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Authors: Bajracharya, Birendra, Uddin, Kabir, Chettri, Nakul, Shrestha, Basanta, and Siddiqui, Salman Asif

Source: Mountain Research and Development, 30(2) : 143-156

Published By: International Mountain Society

URL: https://doi.org/10.1659/MRD-JOURNAL-D-09-00044.1

Mountain Research and Development (MRD)
An international, peer-reviewed open access journal
published by the International Mountain Society (IMS)
www.mrd-journal.org

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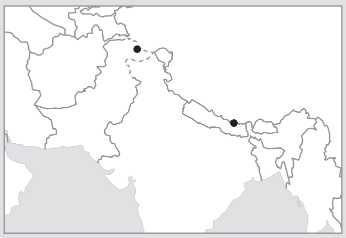
Understanding Land Cover Change Using a Harmonized Classification System in the Himalaya

A Case Study From Sagarmatha National Park, Nepal

Birendra Bajracharya, Kabir Uddin, Nakul Chettri, Basanta Shrestha, and Salman Asif Siddiqui*
** Corresponding author: bbajracharya@icimod.org; birendra.bajracharya@gmail.com*
International Centre for Integrated Mountain Development, GPO Box 3226, Khumaltar, Lalitpur, Kathmandu, Nepal



Land cover assessment and monitoring of land cover dynamics are important to understand social and ecological processes in mountain protected areas. However, variations in the use of legends and classification systems sometimes pose challenges. The landscape of Sagarmatha National Park and Buffer Zone (SNPBZ) has seen many changes in the past few decades. Mapping of land cover in SNPBZ was carried out to fill gaps in basic databases for the area. A review of past land cover initiatives and existing data revealed differences in methodologies and definitions that made them incompatible for cross-region applications. For the present study, a legend was developed using the standard Land Cover Classification System (LCCS) methodology developed by the Food and Agriculture Organization and the United Nations Environment Programme, a comprehensive and standardized a priori classification system designed for mapping exercises independent of scales or means. The changes in land cover were analyzed using Landsat Thematic Mapper, Landsat Enhanced Thematic Mapper Plus, and Advanced Spaceborne Thermal Emission and Reflection Radiometer images from 1992 to 2006. Land cover maps were generated using object-based image analysis supplemented by ancillary information. Extensive fieldwork was carried out for ground truthing and validation. The use of LCCS was instrumental in bringing general understanding of the classification systems and helping to gain greater clarity and accuracy in the results. About 70% of the SNPBZ area is covered by snow and ice, glaciers, bare rocks, and bare soil. Altitude and its influence on climatic conditions have dominated the distribution pattern of vegetation in SNPBZ. The analysis showed that forest is being converted into shrub at elevations between 3000 and 4000 m, while shrub is decreasing between 4000 and 5000 m. A major decrease in snow cover is seen above 5000 m. Harmonization of the classification system helped to gain more reliable information on changes, as comparisons were made between the classes with consistent definitions.

Keywords: *Land cover classification; LCCS (Land Cover Classification System); remote sensing; harmonization; Hindu Kush–Karakoram–Himalaya (HKKH).*

Peer-reviewed: *February 2010* ***Accepted:*** *March 2010*

Introduction

Land use and land cover changes are the most important and easily detectable indicators of global ecological change (Turner et al 1990; Vitousek 1994; Lambin et al 1999; Di Gregorio 2005). They directly impact biological diversity (Sala et al 2000); contribute to local, regional, and global climate change (Chase et al 1999; Houghton et al 1999); and may cause land degradation by altering ecosystem services and livelihood support systems, thereby disrupting the sociocultural practices and institutions associated with managing them (Vitousek et al 1997). Such changes also affect the vulnerability of people and places to climatic, economic, and sociopolitical perturbations (Sharma et al 2009).

Thus a robust understanding of land use and cover is essential to understand landscape patterns and their changes, which is useful for the assessment of human-induced drivers and their impacts on the ecosystem. However, despite improvements in land cover characterization made possible by earth-observing satellites (Loveland et al 1999, 2000; Friedl et al 2002; Di Gregorio 2005), global and regional land cover has been poorly evaluated (Intergovernmental Panel on Climate Change 2000; Knight and Lunetta 2006). Moreover, we lack consistency in the use of data and layers for interpretation, as the legends vary from biome to microvegetation types. Global scale assessments may therefore conflict with the findings of micro- or mesoscale data sets because they are specific to time and place.

In order to address these differences, a number of organizations and institutions are working to create general classification systems and legends for global consistency, such as terrestrial ecoregions (Olson and Dinerstein 2002; Fritz et al 2003; Global Observation for Forest and Land Cover Dynamics [GOFC-GOLD] 2004).

TABLE 1 Land cover classes in SNPBZ. (Table continued on next page.)

LCCCode	LCCLevel	LCCOwnLabel	LCCLabel	Description
6002-1	A3-A7	Bare rock	Bare rock(s)	Rock outcrops dominated by a continuous rock surface
6002-2	A3-A8	Gravel, stones, and boulders	Gravel, stones, and/or boulders	Area covered by unconsolidated material such as rocks and boulders
6005	A5	Bare soil	Bare soil and/or other unconsolidated material(s)	Area covered by unconsolidated material, usually fine grain deposits
5001	A1	Builtup area	Builtup area(s)	Nonlinear area covered with artificial impervious cover
8001-1	A1-A4	River	Natural water bodies (flowing)	Natural flowing water bodies
8001-5	A1-A5	Glacier lake	Natural water bodies (standing)	Perennial standing water bodies associated with glacier
8005	A2	Snow	Snow	Perennial snow (persistence > 9 months per year)
8008-9	A3-A6	Glacier	Ice (moving)	Perennial ice in movement with typical elongated shapes
7001-5	A1-A5	Artificial water bodies	Artificial water bodies (standing)	Perennial standing water bodies created due to manmade structure such as a dam or reservoir
11498	A3XXXXXXD1	Cultivated area	Rainfed herbaceous crop(s)	Herbaceous rainfed crops, no distinction made on the basis of field size and geomorphologic context
20611-15047	A3A10B2XXD2E1F2F5F7G2-E3F9	Multilayered mixed forest	Multilayered mixed trees	A mixture of broadleaved deciduous and needleleaved evergreen trees (height 3–30 m) with closed to open crown cover (15–100%)
20091	A3A10B2XXD2	Needleleaved closed forest	Needleleaved closed trees	Area with more than 75% needleleaved evergreen trees (height 3–30 m) and crown cover above 65%
20133	A3A11B2XXD2	Needleleaved open forest	Needleleaved woodland	Area with more than 75% needleleaved evergreen trees (height 3–30 m) and crown cover 15%–65%

