DOI: 10.1007/s00267-004-0338-9

Emergence of Indigenous Vegetation Classifications Through Integration of Traditional Ecological Knowledge and Remote Sensing Analyses

ROBIN NAIDOO*
Conservation Science Program
World Wildlife Fund (U.S.)
1250 24th Street NW
Washington, DC 20037, USA

KIM HILL
Department of Anthropology
University of New Mexico
Albuquerque, New Mexico 87131-1086, USA

ABSTRACT / Traditional ecological knowledge (TEK) can play an important role in the understanding of ecological systems. Although TEK has complemented scientific and managerial programs in a variety of contexts, its formal incorporation into remote sensing exercises has to date been limited. Here, we show that the vegetation classifications of the Ache, an indigenous hunter-gatherer tribe of the Mbaracayu Forest Reserve in Paraguay, are reflected in a supervised classification of satellite imagery of the reserve. Accuracy of classification was toward the low end of the range of published values, but was reasonable given the difficult nature of separating forest classes from satellite images. Comparison of the resultant map with a more traditionally elaborated vegetation map highlights differences between the two approaches and the gain in information obtained by considering TEK classifications. We suggest that integration of TEK and remote sensing may provide alternative insights into the ecology of vegetation communities and land cover, particularly in remote and densely forested areas where ecological field research is often limited by roads and/or trail systems.

Traditional ecological knowledge (TEK) has been defined as "a cumulative body of knowledge, practice, and belief, evolving by adaptive processes and handed down through generations by cultural transmission, about the relationship of living beings (including humans) with one another and with their environment" (Berkes and others 2000). TEK is often associated with indigenous groups that retain traditional resource use practices and/or cultural beliefs.

In the last decade there has been an increased awareness of the role that indigenous peoples may play in conservation (Redford and Stearman 1993; Schwartzman and others 2000), as well as a reemergence of TEK as a scientifically acceptable means of understanding the natural world (Berkes and others 2000). This has resulted in renewed interest in the combined use of Western science and TEK as a way of increasing understanding of intertwined ecological and socioeconomic systems. Combining both types of knowledge has led to benefits or novel recommendations in a number of different research and management applications, including fisheries management in the South Pacific (Johannes 1998), nontimber forest product management in Mexico (Ticktin and Johns 2002), biodiversity in India (Gadgil and others 2000), and wildlife habitat in the Yukon (Danby and others 2003).

Recent remote sensing applications of TEK have taken a number of different forms. Most involve participatory aspects of indigenous groups and/or local communities. Counter-mapping involves the development of maps using TEK for political purposes, such as reclaiming sovereignty over natural resources or land (Herlihy and Knapp 2003). Participatory Geographic Information System (GIS) directly involves indigenous groups by encouraging data collection, analysis, and use of GIS to develop maps of resources and land cover based on their own priorities and worldviews (Robbins 2003). These approaches have evolved from simple sketching of resource boundaries, which has long been used in indigenous cartography (Herlihy and Knapp 2003). In a strict remote sensing or GIS sense, they are equivalent to the digitization of polygons from a particular source, whether through visual interpretation or collective memory/tradition.

The integration of TEK with more advanced remote sensing techniques, such as the use of multi- or hyper-

KEY WORDS: Mbaracayu; Ache; Landsat; Paraguay; Rainforest; Tribal

---

*Author to whom correspondence should be addressed; *email:* robin.naidoo@wwfus.org spectral satellite imagery in combination with supervised classifications and georeferenced, ground-truthed indigenous classifications of vegetation, has been more limited (Robbins 2003). This is particularly true for forested areas, where we could find no examples in the published literature of this type of exercise. However, forested ecosystems are precisely where TEK from indigenous groups that live inside the forest could provide significant benefits to our understanding of vegetation patterns.

