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Mapping regional land cover with MODIS data for biological conservation: Examples from the Greater Yellowstone Ecosystem, USA and Pará State, Brazil

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Abstract

The paper investigated the application of MODIS data for mapping regional land cover at moderate resolutions (250 and 500 m), for regional conservation purposes. Land cover maps were generated for two major conservation areas (Greater Yellowstone Ecosystem—GYE, USA and the Pará State, Brazil) using MODIS data and decision tree classifications. The MODIS land cover products were evaluated using existing Landsat TM land cover maps as reference data. The Landsat TM land cover maps were processed to their fractional composition at the MODIS resolution (250 and 500 m). In GYE, the MODIS land cover was very successful at mapping extensive cover types (e.g. coniferous forest and grasslands) and far less successful at mapping smaller habitats (e.g. wetlands, deciduous tree cover) that typically occur in patches that are smaller than the MODIS pixels, but are reported to be very important to biodiversity conservation. The MODIS classification for Pará State was successful at producing a regional forest/non-forest product which is useful for monitoring the extreme human impacts such as deforestation. The ability of MODIS data to map secondary forest remains to be tested, since regrowth typically harbors reduced levels of biodiversity. The two case studies showed the value of using multi-date 250 m data with only two spectral bands, as well as single day 500 m data with seven spectral bands, thus illustrating the versatile use of MODIS data in two contrasting environments. MODIS data provide new options for regional land cover mapping that are less labor-intensive than Landsat and have higher resolution than previous 1 km AVHRR or the current 1 km global land cover product. The usefulness of the MODIS data in addressing biodiversity conservation questions will ultimately depend upon the patch sizes of important habitats and the land cover transformations that threaten them.

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1. Introduction

The transformation of natural habitat by human activities such as logging, crop cultivation and urban expansion poses the single most important threat to biodiversity (Sala et al., 2000; Soulé, 1991; Wilson, 1988). Land cover refers to the suite of natural and man-made features that cover the earth's surface. Thus, it is essential to accurately map land cover in an effort to understand the human land uses that threaten natural habitats. Remote sensing data are increasingly used to map land cover for conservation planning purposes, e.g. prioritizing locations in greatest need of conservation and monitoring important habitats (Steininger et al., 2001; Turner et al., 2003; Wessels et al., 2000, 2003). The United States Geological Survey's Gap Analysis Program, for example, uses Landsat data to map land cover throughout the United States for regional conservation assessments of native vertebrate species (Scott & Jennings, 1998). In tropical rainforests, remote sensing has been extensively used to map deforestation (INPE, 2000; Sader et al., 2001a; Skole & Tucker, 1993; Townshend et al., 1995). Deforestation affects biological diversity through habitat destruction,

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fragmentation of former contiguous habitat (Gascon et al., 1999; Laurance et al., 2000, 2002) and edge effects within forest boundaries (Laurance et al., 1997; Skole & Tucker, 1993). Satellite-based deforestation mapping does not always reflect the full magnitude of human influences on forests, such as surface fires and logging that reduce forest cover but does not fully eliminate it (Nepstad et al., 1999, 2001). Remote sensing is however, viewed as an indispensable tool for monitoring the most extreme forms of land cover change over large areas at low cost (Nepstad et al., 1999).

Advances over the past decade in characterizing land cover from satellite data have contributed substantially to understanding the global distribution of vegetation types and land uses (DeFries & Townshend, 1994; Friedl et al., 2002a; Hansen et al., 2000b; Loveland et al., 2000). However, conservation plans are most appropriately developed at the regional scale to account for spatial processes and varying biophysical and socioeconomic conditions. Until recently, satellite data have generally offered only two options for regional-scale analyses covering spatial extents on the order of thousands of square kilometers: (1) subsets of data from coarse-resolution, globally acquired data from sensors such as the Advanced Very High Resolution Radiometer (AVHRR; e.g. Hansen et al., 2000b) and SPOT Vegetation (e.g. Malingreau et al., 1995; Mayaux et al., 1998) and (2) mosaics of high resolution data from sensors such as Landsat and SPOT HRV (e.g. Chomentowski et al., 1994; INPE, 2000; Skole & Tucker, 1993; Townshend et al., 1995; Tucker & Townshend, 2000). The former has the advantage of high, daily temporal resolution but the disadvantage of coarse spatial resolution of 1 km or greater. The latter, high resolution data has the advantage of high spatial resolution (15–30 m), but infrequent temporal resolution. Limited acquisitions from the Landsat sensor, since improved with the launch of the Landsat Enhanced Thematic Mapper Plus (ETM+) in 1999 (Goward & Williams, 1997), pose challenges to historical analyses, as do the limitations imposed by the need for visual interpretation rather than automated analysis in hazy and poorly calibrated scenes (Townshend et al., 1997) and the labor-intensiveness of handling many scenes (Tucker & Townshend, 2000). Data from the Moderate Resolution Imaging Spectroradiometer (MODIS), acquired daily at spatial resolutions from 250 m to 1 km, offer the possibility for frequent temporal coverage at moderate resolution. A number of global products are being derived from MODIS data, such as land cover, net primary production, and leaf area index (Justice et al., 2002a), but their applicability to regional-scale analyses needs to be thoroughly explored.

The MODIS 1 km land cover is one of the suite of available global MODIS products. It is generated from various MODIS-derived inputs, e.g. surface reflectance, vegetation index, surface temperature and texture, and provides a global product according to the global IGBP (International Geosphere–Biosphere Programme) classification system (Friedl et al., 2002b). The global MODIS land cover product is useful for global and continental applications, but surface reflectance data available at 250 and 500 m can also be used to map regional land cover at higher spatial resolution according to a user-specified classification scheme. Empirical analyses by Townshend and Justice (1988) illustrated that resolutions finer than 1 km are highly desirable for mapping human impacts on land cover and, accordingly, the MODIS instrument was designed to deliver 250 and 500 m resolution data (Justice et al., 2002a,b; Townshend & Justice, 2002). Therefore, this paper investigated the value of MODIS data for mapping regional land cover at these moderate resolutions (250 and 500 m resolution). We generated land cover classifications from MODIS data (250 and 500 m) for two major conservation areas and compared the results to existing Landsat TM land cover classifications of the same study areas. We selected two very different study areas: the Greater Yellowstone Ecosystem, USA and the Pará State, Brazil. We selected these areas because (1) they are important for conservation, (2) reliable Landsat classifications were available, and (3) we have ground knowledge and expertise to aid in interpretation of the results. The Pará State, Brazil represents a wet tropical forest where deforestation is the major threat to biodiversity. In contrast, within the cold and dry GYE changes in coniferous tree cover and riparian vegetation due to logging, agriculture and rural residential expansion are the key conservation issues. Together, these two very different sites should test the versatility of MODIS data for conservation applications.

2. Study areas

2.1. Greater Yellowstone Ecosystem

The Greater Yellowstone Ecosystem (GYE), USA, is made up of Yellowstone and Grand Teton National Parks and surrounding public and private lands (Fig. 1). The GYE is delineated as an area of strong ecological and socioeconomic connection between public lands and the surrounding private lands (approximately 350 × 440 km). It includes the watersheds of the GYE down to the lower forest boundary and adjacent grasslands (Wright Parmenter et al., 2003). The national parks are relatively high in elevation, while private lands are generally in lower elevations including the principal valley bottoms. Low-elevation valley bottoms have fertile soils, longer growing seasons, and higher primary productivity. Consequently, many native species are concentrated in small hot spots at lower elevations. Outside of the public lands, agriculture, range and rural residential development are common land uses on private lands. The GYE has 350,000 residents, most living in small cities. Yellowstone National Park, one