TABLE 1 Continued. (First part of Table 1 on previous page.)

LCCCode	LCCLevel	LCCOwnLabel	LCCLabel	Description
20088	A3A10B2XXD1	Broadleaved closed forest	Broadleaved closed trees	Area with more than 75% broadleaved trees (height 3–30 m) and crown cover above 65%
20130	A3A11B2XXD1	Broadleaved open forest	Broadleaved woodland	Area with more than 75% broadleaved trees (height 3–30 m) and crown cover 15–65%
20151	A4A10B3XXD1	Broadleaved closed shrubland	Broadleaved thicket	Medium to high broadleaved shrubs (from 0.5 m to 5 m) and crown cover ranging above 65%
20172	A4A11B3XXD1	Broadleaved open shrubland	Broadleaved shrubland	Medium to high broadleaved shrubs (height 0.5–5 m) and crown cover 15–65%
20155-15045	A4A10B3XXD2E1-E3	Mixed closed shrubland (thicket)	Mixed thicket	Area covered with a mixture of broadleaved deciduous and needleleaved evergreen shrubs (height 0.5–5 m) with crown cover over 65%
20176-15045	A4A11B3XXD2E1-E3	Mixed open shrubland	Mixed shrubland	Area covered with a mixture of broadleaved deciduous and needleleaved evergreen shrubs (height 0.5–5 m) with crown cover 15–65%
20154	A4A10B3XXD2	Needleleaved closed shrubland	Needleleaved thicket	Medium to high needleleaved shrubs (height 0.5–5 m) and crown cover above 65%
20175	A4A11B3XXD2	Needleleaved open shrubland	Needleleaved shrubland	Medium to high needleleaved shrubs (height 0.5–5 m) and crown cover 15–65%
20018-12050	A4A10B3-B10	Dwarf closed shrubland	Closed dwarf shrubland (thicket)	Dwarf shrubs (height < 0.5 m) with a cover above 65%
20022-12050	A4A11B3-B10	Dwarf open shrubland	Open dwarf shrubs (shrubland)	Dwarf shrubs (height < 0.5 m) with cover 15–65%
21454-121340	A2A20B4-A21	Closed to open herbaceous vegetation	Herbaceous closed to open (100–40%) vegetation	Area with herbaceous vegetation with a cover ranging from closed to open (40–100%)

However, very few efforts have been made to date to bring consistency to global legend use (Olson and Dinerstein 2002; Giri et al 2005), and a consistent land use legend for the Himalayan region has always been in demand (Gautam and Watanabe 2004). To address this urgent need, the Food and Agriculture Organization (FAO) has developed a system for land cover classification (Di Gregorio 2005).

The International Centre for Integrated Mountain Development initiated research to harmonize land cover classification at the regional scale and address the immediate needs of the Hindu Kush–Karakoram–Himalaya (HKKH). The objective of the research was to develop a common set of legends to be used in Qomolangma National Nature Preserve (QNNP) in the Tibet Autonomous Region (TAR) of China, Sagarmatha National Park and Buffer Zone (SNPBZ) in Nepal, and Central Karakoram National Park in Pakistan. Harmonization of the classification system is facilitating the generation of land cover maps that can be used consistently for studies of change. The planned land cover maps must be useful for applications at different scales; therefore, it is important to design a system that follows a uniform approach and allows for aggregation at different levels of detail. This paper presents the results of land cover mapping from Sagarmatha National Park and discusses the advantages and limitations of using a harmonized classification system to understand land cover change.

Study area

SNPBZ is located in northeastern Nepal at 27°45′–28°07′N and 86°28′–87°07′E. It shares its northern border with the QNNP in TAR of China. The park encompasses the upper catchment of the Dudh Koshi River system, which forms a distinct geographical unit enclosed on all sides by high mountain ranges. The national park is located amidst the world's tallest peaks—Mount Everest (8850 m), Lhotse (8601 m), and Cho Oyu (8153 m). The elevation rises from 1800 m to 8850 m at the top of Everest within a distance of less than 50 km.

The climate of SNPBZ is generally moist and cool in the summer and cold and dry in the winter. Marked variations in temperature and precipitation are influenced by altitude and seasons. Nearly 100 large and small settlements are scattered throughout the Park. The landscape of SNPBZ has been shaped by centuries of human use since the ancestors of the Sherpa people entered the vacant valley of Khumbu around 400 years ago (Sherpa and Bajracharya 2009). These socioeconomic activities have changed the landscape of the area, as evidenced by many repeat photographs (Byers 1997). Similarly, the study of satellite images dating from the 1960s has shown dramatic changes in the higher mountain environments, with new lakes and retreating glaciers (Bajracharya et al 2007). While there have been claims of forest and general environmental degradation in the region, studies by Stevens (2003) and repeat photography by Byers (1997) report a relatively intact and stable landscape. However, so far, there is a lack of spatially explicit information and quantitative analysis of changes in SNPBZ. To cope with these social and natural changes and to enable the sustainable management of the park, it is important to have basic information on its land resources.

