Analysis of Climate and Vegetation Characteristics along the Savanna–Desert Ecotone in Mali Using MODIS Data

Sigrid Rian, Yongkang Xue,[1] and Glen M. MacDonald[2]
Department of Geography
University of California, Los Angeles
Los Angeles, California 90095-1524

Mahamadou B. Touré
Malaria Research and Training Center
Faculté de Médecine, de Pharmacie et d'Odonto-Stomatologie
Université de Bamako, BP 1805, Bamako, Mali

Yifan Yu
Department of Atmospheric and Oceanic Sciences,
University of California, Los Angeles
Los Angeles, California 90095-1524

Fernando De Sales and Paul A. Levine
Department of Geography
University of California, Los Angeles
Los Angeles, California 90095-1524

Seydou Doumbia
Malaria Research and Training Center
Faculté de Médecine, de Pharmacie et d'Odonto-Stomatologie
Université de Bamako, BP 1805, Bamako, Mali

Charles E. Taylor
Department of Ecology and Evolutionary Biology
University of California, Los Angeles
Los Angeles, California 90095-1606

---

[1]Also Department of Atmospheric and Oceanic Sciences, University of California, Los Angeles, Los Angeles, CA 90095-1524. Corresponding author; email: yxue@ssc.ucla.edu

[2]Also Department of Ecology and Evolutionary Biology and Institute of the Environment, University of California, Los Angeles, Los Angeles, CA 90095-1606.

GIScience & Remote Sensing, 2009, **46**, No. 4, p. 424–450. DOI: 10.2747/1548-1603.46.4.424

Abstract: MODIS data were used in conjunction with 600 ground survey points to create a 500 m resolution land cover product of Mali. It improves upon previously published land cover products for this region in resolution and accuracy. Of particular importance is the ability to detect small-scale, but important, wetland features such as rice cultivation areas. A combination of classical ground survey of vegetation type and structure, meteorological data, and remote sensing was used to quantify the relationship between vegetation and climate along the sensitive Sahel savanna–desert transition. The study demonstrates the effectiveness of using MODIS data for regional-scale studies.

INTRODUCTION

The human impacts of climate change could be especially destructive in already socioeconomically vulnerable regions of the world. Africa is at particular risk due to multiple stresses, including extensive poverty, inadequate economic, technological, and infrastructural development, widespread dependence on non-irrigated agriculture, and prevalence and spread of infectious diseases. Climate change will have implications for type, extent, and success of agricultural and pastoral farming, food security and environmental migration, socio-economic development, disease vector habitat and transmission rates, and availability of water and energy sources. While the impacts of climate change will vary across the continent, one region of particular concern is the Sahel. Long-term drought and poverty, reliance on climate-dependent resources, and low adaptive capacity contribute to making this region of savanna–desert ecotone particularly sensitive to effects of climate change and local human activity on the natural environment, agriculture, economy, and public health (Boko, 2007).

Working Group II of The Intergovernmental Panel on Climate Change Fourth Assessment (IPPC; Parry et al., 2007) projects increased aridity for most of the African continent, with a rise in temperatures greater than the global average for the continent as a whole, and for the Sahel in particular (Boko, 2007). The IPCC reports that model discrepancies prevent a conclusive projection of precipitation patterns and river flow in the western Sahel (Christensen et al., 2007). Nevertheless, widespread water scarcity is expected for parts of the region (Arnell, 2006), along with an increase in extreme weather events (Huntingford et al., 2005), shifts in the geographic range of transmission for vector-borne diseases (Thomas et al., 2004), and changes in land cover and agricultural potential (Fischer et al., 2005, Mendelsohn, 2007). Observed increases in temperature and aridity have already reduced the length of the cropping season in the Sahel, affecting accessibility to arable land and resulting in adaptive strategies including seasonal migration and land cover conversion (Boko, 2007). While the majority of Sahelian agriculture is rain-fed, irrigation technology applied to rice farming has allowed socio-economic improvement and increased food security in several communities. IPCC projections of higher temperatures, increased water stress, and changes in growth season are likely to pose severe problems in the yield, quality, and timing of rice production (Dingkuhn, 1995; Matthews et al., 1997; Peng et al., 2004). Recent fluctuations in the cost of rice and other crops combined with consistently low food security in northern and other isolated areas emphasize the importance of monitoring key crop areas such as the rice-growing districts (FEWS NET, 2008).

Any changes in the Sahel land cover can in turn influence the climate. The land surface plays a significant role in the climate system, acting as a boundary layer for the lower atmosphere in the exchange of moisture, heat, momentum, and trace gases. The interaction of land surface properties with these factors helps determine the vegetation environment, and leads to variations in albedo, which in turn affects evaporation, precipitation, and vegetation (Dickinson, 1992). These land–vegetation–atmosphere interactions have been the subject of extensive research, including various modeling efforts specifically focusing on the Sahel and the savanna–desert ecotone, demonstrating that this feedback mechanism is certain to influence the climate and vegetation structure of the Sahel (Xue and Shukla, 1993; Zeng and Neelin, 2000; Nicholson, 2001).

The ability to detect and adapt to changes in the land cover of the Sahel depends upon an understanding of current relations between climate and vegetation distribution and structure, and a baseline snapshot of current conditions with which comparison to future conditions can be made. Remotely sensed land cover classification products are constructive tools in studies aiming to describe and assess the link between climate and environment. Many tropical areas are poorly represented by field-based data and too extensive to be mapped by any other means other than remote sensing (Apan, 1997; Mayaux et al., 2004; Fuller, 2006), yet the lack of intensive field-based observations can often lead to uncertainties in remote sensing products (Stuart et al., 2006). Land cover classification products can serve as important supplements to General Circulation Model (GCM) projections by using verified ground survey data (Fennessy and Xue, 1997).

The present study provides a ground-referenced land cover product of the savanna–desert ecotone in Mali, and serves to link classical ground surveys of vegetation type, measures of change in vegetation structure, and remote sensing along the sensitive Sahel savanna–desert transition. The resulting product describes the present state of the ecotone and exemplifies how that vegetation cover structure is represented by the Moderate-Resolution Imaging Spectroradiometer (MODIS).

This study complements existing land cover products that include the Sahel region, such as the International Geosphere-Biosphere Programme Data and Information System (IGBP-DIS) DISCover product (Townshend, 1992, Loveland et al., 1999), the University of Maryland Global Land Cover Classification (UMD; Hansen et al., 2000), the Joint Research Center (JRC) of the European Commission (EC) Global Land cover 2000 (GLC2000) (Mayaux et al., 2004), and the European Space Agency (ESA)'s GLOBCOVER (Defourny et al., 2006). The new product presented here provides much greater density of ground survey sites than any of the satellite data–based land cover products that include this Sahel transition, information on how structure changes along the transition, and an assessment of the relationship between variations in climate and the major land cover classes in the region as represented in the ground survey network and the remote sensing product. These characteristics of the new land cover product contribute to a comprehensive picture of current conditions in the study area, with which future scenarios can be compared.

STUDY AREA

The focus of this study is the Republic of Mali in West Africa, a country of 1.24 million km^2 with a population of 12 million (CIA, 2008). Mali lies approximately between 10°N and 25°N Lat., and between 12°E and 5°W Long. The savanna–desert transition in Mali exhibits a strong gradient in climate and vegetative cover typical for the Sahel region. Characteristic is the pronounced southwest–northeast gradient in climate, vegetation, soil, and human activities. This section describes general climate and vegetation features in Mali. The further quantitative examination of vegetation distributions and their relationship with climate will be discussed in subsequent sections. Composition and structure of vegetation is a function of physical conditions as well as biological factors and history, and a high correlation can generally be found between a particular region's moisture and energy balance on one hand and the physiology, morphology, and distribution of plants on the other (MacDonald, 2003). This relationship is clearly reflected in the changing vegetation characteristics in the Sahelian savanna–desert ecotone, where a broad pattern of decreased moisture and increased temperatures results in a pattern of shorter plants, less complex vegetation structure, and sparser coverage in a gradient from south to north.

Climate

Both temperatures and precipitation show a strong latitudinal gradient in Mali. Average July temperatures range from 26°C in the relatively moist woodland savanna zone in the far south to 36°C in the hot and arid Sahara Desert in the north. Precipitation is the central limiting factor for vegetation growth and human land use in the Sahel, and insight into the governing precipitation patterns is therefore important. The Sahel is characterized by great annual and multiannual rainfall variability (Nicholson, 1993, 2001; Hulme, 1996), expressed most notably in the development of severe and persistent droughts, which has incited extensive research into the patterns, influence, and consequences of long-term precipitation variability in the region over the past several decades (e.g., Charney, 1975; Nicholson, 1993, 2001; Xue and Shukla, 1993; Xue et al., 2004b). The West African monsoon is associated with northward migration of the Inter-Tropical Convergence Zone (ITCZ), which brings precipitation to the Sahel region during the Northern Hemisphere summer. There are no great topographical divides in the region, facilitating the northward transport of moist air from the Gulf of Guinea, which cuts off the drier desert air from the northeast. The mixing of these two air masses may cause bursts of thunderstorms due to local convective activity. Thunderstorm activity and annual precipitation totals increase with the higher influx of humid air in the south. The rainy season lasts from two to four months between May and October, gradually increasing in duration southward. The northern areas may receive the first rain as late as July, while the highest amount of rainfall invariably arrives during the month of August across the study area. The intertropical front leaves the region and the rainy season comes to an end in September or October, depending on latitude. The remainder of the year is characterized as the dry season, when little to no moist air is available.