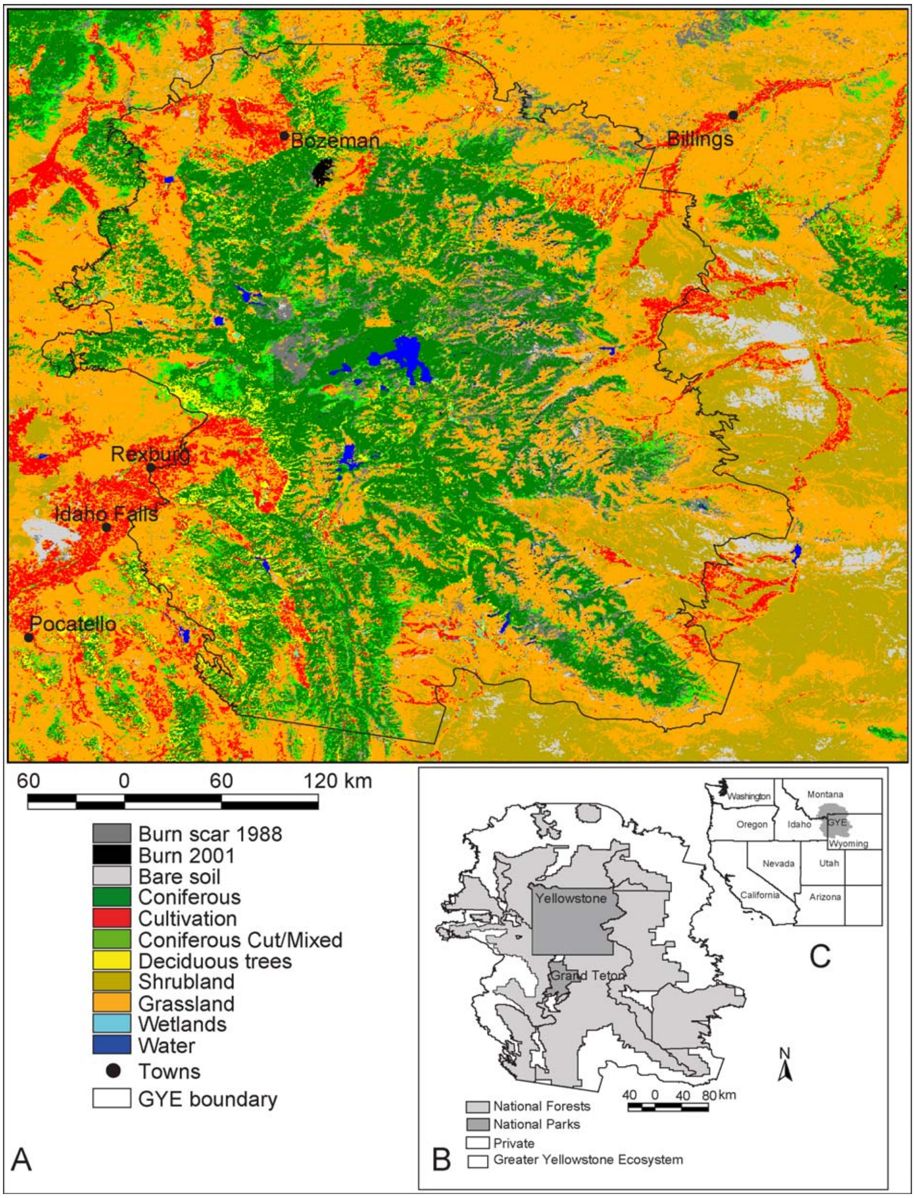

Fig. 1. (A) Land cover of the Greater Yellowstone Ecosystem (GYE) mapped with 250 m MODIS data for summer 2001. (B) National parks and National forests in the GYE study area. (C) Location of GYE in relation to the states of western USA.

of the best-known nature reserves in the world, is unique in supporting wilderness species such as grizzly bear (*Ursus arctos*) and free-roaming populations of large ungulates. The GYE is undergoing a transition in demography and land use (Hansen et al., 2002). The population has grown 55% since 1970, fueled largely by wealthy immigrants that are attracted by the natural amenities. Because of the strong biophysical gradients, hot spots for native species and intense land use tend to be concentrated in the same relatively small areas of the landscape. Consequently, development on private land negatively impacts several native species and appears to be increasing the potential for species depletion in the national parks (Hansen & Rotella, 2002). This study area covers approximately seven Landsat scenes.

2.2. Pará State, Brazil

To evaluate the use of MODIS data for regional land cover mapping, the study area was taken as the intersection between the Pará State of Brazil and one MODIS L2G image tile, which covers approximately 50% (850 × 900 km) of the state (Fig. 2; hereafter referred to as Pará State study area). The area is primarily covered by moist tropical forest. The region has been subjected to substantial land cover transformation along highways and around rapidly growing cities. For example, the urban population of Santarém has increased 211% since federally sponsored construction of the Cuiabá–Santarém highway in the early 1970s. The highway linked Santarém to Brazil's southern, more industrialized regions and opened up vast areas of land

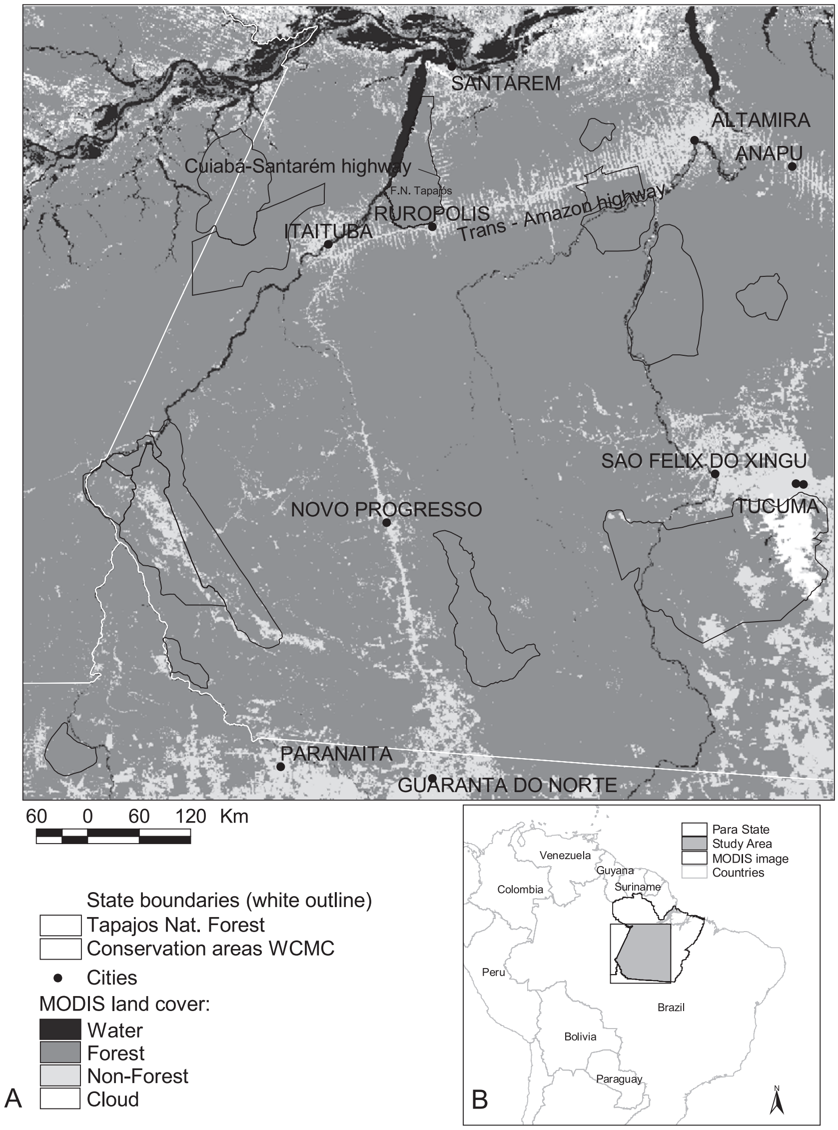

Fig. 2. (A) Land cover for the Pará study area, Brazil mapped with 500 m MODIS data for 6 August 2001. (B) Location of study area in relation to the states of Brazil.

along its southwest path to federally planned colonization and spontaneous land invasion. In addition, with improved energy sources, the Amazon Development Agency (SUDAM) instigated a development plan, the *Primeiro Polo Agroflorestal-Industrial*, which includes a component to harvest 613 million m^3 of high-value timber in the area and develop an industrial park to process raw materials. This project has introduced logging activities into the rural periphery but caters to distinctly urban interests. The region of Santarém includes the largest national forest, the Flona Tapajós, in the Amazon. The Flona is bounded on the left by the Tapajós River and on the right by the Cuiabá–Santarém Highway (Fig. 2). This highway is currently being paved, and migration, logging (Stone & Lefebvre, 1998) and agriculture (Uhl et al., 1988; Walker & Homma, 1996) are expected to increase dramatically (Sorrensen, 2000). Substantial deforestation has also taken place along the Trans-Amazon Highway that connects the cities of Altimira and Ruropolis (Moran et al., 1996). The larger Santarém region and the Pará State as a whole therefore face the two main factors driving deforestation, namely increasing human population density and highways (Laurance, 1999). These are expected to have major impacts on land cover and the biodiversity inside and outside conservation areas (Moran, 1993; Moran and Brondizio, 1998) (Fig. 2). This study area covers approximately 22 Landsat scenes.

3. Data

3.1. MODIS data

The MODIS instrument on the NASA Terra Platform has a swath of 2330 km, a near daily global repeat coverage, onboard spectral calibration and seven spectral bands for land remote sensing with a spatial resolution of 250 m (bands 1–2) and 500 m (bands 3–7) (Justice et al., 2002a; Townshend & Justice, 2002). Although various multi-date composite surface reflectance products (e.g. 8 day MOD09) are potentially useful for land cover mapping (Braswell et al., 2003), preliminary investigations showed that the variable view geometry of the composites (MOD09, collection 3) caused adjacent pixels to have large radiometric differences for the same cover type, leading to classification errors (Cihlar, 2000). The new 16-day Nadir Bidirectional Reflectance Distribution Function—Adjusted (NBAR; MOD43B) was developed to address the aforementioned problems (Schaaf et al., 2002), but was only available at 1 km resolution. Instead, we used single date near-cloud-free 250 and 500 m imagery for this study.