Forests, especially remote tropical forests, are often highly inaccessible over large scales to ecologists and other scientists who wish to study ecological patterns and processes in the field. A more typical form of study involves the establishment of a research station on a relatively small parcel of land, followed by intensive ecological investigation within a tight radius of the station along a trail and/or river network (e.g., the Cocha Cashu research station in Manu National Park, Peru; Terborgh 1990). In contrast, nomadic or semi-nomadic native groups that have lived for generations within the forest will likely have a broader familiarity with the forest at much larger scales, although their level of detailed understanding will likely be limited to those aspects of the forest that are relevant to their own subsistence needs. The potential for Western scientific methods and TEK to complement one another in this situation is quite clear.

In the present study, we combine principles of remote sensing with the traditional ecological knowledge of a native hunter-gatherer tribe to ask the following questions:

1) Do indigenous vegetation classifications emerge as spectrally distinct classes when they are used in supervised classification of satellite imagery?
2) Can vegetation maps produced by the combination of TEK and remote sensing provide additional information as compared to maps elaborated in a more typically "scientific" manner?

Our study was conducted in the Mbaracayu Forest Reserve, eastern Paraguay, with the help of the Ache tribe, who have lived in forests of this region for many generations. Our approach used georeferenced points that were previously classified by the Ache using their own vegetation categorizations, along with remote sensing methodologies such as supervised classification of multispectral satellite imagery. We compared the resulting land cover map with an alternate scientific categorization of the vegetation in the Reserve. We show that the combined use of TEK and remote sensing results in a different view of the vegetation at Mbaracayu Forest Reserve, and discuss the benefits this can have in scientific understanding and management of the area.

Methods

Study Area

The study area was the Reserva Natural del Bosque Mbaracayu (referred to hereafter as "Mbaracayu" or "the Reserve"), a 640 km^2 protected area composed mostly of Upper Parana Atlantic Forest (Di Bitetti and others 2003). The Upper Parana Atlantic Forest ecoregion is one of WWF's Global 200 priority ecoregions for conservation (Olson and Dinerstein 1998), and is characterized by outstanding levels of biodiversity, as well as a high degree of threat to remaining forests, which are only about 7% of the original extent (Di Bitetti and others 2003).

Mbaracayu was established in 1991, and is privately managed by a Paraguayan NGO (Fundacion Moises Bertoni). However, Mbaracayu was created by a national law, and the law also states that the Ache peoples of the region can continue to use Mbaracayu for traditional activities relating to subsistence and cultural needs. Several Ache communities that have been resettled outside Mbaracayu continue to hunt, fish, and gather plants inside the Reserve (Hill and Hurtado 1996). In addition, several group members are employed as park rangers, and others have worked as field assistants for various ecological studies within the Reserve (Hill and others 1997, 2003).

The Ache

The earliest written accounts of the Ache people are found in Jesuit documents from the 1600s, although archaeological evidence suggests that groups with similar technologies and lifestyles may have been present in the forests of eastern Paraguay for several thousands of years (Hill and Hurtado 1996). Prior to contact with Western civilizations, the Ache were nomadic hunter-gatherers who permanently inhabited the forest and used a wide variety of forest resources for subsistence and cultural purposes. All groups of Ache have now been settled onto permanent reservations outside the Mbaracayu Forest Reserve (the last uncontacted group was resettled in 1978), but several groups continue to forage in the Reserve in a manner similar to their traditional use of the forest. Because of their dependence on the forest, the Ache have evolved into unparalleled trackers of wild game, and have also developed a detailed system of vegetation classification to describe the types of forest present within their hunting ranges (Hill and others 2003; Hill and Hurtado 1996).

The Ache vegetation classification system revolves around a practical designation of various forest cover types into units that reflect characteristics such as ease of travel, game abundance, and distance from water. Because of their long and intimate association with the forest environment, vegetation classes are highly nuanced, spatially explicit categorizations that can change within a matter of meters. The Ache recognize 69 different classes of vegetation, based primarily on vegetation structure, dominant species, proximity to other habitat types or geographical features (e.g., rivers, meadows), topography, and moisture. Of these, 16 appear to be more appropriately described as geographical classes, rather than vegetation classes, because they are defined primarily, if not exclusively, by geographic location (e.g., "ykmambu": on hillside going up from water).