Precipitation patterns vary with latitude, and the highest amounts of mean annual precipitation are recorded in the southernmost region, reaching totals of up to 1200 mm in some locations. Precipitation gradually decreases northwards, and reaches 0–100 mm in the extremely arid Sahara Desert.Vegetation zones change accordingly, and a detailed description of this pattern is presented in the next section. As the vast majority of annual Mali precipitation is produced by the West African Monsoon during summer, June, July, and August (JJA) precipitation accounts for 60–80% of annual precipitation in the study area. In addition to the general scarcity of water due to low influx of moisture into the region, soils typically have low water-retaining abilities, a low natural yield potential, and runoff is generally high due to crust formation (Xue et al., 2004a).

Vegetation Zonation

Tropical African savanna ecosystems represent the spatially extensive and complex ecotone between forest and desert. The proportions of treed, shrubby, graminoid, and bare surface cover are largely determined by large- and small-scale gradients of precipitation and its induced soil moisture, and the complexly related factors of edaphic conditions, wildfire, grazing, and human land cover modification (e.g., Walter, 1971; Walker and Noy-Meir, 1982; Scholes and Walker, 1993; Jeltsch et al., 1998; Scholes et al., 2002; Caylor and Shugart, 2006).

Four broad ecological zones corresponding to mean annual precipitation have been qualitatively defined in Mali (Jaeger, 1968; Schnell, 1976; Arbonnier, 2002). These classes can be generally correlated with land cover classes generated from the new Mali land cover classification product presented in this study, as well as with climate characteristics associated with each zone.

Sudano-Guinean Zone (Mean annual precipitation ≤1200 mm). The Sudano-Guinean Zone in the southern Sahel may be subdivided into the Doka woodland zone and the Guinea woodland zone, where the former is characterized by savanna–forest mosaic whereas the latter is primarily forested (Cockrum, 1976) and receives the highest amount of rainfall in the study area. A typical species found in this area is *Vitellaria paradoxa* (*Butyrospermum parkii*), the economically important shea-butter tree, which is also very common across the Sudanian zone to the north. Examples of other widespread species in this region are *Anogeissus leiocarpus, Daniella oliveri, Isoberlinia doka, Monotes kerstingii, Khaya senegalensis, Pterocarpus erinaceus,* and *Terminalia macroptera* (Jaeger, 1968; Schnell, 1976; Cuny et al., 1997; Arbonnier, 2002). Trees in the Sudano-Guinean zone can reach heights up to 40 meters, although this was rarely observed during the ground survey.

Sudanian Zone (Mean annual precipitation 700–1000 mm). The Sudanian Zone has lower density of woody vegetation, consistent with lower mean annual precipitation. Soils are typically rocky or hardpan, and land cover ranges from open grassy plains and shrubby thickets to wooded savanna and open forests. The natural wooded savannas are often converted to agroforestry parks with large trees such as *Adansonia digitata, Ficus* sp., *Parkia biglobosa,* and *V. paeadoxa*. Common trees thus include many of the same species as the Sudano-Guinean zone. Trees are often drought-deciduous, and gallery forests are found along drainages and low areas. The grassland cover is often dominated by *Andropogon pseudapricus* (Ruthenberg, 1974).

Sahelo-Sudanian Zone (Mean annual precipitation 500–700 mm). This zone, which incorporates the more riparian Niger Delta, and has a mosaic of various vegetation types, with fewer and shorter trees, but with dense shrubland as well as agroforestry parks and some parkland savanna–type landscapes. There are also gallery forests near rivers or ponds, and some thickets where termite mounds are typically found. Many of the same species as in the Sudanian zone are found here, including *A. digitata, Combretum* spp*., A. leiocarpa, Pterocarpus* spp*., and Terminalia* spp*.* Vegetation density often depends on the clay content of the soil, with higher density on clay or silt soils over sandy soils (Arbonnier, 2002).

Saharo-Sahelian Zone (Mean annual precipitation 200-500 mm). This northern zone is characterized by perennial tussock grasses, specifically *Aristida pungens* in the north and *Parnicum turgisum* in more humid areas toward the southern range of the zone. The open shrubland landscape is dominated by thorny acacia shrubland with species such as *Acacia ehrenbergiana, A. senegal,* and *A. tortilis raddiana, Balanites aegyptiaca, Piliostigma reticulatum*, and patches of bush where *Combretum micranthum* is the most common. The northernmost part of the Saharo-Sahelian zone may receive 200 mm precipitation annually, and transitions into the predominately unvegetated Sahara Desert, where mean annual rainfall does not surpass 100 mm. Vegetation and species are similar to open shrubland assemblages and usually found along wadis or creeks, but with much lower vegetation density, sandier soils, and severely stunted growth forms. Soils in this region are for the most part undifferentiated and not well developed (FAO, 2003).

DATA AND METHODS

Ground Survey of Vegetation Cover and Structure

More than 600 ground survey points were collected along a SW–NE gradient in Mali during the rainy seasons of 2003, 2004, and 2005 for use in training the classification. At each point releve methods were used to estimate overall vegetation type and specific land cover percentages of Low Vegetation (seedlings, herbs, and graminoids), Open Shrub, Dense Shrub, and Woody Savanna, Bare Ground, Wetland/Rice and Water Cover, as well as soil moisture and Leaf Area Index (LAI) measurements in select locations. The methodology used for the ground survey was simple and can be carried out locally using basic field equipment at low cost.

To further develop our understanding of the vegetation structure and nature of changes in LAI across the main vegetation zones, vegetation structural data were obtained and 10 transects considered as representative of these vegetation zones were completed. At each of these 10 locations, we recorded vegetation height, type, and coverage, number of canopy layers, and percent vegetation cover, soil moisture, and LAI along a 50-meter transect. LAI was measured using a LI-COR 2000 Plant Canopy Analyzer. Sites were selected to represent the different major land cover types, and an effort was made to identify locations that were as undisturbed as possible, largely homogenous, and representative of each specific region along the transect.

The distribution of ground survey points (GCPs) and transect locations is shown in Figure 1. The underlying 1 km resolution global land cover product was generated by researchers at the University of Maryland (UMD) downloaded from the Global Land cover Facility (GLCF; http://glcf.umiacs.umd.edu/index.shtml) (Hansen and Reed, 2000). This product was used in the initial planning of the ground survey to

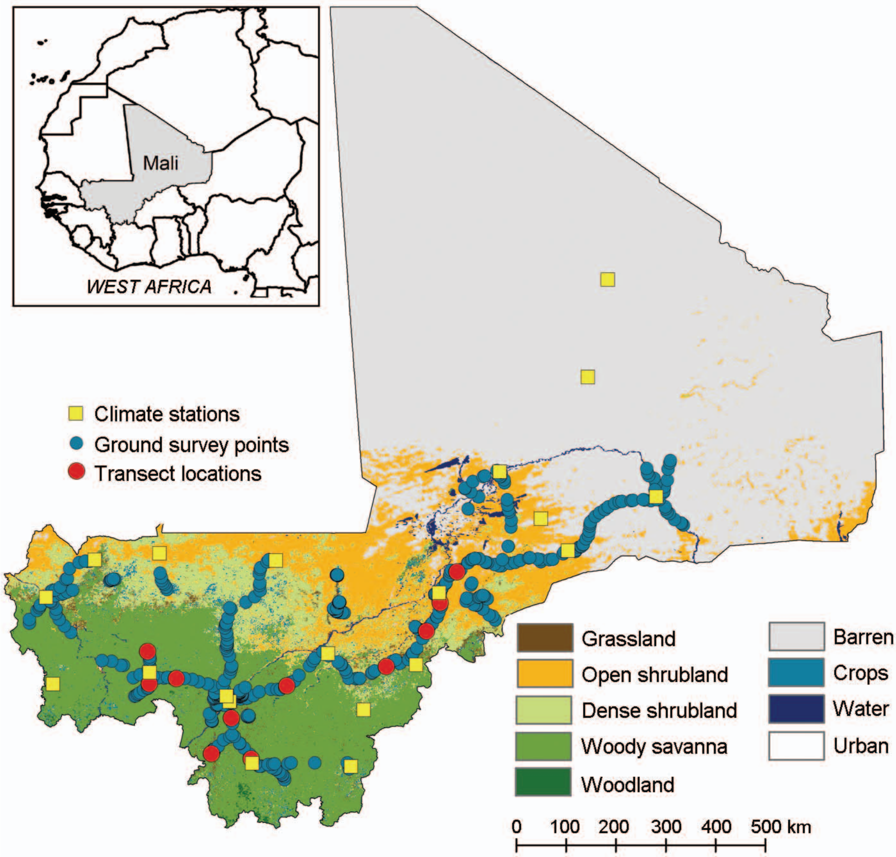

Fig. 1. Distribution of ground survey points, transect locations, and climate stations. Overlain on University of Maryland 1 km land cover classification derived from AVHRR (Hansen et al., 2000).

ensure satisfactory distribution of ground control points across the different vegetation zones. Further information on species and assemblages were established with the help of local experts and vegetation books (e.g., Schnell, 1976; Cuny et al., 1997; Arbonnier, 2002). No points were collected north of Timbuktu, with the northernmost point located at 16.74°N. This northern limit was established mainly because the vegetatively sparse Sahara Desert occupies the northern part of the country.

Climate Data

Meteorological data was obtained from Institut de Recherche pour le Développement-France (IRD) daily rainfall database (Poccard and Xue, 2004) over West Africa and data from the Mali National Meteorological Office, resulting in continuous records of precipitation and surface temperature averaged from 1990 to 2004. In addition, global datasets with about 50 km spatial resolution from the National Center for Environmental Prediction Climate Prediction Center (NCEP CPC; Xie and Arkin,

1997) were interpolated from stations. The distribution of climate stations is also shown in Figure 1.