For GYE, three near-cloud-free, near-nadir, single date (1 August, 26 August and 1 October 2001), Level 1B 250 m (MOD02QKM, collection 3) radiance images were acquired to capture and utilize the phenological changes of the different vegetation and land use types. Cloud-free images were not available for the early summer period of 2001 and the MODIS sensor was also not operational from mid-June to early July 2001 (Justice et al., 2002a). The data were projected to Plate Carée projection using algorithms based on the USGS General Cartographic Transformation Package (GCIP). For each of the three dates, we calculated the normalized difference vegetation index (NDVI, a measure of photosynthetic activity calculated as the difference between red and near-infrared reflectances normalized by their sum) thus providing three bands (band 1, band 2 and NDVI) per date to the classification.

Braswell et al. (2003) previously used 1 km MODIS 16-day composite data (MOD43) to investigate sub-pixel land cover mixture around the Tapajos National Forest in the northern parts of the Pará study area. In the current study a single date (6 August 2001) near-cloud-free, 500 m, seven-band, Level 2G (MOD09, collection 3) surface reflectance image was used for the Pará State. Preliminary results showed that the additional infrared bands of the 500 m imagery provided better land cover mapping results than when using only the two 250 m bands. The image was projected to Plate Carrée projection using the MODIS Reprojection Tool.

3.2. Training data for GYE MODIS classification

The primary training data were generated from 32 color and color-infrared aerial photo transects (for details, see Wright Parmenter et al., 2003). Approximately 1400 2.25 ha (150 × 150 m) sites were sampled and the percentage composition of the land cover types estimated by point-interception of a 20-dot matrix overlaid onto the photograph (Wright Parmenter et al., 2003). An additional six hundred 0.81 ha (90 × 90 m) sites were sampled using a nearly identical method with a 10-dot matrix (unpublished data). Sites that were at least 70% pure were assigned to the dominant cover type, while mixed sites (e.g. 65% conifer and 35% herbaceous) were classified as mixed coniferous/herbaceous. Where necessary, USDA Forest Service (USDAFS) maps for Gallatin, Bridger-Teton, and Caribou-Targhee National Forests were used to add a small number of training sites ($N = 150$). The USDAFS vector data were displayed over the MODIS image and pixels were selected from the center of USDAFS polygons when the specific cover type could be visually distinguished from adjacent cover types. Additional field surveys were undertaken to clarify specific uncertainties. The values of MODIS pixels coinciding with the centroids of all the abovementioned sites were extracted, providing between 120 and 400 values per land cover class. Table 1 gives the list of classes for the training data that were chosen to represent the most important habitats and land uses. All willow, cottonwood and aspen tree cover were grouped into one deciduous tree cover class.

3.3. Training data for Pará State, Brazil MODIS classification

Training data were generated using visual interpretation of the 2001 MODIS image guided by the Tropical Rain Forest Information Centre (TRFIC) 1997 land cover data. The TRFIC data were generated from Landsat TM images by Michigan State University. The deforestation, cerrado

Table 1
The percentage of pixels in of the MODIS decision tree classification (rows) of GYE that matched the training data (columns)

	Burn 1988	Burn 2001	Coniferous	Cultivated	Mixed coniferous	Deciduous	Shrublands	Grasslands	Wetlands	Bare soil	Water
Burn 1988	82	0	0	0	6	0	0	4	0	8	0
Burn 2001	1	99	0	0	0	0	0	0	0	0	0
Coniferous	1	1	99	0	0	0	0	0	0	0	0
Cultivated	0	0	0	94	0	0	0	6	0	0	0
Mixed coniferous	3	0	0	0	97	0	0	0	0	0	0
Deciduous	0	0	11	0	0	80	0	7	2	0	0
Shrublands	0	0	0	0	0	0	96	3	0	1	0
Grasslands	1	0	0	3	1	0	1	83	0	10	0
Wetlands	0	0	0	18	0	28	0	2	53	0	0
Bare soil	0	2	0	0	0	0	12	4	0	82	0
Water	0	1	0	0	0	0	0	0	0	1	98

Table 2
Reclassification of MRLC data used in current study

MRLC classes		Reclassified MRLC
Water	11 open water	Other 1
	12 perennial ice/snow	
Barren	31 bare rock, sand/clay	
	32 quarries/strip mines/gravel pits	
	33 transitional/burn scars	Transitional 10
Developed	21 low intensity residential	Developed 2
	22 high intensity residential	
	23 commercial/industrial/transport	
Herbaceous planted/cultivated	81 pasture/hay	Agriculture 3
	82 row crops	
	83 small grains	
	84 fallow	
	85 urban recreational grasses	
Non-natural woody	61 orchards/vineyards	
Shrubland	51 shrubland	Shrublands 4
Herbaceous upland natural	71 grasslands/herbaceous	Grasslands 5
Forested upland	41 deciduous forest	Deciduous 6
	42 evergreen forest	Evergreen 7
	43 mixed forest	Deciduous 6
Wetlands	91 woody wetlands	Woody wetlands 8
	92 emergent herbaceous wetlands	Herbaceous wetlands 9

(savanna) and secondary growth classes of the TRFIC maps were reclassified into a single non-forest class. MODIS pixels were selected as training data only when the visual interpretation agreed with the overlaid 1997 TRFIC vector data. The high reflectance values of non-forest areas visually distinguished them from forest areas (Skole & Tucker, 1993). Approximately 600 points per class were evenly distributed throughout the entire MODIS image to account for variation in view geometry.

3.4. Landsat TM land cover data for GYE

The Multi-Resolution Land Characteristics Consortium National Land Cover Data Base (MRLC) was produced from the early to mid-1990s Landsat TM data (Vogelmann et al., 1998a,b; 2001). Based on the methods described by Stehman et al. (2003), the overall accuracy of MRLC data for federal region 8 covering the study areas was calculated at 60–65% (unpublished data). The MRLC data was processed to a 250 m resolution according to the methods described below. MRLC data was reclassified according to Table 2. The land cover classes of the MRLC and the MODIS land cover products were not identical, but highly comparable.

3.5. Landsat TM land cover data for Pará State, Brazil

Brazil's National Institute of Space Research (Instituto de Pesquisas Espaciais—INPE) produces annual maps of deforestation from Landsat data (INPE, 2000). The INPE data are widely used to estimate deforestation in the Amazon (Nepstad et al., 2001) and are supplied at 60 m resolution in raster format. Data for the Pará State were acquired for the year 2001 to coincide with the MODIS data and were projected to the Plate Carrée projection. All the INPE map classes for deforestation during specific years were lumped into a single deforestation class for this evaluation. The natural non-forest class was retained in the comparison.

4. Methods

Fig. 3 presents an overview of the data flow and evaluation methods. For each study area, MODIS imagery and training data were acquired. MODIS land cover products were generated using decision tree classifications. The MODIS land cover products were then evaluated using existing Landsat land cover maps (Fig. 3).

4.1. Decision tree classification

For both study areas, decision tree analyses (Venables & Ripley, 1994) of the S-plus statistical package (Clark & Pergibon, 1992) were used to classify the dependent variable of class membership using the independent variables of the MODIS bands (Hansen et al., 1996, 2000b; Lawrence & Wright, 2001). The decision trees are non-parametric, hierarchical classifiers that predict class membership by recursively partitioning the data set into more homogenous subsets based on the reduction of deviance. The training data were randomly split into two equal sets per class so that one set could be used to grow the tree and the other to prune the tree by eliminating nodes that increased error. The optimal number of nodes was determined using a cost-complexity plot to establish the num-

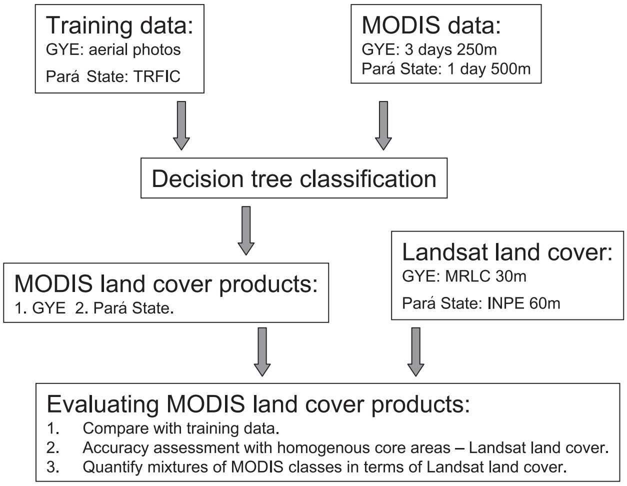

Fig. 3. Flow diagram of data inputs and MODIS land cover evaluation methods.

ber of terminal nodes beyond which the percentage accuracy ceased to increase and started to decrease (Hansen et al., 1996, 2000b). One of the main advantages of this procedure is that it is non-parametric and nonlinear and therefore multiple terminal nodes can be created for classes which have multi-modal distributions in spectral space (Hansen et al., 2000b). The trees provide explicit relationships between the dependent class membership and independent remote sensing variables, thus allowing the identification of remote sensing variables that are most useful separating land cover classes.

