and large lawns) are spectrally similar to other land cover classes and consequently are difficult to accurately classify using spectral data alone. However, when spatial characteristics are combined with their spectral properties, these areas can often be readily discerned in the TM imagery. Such classes are obtained through onscreen digitizing of the TM images. These digitized data sets are rasterized and recoded into the appropriate land cover categories and are incorporated into the land cover mosaics. The resulting product is then compared with the raw imagery, and obvious errors are corrected on a case by case basis.

6. Sample Land Cover Products

A mosaic of leaf-off Landsat TM images is shown for Federal Region 2 (Figure 1). This mosaic was produced using TM bands 5, 4, and 3 in red, green, and blue color planes. In this image, bright green areas correspond with areas of hay and pasture, pink areas are mostly deciduous forest, dark green areas are evergreen forest, purple areas are urban centers, and turquoise areas relate to snow cover. Note the spruce-fir forests associated with the high peaks region of the Adirondack Mountains in the northeastern part of the image, and the Pine Barrens in southern New Jersey (both dark green). Because of the normalization process, the mosaic is mostly seamless; this data set was produced using 14 TM scenes.

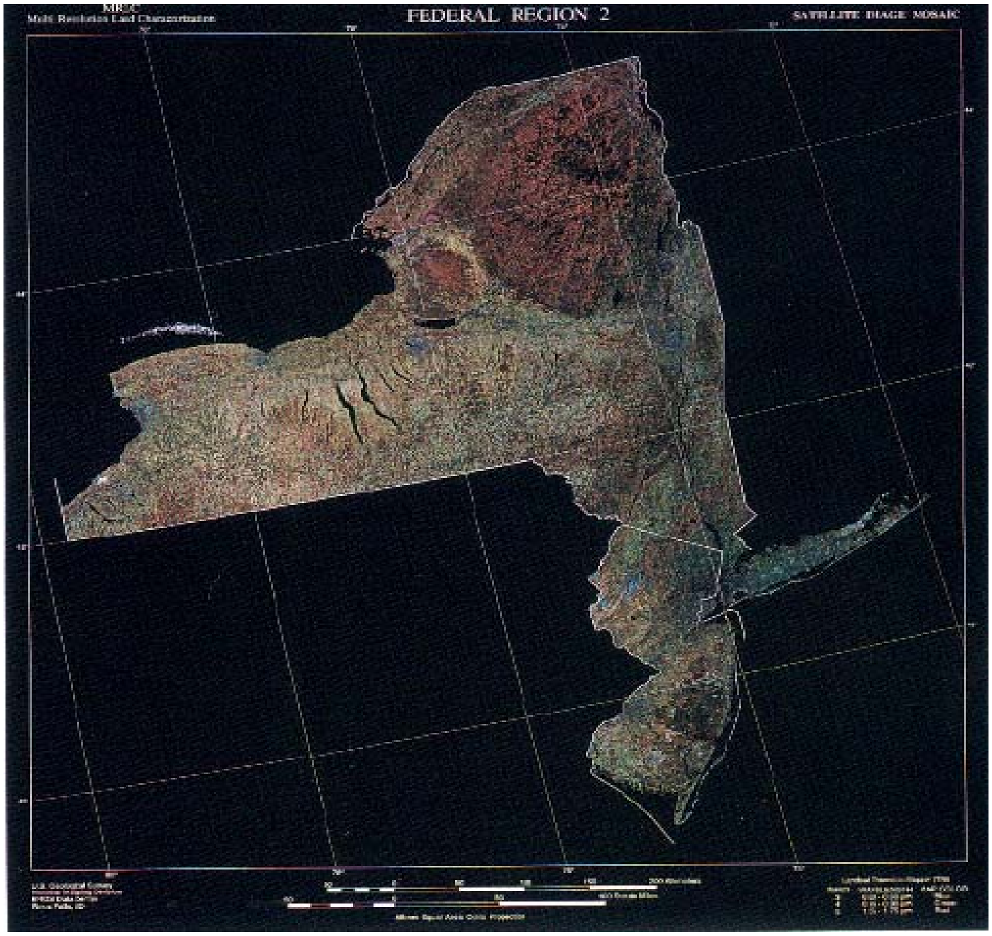

Fig. 1. Landsat thematic mapper mosaic of Federal Region 2 produced using bands 5, 4, and 3 in the order of red, green and blue. Data represent leaf-off conditions.