Remote Sensing Data

The data used for this classification were obtained from the National Aeronautics and Space Administration's (NASA) Earth Observation System (EOS) Data Gateway (http://delenn.gsfc.nasa.gov). We used data from MODIS, which was launched by NASA aboard the Terra (EOS AM) satellite on December 18, 1999. Principal characteristics of the 250–1000 m sensor include a 2330 km swath and spectral coverage of 405–14,385 nm across 36 bands. The product employed in this study is MODIS/Terra Surface Reflectance 8-Day L3 with 500 m resolution. This product consists of surface spectral reflectance for each of bands 1–7, computed with integrated corrections for atmospheric contamination from gases, clouds, and aerosols. In addition, values were extracted from MODIS/Terra Leaf Area Index/FPAR 8-day global 1 km and MODIS/Terra Vegetation Indices 16-day L3 global 250 m for use in the quantitative vegetation/climate analysis.

For the land cover classification, six scenes with minimal cloud cover were selected to provide coverage for the entire study area, from each of eight consecutive dates during the rainy season, specifically August 5–October 7, 2004. Eight MODIS/Terra Surface Reflectance 8-day composites for this period were required to cover the entire study area. The eight resulting scenes were clipped to contain only the country of Mali, using a vector boundary file from Digital Chart of The World (Defense Mapping Agency, 1992). The eight resulting subsets were used to create a composite that was compiled using an NDVI-based maximum value approach. The Environment for Visualizing Imagery (ENVI) was used for compilation and analysis of the images. The final base image used for classification thus consists of a 64-day composite from the rainy season of 2004. Due to contamination in band 5, only bands 1–4 and 6–7 were used for the composite. Obtaining completely cloud free MODIS imagery from this region during the rainy season is virtually impossible, due to the fact that the ITCZ brings moisture into the region during summer, with the Niger Delta as well as other areas of the country receiving large amounts of precipitation. The maximum value composite served not only in compiling multiple dates, but also helped reduce cloud contamination in the imagery. We recognize that not all cloud contamination can be removed successfully using this method, and remaining clouds were removed manually.

RESULTS

The ground survey network including the 10 transects at representative locations provides an outline of the changing vegetation structure across the study area. The results of the transect study clearly show the decreasing values in soil moisture, LAI, NDVI, vegetation height, and structural complexity as one moves northward from the Sudano-Guinean vegetation zone to the Sahara Desert transition (Fig. 2). Values for LAI and NDVI were extracted from mean rainy-season MODIS imagery. The data are plotted against latitude, and each point represents ground survey and vegetation transect locations. Although soil moisture is characterized by a steady and gradual

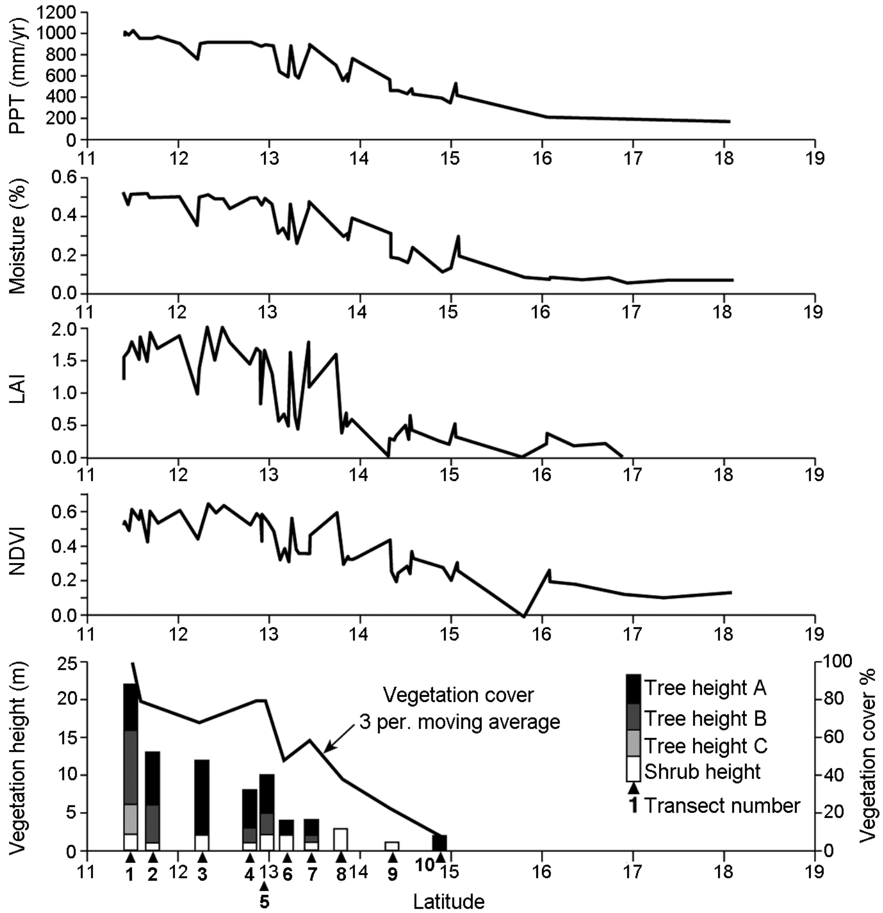

Fig. 2. Patterns of climate and vegetation characteristics along a SW–NE gradient.

decline across the transect, there is some evidence of a particularly sharp decrease in vegetation cover and associated LAI at the point of transition between wooded savanna and shrubby savanna and desert transition.

Classification of Land Cover Classes and Boundaries by Maximum Likelihood Methods

This study employs a supervised maximum likelihood classification approach, where each training pixel is categorized by the analyst, and the computer algorithm extends this information to the entire scene. In this way, each pixel in the scene is assigned to the land cover type its spectral properties resemble the most, according to the training information entered. Ground survey points collected during field work train the algorithm used in the classification (Jensen, 2005). Following this procedure, the maximum likelihood classifier was applied to the composite images we created from the eight 8-day MODIS composites based on the maximum NDVI values. The

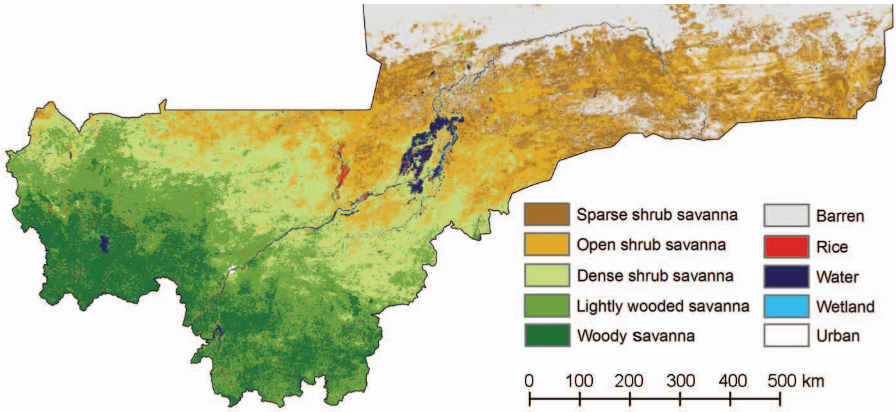

Fig. 3. UCLA product: land cover classification of Mali.

600 ground survey points were entered into a data base and coded according to their land cover class as defined through the ground survey. The coordinates were imported into the image processing package ENVI class by class, and the training sites were entered as regions of interest (ROIs) in the satellite imagery used to create the classification product.

In order to verify the classification results, the ground survey data were split into two data sets using stratified random sampling. One half of the points were used as training data for the maximum likelihood classifier in the production of a preliminary classification. As a simple test of classification accuracy, an error matrix was generated using the second half of the ground survey data. The resulting overall accuracy was 94.65%. All classes were classified with 72–97% accuracy. Some confusion was observed between adjacent savanna classes, and some rice and wetland pixels were confused with water. This is to be expected at this resolution due to the fact that many water bodies have some vegetation growing in or near them, especially seasonal ponds or semi-dry lakes. In addition, the spectral properties of flooded vegetation may be confused by reflectance between the surface and various canopy layers. Previously published comparative studies have shown that inconsistencies in class definition are prevalent especially for land cover classes savanna/shrublands and wetlands (Hansen and Reed, 2000; Giri et al., 2005, Frey and Smith, 2007).

A final classification was carried out using all of the ground survey data to train the algorithm. The preliminary and final classifications are similar, and a comparison between the two products yielded 94.19% agreement (Appendix A). The resulting final land cover classification is presented in Figure 3, and will be referred to as the UCLA product in this paper. This new product shows great heterogeneity in land cover types across the study area, with a clear gradient from south to north. The Sahara Desert was excluded in this figure since this area has largely homogenous and predominantly barren desert cover, and it is not a key land cover class for this study.

The southernmost part of Mali is designated as woody savanna from ground survey and satellite imagery classification, and correlates with the Sudano-Guinean Zone. This area is characterized by savanna and forest mosaic, including thickets of

Table 1. Areal Extent of Land Cover Classes in the UCLA Product

Class	Area (km^2)	Pixels	Percent
Barren	690,983	3,217,865	55.06
Sparsely Vegetated Grassland	83,425	388,504	6.65
Open Shrub Savanna	139,757	650,842	11.14
Dense Shrub Savanna	125,445	584,190	9.98
Lightly Wooded Savanna	123,242	573,932	9.81
Woody Savanna	76,565	356,558	6.09
Rice	2,854	13,292	0.23
Wetland	2,776	12,927	0.22
Water	9,486	44,175	0.74
Urban	1,256	585	0.01

trees, shrubs, and lianas, open forests, gallery forests, and patches of the densely forested Guinea woodland in the far south. The lightly wooded savanna landscape directly to the north corresponds to the Sudanian Zone, with lower density of woody vegetation and a continuous grassy groundcover that can reach 1.5 m in height. Further decreases in vegetation height, density, and complexity of structure are apparent when moving northwards into the dense shrub savanna, typical of the Sahelo-Sudanian Zone. Changes in vegetation are also evident in relation to the position of the Niger River, where large areas of wetlands and seasonally flooded vegetation dominate regions of the Inner Delta, and high density and lush vegetation grow in immediate riparian areas. The open and sparse shrub savanna landscapes of the Saharo-Sahelian Zone transition into the Sahara Desert, where very little vegetation grows, with the exception of some shrubs and grasses along streams and creeks.