4.2. Evaluating the MODIS classification

To fully understand the origins of the potential classification error and evaluate the MODIS classifications, we carried out three assessments (Fig. 3):

4.2.1. Comparison of the MODIS classification to the training data

All training data were used in the production of the decision trees. Before comparing the MODIS classification to the Landsat land cover, it was valuable to first assess how well the classification represents the training data (Hansen et al., 2000b). This comparison does not constitute an accuracy assessment, but merely a method to identify any inherent errors in the classification procedure.

4.2.2. Accuracy assessment using homogenous core areas of the Landsat land cover

An independent evaluation of the MODIS classifications was obtained by measuring their concurrency with the existing Landsat TM-derived land cover products (described above). The Landsat TM-derived maps were reprojected, resampled and processed to their fractional composition at the MODIS resolution (250 and 500 m). The resampled Landsat TM maps were aggregated to the dominant (highest fractional coverage) Landsat land cover class in the 250 or 500 m pixels (Hansen et al., 2000b). Homogenous or core areas were identified as 250 or 500 m pixels consisting of greater than 90% of a single cover type in the high resolution Landsat land cover maps. Comparing homogenous areas provided a measure of thematic agreement and minimized problems associated with the inherent incompatibility of disparate resolutions and the mixtures of land cover within large pixels (Foody, 2002; Hansen et al., 2000b). Although the classes of the MODIS and the reference Landsat land cover data were not identical, an accuracy assessment was applied to provide a basis for comparison and discussion (Foody, 2002). The producer's accuracy (PA, or errors of omission) relates to the probability that a Landsat land cover reference pixel will be correctly mapped by the classified MODIS product. The user's accuracy (UA, or errors of commission) relates to the probability that a pixel in the classified MODIS product matches the Landsat land cover reference data.

4.2.3. Quantification of the mixtures of the MODIS classification classes in terms of the higher-resolution Landsat TM land cover data

After calculating the percentage area of each of the Landsat land cover classes contained within the MODIS pixels (described above), instead of using the dominant Landsat land cover class (above), the average mixtures of all the MODIS pixels belonging to each of the MODIS land cover classes were calculated. For example, all the MODIS pixels in the coniferous MODIS land cover class were used to calculate their average percentage composition in terms of the Landsat land cover classes, e.g. 80% evergreen, 10% grasslands and 10% shrublands.

5. Results

5.1. GYE MODIS classification product compared to training data

As expected, a very high percentage of the pixels in the MODIS classification matched the training sites, e.g. coniferous 99%, bare soil 100%, cultivated 94%, shrubland 96% (Table 1). For the deciduous class, the agreement was high (80%) with some confusion with coniferous forests and grasslands (Table 1). The wetlands training pixels showed the most confusion with deciduous trees (28%) and cultivation (18%), since all three of these cover types occur in close proximity along waterways. This indicated that the wetlands class had inherent problems. Bare rock and areas with very low vegetation cover in shrublands and grasslands also showed some confusion. With the exception of the wetlands, the MODIS data and the decision tree procedure appear to be very successful at classifying the training data they were given.

5.2. GYE MODIS land cover classification compared to MRLC

5.2.1. Homogenous core areas

Visual comparison of the MRLC and MODIS land cover maps showed a high level of general agreement between the two products (Figs. 1 and 4). Table 3 provides the percentage of the total number of pixels in the MODIS classes that were more than 90% covered by a single MRLC cover type. Some of the smaller, patchy MODIS cover classes, e.g. deciduous and wetlands, had a relatively small percentage of homogenous 250 m pixels (37% and 44%, respectively; Table 3). It should be noted that this accuracy assessment is only applicable to the homogenous pixels and not to the entire map products (Latifovica & Olthof, 2004). The coniferous MODIS class had a UA of 77% and PA of 84% (Table 3), demonstrating the ability of MODIS data to map extensive forest cover. The MODIS mixed coniferous class was composed of nearly equivalent percentages of evergreen (23%), shrubland (20%) and

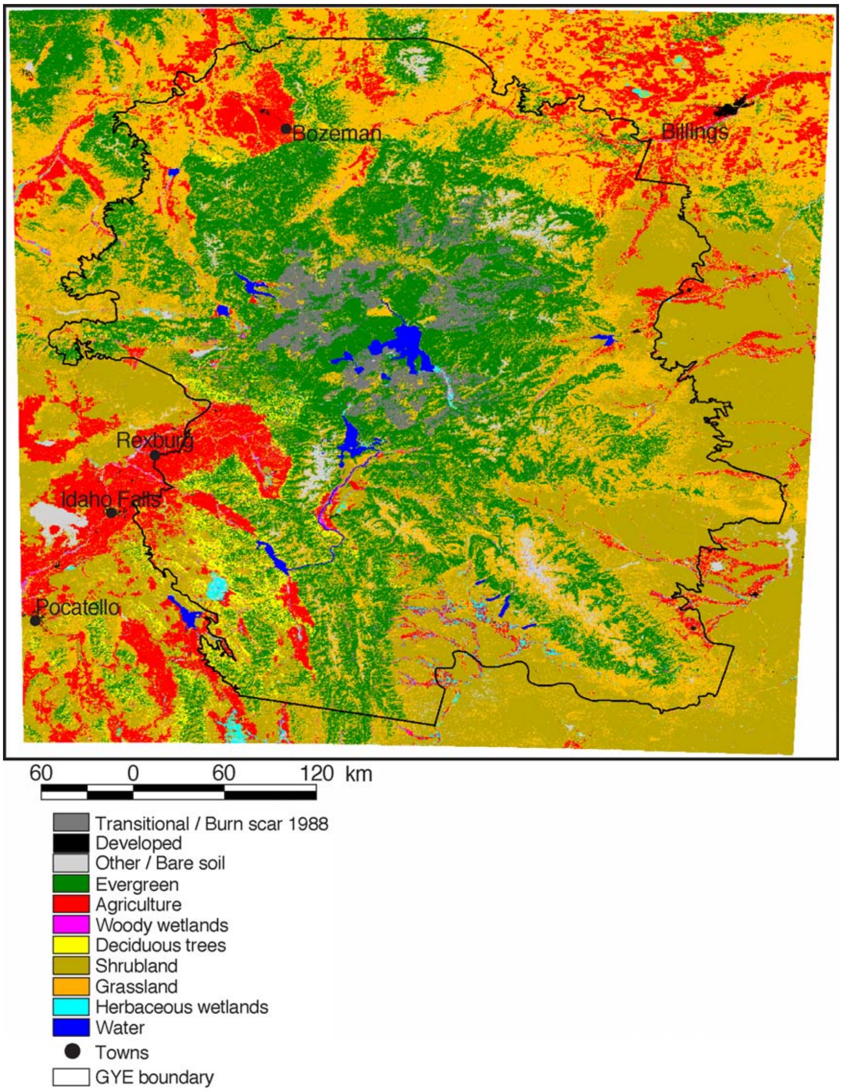

Fig. 4. Land cover of the Greater Yellowstone Ecosystem (GYE) as mapped by Multi-Resolution Land Characteristics Consortium National Land Cover Data Base (MRLC) produced from the early to mid-1990s Landsat TM data.

grassland (34%) MRLC classes. The coniferous MODIS classes covered 21.8% of the study area which compares well with the 19% estimated by MRLC at 250 m resolution and the recovering 1988 burn scar accounts for part of the difference (Table 3; Figs. 1 and 4; Wright Parmenter et al., 2003).

The MODIS cultivated class had a UA of 69%, but a PA of only 30.7%. The MODIS cultivated class covered 7.7% of the area, while the MRLC estimated this figure at 16.7% (Table 3). The MODIS cultivated class only includes pixels that contained actively growing crops during the 2001 summer season and therefore some disparity with the early to mid-1990s MRLC agriculture class was expected. Visual inspection of the MODIS images confirm that most areas of disagreement that were mapped as agriculture by MRLC and grasslands by the MODIS classification (e.g. northwest of Billings, Fig. 4) were not covered by actively growing crops on the dates of the MODIS images. These areas may have been harvested before the dates of the MODIS images which cover the latter part of the 2001 summer. This discrepancy can also be attributed to the fact that MRLC agriculture class included fallow land, pasture and hay and not only cultivation. The MODIS product does however appear to map cultivated areas accurately, e.g. around Bozeman and Idaho Falls (Fig. 5). Scattered single pixels that were misclassified as cultivation in the MODIS product could be filtered out (Fig. 5).