Comparison of the land cover classification data set for Federal Region 2 (Figure 2) with the imagery indicates good general agreement between the two products. Although the classification product was derived using 14 leaf-off and 14 leaf-on TM scenes, the methods used produced a nearly seamless classification product. It should be noted that both Figures 1 and 2 have been resampled for the purposes of presentation, and that substantial additional spatial detail is contained within the actual digital data files. An enlarged sample of the classified Region 2 data set (Figure 3) provides an example of the full-resolution characteristics and quality of the regional data sets being produced. Class area estimates (Table II) indicate that about 54 percent of the Federal Region 2 is forested, about 22 percent is in agriculture, and about 6.5 percent is urban/residential. A product of similar quality was produced for the mid-Atlantic region (Federal Region 3; Vogelmann *et al.,* 1997b).

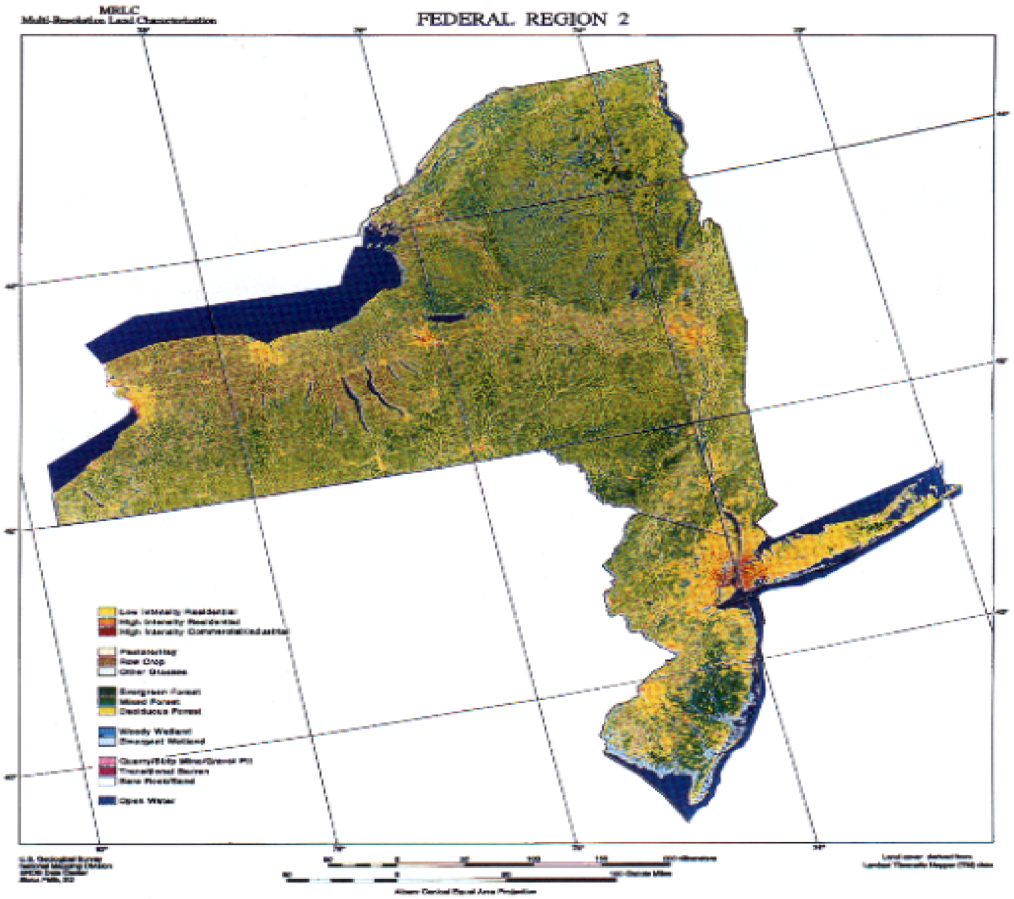

Fig. 2. Land cover data set developed for Federal Region 2.

7. Error Assessment and Consistency Checks

Once a land cover data set for a given region has been generated, three general stages of error assessment are conducted. Phase 1 includes initial checks, in which the classification product is compared with the imagery and obvious errors are fixed. During this phase, the preliminary land cover product is released to selected groups, especially those most familiar with the area. Feedback from these individuals is encouraged, and misclassifications are fixed when warranted. During phase 2, the land cover data set is compared with other sources of data from the region. Possible data sources for comparison include, but are not limited to, other classifications (often done for smaller parts of the regions), Census of Agriculture (Bureau of the Census, 1993) information, and aerial photograph point observation data. Comparisons with such data sources do not provide users with absolute values of accuracy, but do provide general information regarding the degree of consistency between the data sets being compared. This approach was found to be useful in Federal Region 3 (Vogelmann *et al.,* 1997b), where the combined assessments of comparisons with several sources of data provided information regarding which classes were the most trustworthy. During phase 3, a formal, statistically designed accuracy assessment (Congalton, 1991) will be done. The most appropriate methods for conducting phase 3 are being explored.