The areal extent of each of the land cover classes in the UCLA product is shown in Table 1. The Sahara Desert occupies a large part of the country, accounting for 55% of the total land area. The various savanna types each account for between 6% (woody savanna) and 11% (open shrub savanna). Rice, wetland, and water each occupy less than 1% of the total land area of Mali.

The UCLA product is consistent with the vegetation distribution described under "Vegetation Zonation," and shows a general resemblance to existing global classification products from UMD, IGBP, GLC2000, and IGBP- and UMD-based MODIS classification products (Friedl et al., 2002). UMD (Fig. 1) and GLC2000 show the same general transitional pattern as the UCLA product, whereas IGBP has a different pattern with the class savanna appearing both in the far south and in an east–west belt south of the Niger Delta. The UCLA product and GLC2000 identify five or more vegetation land cover classes in a south–north direction, whereas UMD and IGBP has four clear transitional zones of different vegetation types, excluding croplands.

Not every classification scheme includes wetlands, and with this land cover type accounting for less than 1% of the land cover in Mali, it is difficult to make an assessment of each product's performance in delineating this class as well as the rice class at km resolution (Giri et al., 2005). Of more pertinent interest than the overall accuracy is the agreement among individual classes. A confusion matrix summarizes the per pixel agreement with the UCLA product between all aggregated classes for each of the five classification products (Appendix B). The overall accuracies when all classes are considered range from 62.29% (IGBP) to 75.68% (GLC2000). The problems in delineating wetlands and irrigated crops are evident for the schemes where these classes are incorporated. In the per pixel comparison between the UCLA product and GLC2000, these two classes have the lowest accuracy, with GLC2000 confusing rice for water in the Inner Delta.

A comparative analysis of a subset of existing land cover classifications against the UCLA product was carried out in order to identify certain areas of disagreement, and such a comparison could also serve as potential validation of existing products (Hansen and Reed, 2000). The comparison presented here was carried out in important rice cultivation areas in Mali. Rice fields in Mali typically exist in smaller areas with irrigation projects or dams, and two notable regions that fit this description are the rice cultivation region near the Selinkenyi Dam south of Bamako and the Niono area north of Bamako. A visual comparison of these two areas of exemplifies the importance of ground survey data and the strength of the UCLA product.

Subsets of land cover products were created for the Selinkenyi area (Fig. 4) and for the Niono area (Fig. 5). Landsat scenes obtained during the rainy season are used to verify the extent of rice fields. Rice is shown in red, crops are shown in teal, and crops/natural vegetation mosaic in IGBP is shown in purple.

Visual inspection shows that most of the land cover products misclassify rice fields and wetlands. In the Selinkenyi area, only the UCLA product correctly identifies the rice field along the upper branch of the Niger River. In the Niono area, GLC2000 correctly classifies some of the irrigated crops, but to a much smaller extent. UMD correctly identifies some rice as crops, but other rice and wetland areas are classified as grassland or closed shrubland. IGBP does a good job of identifying rice as crops or crops/natural vegetation mosaic, yet portions of rice fields are categorized as bare ground. At the smaller scale, the UCLA product performs better in identifying these key areas.

Climate–Vegetation Relations

A general description of the broad relationship between climate and vegetation was presented under the section entitled "Study Area." This section discusses correlations between climate data and vegetation cover within Mali to quantitatively examine this relationship based on the newly derived high-resolution vegetation map and climate data. Because a process-oriented field-study approach (e.g., Kahan et al., 2006) is beyond the scope of this paper, this broad-scale empirical approach to study climate-vegetation relations employed here is appropriate given the sparsity of long climate station records or vegetation monitoring in the region. The climate data examined were from the rainy season months of June, July, and August, consistent with the satellite data used for the classification of the vegetation map. An initial attempt to use NCEP CPC (National Center for Environmental Prediction Climate Prediction Center) 50 km resolution climate data to analyze correlations with vegetation found that due to the CPC data being derived based on few stations over Mali, fine-scale spatial variations were not captured correctly. Given the apparent sharp transition

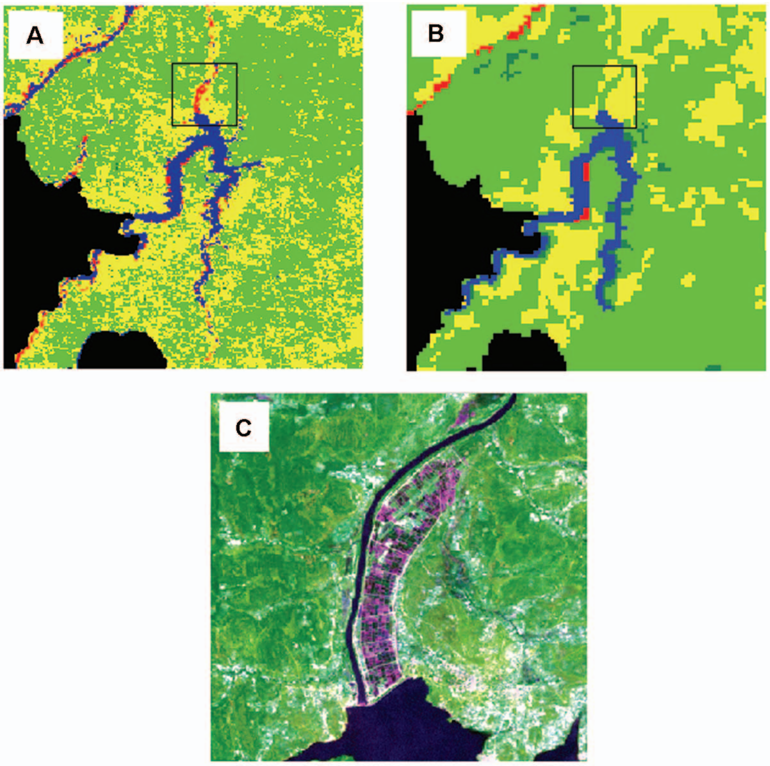

Fig. 4. Comparison of UCLA product with GLC2000 land cover product and Landsat ETM+ (30 m spatial resolution) for the Selinkenyi area in Mali. A. UCLA. B. GLC2000. C. Landsat ETM+ subset of the area outlined in Figures 4A and 4B.

between vegetation cover types, the interpolated climate data caused a serious mismatch in spatial scales between vegetation map and climate data. Due to limitations of the availability of "ground truth" measurements and the lack of climate data with large spatial coverage and fine spatial resolution, we found the best approach was to use the simple point data from Mali stations for this analysis.

For each station location, a window of approximately 10 km × 10 km was selected to derive fractional coverage of different vegetation types from the vegetation classification map. Different radii were tested, and we found that reasonable correlations appeared only with a radius smaller than 20 km. In order to obtain statistically significant results, the classes of barren and sparsely vegetated (<10% vegetation cover) were combined into one Low Vegetation class. Based on the same consideration, the classes of lightly wooded savanna and wooded savanna were combined into one woody savanna class. Figure 6A shows that the four class types have distinct ranges of JJA precipitation: the Low vegetation type mainly covers the area receiving precipitation less than 2 mm/day, while woody savanna covers areas with more than 6.5 mm/day. These results are consistent with previously described precipitation ranges for each vegetation zone: areas receiving ≤2 mm/day during JJA are