The extensive shrublands and grasslands were effectively distinguished from other classes by the MODIS data (Figs. 1 and 4), although there was some confusion between shrublands and grasslands within the MODIS grassland class (Table 3). The shrublands class had a UA of 88.5% and a PA of 43.5%. This is attributed to the fact that a larger part of MRLC shrublands class was mapped as grasslands by the MODIS products (Figs. 1 and 4). Grouping the shrublands and grasslands together, 57% and 52% of the study area was

Table 3
Error matrix for MODIS land cover classification of GYE using >90% pure MRLC pixels as reference data

	%>90% pure	Evergreen	Agriculture	Shrublands	Grasslands	Deciduous	Woody wetlands	Herb.	Transitional	Other	Developed	Total	UA	% Area
Coniferous	69.0	412,520	7480	9948	78,714	6437	4933	254	16,053	1382	5116	537,721	76.7	21.8
Mixed coniferous	50.2	20024	9448	16,343	28,924	513	1439	49	5904	885	5886	83,529	NA	3.6
Cultivated	68.0	1862	12,7431	9123	25433	815	396	1130	136	17,941	6463	184,267	69.2	7.7
Burn 1988	55.0	29,913	7685	5471	27,392	76	2775	95	17,362	1381	2373	92,150	18.8	3.8
Burn 2001	65.9	4380	205	33	1099	7	31	0	17	879	65	6651	NA	0.3
Deciduous	37.4	6166	4749	8072	10,726	6092	913	351	1009	1081	3164	39,159	15.6	1.7
Shrublands	93.4	49	16,513	301,503	20,283	4	8	56	0	2437	18,140	340,853	88.5	14.4
Grasslands	70.1	10,304	233,010	288,663	396,645	1416	2429	2642	7406	45,036	69,373	987,551	40.2	42.5
Wetlands	44.6	154	2215	224	1340	152	62	267	24	591	150	5029	5.3	0.2
Bare soil	83.2	2727	6769	53,491	7855	20	98	93	299	7522	2660	78,874	9.5	3.3
Water	93.2	889	36	3	201	1	5	0	0	14,939	9	16,074	92.9	0.6
Total		488,988	415,541	692,874	598,612	15,533	13,089	4937	48,210	94,074	113,399	2,371,858		
PA		84.4	30.7	43.5	66.3	39.2	NA	5.4	36.0	23.9	NA			
% Area>90% pure		19.7	16.7	27.9	24.1	0.6	0.5	0.2	1.9	3.8	4.6			

PA = producer's accuracy; UA = user's accuracy; herb. = herbaceous wetlands.

mapped by the MODIS and MRLC data, respectively (Table 3).

According to Table 3, the MODIS deciduous class included many areas that were not >90% pure deciduous vegetation according to the MRLC. The deciduous class had a UA of 15.6% and a PA of 39.2%. This can be attributed to the MODIS deciduous class including entire 250 m pixels containing low densities (< 90% pure) or small patches of deciduous tree cover (Fig. 6). This in turn could have been caused by using entire 250 m MODIS pixels as training data, while the deciduous trees covered only a much smaller area of the pixels than 250 × 250 m. This problem was most likely introduced when the training data for the deciduous class were supplemented using the USDA Forest Service maps, as there were not enough homogenous deciduous sites provided by the aerial photo interpretation (Wright

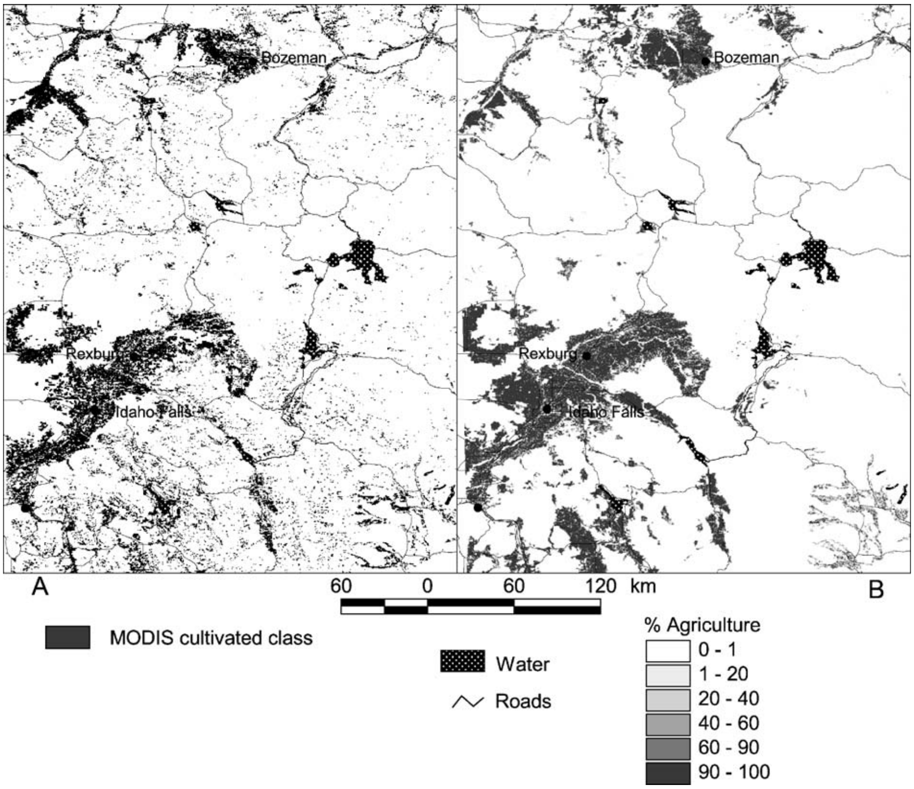

Fig. 5. MODIS cultivated class (A) and fractional coverage per 250 m pixel by MRLC (Landsat TM) agriculture class (B) in southwestern part of the Greater Yellowstone Ecosystem.

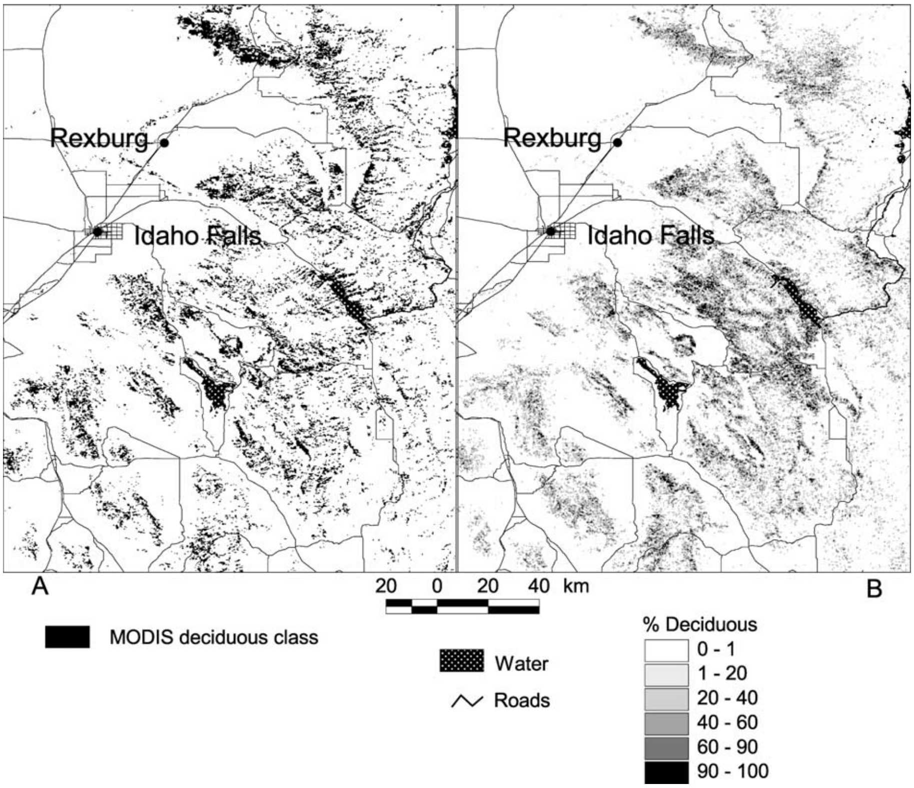

Fig. 6. MODIS deciduous class (A) and fractional coverage per 250 m pixel by MRLC (Landsat TM) deciduous class (B) in southwestern part of the Greater Yellowstone Ecosystem.