Material and methods

Harmonization of legends

We reviewed the existing land cover data on Nepal. The first measurement of forest resources in Nepal was carried out between 1963 and 1965 by the U.S. Agency for International Development and the Government of Nepal (Wallace 1988). Another extensive mapping effort was carried out by the governments of Nepal and Canada through the Land Resources Mapping Project (1986) in the early 1980s. This project developed a land use classification system and completed mapping of nationwide land use at a scale of 1:50,000. The most recent land cover mapping was carried out by the Department of Forest Resources Survey (1999) with the cooperation of the Japan Forest Technology Association (2001). Past enumerations of land use and land cover types in the region (Champion et al 1965; Champion and Seth 1968; Stainton 1972; Dobremez 1976; Olson and Dinerstein 2002) were also reviewed.

The initiatives taken by FAO and the United Nations Environment Programme in developing the Land Cover Classification System (LCCS) provided an opportunity for harmonization (Roy et al 2004). Because LCCS was developed as a worldwide reference system for land cover (Di Gregorio 2005) and is in the process of being established as a standard by the International Organization for Standardization, it was chosen as the most appropriate approach for the study. A consultative workshop was organized to inform stakeholders of the needs for harmonization and interdisciplinary collaboration, to train them in concepts and tools, and finally to come up with an LCCS-based legend for SNPBZ. Table 1 presents the legend developed for SNPBZ through the consultative workshop. It was further refined after a field mission to the park.

Classification methodology

For the analysis, 1992 Landsat Thematic Mapper images, 2000 Landsat Enhanced Thematic Mapper Plus images, and 2006 Advanced Spaceborne Thermal Emission and Reflection Radiometer images were classified using the same classification scheme and methodology. A change analysis was carried out for 2 periods, from 1992 to 2000 and from 2000 to 2006, to detect trends, as well as for 1992 and 2006 to see the overall change scenario. IKONOS images from 2000 and 2001 were also used for a

TABLE 2 List of satellite images used for land cover mapping.

Satellite	Sensor	Band (μm) [a)]	Resolution	Acquisition date
IKONOS	IKONOS-2	Pan 0.45–0.90	1 m	1 Jan 2002
		Band 1 0.45–0.53 (blue)	4 m	
		Band 2 0.52–0.61 (green)	4 m	29 Nov 2001
		Band 3 0.64–0.72 (red)	4 m	
		Band 4 0.77–0.88 (NIR)	4 m	
LandSat	ETM+	Band 1 0.45–0.52 (blue)	30 m	30 Oct 2000
		Band 2 0.52–0.60 (green)	30 m	
		Band 3 0.63–0.69 (red)	30 m	
		Band 4 0.75–0.90 (NIR)	30 m	
		Band 5 1.55–1.75 (IR)	30 m	
		Band 6 10.4–12.50 (TIR)	60 m	
		Band 7 2.08–2.35 (NIR)	30 m	
		Band 8 0.52–0.90 (green–NIR)	15 m	
LandSat	TM	Band 1 0.45–0.52 (blue)	30 m	17 Nov 1992
		Band 2 0.52–0.60 (green)	30 m	
		Band 3 0.63–0.69 (red)	30 m	
		Band 4 0.76–0.90 (NIR)	30 m	
		Band 5 1.55–1.75 (IR)	30 m	
		Band 6 10.40–12.50 (TIR)	120 m	
		Band 7 2.08–2.35 (NIR)	30 m	
Terra	ASTER	Band 1 0.52–0.60 (Green)	15 m	1 Feb 2006
		Band 2 0.63–0.69 (Red)	15 m	
		Band 3 0.76–0.86 (NIR)	15 m	
		Band 4 1.60–1.70 (SWIR)	30 m	
		Band 5 2.145–2.185 (SWIR)	30 m	
		Band 6 2.185–2.225 (SWIR)	30 m	
		Band 7 2.235–2.285 (SWIR)	30 m	
		Band 8 2.295–2.365 (SWIR)	30 m	
		Band 9 2.36–2.43 (SWIR)	30 m	
		Band 10 8.125–8.475 (TIR)	90 m	
		Band 11 8.475–8.825 (TIR)	90 m	
		Band 12 8.925–9.275 (TIR)	90 m	
		Band 13 10.25–10.95 (TIR)	90 m	
		Band 14 10.95–11.65 (TIR)	90 m	

[a)] IR, infrared; NIR, near-infrared; SWIR, shortwave infrared; TIR, thermal infrared.

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detailed classification and validation. Details of images used are given in Table 2.

Classification was carried out with the object-based image analysis (OBIA) approach using Definiens® software. Compared with pixel-based methods, this approach has shown better classification results with higher accuracy as it uses both spectral and spatial information (Civco et al 2002; Yoon et al 2004; Harken and Sugumaran 2005; Gao et al 2007), including texture information, neighborhood information, context information, and other related ancillary data (Blaschke et al 2000, Benz et al 2004).

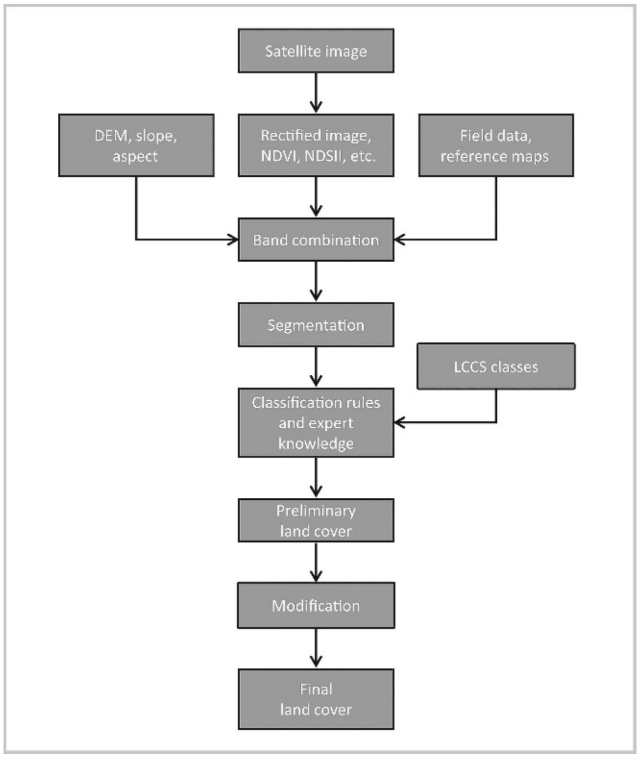
The framework for analysis is presented schematically in Figure 1. After the satellite images were georeferenced, indices such as a normalized differential vegetation index (NDVI) and normalized differential snow ice index (NDSII), were generated from the images. A digital elevation model generated from the contour data was used for the elevation information. The rectified image—along with the above information layers—were loaded into Definiens® for band combination.