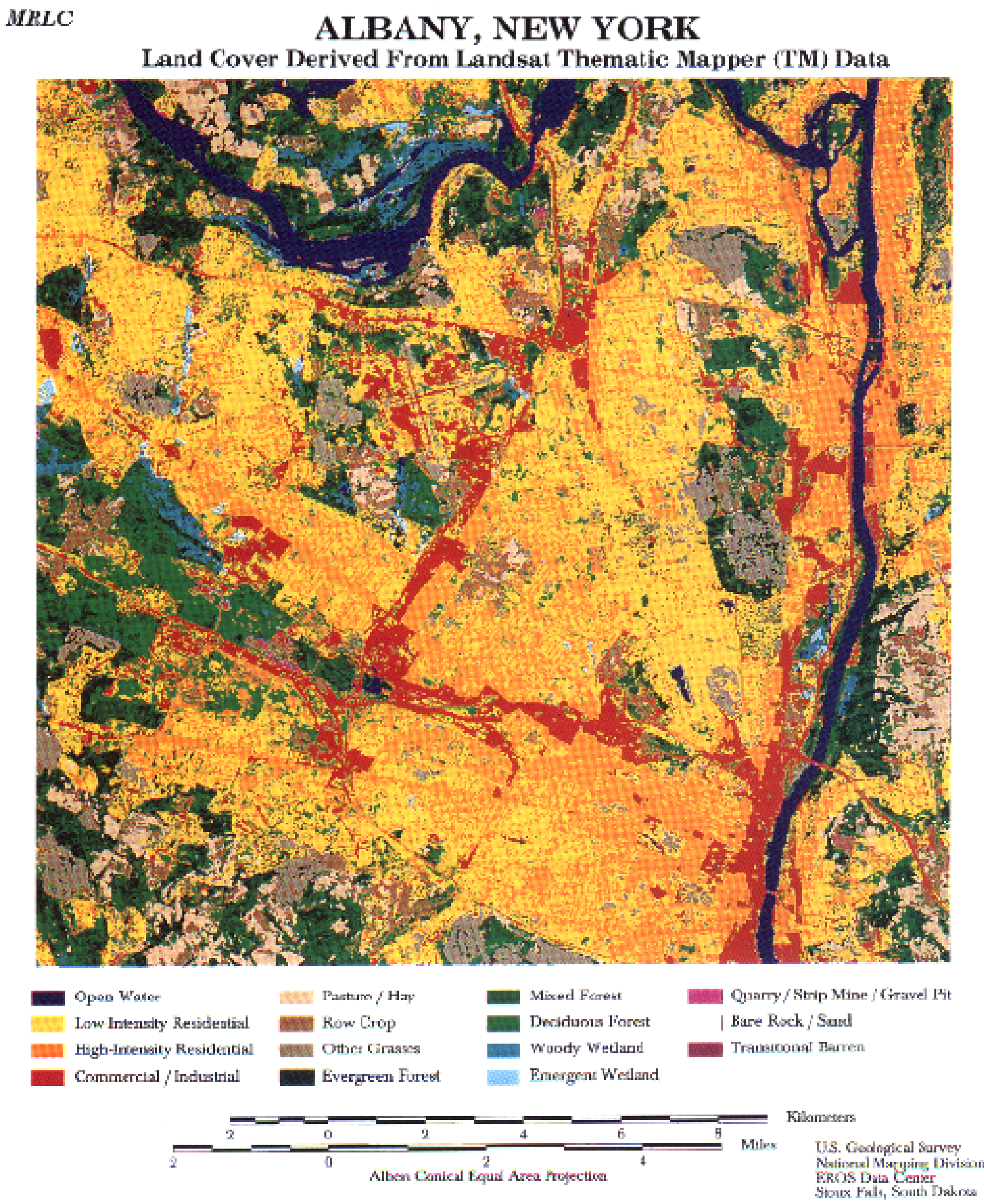

Fig. 3. Full resolution land cover data developed for the Albany, New York region.