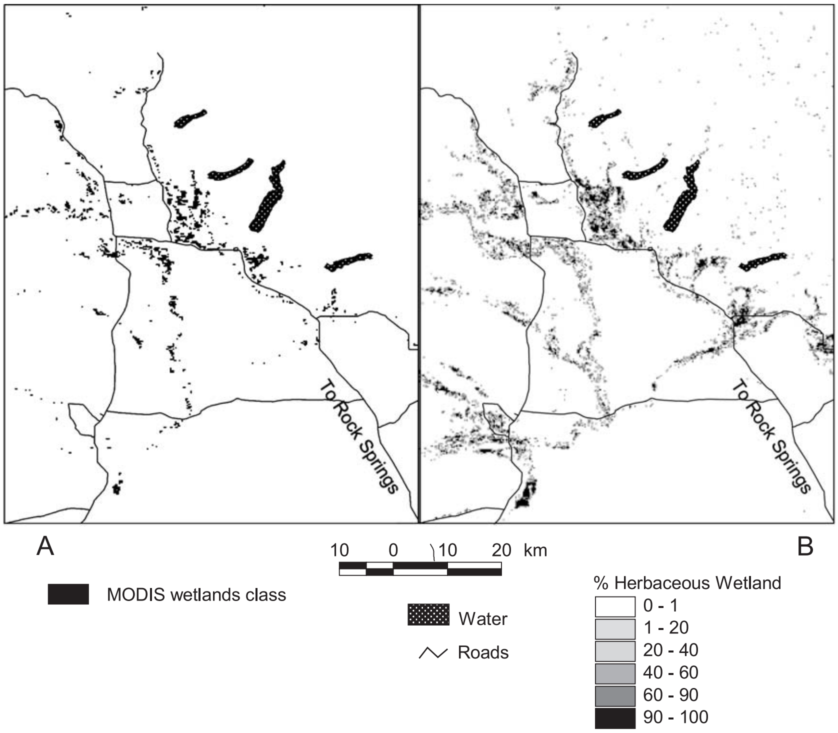

Fig. 7. MODIS wetlands class (A) and fractional coverage per 250 m pixel by MRLC (Landsat TM) herbaceous wetlands class (B) in southern part of the Greater Yellowstone Ecosystem.

Parmenter et al., 2003). Fig. 6 illustrates how low density deciduous tree cover (< 60% of 250 m pixel) was included in the MODIS deciduous class. The multi-temporal MODIS data were therefore successful at capturing the contrasting spectral properties of the leaf-on leaf-off phases of the deciduous vegetation. The MODIS deciduous class also included deciduous vegetation along rivers that was designated as woody wetlands by the MRLC (Fig. 6). According to the MRLC, only 0.6% of the study area was covered by >90% pure deciduous tree cover while the MODIS product estimated this figure as 1.7%. It should be noted that according to the accuracy assessment (Stehman et al., 2003), the MRLC data in federal region 8 were also not very effective at mapping deciduous forests (unpublished data) and this could have increased the apparent error of the MODIS classification.

The burn scar 1988 MODIS class corresponded to the transitional MRLC class (Figs. 1 and 4). The MODIS burn class only included the parts of the 1988 burn scar that still remained spectrally distinct (Fig. 1). Much of the land burned in 1988 has succeeded to other cover classes (Wright Parmenter et al., 2003), thus explaining most of the disagreement between the MODIS burn class and the MRLC transitional class. The MODIS burn 2001 class mainly included area burned during the Fridley fire.

No attempt was made to include training data for a developed class in the MODIS classification, since these areas were relatively small, heterogeneous and not visually discernable in the MODIS imagery. The accuracy assessment for wetlands showed very poor results (Table 3). Some of the woody wetlands of the MRLC were mapped by the deciduous tree class of the MODIS product. Some of the large patches of herbaceous wetlands mapped by MRLC were detected by the MODIS classification (Fig. 7), but results were generally poor since the wetlands typically cover relatively small areas.

5.2.2. Mixtures of MODIS land cover classes for GYE

Table 4 gives the average percentage mixtures of the MODIS classification classes at 250 m resolution in terms of the MRLC classes at 30 m resolution. It should be stressed that the 250 m resolution of the MODIS data forces the classification to classify mixed pixels and that the compositions described in Table 4 do not represent errors, but rather mixtures. Thus the MODIS cultivation class contained pixels with an average of 51% agriculture, 12% shrubland and 21% grassland according to the MRLC data. The MODIS coniferous class pixels have an average mixture of 69% coniferous, 8.2% shrubland and 8.5% grassland, and other fractional components (Table 4). The MODIS deciduous class pixels had an average mixture of only 19% deciduous trees, while containing equivalent percentages of shrubland, grassland and coniferous trees. As discussed above, this could be attributed to mixed deciduous 250 m pixels used as training, while big homogenous patches (>250 × 250 m) of deciduous trees are rare in the field (Fig. 6b, >90% deciduous MRLC). This MODIS class could therefore potentially be renamed "mixed deciduous trees". The MODIS mixed coniferous class contains a mixture of equal proportions (approximately 28%) of shrubland, grassland and coniferous MRLC classes (Table 4).

Table 5
The percentage of pixels in the MODIS decision tree classification (rows) of Pará State, Brazil that matched the training data (columns)

	Forest	Non-forest	Cloud	Water
Forest	98	2	0	0
Non-forest	2	97	1	0
Cloud	0	1	99	0
Water	0	0	0	100

Table 4
Average mixtures/fractional coverage (%) of pixels in GYE MODIS land cover classes (rows) in terms of MRLC data (columns)

	Coniferous	Agriculture	Shrublands	Grasslands	Deciduous	Woody wetlands	Herbaceous wetlands	Transitional	Other	Developed
Coniferous	69	0	8	9	4	0	0	4	1	0
Mixed coniferous	28	1	26	28	3	1	0	4	1	0
Cultivation	3	51	12	21	2	1	2	0	1	1
Burn scar 1988	38	1	14	25	0	0	0	13	3	0
Burn scar 2001	63	1	17	19	0	0	0	0	0	0
Deciduous	20	4	24	23	19	2	1	2	1	0
Shrubland	0	3	57	7	0	0	0	0	1	0
Grassland	4	9	28	44	1	1	1	1	1	0
Wetlands	6	25	14	30	6	4	9	1	3	0
Bare soil	2	18	23	28	0	0	1	0	14	0
Water	7	0	1	1	0	0	0	0	90	0
Burn scar 1988/2001	38	1	14	25	0	0	0	13	3	0

5.3. Pará State MODIS classification compared to training data

As expected, a very high percentage of the pixels in the MODIS classification matched the training (Table 5). Approximately 2% of the training pixels for the forest and non-forest classes were confused during the classification (Table 5). One percent of the cloud training pixels were classified as non-forest. The MODIS data and the decision tree procedure were therefore very successful at classifying the training data.

5.4. Pará State MODIS land cover compared to INPE

5.4.1. Homogenous core areas

Visual comparison of the INPE and MODIS land cover maps showed a high level of general agreement between the two products (Figs. 2, 8 and 9). Homogenous or core areas were identified as 500 m pixels consisting of greater than 90% of a single cover type in the INPE high resolution data (Table 6). Generally, only pixels along the boundaries between the major land cover classes were not covered by more than 90% of a single INPE cover class. Pixels covered by clouds in either the INPE or MODIS data were excluded from the accuracy assessment. The INPE non-forest and deforestation classes were grouped together for the accuracy assessment. The MODIS forest class had a UA of 96.5% and a PA of 98.1% (Table 6). The non-forest MODIS class had a UA of 80% and a PA of 69%. The non-forest MODIS class contained 18% forest according to the INPE data. This disagreement was caused by (i) small, thin clouds over forest that were misclassified as non-forest or (ii) single pixels of disagreement along the boundaries between forest and non-forest which may have been caused by slight misregistration of the two land cover maps (Fig. 10). The MODIS data mapped 89.1% of the study area as forest while the INPE data mapped 87.7% of the area as forest (Table 2; Figs. 2 and 8). The MODIS data mapped 8.5% of the study area as non-forest, while the INPE data mapped 10% of the area as non-forest or deforestation. This could be due to the well-known underestimation of non-dominant classes when classifying coarse resolution pixels (Braswell et al., 2003; Hansen et al., 2000b; Nelson & Holben, 1986).