In preliminary analyses, we attempted to classify all 53 vegetation classes that the Ache recognize, but it proved impossible to accurately classify this many categories. However, because many of the Ache vegetation classes appear similar, even to the Ache themselves, Hill and others (1997) lumped vegetation classes into seven broader categories: meadows, swamps, bamboo understory forests, thick undergrowth vine forests, low forests, high forests, and big bamboo forest (these classes are easily recognized in the field by Ache hunters and KH). They showed that these aggregated habitat types were correlated with the abundance of a number of large vertebrates preyed on by the Ache. It is these aggregate categories that were the subject of our classification using satellite imagery, and we describe them in more detail below. See Hill and others (1997, 2003) for additional details.

Meadows are naturally open, unforested areas, with few trees and a predominance of grassy vegetation. They are usually wet for at least part of the year, and are typically found in low-lying areas, often near streams or rivers.

Swamps are characterized by bushy, scrubby vegetation with few tall trees. They are usually found directly alongside streams or rivers, and may be partially flooded during the wet season.

Bamboo understory forests are forests with canopy trees 15–25 m in height, and with a thick undergrowth of *Merostachys clausseni* bamboo, which grows 1 to 3 m in height.

Thick undergrowth vine forests are medium to high forests with an abundance of lianas in the understory. Game species are generally infrequently encountered in this forest type (Hill and others 2003).

Most trees in low forests are less than 15 m high, and less than 10 cm in diameter at breast height (DBH). They are found in drier areas, and ground cover is dominated by bromeliads.

High forests are widespread throughout the Reserve, and are dominated by trees reaching heights of 25 m or greater. Ground cover is sparse, and composed of ferns, heliconias, and bromeliads (Hill and Padwe 2000).

Big bamboo forest is characterized by few trees and a predominance of *Guadua angustifolia* bamboo that can reach 10–15 m in height.

The Ache also recognize an eighth aggregate forest category called "forests near water." This category is exclusively locational and reflects proximity to a geographical feature, rather than a unique vegetation community (10 of the 16 classes earlier described as being better described as geographical classes are in this category). There is therefore little reason to expect that this aggregate category could be identified from satellite imagery based on unique spectral characteristics, and indeed preliminary analyses confirmed that we were unable to consistently distinguish points categorized as forest near water by the spectral characteristics of image pixels. In addition, the "forests near water" class was so uncommon (0.7% of all observations in our data set) that in preliminary analyses, excluding or reclassifying this category did not substantially alter the resulting vegetation map. We therefore did not consider this class in our satellite imagery analyses.

Transect Study

The transect study of Hill and collaborators from which we drew our vegetation data has been described in detail elsewhere (Hill and others 1997, 2003), and we emphasize here only the aspects that are relevant to the current study. Transects covered almost the entire area of the Reserve (Figure 1), and were conducted from 1994 to 2003 by Ache field assistants trained to record vertebrate encounters and associated vegetation. Every 200 m, five field assistants walking ~50 m apart stopped to record the forest type (i.e., one of the 69 vegetation classes the Ache recognize, as described above) in their immediate surroundings. These were then radioed back to the lead assistant in the middle position of the transect, and he recorded all data from each field assistant and also took a Global Positioning System (GPS) reading of the spot's geographic coordinates.

Our unit of analysis was each 200-m transect segment, because these were the finest-scale units that had unique spatial positions. Because only one GPS point was recorded for the five field assistants reporting every