8. Conclusions

The approach being implemented appears to have provided users with very good general land cover classification products for large regions. Although there are some classification errors within the data sets, the products appear to have many desirable characteristics (e.g., mostly seamless, and reasonable in terms of accuracy on the basis of visual inspection and consistency checks). The data sets produced to date are being used by researchers in the

Environmental Protection Agency's Landscape Ecology Program, Mid-Atlantic Integrated Assessment, and Regional Vulnerability Assessment Program. In addition, some GAP principal investigators in the mid-Atlantic and southeastern United States are using MRLC-derived land cover data to help map their state's natural and semi-natural vegetation. Additionally, USGS National Water Quality Assessment personnel are using the data to of landscape ecology (Forman and Godron, 1986) also has strong requirements for accurate and consistent land cover data. A series of landscape metrics using intermediate-scale land cover data (Riiters *et al.,* 1995) has been developed for assessing ecologically significant landscape patterns and processes, including forest contiguity and fragmentation, wildlife corridors, and patch size variables.

Despite the demand for land cover in these applications, many of the intermediate-scale spatial land cover data sets now available for the United States are outdated and of questionable accuracy. The only intermediate-scale land cover data set currently available for the conterminous United States is the Land Use and Land Cover (LUDA) data set (USGS, 1990). This data set, which was developed in the 1970's by interpreting and digitizing high-altitude aerial photographs, is probably still adequate for some applications. However, many land cover changes have occurred since the data set was compiled, and a more up-to-date national data set is needed. Recently, a land cover classification for the conterminous United States using 1-km advanced very high resolution radiometer (AVHRR) data (Loveland *et al.,* 1991; Brown *et al.,* 1993) was developed. Although it meets the needs of many researchers within the global change research community (Reed *et al.,* 1994), this data set is spatially too coarse for dealing with the problems and questions being addressed by other groups.

The Multi-Resolution Land Characteristics (MRLC) Interagency Consortium project was established as a partnership among Federal programs responsible for producing or using land cover data (Loveland and Shaw, 1996). Current partners include the U.S. Environmental Protection Agency, the U.S. Forest Service, NOAA, and the USGS. Initial priorities of the MRLC were concentrated on acquiring a common set of Landsat thematic mapper (TM) data sets for the conterminous United States from 1991 to 1993, and processing and georeferencing them to a set of standard specifications for a multitude of agency-specific purposes. More recently, MRLC activities have focused on using these processed data sets to help develop an intermediate-scale (30 m) land cover data set for the conterminous United States. One of the goals of this work is to produce a thematically consistent, seamless, and reasonably accurate land cover data set for the United States for multiple applications. This effort is the primary focus of this paper.

2. National Land Cover Initiative

The genesis of the MRLC's National Land Cover Initiative (NLCI) can be found in the March 1995 Memorandum of Understanding (MOU) signed at the director's level of the program's agencies. The MOU identified several long-term goals, including the development of a flexible and functional land characteristics data base for use by the MRLC and other federal, state, and local organizations. Although the overall vision of the MRLC is to provide a multi-resolution data base, current efforts are focused on generating an intermediate-scale national land cover data set that is based on remotely sensed satellite data acquired by the Landsat TM. The classified land cover data will be maintained at the develop pesticide and herbicide runoff models. Because of the scope of the analyses, it needs to be emphasized that the data sets are especially appropriate for regional analyses and applications. It should be cautioned, however, that many local-scale phenomena may be missed in such efforts, and that there is no surrogate for more in-depth analyses to obtain more detailed and precise information relating to localized conditions. For these latter purposes, however, we believe that the data sets being produced may be useful for providing a first-order overview.

Table II
Class area estimates for Federal Region 2.

Class	Area (km^2)	Percentage Area
Low Intensity Residential	6,881	4.2
High Intensity Residential	2,013	1.2
Commercial/Industrial	1,770	1.1
Pasture/Hay	15,034	9.2
Row Crop	20,001	12.3
Other Grasses	1,222	0.8
Evergreen Forest	8,931	5.5
Mixed Forest	26,814	16.4
Deciduous Forest	52,111	31.9
Woody Wetland	4,750	2.9
Herbaceous Emergent Wetland	1,170	0.7
Quarry/Mines/Gravel Pits	210	0.1
Bare Rock/Sand	114	0.1
Transitional Bare	78	0.1
Open Water	22,326	13.7

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