Overall, the MODIS classification was very successful at distinguishing forest from non-forest (Table 2b). The deci-

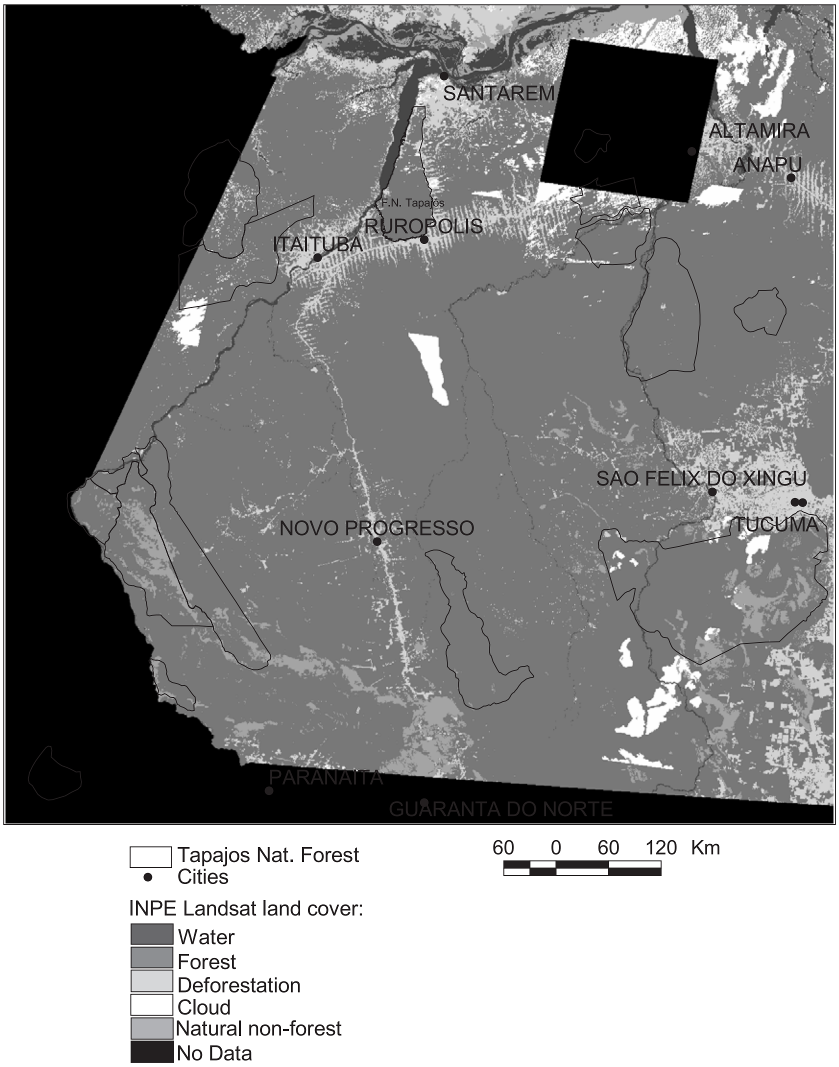

Fig. 8. Land cover data for Pará study area, Brazil as mapped by Instituto de Pesquisas Espaciais (INPE) from 1997 to 2000 Landsat ETM data. (The straight edges of the clouds were caused by mosaicking multiple Landsat images).

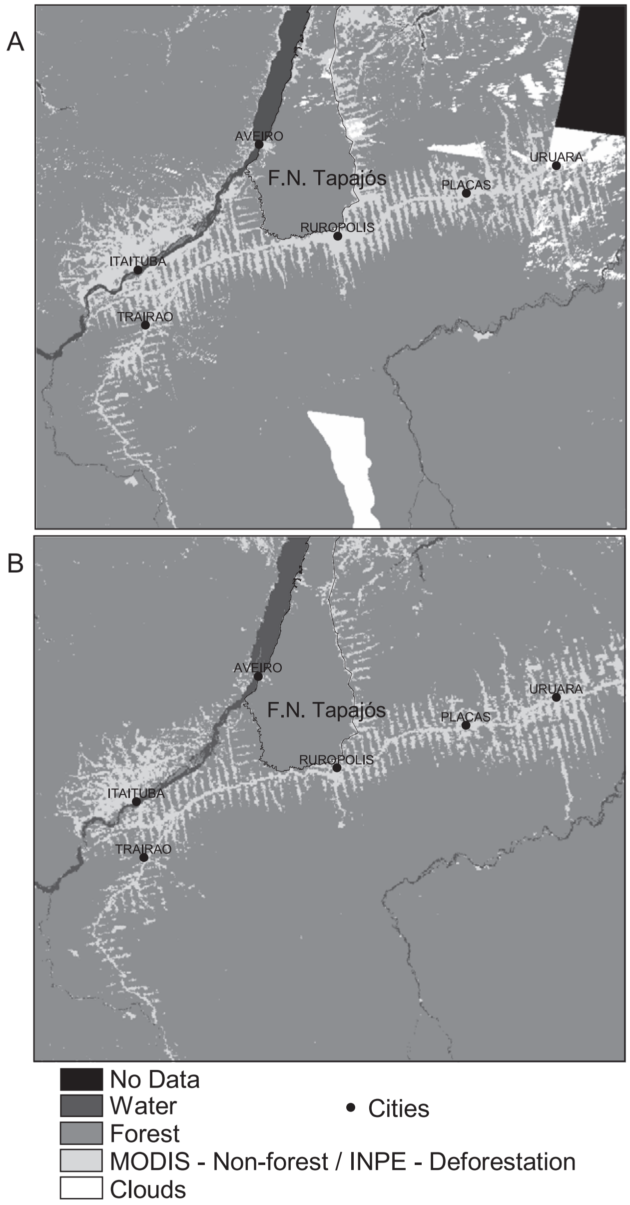

Fig. 9. Land cover around Tapajós National Forest according to INPE (Landsat ETM) data (A) and MODIS product (B), both at 500 m resolution.

sion tree classification primarily used band 2 (near infrared, 841–876 nm) and band 5 (mid-infrared, 1230–1250 nm) to distinguish between forest and non-forest.

Table 6
Error matrix for MODIS land cover classification of Pará State using >90% pure INPE pixels as reference data

	Forest	Non-forest	Water	Total	UA	% Area
Forest	2,117,542	74,099	3479	2,195,120	96.5	89.1
Non-forest	39,281	168,790	1906	209,977	80.4	8.5
Water	2626	2287	53,511	58,424	91.6	2.4
Total	2,159,449	245,176	58,896	2,463,521		
PA	98.1	68.8	90.9			
% Area	87.7	10.0	2.4			

PA = producer's accuracy; UA = user's accuracy.

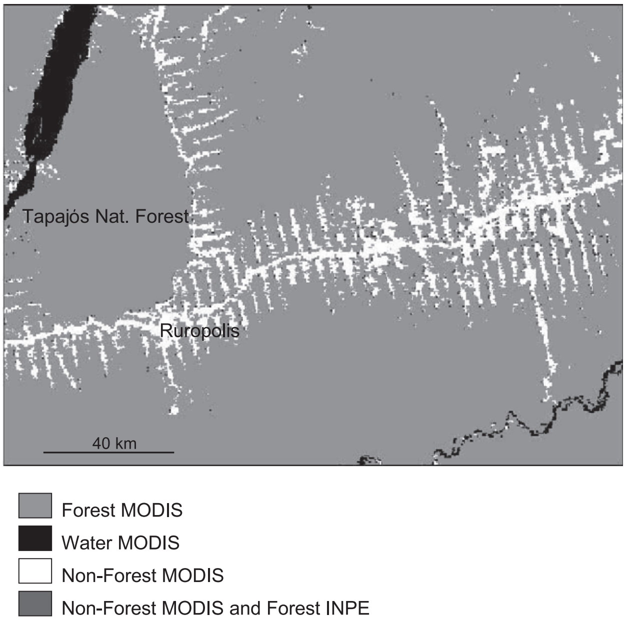

Fig. 10. Misclassification of forest (according to INPE) as non-forest by MODIS land cover around Tapajós National Forest, Brazil as a result of misregistration of the two land cover maps.

5.4.2. Mixture of MODIS classification classes for Pará State, Brazil

Table 7 provides the average percentage mixture of the MODIS classification classes at 500 m resolution in terms of the INPE classes at 60 m resolution. The MODIS forest class contained 91% forest, 2% natural non-forest and 3% deforestation according to the INPE data (Table 7). The MODIS non-forest class contained 15% forest according to the INPE data. As discussed above, this could be partially explained by the slight misregistration of the two land cover maps and the mixture of forest and non-forest within the 500 m pixels along forest edges which may have an adjacency effect (Townshend et al., 2000). The fact that deforestation in this study area follows narrow linear patterns further exacerbated the situation, since it elevates the influence of the aforementioned forest edges on these results.

6. Discussion and conclusion

The MODIS-derived land cover maps were very successful at mapping extensive cover types and far less successful at

Table 7
Average mixtures/fractional coverage (%) of pixels in Pará State MODIS land cover classes (rows) in terms of INPE data (columns)

	Forest	Non-forest	Deforestation	Cloud	Water
Forest	91	2	3	3	1
Non-forest	15	19	62	3	1
Cloud	46	24	10	14	6
Water	10	6	2	1	82

mapping smaller cover types (e.g. wetlands and deciduous forest, Table 3) that typically occur in patches smaller than the MODIS pixels. In the case of the GYE, other studies also reported that deciduous/hardwood tree cover was very difficult to map with Landsat TM, since they are distributed in small or narrow patches (Lawrence & Wright, 2001; Wright Parmenter et al., 2003). In fact, a low accuracy for mapping deciduous forests and herbaceous wetlands was also reported for the MRLC data in this area (unpublished data; http://landcover.usgs.gov/accuracy/). In the GYE, cottonwood, willow and aspen woodlands are keystone habitats for many species of plants, vertebrates and invertebrates (Hansen & Rotella, 2002; Hansen et al., 2000a). In fact, the woody deciduous habitats have the highest bird diversity in the GYE (Hansen et al., 1999). The observed loss of deciduous woodlands, specifically aspen (Gallant et al., 2003; Kay & Wagner, 1996), pose a serious threat to biodiversity and therefore this habitat requires accurate, high resolution mapping. The results nevertheless showed that MODIS data are capable of detecting deciduous tree cover (Fig. 6), although the spatial resolution may be inappropriate for detailed monitoring.