The next step was segmentation of the image into unclassified basic image objects. Segmentation is the subdivision of an image into separated regions represented by image objects based on its spectral characteristic, color, tone, and texture, as well as information about its neighborhood (Definiens 2006). Segmentation algorithms were used to subdivide the entire image. A convenient approach was to run segmentations with different parameters until the result was satisfying. In the present analysis, the "multiresolution" algorithm was used; this algorithm locally minimized the average heterogeneity of image objects for a given resolution. Shape was given priority during the first-level segmentation process, while color was given priority in the second-level process to get suitable segmentation of the images. For each segment, information on average NDVI, NDSII, slope, etc was derived.

This information was used to develop suitable classification algorithms for individual classes. The LCCS classes were inserted before starting the classification. Image objects were linked to class objects and each classification link stored the membership value of the image object to the linked class. With each polygon assigned to a specific class, a land cover map was generated for the landscape. After the classification, the land cover data were exported to .img (ERDAS Imagine®) format for further processing, such as the elimination of areas smaller than the defined minimum mapping units.

A field mission was carried out for the validation of the land cover classification. An error matrix is the most commonly used form for reporting site-specific accuracy, as it effectively summarizes the key information obtained from the sampling and response designs (Stehman and Czaplewski 1998). To this end, a uniform 500 × 500 m grid was generated over the area, and 15% of these points were selected randomly and used for accuracy assessment. The land cover at each point was interpreted with the help of field data, IKONOS 4-m multispectral and 1-m panchromatic images, and available field photographs. These were then compared with the land cover map to calculate the error matrix. The accuracies were 86.6%, 86.6%, and 83.8% for 1992, 2000, and 2006, respectively. When the classes were generalized by aggregating forests and shrubs to single classes, the accuracies were 94.9%, 96.46%, and 98.2%, respectively (Supplemental material, Table S1A–C; http://dx.doi.org/10.1659/MRD-JOURNAL-D-09-00044.S1).

FIGURE 1 Classification methodology and process.



Results

Our review showed that past enumerations have different legends, mainly manifested in the vegetation and land cover types used and the objective of the respective work (Tables 3A, 3B). It clearly showed inherent differences in the methodologies and the classification approaches.

Regarding the analysis of land cover, about 70% of the SNPBZ area is covered by snow and ice, glaciers, bare rocks, and bare soil. The land cover change analysis showed that major changes occurred in grass, snow, and bare areas. The grass cover showed an increase of 52.8 km^2 between 1992 and 2000, while it decreased by 34.1 km^2 between 2000 and 2006. Snow cover decreased by 18.4 km^2 between 1992 and 2000 and further decreased by 94.5 km^2 between 2000 and 2006. Bare area showed a decrease of

TABLE 3A Land cover classification systems adopted by earlier initiatives in Nepal.

Land cover classes adopted by JAFTA (2001)		Classification system adopted by LRMP (1986)	
Class	**Description**	**Classification system**	**Classes**
Agriculture land/ grass	Cultivated land and areas covered by herbs	1. Agricultural land use classification	Terai cultivation
			Hillslope cultivation
			Valley cultivation
			Grazing land
Snow	Snow-covered areas	2. Nonagricultural land	Perpetual snow and ice
Bare land	Bare land, rocky zones, riverbeds, etc		Rock
			Sand/gravel/boulders
			Swamps
			Urban centers
Water bodies	Inland water areas		Lakes
			Abandoned land
Tropical mixed hardwood	Terai mixed hardwood, *Acacia catechu* and *Dalbergia sissoo*	3. Forest classification system *(Except for shrub, these categories are then further subdivided into species or species group types. Each is then given a density and a maturity rating.)*	Hardwood
Upper/lower mixed hardwood	Lower mixed hardwood and upper mixed hardwood, oak, birch, and deciduous mixed broadleaved		Coniferous
Sal	*Shorea robusta* > 60% dominant		Mixed wood
***Chir* pine**	Forest with *Pinus roxburghii* > 60% as dominant species		All other combinations of tree species
Fir/hemlock	Forests composed of fir, hemlock, spruce, and cedar		Shrub
Blue pine/ cypress/yew	*Pinus wallichiana* > 60% with other conifers		
Shrub	Low shrub forest and young secondary forest		

26.1 km^2 and an increase of 120 km^2 in the 2 periods, respectively. Looking at the total changes between 1992 and 2006, broadleaf and needleleaf forests increased by 7.3 km^2 and 2.8 km^2, respectively, while mixed forest decreased by 14.1 km^2. This resulted in an overall decrease in forest area of 3.9 km^2. Needleleaf shrub and mixed shrub decreased by 9.9 km^2 and 3.6 km^2, respectively, while dwarf shrub increased by 14 km^2. Glacial lakes increased by 2.4 km^2 during this period. The distribution of land cover classes in the 3 years and the overall change between 1992 and 2006 are presented in Figure 2. The change matrix from 1992 to 2006 is presented in Figure 3.