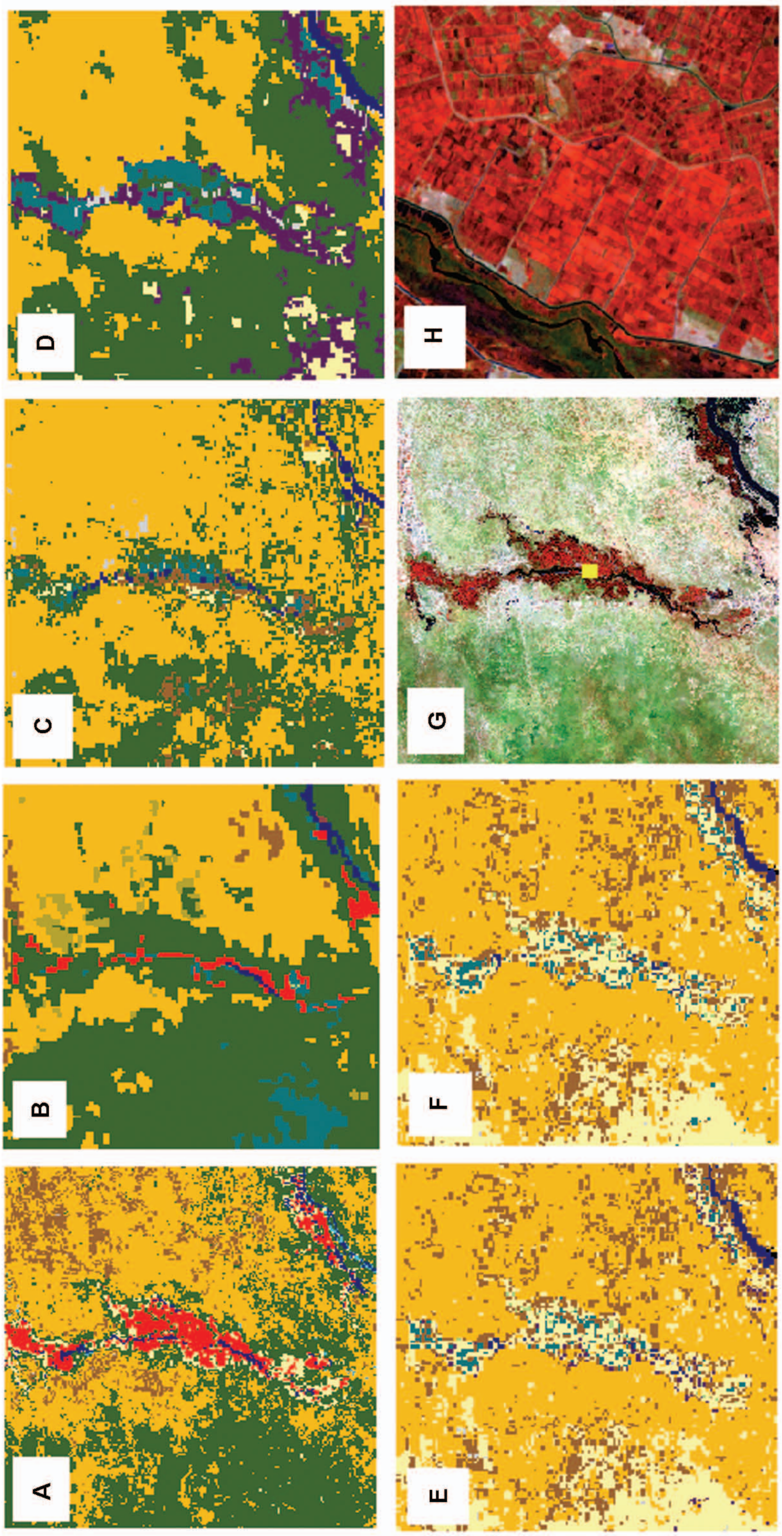

Fig. 5. Comparison of UCLA product with existing land cover products and Landsat ETM+ (30 m spatial resolution) for the Niono area in Mali. A. UCLA. B. GLC2000. C. UMD. D. IGBP. E. MODIS IGBP. F. MODIS UMD. G. Landsat ETM+. H. Detail of rice fields from Landsat ETM+ for the area indicated by a yellow square in Figure 5G.

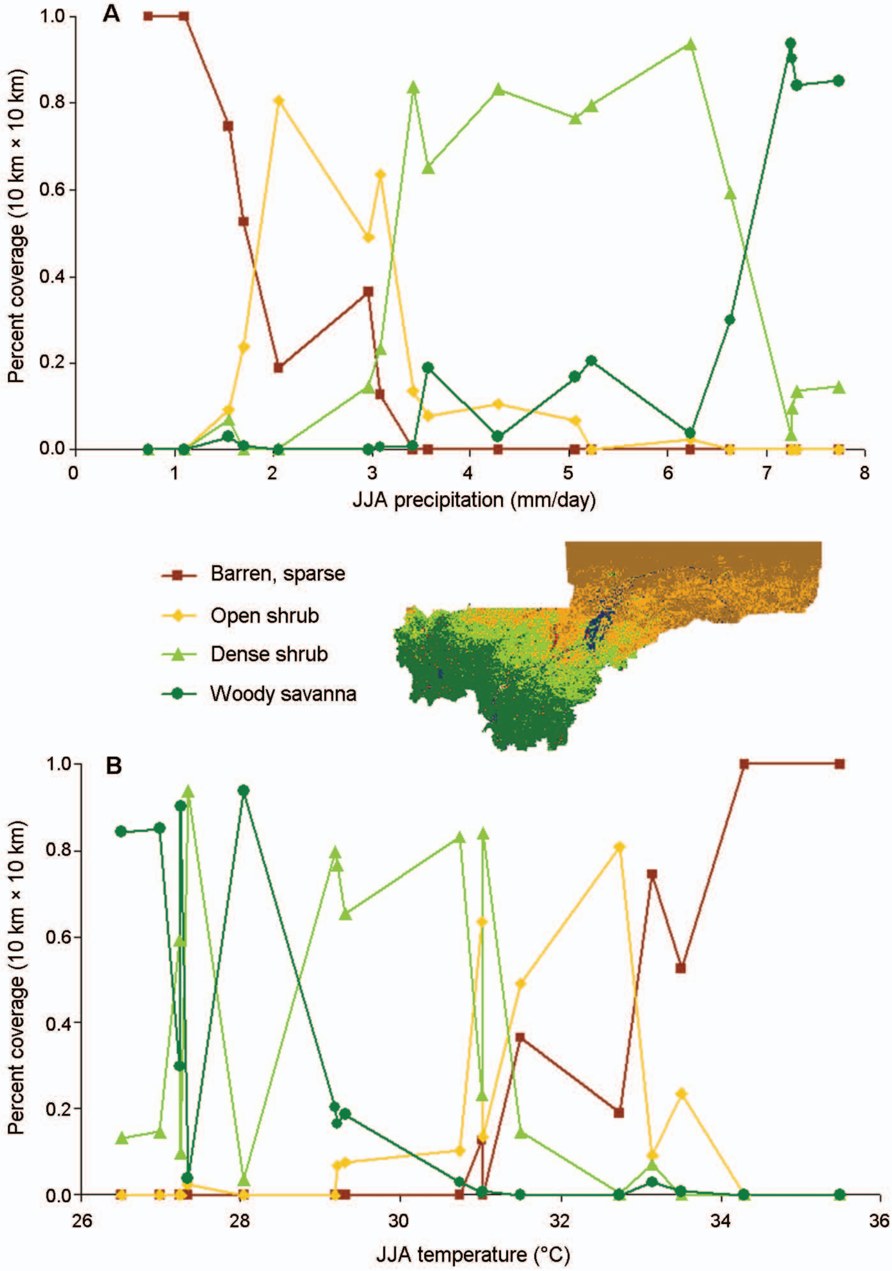

Fig. 6 . Relationship between land cover classes and (A) JJA precipitation (mm/day) and (B) JJA temperature (C°).

located in the northern shrub savanna landscape along the desert fringe and in the Sahara Desert, with mean annual precipitation of ≤200 mm, while >6.5 mm/day corresponds with the southern woody savanna landscapes that receive up to 1200 mm annual precipitation. Temperature was found to be highly correlated with precipitation (not shown), but it did not clearly define boundaries for different vegetation types (Fig. 6B). The surface heterogeneity seems to confuse the relationship between vegetation types and temperature in the lower temperature regimes.

To more clearly identify the relationship between vegetation and climate, a single LAI value for each window was calculated as a measure of the overall amount of vegetation for the given location. LAI values were extracted from mean rainy-season MODIS imagery to ensure coverage for the entire study area to augment the ground-derived LAI data collected at transect locations using the LI-COR 2000 Plant Canopy Analyzer. Figure 6 shows the relationship between LAI and percentage coverage of open shrub. It is clear that when the percent cover increases, the LAI of open shrubs converges to 0.33. With this approach, we determined the average LAI for low vegetation, open shrub, dense shrub, and woody savanna as 0, 0.33, 0.63, and 1.7 respectively.

For each climate station site, an average LAI value was calculated using the weighted average of each class based on its area of coverage. The regressions between LAI and climate and statistics were calculated using Igor Pro software. The overall LAI showed a high linear correlation with the mean JJA precipitation (R^2 of 0.9) and JJA temperature with R2 of 0.82. In both cases, p is smaller than 0.0001. Figures 7A and 7B show the relationship between overall LAI and precipitation and temperature, respectively.

In terms of vegetation patterns, the results are consistent with the impact of decreasing precipitation causing reduced soil moisture, reduced vegetation structural complexity, reduced vegetation height, reduced LAI, and generally reduced vegetation cover northward along the savanna–desert transition in Mali. The stronger relationship between reduced precipitation and the identified decreases in vegetation measures compared to temperature suggests that precipitation differences and the resulting impact on available soil moisture, rather than differences in evapotranspiration rates, are the main drivers of this land cover transition. One interesting observation with regards to climate–vegetation relations in Mali is the sharp transition that occurs between woody and shrubby savanna when precipitation falls below 7 mm/day and similarly sharp transition that occurs when precipitation falls to the range of 3–4 mm/day (Fig. 6A). At this latter point there is a loss of remaining woody savanna and a sharp decline in dense shrub savanna. These relatively sharp vegetation transitions are not reflective of abrupt transitions in climate or soil moisture gradients, and could reflect a number of possibly interacting factors related to plant competition, disturbance regimes, and land use practices that influence vegetation patterns in African savannas (Walter, 1971; Walker and Noy-Meir, 1982; Scholes and Walker, 1993; Jeltsch et al., 1998; Scholes et al., 2002; Caylor and Shugart, 2006). The influence of these various factors may serve to produce sharp vegetation breaks along relatively gradual climatic and soil moisture gradients in the savanna zone. This prototype preliminary analysis has shown the promise in using satellite products to explore the climate/vegetation relationship. Diagnostic studies with more a data- and process-oriented approach are necessary to explore this subject further.