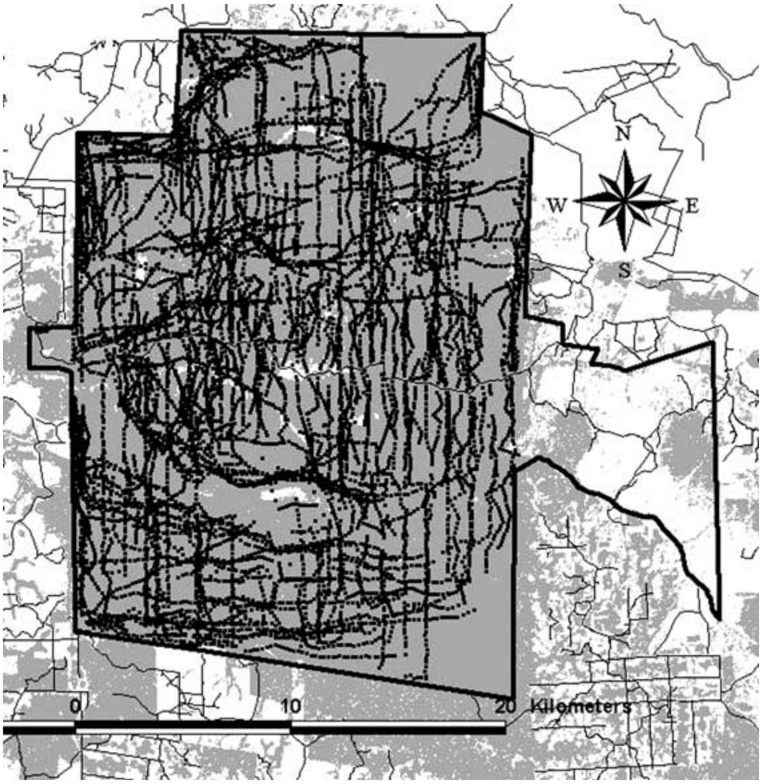

Figure 1. Mbaracayu Forest Reserve, Paraguay (delimited by heavy black borders). Gray represents forested areas, white nonforested areas. Black circles are locations of transect units from Hill and others (2003). The local road network is also shown.

200 m, it was possible for one point to have up to five different vegetation characterizations. We were interested in relating the spectral characteristics of the satellite image pixels to transect vegetation classifications, and to do so needed as reliable a signal from both data sources as possible. We therefore focused exclusively on transect units that were classified as the same vegetation type by all five Ache field assistants. We interpret these areas as containing a relatively uniform vegetation type at the level of the transect unit, although because the Ache record vegetation in their immediate vicinity and not further afield, even these transects may be heterogeneous at a scale that we cannot detect. This procedure resulted in the retention of 6129 transect units for analyses (slightly more than 50% of all transect units).

Classification Methods

We acquired a Landsat 7 TM satellite image of the Mbaracayu area from February 28, 2003; this corresponds to the end of the transect study from which our ground data are derived. The image included the standard six optical bands (30-m resolution) and one thermal band (120-m resolution), all of which we used in our analyses. The image was georeferenced using a previously georeferenced Landsat image of the study area as a reference; the average RMS error (Root Mean Square error, a measure of the accuracy of the georeferencing) was 14.9 m. We performed no atmospheric corrections on the image because of its exceptional clarity, and because we were not comparing this image to others taken at different dates and under different atmospheric conditions.

Of the 6129 transect units whose vegetation class was uniformly categorized by all five Ache field assistants, we randomly selected ~50% to be used in creating training fields for our supervised classification, with the remaining ~50% used in a post-classification accuracy assessment. The transect study of Hill and others (2003) covered only the main forested area of Mbaracayu, and therefore we did not classify the eastern cerrado extension of the Reserve (Figure 1). We delineated training fields on the Landsat image of Mbaracayu by visually inspecting color composites (a composite involving bands 1, 2, and 7, with a Gaussian stretch, was particularly useful) in combination with the homogeneous transect units selected for training. For each of the 7 vegetation classes, we created between 10 and 44 training fields, each having between 188 and 1285 pixels. The distribution of pixel values was approximately normal for each vegetation class. We used the Multispec program (Landgrebe and Biehl

2001) to classify the image, using a maximum likelihood algorithm that assigns pixels to the class for which it has the highest probability of belonging. We assigned every pixel to a class, i.e., we did not set a threshold probability below which pixels were unassigned. As is typical in supervised classification procedures, we followed an iterative procedure whereby the accuracy of preliminary classifications was evaluated, training sites updated and improved, and new maps produced, until we arrived at a final classification. We then implemented a 3 × 3 majority filter and used this filtered classification as the final product of our analyses.

