Remote Sensing of Environment 128 (2013) 246–258

Contents lists available at SciVerse ScienceDirect

Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

Long-term land cover dynamics by multi-temporal classification across the Landsat-5 record

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ARTICLE INFO

Article history:
Received 5 August 2009
Received in revised form 12 October 2012
Accepted 13 October 2012
Available online 10 November 2012

Keywords:
Landcover
Landsat
Multi-temporal
Land cover change
Supervised classification
Validation
Land cover dynamics
Sampling bias

ABSTRACT

Supervised classification of land cover across space and time is a long-standing goal of the Earth Science community. Although most past and current analyses focus on detecting changes between two or more times, the opening of the USGS Landsat archive in 2009 has enabled exploration of methods for higher-frequency, time-serial monitoring of land cover dynamics. Modifying the protocols used to develop the 2001 National Land Cover Database (NLCD 2001), we fit a single classifier to a spatio-temporally distributed reference sample and applied the model to 55 Landsat-5 images covering a section of the North Carolina Piedmont Plateau from 1984 to 2007. A generalized classification scheme, multi-temporal sampling design, supervised classification based on intra-annual spectral indices, and design-based accuracy assessment yielded a time-series of 16 land cover maps from 1985 to 2006 with a spatial extent of 1.7×10^6 ha, minimum mapping unit of 1 ha, and mean temporal interval of <2 years. Comparable to accuracy of the NLCD 2001 Land Cover Layer for the region, overall accuracy for a spatio-temporally independent test sample was 75%, with $\kappa=0.7$. When weighted by class proportions, percent correctly classified and kappa rose to 88% and 0.84, respectively. The resulting map series shows spatially and temporally complex changes in water, urban, forest, and herbaceous cover resulting from natural and anthropogenic processes that would not be observable in either uni- or bi-temporal maps. Agricultural crop area dropped from ~45% in the 1980s to ~36% in the 1990s and then rose slightly to ~38% at the end of the period. Forest area increased to a maximum of ~55% in the 1990s and then dropped to ~53% in 2005. Urban growth appeared to be most rapid in the 1980s and 1990s and slowed thereafter. With continued focus on the semantics, causation, sampling, and uncertainty underlying spectral land cover classification, long-term series of Landsat images will provide increasingly robust, reliable records for a growing scientific user community. These multi-temporal datasets will be indispensable for understanding past land cover dynamics and predicting the implications of future change on the provision and management of ecosystem services.

1. Introduction

The Landsat satellites have imaged Earth's terrestrial and near-shore marine surfaces for over thirty years. These images support numerous scientific applications, providing assessments of ecosystem quality, resources, services, and changes due to natural and anthropogenic forcing (National Academy of Science, 2005). Such a long and consistent record allows scientists to study current phenomena, relating satellite data to ground-truth or other references before interpreting patterns, but also to retrieve information from the past, over periods for which little or no reference data are available.

Among the most widely used, the 2001 National Land Cover Database ("NLCD 2001"; Homer et al., 2004) consists of fractional tree canopy and impervious surface cover and categorical land-cover/land-use layers covering the United States. Datasets such as NLCD 2001 are increasingly accurate and consistent sources of information for each dataset's reference year. However, no such data are available spanning multiple years over the long term. To capture the complexities of Earth's changing surface, time-serial landcover maps are needed.

Monitoring changes over time requires consistency among maps, both ontologically and statistically. That is, the maps must have identical semantics between real-world ecosystem types and thematic classes; and, unless accuracy is extremely high, they must also be based on similar correlations to the image data on which they are based. Without these two properties, it is impossible to determine whether changes observed are due to actual landscape changes or to ontological and statistical artifacts from the underlying data model.

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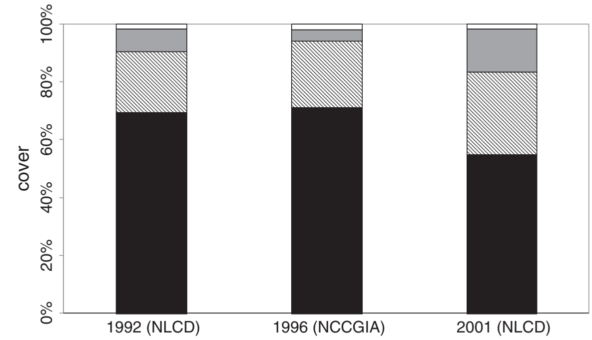
0034-4257/$ – see front matter
http://dx.doi.org/10.1016/j.rse.2012.10.010



	1992 (NLCD)	1996 (NCCGIA)	2001 (NLCD)
□Water	2.0	2.2	1.9
▩Urban	8	4	15
▧Field	21	23	29
■Forest	70	71	55

Fig. 1. Unreliable regional landcover change from three different sources: the 1992 National Land Cover Database (NLCD), the North Carolina Center for Geographic Information and Analysis (NCCGIA, 1996), and the 2001 National Land Cover Database. Observed changes are due to an unknown combination of real change and artifacts from schematic and statistical inconsistencies between the datasets. Despite rounding artifacts, class proportions sum to 100%.