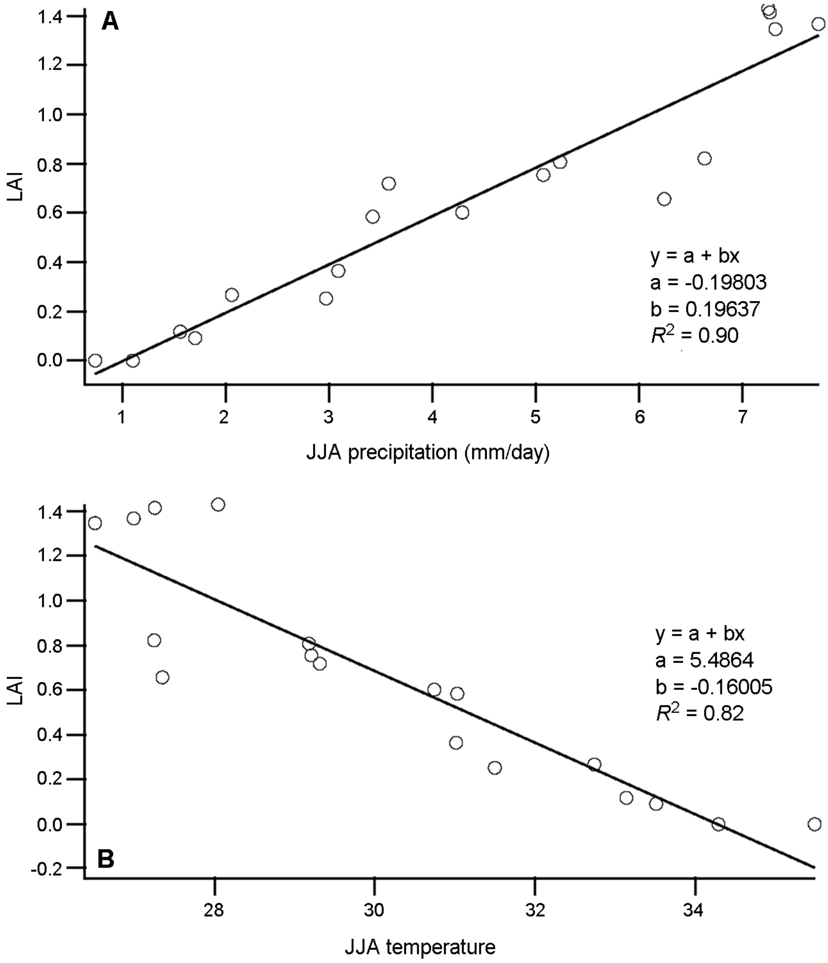

Fig. 7. Relationship between overall LAI and (A) JJA precipitation (mm/day) and (B) JJA temperature (C°).

DISCUSSION

This study demonstrates the capacity of MODIS in producing a moderate-resolution product of land cover in the Sahel transition, including discrete agricultural areas such as rice-growing districts. The maximum likelihood classifier used for developing the product successfully separates classes in the savanna–desert transitional zone in Mali. Existing land cover products showed similar general patterns in the study area, but with several discrepancies when compared to the new ground-referenced product.

Most existing land cover products are derived from global or continental products, which are often not intended for downscaling to local applications (Stuart et al., 2006). While not ideal for this study, many of these products have been used successfully in a number of global and continental applications. Products such as UMD and IGBP have both been used in a variety of environmental research and modeling applications, including climate studies (e.g., Xue et al., 2004b), and GLC2000 is an important addition to previous products in that it uses the approach of adapting methodologies for different regions in order to optimize the requirements and available data for different parts of the world (Fritz et al., 2003).

It is important to note that the five existing classification products discussed in this study were created on a different temporal scale than the UCLA product. Most of these products use multi-annual or annual data in the production of land cover maps, while the product in this study is created from imagery collected during the rainy season only, in order to make a realistic assessment of the land cover during the season of maximum vegetation growth. We focused our effort on the rainy season only, and images from two months in one single year were employed. This constitutes a significant difference from products created on annual and multi-annual scales. Issues of seasonality and current vegetation conditions are difficult to address when land cover characteristics may be obscured by multi-season or multi-year compilations of data.

A similar problem is significant with regards to spatial resolution and scale. There is a general advantage presented by using a smaller pixel size of 500 m, rather than 1 km which is the norm in most available global products. In this regard, the focus on images obtained over our specific study area circumvents the issue of downscaling from continental or global products not optimized for local applications. Such important differences in product generation are bound to create significant discrepancies between products, as has been found in previous comparative studies (Defries and Townshend, 1994; Hansen and Reed, 2000; Giri et al., 2005).

Some of the discrepancies noted between various classification schemes are related to the problems of classifying wetlands and transitional zones as discussed earlier. However, much of the divergence can be attributed to differences in the source and quality of input images and other data, methodologies, classifiers and algorithms used, as well as issues pertaining to spatial and temporal resolution. A key factor is the availability of ground survey information. Most of the land cover products have no or very scarce ground survey data for our study area, and we therefore have high confidence in the new classification for Mali over other products where discrepancies are present.

Geographic changes in land cover detected by MODIS reflect the changes in cover and structure identified through ground survey, and corresponds with the identified north–south climate gradient in the region. Higher soil moisture and precipitation in the southern part of the study area are closely related to the observed denser, greener vegetation and higher leaf area index, a combination of vegetation characteristics resulting in a lower albedo. As we move north along the gradient, vegetation density, LAI, and greenness decrease along with moisture, and we encounter more bare ground with an associated increase in albedo, which in turn leads to higher evaporation rates and a drier environment. Land cover and vegetation structure expressed by overall LAI were found to be highly correlated with mean JJA precipitation and mean JJA temperature, where precipitation was identified as the main driver of changes in vegetation coverage, structure, and variation across the desert–savanna transition.

CONCLUSION

The remote sensing–derived product presented in this study was developed with extensive ground survey and 500 m MODIS imagery, and shows encouraging promise for use in research where up-to-date land cover information with moderate resolution is necessary. The product is an improvement over existing land cover products for the region in spatial resolution and in accuracy, resulting from the inclusion and analysis of extensive ground survey data in its development. The use of GPS for *in situ* identification and verification of land cover classes reduces discrepancies between remote sensing imagery and ground observations. Such *in situ* data is important for an applied approach to actual vegetation dynamics and potential changes in regional patterns under future climate change scenarios.

The maximum likelihood classifier used for developing the product successfully separates most classes in the savanna–desert transitional zone in Mali. Problems of class confusion for savanna/shrublands and wetlands confirm assertions from previously published land cover classification products regarding the complex spectral response pattern and obstacles involved in delineation of boundaries for savanna-type vegetation.

The differences between our product and existing land cover products subsets indicate the value and importance of intensive ground observation for correct classification when possible. The GLC2000 is the most recent and most similar product to the UCLA product. A problem with the GLC2000 product is that the methodology does not allow for easy reproduction. Additionally, SPOT vegetation data that were used as input are expensive and therefore not readily accessible to all users, especially in developing countries, whereas MODIS data can be obtained free of charge.

This study also quantitatively identifies strong relationships between vegetation types, LAI, and climate variables (precipitation and surface temperature), and distinguishes features in the vegetation/climate transition, which should provide useful information for possible responses of this vulnerable ecosystem under global climate change scenarios. Furthermore, the study indicates that precipitation differences and the resulting impact on available soil moisture are the main drivers of the land cover transition in this region. The analysis shows the dominant control of summer (JJA) precipitation on vegetation zonation and structure, with woody savanna being restricted to areas receiving >1000 mm mean annual precipitation, the lightly wooded savanna to areas of >700 mm precipitation, the dense shrub savanna to areas of >500 mm precipitation and the open and sparse shrub savanna to areas of >200 mm.

The study demonstrates the effectiveness of using MODIS data for regional-scale studies, especially for developing countries where expensive satellite data may be difficult to obtain. Field procedures consisting of basic and inexpensive releve survey methods can easily be carried out locally, and thus provide an efficient and affordable option for local resource management applications for gathering usable ground-truthing data. In combination with the free satellite imagery, the methodology of the project provides an inexpensive alternative compared with other types of imagery used in similar projects. Finally, the new land cover product describes the current state of the Sahel savanna ecotone and allows for identification of relations between climate and vegetation. As such, the product provides a comparative data set of ground, structure, and remote sensing data that can serve as a baseline for detecting future changes and assessing potential impacts of climate change in the Sahel region.

ACKNOWLEDGMENTS

This study was supported by National Institutes of Health (NIH) grants 1R56AI072549 and R01 A1040308-06, and by National Aeronautic and Space Administration (NASA) grant NNX08AL56G.

REFERENCES

Apan, A. A., 1997, "Land Cover Mapping for Tropical Forest Rehabilitation Planning Using Remotely-Sensed Data," *International Journal of Remote Sensing*, 18(5):1029–1049.

Arbonnier, M., 2002, *Arbres, arbustes et lianes des zones sáeches d'Afrique de l'Ouest* (*Trees, Shrubs, and Lianas of West African Dry Zones*), Montpellier and Paris, France: CIRAD/Muséum National d'Histoire Naturelle.

Arnell, N. W., 2006, "Climate Change and Water Resources: A Global Perspective," in *Avoiding Dangerous Climate Change,* Schnellnhuber, H. J. and W. P. Cramer (Eds.), New York, NY: Cambridge University Press, 167–175.

Boko, M., Niang, I., Nyong, A., Vogel, C., Githeko, A., Medany, M., Osman-Elasha, B., Tabo, R., and P. Yanda, 2007, "Africa," in *Climate Change 2007: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Parry, M. L., Canziani, O. F., Palutikof, J. P., van der Linden, P. J., and C. E. Hanson (Eds.), Cambridge, UK: Cambridge University Press, 433–467.

Caylor, K. K. and H. H. Shugart, 2006, "Pattern and Process in Savanna Ecosystems," in *Dryland Ecohydrology*, D'Odorico, P. and A. Porporato (Eds.), Dordrecht, The Netherlands: Springer, 259–281.

Charney, J. G., 1975, "Dynamics of Deserts and Drought in Sahel," *Quarterly Journal of the Royal Meteorological Society,* 101(428):193–202.