Regarding changes by elevation zones, major changes are seen above 5000 m, with a decrease in snow cover of 102.7 km^2, contributing to an increase of 93.6 km^2 in bare area and 6 km^2 in grass cover. At elevations from 3000 to 4000 m, broadleaf and needleleaf forests increased by 7 km^2 and 1.6 km^2, respectively, while mixed forest decreased by 10.5 km^2, resulting in an overall decrease of 1.9 km^2. At elevations from 4000 to 5000 m, broadleaf, needleleaf, and mixed shrubs decreased by 2, 7.9 and 3.4 km^2, respectively, while dwarf shrubs increased by 11.1 km^2.

Again, the most marked changes occurred in the northern aspect in terms of snow and bare area. Broadleaf forest showed a decrease of 1 km^2 in the southern aspect, while it increased from 2.2 to 3.2 km^2 in the other 3 aspects. Mixed forest showed a decrease in all 4 aspects, ranging from 2.2 to 4.4 km^2. Shrubs showed a decrease of 5.6 km^2 in the southern aspect, while dwarf shrubs

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TABLE 3B Major types of land classification based on different classification criteria available from the HKKH region.

Categories	Classifications	Examples	References
1	Land use classes	Forested land Cultivated land Builtup area Water bodies Barren land Snow cover	Olson and Dinerstein 2002 NARMSAP 2002
2	Life forms	Forest Shrub Scrub Grassland Savanna Meadow	Schweinfurth 1957 Dobremez 1976 Olson and Dinerstein 2002 NARMSAP 2002
3	Canopy coverage	Open forest Closed forest Abandoned *jhum* Vegetated Nonvegetated Tree cover Shrub cover Herbaceous cover	Champion and Seth 1968 Roy et al 2004 Di Gregorio 2005
4	Climatic factors, eg precipitation	Moist Wet Dry Humid Swamp	Schimper 1903 Shangbag 1958 Gaussen 1959 Champion and Seth 1968 Dobremez 1976 Roy et al 2004
5	Bioclimatic zones or ecoregions	Subtropical Tropical Subtemperate Temperate Subalpine Alpine Montane	Schweinfurth 1957 Champion and Seth 1968 Dobremez 1976 Olson et al 2001 Wikramanayake et al 2001 Olson and Dinerstein 2002 NARMSAP 2002
6	Species types	Needleleaf Thorn Pine Conifer Broadleaf Mixed Evergreen Deciduous	Kihara 1956 Schweinfurth 1957 Hara 1966 Champion and Seth 1968 Wikramanayake et al 2001 Olson and Dinerstein 2002
7	Species dominance	Oak Oak–rhododendron Pine–birch Pine–spruce–fir etc	Schweinfurth 1957 Hara 1966 Champion and Seth 1968 Dobremez 1976 NARMSAP 2002
8	Climatic and vegetation division	East Central West Trans-Himalaya	Champion and Seth 1968 Dobremez 1976 NARMSAP 2002

FIGURE 2 (A) Distribution of land cover classes in 1992, 2000, and 2006; (B) overall land cover change between 1992 and 2006.