The results for the GYE showed that the most extreme and extensive land cover transformations, namely cultivation, clear-cutting (e.g. along the western boundary of Yellowstone National Park—mixed coniferous class in Fig. 11) and fire scars can be easily mapped with MODIS data (Fig. 11). However, currently, the most prevalent change in land use in GYE is from natural and agricultural land uses to urban and exurban development. The area under agriculture actually decreased by 9% during the last 25 years (Wright Parmenter et al., 2003). Exurban development (rural homes at densities of less than one home per 20 ha) has increased radically in the

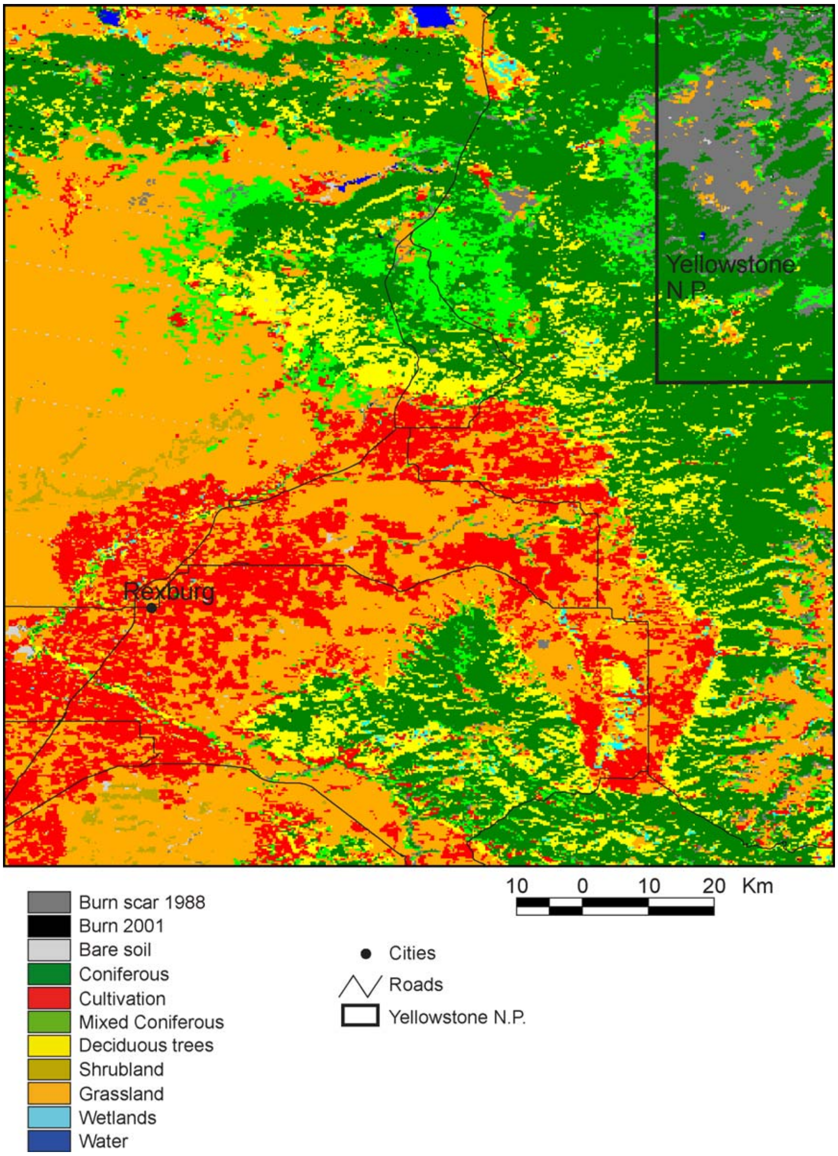

Fig. 11. Enlarged view of 250 m MODIS land cover for a portion of the Greater Yellowstone Ecosystem along the southwestern boundary of Yellowstone National Park.

GYE and appears to be concentrated in biodiversity hotspots at lower elevations (Hansen et al., 2002; Theobald, 2004). These changes may have significant ecological impacts, but since low density exurban development does not involve extensive land cover transformation, it is not readily detectable with either Landsat (Wright Parmenter et al., 2003) or MODIS data.

The MODIS classification for Pará State was successful at producing a regional forest/non-forest product which is useful for mapping the extreme human impacts such as deforestation. The single MODIS classification covered approximately 22 Landsat scenes and therefore provides a cheaper and faster monitoring tool (Nepstad et al., 1999). Although a single 500 m MODIS forest/non-forest product cannot be expected to reflect all the complex human impacts on biodiversity, such as secondary regrowth, local land use matrix dynamics or low intensity logging (Asner et al., 2003; Batistella et al., 2003; Lu et al., 2003; Mausel et al., 1993; McCracken et al., 1999; Moran et al., 1996; Nepstad et al., 1999; Zhan et al., 2002), it can provide rapid regional land cover information to alert us to areas where higher-resolution remote sensing and field surveys can be undertaken. Future research will furthermore test the ability of MODIS data (especially multi-temporal 250 m data) to map secondary growth, pasture and cultivation in the Amazon although it may prove difficult to assimilate reliable training data for these dynamic classes at a regional scale.

The independently generated Landsat land cover classifications provided the best available regional reference data with which to evaluate the MODIS land cover classifications. However, this comparison posed a number of problems. Firstly in the case of the GYE, some of the differences between the MRLC and MODIS land cover maps could be attributed to differences between the training data used in the MODIS classification and the MRLC land cover rather than a lack of ability of the MODIS data to accurately detect the land cover classes. Although the MODIS land cover classification may have compared more favorably with the MRLC land cover if the original training data (for MODIS classification) was generated from the MRLC, the two independently generated land cover maps provide a more objective and general evaluation. The disagreement was further exacerbated by the fact that the land cover classes were not the same for the MODIS product and the MRLC and there was a 9-year difference between the date of the MRLC (1992) and MODIS (2001) land cover products. In addition, the errors contained in the MRLC data (Stehman et al., 2003) or INPE data were compounded in these assessments. Unfortunately, these issues are difficult to avoid when assessing the accuracy of a coarse resolution land cover maps with other remotely sensed land cover maps (Foody, 2002; Powell et al., 2004).

The two case studies illustrate the versatile application of MODIS data in two contrasting environments experiencing different human impacts. These examples showed the value of using multi-date 250 m data with only two spectral bands (in the GYE), as well as single day 500 m data with seven spectral bands (in Pará State, Brazil), thus illustrating the flexibility of MODIS data. The regular availability of multi-date imagery enabled us to use vegetation phenology to distinguish different vegetation and land use types (e.g. deciduous trees in the GYE). MODIS data provide new options for regional land cover mapping that are less labor-intensive than Landsat and have higher resolution than previous 1 km AVHRR or the current 1 km global land cover product (Friedl et al., 2002b). The MODIS continuous fields (MOD44B) would be useful for mapping mixtures of the general cover types, i.e. tree, bare and herbaceous (Hansen et al., 2003), but do not map specific small habitats (e.g. wetlands and deciduous trees) that are often important to conservation. The usefulness of the higher-resolution MODIS surface reflectance data (250 and 500 m) in addressing biodiversity conservation questions will however depend upon the patch sizes and shapes of important habitats and the land cover transformations that threaten them. Although this will vary on a case-by-case basis, the MODIS data clearly provide additional options that were not previously viable. As described in this study, conservation agencies can utilize MODIS data in the same fashion as Landsat data, while capitalizing on the daily, multi-temporal, regional coverage.

The two case studies provide insight into the wider applicability of MODIS data for regional-scale conservation initiatives. Such initiatives include the Yellowstone to Yukon Conservation Initiative (Y2Y) and the Mesoamerican Biological Corridor (MBC). Y2Y, still in the development phase, links protected areas and surrounding lands in the Northern Rocky Mountains to protect biological diversity and the wilderness character of the region (Chester, 2003). The MBC grew out of an earlier plan to link a series of protected areas spread throughout seven Central American nations in a corridor known as *Paseo Pantera* or "path of the panther" (Miller et al., 2001; Sader et al., 2001b). Both the Y2Y and MBC conservation initiatives intend to use MODIS data for regional land cover mapping in conjunction with more detailed Landsat ETM land cover mapping in specific areas.

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