Christensen, J. H., Hewitson, B., Busuioc, A., Chen, A., Gao, X., Held, I., Jones, R., Kolli, R. K., Kwon, W.-T., Laprise, R., Magaña Rueda, V., Mearns, L., Menéndez, C. G., Räisänen, J., Rinke, A., and A. S. A. P. Whetton, 2007, "Regional Climate Projections," in *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Avery, K. B., Tignor, M., and H. L. Miller (Eds.), Cambridge, UK and New York, NY: Cambridge University Press.

CIA (U.S. Central Intelligence Agency), 2008, *The World Factbook*, Washington, DC: U.S. Central Intelligence Agency.

Cockrum, E. L., 1976, "An Ecological View of the Sahel–Sudan Region of sub-Saharan West Africa, in *Proceedings of the West Africa Conference*, Paylore, P. and R. A. Haney (Eds.), Tucson, AZ: University of Arizona.

Cuny, P., Sanogo, S., and N. Sommer, 1997, *Arbres du domaine soudanien. Leurs usages et leur multiplication* (*Trees of the Sudanian Zone: Usage and Reproduction*), Sikasso, Mali: Institut d'Economie Rurale, CRRA-Sikasso.

Defense Mapping Agency, 1992, *Digital Chart of the World*, Fairfax, VA: Defense Mapping Agency.

Defourny, P., Vancutsem, C., Bicheron, P., Brockmann, C., Nino, F., Schouten, L., and M. Leroy, 2006, GLOBCOVER: A 300 m Global Land Cover Product for 2005 Using ENVISAT MERIS Time Series," in *ISPRS Commission VII Mid-term Symposium "Remote Sensing: From Pixels to Processes,"* Enschede, The Netherlands, 8–11 May 2006, 59–62.

Defries, R. S. and J. R. G. Townshend, 1994, "NDVI-Derived Land-Cover Classifications at a Global Scale," *International Journal of Remote Sensing*, 15(17):3567–3586.

Dickinson, R. E., 1992, "Land Surface" in *Climate System Modeling*, Trenberth, K. E. (Ed.), Cambridge, UK: Cambridge University Press, 149–172.

Dingkuhn, M., 1995, "Climatic Determinants of Irrigated Rice Performance in the Sahel. 3. Characterizing Environments by Simulating Crop Phenology," *Agricultural Systems,* 48(4):435–456.

FAO (UN Food and Agriculture Organisation), 2003, *Digital Soil Map of the World and Derived Soil Properties Rev. 1*, Rome, Italy: FAO Land and Water Development Division (CD ROM).

Fennessy, M. J. and Y. Xue, 1997, "Impact of USGS Vegetation Map on GCM Simulations over the United States," *Ecological Applications,* 7(1):22–33.

FEWS NET (Famine Early Warning Systems Network), 2008, "MALI Food Security Update," August [http://www.fews.net/].

Fischer, G., Shah, M., Tubiello, F. N., and H. Van Velhuizen, 2005, "Socio-economic and Climate Change Impacts on Agriculture: An Integrated Assessment, 1990–2080," *Philosophical Transactions of the Royal Society B—Biological Sciences,* 360(1463):2067–2083.

Frey, K. E. and L. C. Smith, 2007, "How Well Do We Know Northern Land Cover? Comparison of Four Global Vegetation and Wetland Products with a New Ground-Truth Database for West Siberia," *Global Biogeochemical Cycles,* 21(1):GB1016 [doi:10.1029/2006GB002706].

Friedl, M. A., McIver, D. K., Hodges, J. C. F., Zhang, X. Y., Muchoney, D., Strahler, A. H., Woodcock, C. E., Gopal, S., Schneider, A., Cooper, A., Baccini, A., Gao, F., and C. Schaaf, 2002, "Global Land Cover Mapping from MODIS: Algorithms and Early Results," *Remote Sensing of Environment,* 83(1–2): 287–302.

Fritz, S., Bartholome, E., Belward, A., Hartley, A., Stibig, H. E. H.-J., Mayaux, P., Bartalev, S., Latifovic, R., Kolmert, S., Roy, P. S., Agrawal, S., Bingfang, W., Wenting, X., Ledwith, M., Pekel, J.-F., Giri, C., Mucher, S., De Badts, E., Tateishi, R., Champeaux, J.-L., and P. Defourny, 2003, *Harmonization, Mosaicing and Production of the Global Land Cover 2000 Database* (beta version), Ispra, Italy: European Commission, EUR 20849 EN.

Fuller, D. O., 2006, "Tropical Forest Monitoring and Remote Sensing: A New Era of Transparency in Forest Governance?," *Singapore Journal of Tropical Geography*, 27(1):15–29.

Giri, C., Zhu, Z. L. and B. Reed, 2005, "A Comparative Analysis of the Global Land Cover 2000 and MODIS Land Cover Data Sets," *Remote Sensing of Environment,* 94(1):123–132.

Hansen, M. C., Defries, R. S., Townshend, J. R. G., and R. Sohlberg, 2000, "Global Land Cover Classification at 1 km Spatial Resolution Using a Classification Tree Approach," *International Journal of Remote Sensing,* 21(6–7):1331–1364.

Hansen, M. C. and B. Reed, 2000, "A Comparison of the IGBP DISCover and University of Maryland 1 km Global Land Cover Products," *International Journal of Remote Sensing,* 21(6–7):1365–1373.

Hulme, M., 1996, Climatic Change within the Period of Meteorological Records," in *The Physical Geography of Africa,* Adams, W. M., Goudie, A. S., and A. R. Orme (Eds.), Oxford, UK: Oxford University Press, 88–102.

Huntingford, C., Lambert, F. H., Gash, J. H. C., Taylor, C. M., and A. J. Challinor, 2005, "Aspects of Climate Change Prediction Relevant to Crop Productivity," *Philosophical Transactions of the Royal Society B—Biological Sciences,* 360(1463):1999–2009.

Jaeger, P., 1968, "Mali," *Acta Phytogeographica Suecica,* 54:51–53.

Jeltsch, F., Milton, S. J., Dean, W. R. J., Van Rooyen, N., and K. A. Moloney, 1998, "Modelling the Impact of Small-scale Heterogeneities on Tree–Grass Coexistence in Semi-arid Savannas," *Journal of Ecology,* 86(5):780–793.

Jensen, J. R., 2005, *Introductory Digital Image Processing: A Remote Sensing Perspective*, 3rd ed., Upper Saddle River, NJ: Prentice Hall.

Kahan, D., Xue, Y., and S. Allen, 2006, "The Impact of Vegetation/soil Parameters in Simulations of Surface Energy and Water Balance in the Semi-arid Sahel Area: A Case Study Using SEBEX and HAPEX-Sahel Data," *Journal of Hydrology*, 320(1–2):238–259.

Loveland, T. R., Zhu, Z. L., Ohlen, D. O., Brown, J. F., Reed, B. C., and L. M. Yang, 1999, "An Analysis of the IGBP Global Land-Cover Characterization Process," *Photogrammetric Engineering and Remote Sensing,* 65(9):1021–1032.

MacDonald, G. M., 2003, *Biogeography: Space, Time and Life*, New York, NY: Wiley.

Matthews, R. B., Kropff, M. J., Horie, T., and D. Bachelet, 1997, "Simulating the Impact of Climate Change on Rice Production in Asia and Evaluating Options for Adaptation," *Agricultural Systems,* 54(3): 399–425.

Mayaux, P., Bartholome, E., Fritz, S., and A. Belward, 2004, "A New Land-Cover Map of Africa for the Year 2000," *Journal of Biogeography,* 31(6):861–877.

Mendelsohn, R., 2007, "The Impacts of Climate Change on Africa," in *Human-Induced Climate Change: An Interdisciplinary Assessment*, Schlesinger, M. E., Kheshgi, H. S., Smith, J., de la Chesnaye, F. C., Reilly, J. M., Wilson, T., and C. Kolstad (Eds.), Leiden, The Netherlands: Cambridge University Press, 161–166.

Nicholson, S. E., 1993, "An Overview of African Rainfall Fluctuations of the Last Decade," *Journal of Climate,* 6(7):1463–1466.

Nicholson, S., 2000, "Land Surface Processes and Sahel Climate," *Reviews of Geophysics,* 38(1):117–139.

Nicholson, S. E., 2001, "Climatic and Environmental Change in Africa during the Last Two Centuries," *Climate Research,* 17(2):123–144.

Parry, M. L., Canziani, O. F., Palutikof, J. P., van Der Linden, E. P. J. and C. E. Hanson, 2007, *Climate Change 2007 : Impacts, Adaptation, and Vulnerability: Contribution of Working Group II to the Fourth Assessment Report of the*

Intergovernmental Panel on Climate Change. Cambridge, UK and New York, NY: Cambridge University Press.

Peng, S. B., Huang, J. L., Sheehy, J. E., Laza, R. C., Visperas, R. M., Zhong, X. H., Centeno, G. S., Khush, G. S., and K. G. Cassman, 2004, "Rice Yields Decline with Higher Night Temperature from Global Warming," *Proceedings of the National Academy of Sciences of the United States of America,* 101(27):9971–9975.

Poccard, I. and Y. Xue, 2004, "Evaluation of Sahel Ground Climatology from 1982 to 1990 Based on Satellite-Derived LAI, 200 Raingauge Stations, and a Vegetation Model (SSiB)," *Preprint of 15th Symposium on Global Change Studies, JP 4.15.*

Ruthenberg, H., 1974, "Agricultural Aspects of Shifting Cultivation, FAO/SIDA/ARCN Regional Seminar on Shifting Cultivation and Soil Conservation in Africa," *Soil Bulletin,* 24:99–112.