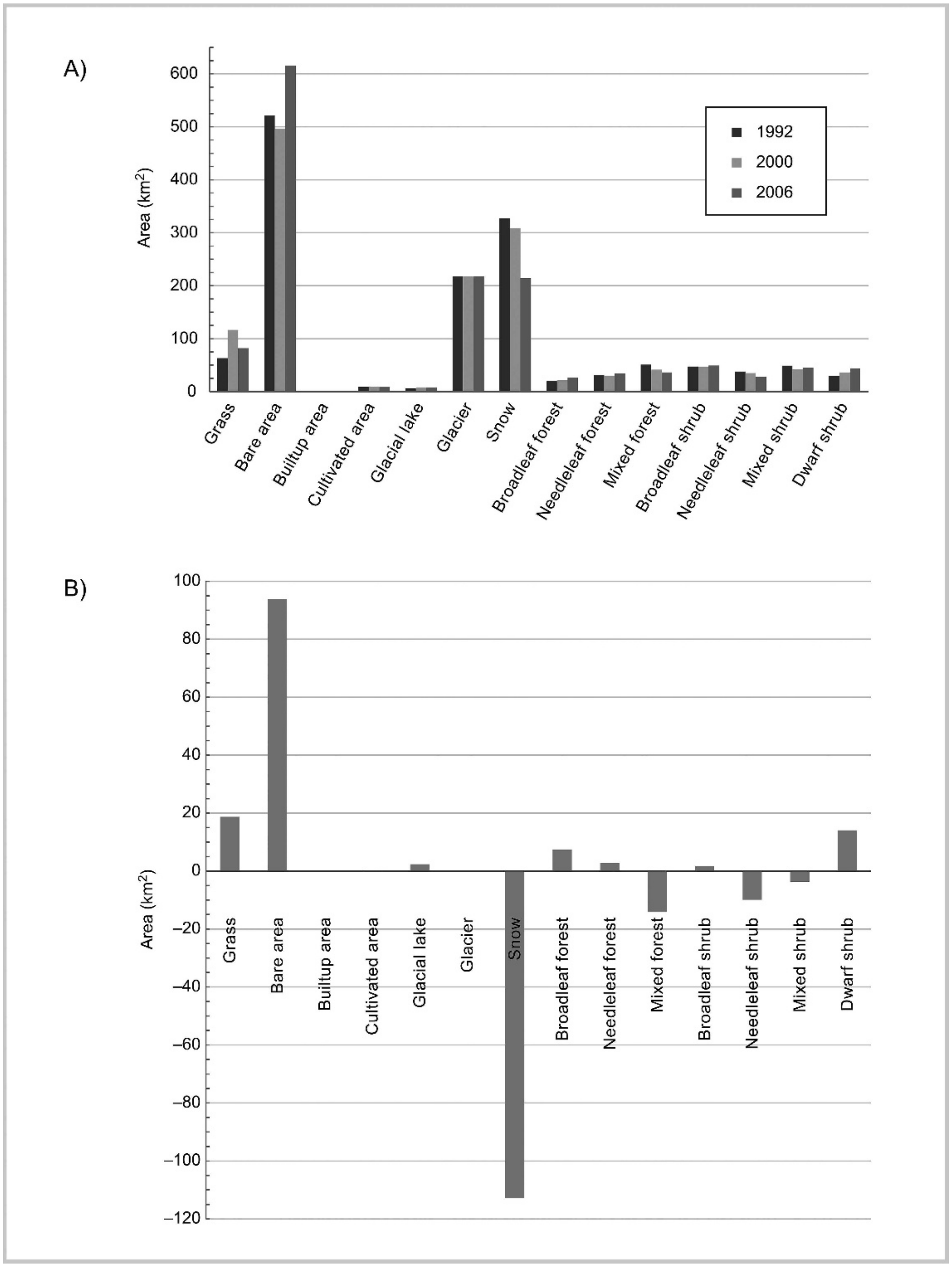

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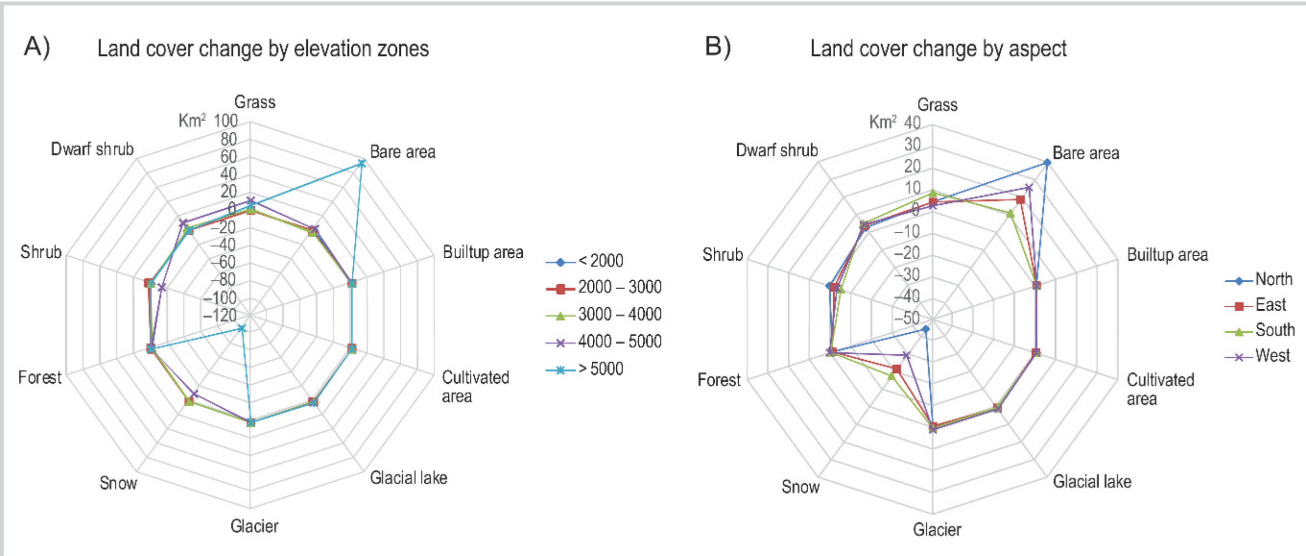
FIGURE 3 Land cover change matrix (1992–2006). Significant changes ($\geq$ 5 km^2) are indicated in boldface. The diagonal cells represent the areas that have remained unchanged; for example, the cell in the first row and first column shows that 39.2 km^2 were grass both in 1992 and 2006, while the cell in the second row and first column shows that 19.9 km^2 were bare area in 1992 and grass in 2006.

		2006														
		Grass	Bare area	Builtup area	Cultivated area	Glacial lake	Glacier	Snow	Broadleaf forest	Needleleaf forest	Mixed forest	Broadleaf shrub	Needleleaf shrub	Mixed shrub	Dwarf shrub	Total 1992
1992	Grass	39.2	**16.3**	0.0	0.1	0.0	0.1	0.3	0.2	0.2	0.1	2.0	0.5	1.7	2.7	63.4
	Bare area	**19.9**	476.7	0.0	0.6	1.4	**5.7**	**5.7**	0.9	1.0	0.6	3.3	1.0	2.5	2.8	522.0
	Builtup area	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4
	Cultivated area	0.1	0.2	0.0	7.7	0.0	0.0	0.0	0.1	0.3	0.1	0.2	0.2	0.1	0.1	9.2
	Glacial lake	0.1	0.4	0.0	0.0	4.8	0.3	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	5.9
	Glacier	0.3	4.8	0.0	0.0	1.2	209.8	1.3	0.0	0.0	0.0	0.0	0.0	0.0	0.1	217.6
	Snow	**7.3**	**110.0**	0.0	0.0	0.8	1.7	206.6	0.0	0.0	0.0	0.1	0.0	0.5	0.2	327.1
	Broadleaf Forest	0.1	0.2	0.0	0.1	0.0	0.0	0.0	12.4	1.9	2.2	0.4	0.8	1.1	0.5	19.5
	Needleleaf Forest	0.4	0.2	0.1	0.1	0.0	0.0	0.0	2.3	23.3	1.2	0.5	1.7	1.6	0.1	31.5
	Mixed Forest	0.3	0.3	0.0	0.1	0.0	0.0	0.0	**8.0**	**5.0**	30.8	1.5	1.5	2.8	0.6	50.8
	Broadleaf Shrub	1.9	2.0	0.0	0.1	0.0	0.0	0.0	0.5	0.3	0.2	35.6	0.4	3.4	3.3	47.7
	Needleleaf Shrub	2.9	0.4	0.0	0.1	0.0	0.0	0.0	1.2	1.3	0.8	2.3	21.4	**6.1**	1.7	38.2
	Mixed Shrub	**8.2**	1.9	0.0	0.1	0.0	0.0	0.0	1.1	1.1	0.6	2.8	0.7	25.1	**7.5**	49.1
	Dwarf Shrub	1.4	2.5	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.1	0.6	0.1	0.7	24.2	29.7
Total 2006		82.1	615.9	0.5	8.9	8.2	217.5	214.2	26.9	34.3	36.8	49.3	28.3	45.5	43.8	1412.2

increased by 4.5 km^2. The patterns of change are presented in Figure 4 by elevation and aspect. A map of changes in total forest cover and glacial lakes is presented in Figure 5.