Comparing inconsistent maps leads to unreliable conclusions. Consider the changing proportions of four land cover classes over time (Fig. 1) for a 1.7 Mha region of North Carolina (Fig. 2). The data were obtained from three publicly available and widely used maps, and the 4-class scheme was generalized from the maps' original schema to maximize comparability. In this depiction, land cover proportions fluctuated erratically, with impossible rates and reversals of change within a decade. Clearly more representative of underlying model differences than of real changes, these measurements would not be useful for further scientific analyses or policy decisions.

A single, robust model applied consistently over time could avoid these ambiguities. As the basis for land cover classification and change detection over space, this "signature extension" was an active topic of research early in the history of Landsat (e.g., Minter, 1978), and remains so today (Olthof et al., 2005; Woodcock et al., 2001). The process of signature extension requires training a classification model of the spectral signature on a relatively small number of land cover observations matched with spectral measurements in time and space and then extrapolating the classifier on image data collected at other times and/or locations for which no such reference is available (Botkin et al., 1984; Cihlar, 2000; Jensen, 1983; Muller, 1988). Whether in space or in time, signature extension relies on invariance of the relationship between cover and its spectral signature—a consistency that can be compromised by numerous factors, including atmospheric contamination, the interaction of illumination and viewing angles with the bidirectional reflectance distribution function of the surface, and plant phenology (Song & Woodcock, 2003). Because images from many dates must often be composited into large regional mosaics, much research has gone into calibrations to remove this unwanted variation.

All of these effects can be accommodated, but to varying degrees (Huang et al., 2009; Masek et al., 2006). Sensor radiometry is calibrated systematically (Chander & Markham, 2003; Chander et al., 2007), and bidirectional and atmospheric correction can be reasonably accomplished through models of varying complexity (Song et al., 2001). Even phenological variation – which is affected by vegetation type and environmental characteristics (Rathcke & Lacey, 1985; Schwartz, 2003) – has been used empirically to interpolate "synthetic" Landsat images between the satellite's 16-day orbital repeat (Hilker et al., 2009). However, remnant effects from both modeled and unmodeled

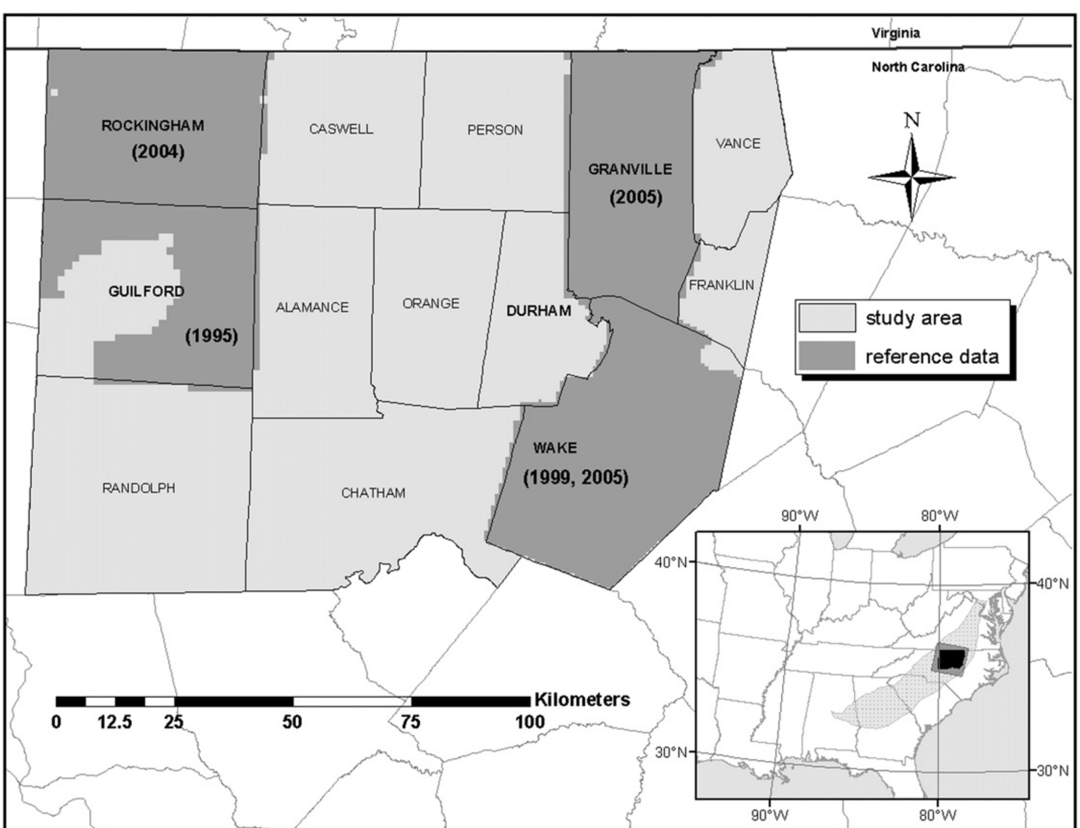


Fig. 2. The 1.7-Mha study area lies on the Piedmont Plateau (inset—shaded, stippled area), partially or entirely covers thirteen North Carolina counties, and is completely within WRS-2 Path 16, Row 35 (inset—shaded box). Split into separate training and test datasets, reference data were collected over 4 counties and four years.