Schnell, R., 1976, *La flore et la végétation de l'Afrique tropicale* (*Flora and Vegetation of Tropical Africa*), Paris, France: Gauthier-Villars.

Scholes, R. J., Dowty, P. R., Caylor, K., Parsons, D. A. B., Frost, P. G. H., and H. H. Shugart, 2002, Trends in Savanna Structure and Composition along an Aridity Gradient in the Kalahari," *Journal of Vegetation Science,* 13(3):419–428.

Scholes, R. J. and B. H. Walker, 1993, *An African Savanna: Synthesis of the Nylsvley Study,* Cambridge, UK and New York, NY: Cambridge University Press.

Stuart, N., Barratt, T., and C. Place, 2006, "Classifying the Neotropical Savannas of Belize Using Remote Sensing and Ground Survey," *Journal of Biogeography*, 33(3):476–490.

Thomas, C. J., Davies, G., and C. E. Dunn, 2004, "Mixed Picture for Changes in Stable Malaria Distribution with Future Climate in Africa," *Trends in Parasitology,* 20(5):216–220.

Townshend, J. R. G., 1992, *Improved Global Data for Land Applications: A Proposal for a New High Resolution Data Set: Report of the Land Cover Working Group of IGBP-DIS*, Stockholm, Sweden: IGBP Secretariat the Royal Swedish Academy of Science.

Walker, B. H. and I. Noy-Meir, 1982, "Aspects of the Stability and Resilience of Savanna Ecosystems," in *Ecology of Tropical Savannas*, Huntley, B. J. and B. H. Walker (Eds.), Berlin, Germany and New York, NY: Springer-Verlag, 556–590.

Walter, H., 1971, *Natural Savannas. Ecology of Tropical and Subtropical Vegetation*, New York, NY: Van Nostrand Reinhold Co.

Xie, P. P. and P. A. Arkin, 1997, "Global Precipitation: A 17-Year Monthly Analysis Based on Gauge Observations, Satellite Estimates, and Numerical Model Outputs," *Bulletin of the American Meteorological Society,* 78(11):2539–2558.

Xue, Y., Hutjes, R. W. A., Harding, R. J. H., Claussen, M., Prince, S. D., Lambin, E. F., Allen, S. J., Dirmeyer, P. A., and T. Oki, 2004a, "The Sahelian Climate," in *Vegetation, Water, Humans, and the Climate: A New Perspective on an Interactive System*, Kabat, C. et al. (Eds.), Berlin, Germany: Springer Verlag, 59–77.

Xue, Y. K., Juang, H. M. H., Li, W. P., Prince, S., Defries, R., Jiao, Y., and R. Vasic, 2004b, "Role of Land Surface Processes in Monsoon Development: East Asia and West Africa," *Journal of Geophysical Research—Atmospheres,* 109(D3):D03105 [doi:10.1029/2003JD003556].

Xue, Y. K. and J. Shukla, 1993, "The Influence of Land-Surface Properties on Sahel Climate .1. Desertification," *Journal of Climate,* 6(12):2232–2245.
Zeng, N. and J. D. Neelin, 2000, "The Role of Vegetation–Climate Interaction and Interannual Variability in Shaping the African Savanna," *Journal of Climate,* 13(15):2665–2670.

Appendix A. Confusion Matrix of Split UCLA Product Dataset (in percent)

	Barren	Sparse	Open	Dense	Light	Woody	Rice	Wetland	Water	Total
Barren	97.30	0	0	0	0	0	0	0	0	4.01
Sparse	2.70	93.33	0	0	0	0	0	0	0	1.67
Open	0	6.67	93.10	10	0	0	0	0	3.01	5.12
Dense	0	0	3.45	82.50	12.82	0	0	0	0	4.34
Light	0	0	0	0	71.79	3.70	0	0	0	3.23
Woody	0	0	0	0	15.38	96.30	0	0	0	3.56
Rice	0	0	0	0	0	0	88.57	0	0	3.45
Wetland	0	0	3.45	7.50	0	0	0	91.67	0.9	2.34
Water	0	0	0	0	0	0	11.43	8.33	96.99	72.27
	100	100	100	100	100	100	100	100	100	100

Overall accuracy = 94.65%; Kappa coefficient = 0.88.

Appendix B. Confusion Matrices Showing Agreement and Disagreement between UCLA Product (rows) and Five Existing Land Cover Products (columns)

GLC2000—Overall = 75.68%; Kappa = 0.6294

	Barren	Grass	Open	Dense	Light	Woodland	Rice	Wetland	Water	Urban	Total
Barren	92.79	28.42	3.68	0.17	0	0.01	0.17	2.71	7.95	0	55.1
Sparse	4.50	29.07	14.77	0.60	0	0.01	0.38	5.36	4.49	0	6.65
Open	2.64	39.17	62.79	16.88	0.27	0.08	8.85	29.27	19.03	0	11.14
Dense	0.01	1.80	18.08	68.60	20.04	0.64	23.93	14.29	9.04	5.07	9.99
Light	0	0.08	0.17	11.74	63.11	38.11	14.26	3.55	7.82	9.62	9.83
Woody	0	0	0	0.06	15.08	59.72	0.26	0	0.74	0	6.10
Rice	0	0	0.01	0.69	0.56	0.74	7.80	0.13	1.97	1.75	0.23
Wetland	0.03	0.94	0.40	0.25	0.02	0	1.18	16.42	7.77	0	0.22
Water	0.02	0.52	0.10	1.01	0.88	0.68	43.11	28.27	41.19	11.36	0.73
Urban	0	0	0	0.01	0.02	0	0.06	0	0	72.2	0.01
Total	100	100	100	100	100	100	100	100	100	100	100

IGBP—Overall = 62.29%; Kappa = 0.4366

	Barren	Grass	Open	Closed	Savanna	Woody	Water	Urban	Total
Barren	92.07	15.54	57.48	0.45	0.01	3.7	9.47	3.76	55.34
Sparse	4.10	20.52	21.15	1.49	0.09	5.56	8.81	6.99	6.68
Open	3.46	45.46	20.65	19.59	3.48	38.89	18.65	8.60	11.19
Dense	0.08	15.67	0.33	37.43	26.83	24.07	19.19	38.17	10.04
Light	0.09	1.38	0.04	28.81	39.39	18.52	14.09	1.08	9.87
Woody	0.02	0.02	0	10.04	29.70	0	5.23	0	6.13
Water	0.18	1.41	0.35	2.15	0.49	9.26	24.41	2.15	0.74
Urban	0	0	0	0.04	0.02	0	0.14	39.25	0.01
Total	100	100	100	100	100	100	100	100	100

	UMD—Overall 72.09%; Kappa = 0.5444								
	Barren	Grass	Open	Closed	Savanna	Woodland	Water	Urban	Total
Barren	85.33	0.13	9.88	0.12	0	0	14.73	9.64	55.34
Sparse	7.57	0.15	15.07	0.64	0	0	11.15	6.63	6.68
Open	6.87	4.60	46.05	15.50	0.20	0.05	22.85	8.43	11.20
Dense	0.11	36.70	24.61	59.85	12.46	1.30	14.56	33.73	10.04
Light	0.01	41.79	2.60	19.45	49.32	35.34	10.34	4.22	9.87
Woody	0	10.62	0.01	2.67	37.30	60.17	2.93	0	6.13
Water	0.11	5.66	1.77	1.73	0.71	3.14	23.35	5.42	0.74
Urban	0	0.36	0.01	0.04	0.01	0	0.08	31.93	0.01
Total	100	100	100	100	100	100	100	100	100

	MOD_IGBP—Overall = 65.69%; Kappa = 0.4838									
	Barren	Grassland	Open	Closed	Savanna	Woody	Wetland	Water	Urban	Total
Barren	93.97	5.12	24.57	1.66	0	0	0	15.78	17.39	55.24
Sparse	2.48	4.67	20.30	0.61	0.08	0	0	10.69	0	6.67
Open	1.13	25.65	35.97	1.80	3.17	0.38	0	21.91	4.35	11.17
Dense	0.53	40.92	13.01	10.43	27.60	19.87	0	15.50	58.70	10.01
Light	1.40	14.67	3.55	35.41	39.92	46.34	11.11	8.29	6.52	9.84
Woody	0.40	2.94	1.30	19.99	28.33	31.58	0	2.20	0	6.11
Wetland	0.03	0.96	0.55	0.35	0.04	0.01	0	4.69	0	0.22
Water	0.06	5.06	0.75	29.74	0.83	1.82	88.89	20.81	5.43	0.74
Urban	0	0.02	0.01	0.01	0.03	0	0	0.13	7.61	0.01
Total	100	100	100	100	100	100	100	100	100	100

Table continues

Appendix B. *Continued*

				MOD_UMD—Overall = 65.93%; Kappa = 0.4864					
	Barren	Grassland	Open	Closed	Savanna	Woody	Water	Urban	Total
Barren	94.00	5.17	24.70	0.96	0	0	16.56	17.39	55.36
Sparse	2.48	4.71	20.41	0.46	0.08	0	11.21	0	6.68
Open	1.13	25.90	36.17	5.05	3.10	0.38	22.99	4.35	11.19
Dense	0.53	41.32	13.08	34.17	27.19	19.87	16.26	58.70	10.03
Light	1.40	14.81	3.57	28.21	40.17	46.34	8.70	6.52	9.86
Woody	0.40	2.97	1.30	12.05	28.63	31.58	2.30	0	6.12
Water	0.06	5.11	0.75	19.07	0.79	1.82	21.85	5.43	0.74
Urban	0	0.02	0.01	0.02	0.03	0	0.14	7.61	0.01
Total	100	100	100	100	100	100	100	100	100