The results show that variations in aspect and slope influence the local vegetation, but altitude and its influence on climatic conditions have dominated the distribution pattern of vegetation in SNPBZ. The analysis by elevation zones revealed that most of the vegetation changes are occurring at elevations between 3000 and 4000 m, with a decrease in forest and an increase in shrub. This is also the zone in which most settlements are located. While the overall vegetation cover looks intact, this may indicate that forests are subject to degradation in this zone. There is a loss of shrub cover at the higher elevation zone between 4000 and 5000 m, and the elevations above 5000 m have seen an increase in grass. Changes in the growth of buildings and their structures are visible in the field, particularly in areas like Phakding, Namche, and Khumjung. However, in terms of the expansion of builtup areas, the changes are very small, which may be due to limited suitable land.

FIGURE 4 (A) Land cover change by elevation zone; (B) land cover change by aspect.



Discussion and conclusion

Land use and land cover analysis is evolving as one of the most fundamental information systems for the study of ecosystems, including protected areas, and for the management of protected areas (Roy and Tomar 2000; Li et al 2006; DeFries et al 2007). The HKKH region is known for its rich biodiversity, and human-induced land cover change is producing alarming signals regarding the fate of biological resources (Myers et al 2000; Pandit et al 2007). Land cover mapping requires significant resources and, due to the gaps in harmonized legends, investments in past initiatives could not be properly used for studies of change.

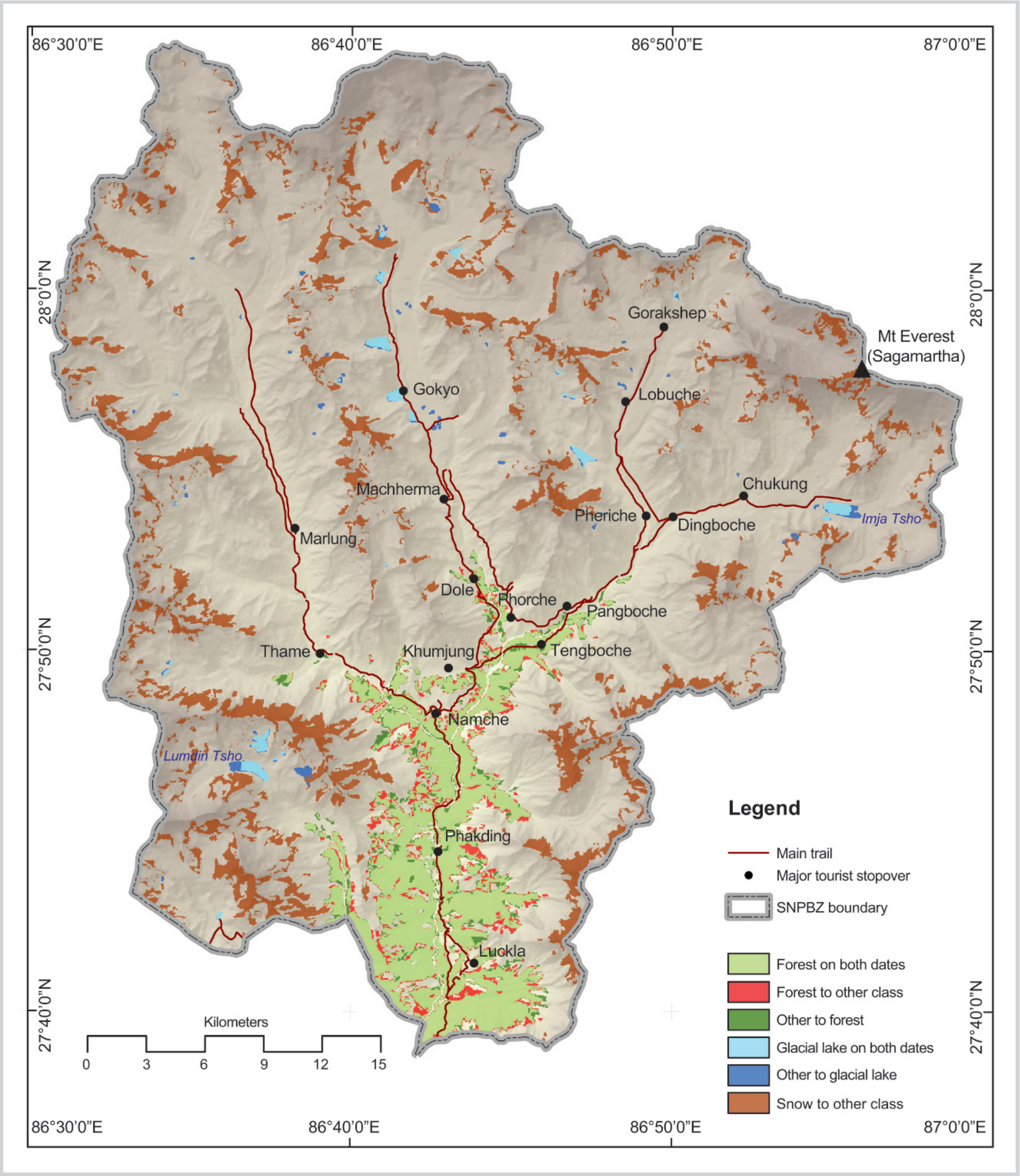
The analysis in Table 3A shows the differences in the use of legends in the earlier land cover classifications, which limits the compatibility of data for comparison. Even within each classification system, there are overlaps and ambiguities in class descriptions. LCCS is the only operational system at present in which land cover classes are clearly and systematically defined. LCCS is being successfully used for land use change detection and for the quantification and modeling of vegetation dynamics at a regional level (Rodgers et al 2007). In addition, LCCS is also compatible with global land cover initiatives such as Global Land Cover 2000 and GlobCover (Fritz et al 2003; GlobCover 2008).

In LCCS, a land cover class is defined by a set of independent diagnostic attributes or classifiers, and the amount of detail in the description of a land cover feature is linked to the number of classifiers being used. The 2-phase design, with the initial *dichotomous phase* and the *modular–hierarchical phase*, results in a land cover class defined by a Boolean formula showing each classifier used, a unique number for use in geographic information systems (GIS), and a name, which can be the standard name as supplied or a user-defined name (see Table 1). The classifiers are categorized as pure land cover classifiers (life form, height, etc), environmental attributes (altitude, climate, landform, etc) and specific technical attributes (floristic aspect, crop type, etc). The LCCS implementation framework urges a new perspective in land cover mapping that is appropriate in the era of GIS and advanced spatial analysis (Herold et al 2006). Our experience shows that it took a while for people to become familiar with the new concept, and there was a tendency to mix up the land cover classifiers with other attributes. However, the free LCCS software facilitated the process of defining the legend by systematically guiding users through the steps.

Although the studies are mostly limited to the images from winter due to cloud cover in other seasons, the availability of temporal data from satellites greatly facilitated studies of land cover change; this is more significant in mountainous areas, where accessibility is very limited due to extreme topography. Field knowledge and photographs as ancillary information help greatly in the correct mapping of these areas. In the present case, the availability of high-resolution satellite images was an added advantage in the interpretation and validation of the results. The adoption of OBIA helped in integrating ancillary information and knowledge in the classification process to produce better results.

The decrease in snow cover is quite significant and may be attributed to seasonal factors. However, the image used for 1992 was from November, which is usually before snowfall, and the image for 2006 was from February, when the snow cover is usually extensive in the Eastern Himalaya. An analysis of permanent snow cover over a

FIGURE 5 Changes in forest, snow, and glacial lakes from 1992 to 2006. (Map by Birendra Bayracharya)



longer period of time will be required to establish whether this decrease is an impact of global climate change. Similarly, a visible increase occurred in the sizes of the glacial lakes Imja Tsho and Lumdin Tsho as well as an in supraglacial lakes in Ngojumba glacier. These changes in glaciers and glacial lakes have been presented as evidence of global warming (Bajracharya et al 2007). Similarly, the large change in forest types observed, particularly from mixed to broadleaf, may be due to differences in the sensors used for the 2 dates. Also, shadows in the mountain areas can make interpretation of forest types difficult. Although LCCS allows us to define very detailed land cover classes, it is still difficult to extract this information from satellite images through automated classification methods, and some level of visual interpretation is required.

While information on land cover and its change over time gives very important insights into ongoing natural and human processes in the ecosystem (Millennium Ecosystem Assessment 2005), managers are more often interested in land use practices. Stevens (1993) gives a detailed account of land use practices in Khumbu, where the Sherpas have been using local forests intensively as an integral part of their subsistence lifestyle and have their own indigenous system of forest management by rotating grazing areas and appointing a forest ward called a *Nawa*. Increasing tourism and the consequent change in Sherpa lifestyle have been considered major drivers of change in forests and alpine vegetation due to increased demand for timber and firewood. Stevens (2003) observes that, although no significant deforestation has occurred, forest thinning and a loss of alpine shrub juniper have occurred in many locations. Our analysis also showed a significant loss of shrub at high altitudes above 4000 m. It showed large patches of forest converted to other classes near Lukla and Phakding, the areas in the buffer zone that faced increasing pressure due to tourism (Stevens 1993, 2003).

Our analysis is limited to land cover change, as LCCS has inherent limitations for integrating land use information since it is designed exclusively for land cover to provide consistency in classification. For this reason, it will be necessary to base a common system for land use classification on existing standards for the assessment of land cover and land use changes (Herold et al 2006). While many studies have examined the changing landscape of SNPBZ in the past, comprehensive land cover mapping activity was lacking. This study has generated land cover maps using both satellite images and extensive fieldwork, and has been able to fill a major data gap in the area.

The results of this study open up areas for new research to find the social and natural linkages to these land cover changes. Such applications will help link efforts at local and regional levels to ongoing international cooperation on a joint harmonization and validation initiative for land cover datasets (Herold and Schmullius 2004). The quantitative data resulting from our study can be used as a baseline, while the methods and approaches can be replicated to other areas to come up with a better harmonized land cover mapping of the Himalaya, which is still a data-scarce region.

ACKNOWLEDGMENTS

This publication was produced within the framework of the project "Institutional Consolidation for the Coordinated and Integrated Monitoring of Natural Resources towards Sustainable Development and Environmental Conservation in the Hindu Kush–Karakoram–Himalaya Mountain Complex," financed by the Italian Ministry of Foreign Affairs–DGCS. The authors are grateful to all those who contributed in various capacities during different phases of the study, such as the development of the methodology, definition of legends, field data collection, image interpretation and analysis, and validation. Special thanks go to Antonio Di Gregorio, of the Global Land Cover Network (FAO), for his contributions in organizing LCCS workshops that were a basis for developing the classification legends.

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Supplemental data

TABLE S1A–S1C. Assessments of the accuracy of image classification.

Found at DOI: 10.1659/MRD-JOURNAL-D-09-00044.S1 (47.7 KB PDF).