We assessed the accuracy of the final classification using the set of transects units held in reserve for this purpose. The class assigned to each transect unit by the classification was compared to the class assigned by Ache field assistants, and standard measures of comparison (producer's accuracy, user's accuracy, Kappa statistic) were produced to help interpret the overall accuracy of the resultant vegetation map. We used a stratified random sampling design with 100 ground points for each category. Some categories had many more points than this in the reference set of transect units, in which case we randomly chose 100. Meadows and swamps had fewer than 100 points; therefore, we supplemented these categories by using high-resolution orthophotos (10-m resolution, taken in 1994 by Fundacion Moises Bertoni, Paraguay) to identify georeferenced points for these easily distinguished classes. The inclusion probability of each class was factored into all accuracy calculations (Stehman and Czaplewski 1998).

Using the newly classified vegetation map, we explored vegetation–topography relationships by overlaying a Digital Elevation Model (elevation and slope, source = USGS) and the local river network (derived from the 1994 orthophotos). We also compared our vegetation map derived from TEK to a recently completed vegetation map of the Mbaracayu Forest Reserve, which is a slight modification of the landform map in Burgos and Rodas (2001) (Figure 2). This map recognized 18 different vegetation–landform classes, and was based partly on vegetation characteristics and partly on soil and topographical characteristics. A couple of these classes have no parallels to our own: we did not consider cliffs as a separate vegetation category, and their cerrado category, which appears as a thin westward extension into the forest from the east, we considered to be a complex of meadows and low forest. We do not further consider these classes. The vegetation map of Burgos and Rodas (2001) is also clearly more specific with regard to open habitats; they recognize seven separate classifications of meadows, as opposed to the Ache's one aggregated class of meadows or grassland.

Advanced techniques to describe the concordance between images such as vegetation maps (Pontius and Schneider 2001) are applicable only in situations where both maps contain the same classes. This was not the case for our analyses, because the Burgos–Rodas map had 18 classes and we classified only 8 Ache categories. Therefore, to more directly compare the two vegetation maps, we calculated for each of our own categories the percent area that was covered by each of the classes in the Burgos–Rodas classification. This allowed us, in a highly simplified way, to determine which classes of the two maps overlapped and which did not. To facilitate these comparisons, we combined all meadow classes from the Burgos–Rodas classification into one category, merged the three high forest classes together, and aggregated vegetation classes representing less than 0.1% into an "other" category.

Results

Supervised classification of the seven vegetation classes resulted in an overall accuracy of 60.1% and a kappa statistic of 0.53 (Figure 3).

By calculating the number of cells classified for each category, and comparing these to the Ache's on-the-ground classifications, we can determine the accuracy with which "true cells" were classified correctly (producer's accuracy), and the accuracy with which we expect classified cells to in fact be correct (user's accuracy). Producer's accuracy ranged from 51% to 75%, whereas user's accuracy was more variable, ranging from 6.3% to 86.1% (Table 1). The user's accuracies for high forest and bamboo understory were substantially lower than the other categories, and this, along with lower producer's accuracies for the same categories, suggests some misclassifications amongst these two classes. Aggregating these two classes together would raise the producer's accuracy of the new class to 82.0%, the user's accuracy to 62.6%, and the overall accuracy of the classification to 68.4%. Nevertheless, the producer's and user's accuracies for high forest and bamboo understory are on average still roughly 2.5 times greater than would be expected by a random (1 in 7) classification of pixels, and therefore we retain both in our subsequent final classification.

High forest was the most common forest type, covering about one-third of the non-cerrado Reserve area (Table 2). Bamboo understory covered about a quarter of the area, whereas other forest types were less common, and meadows/grasslands accounted for less than

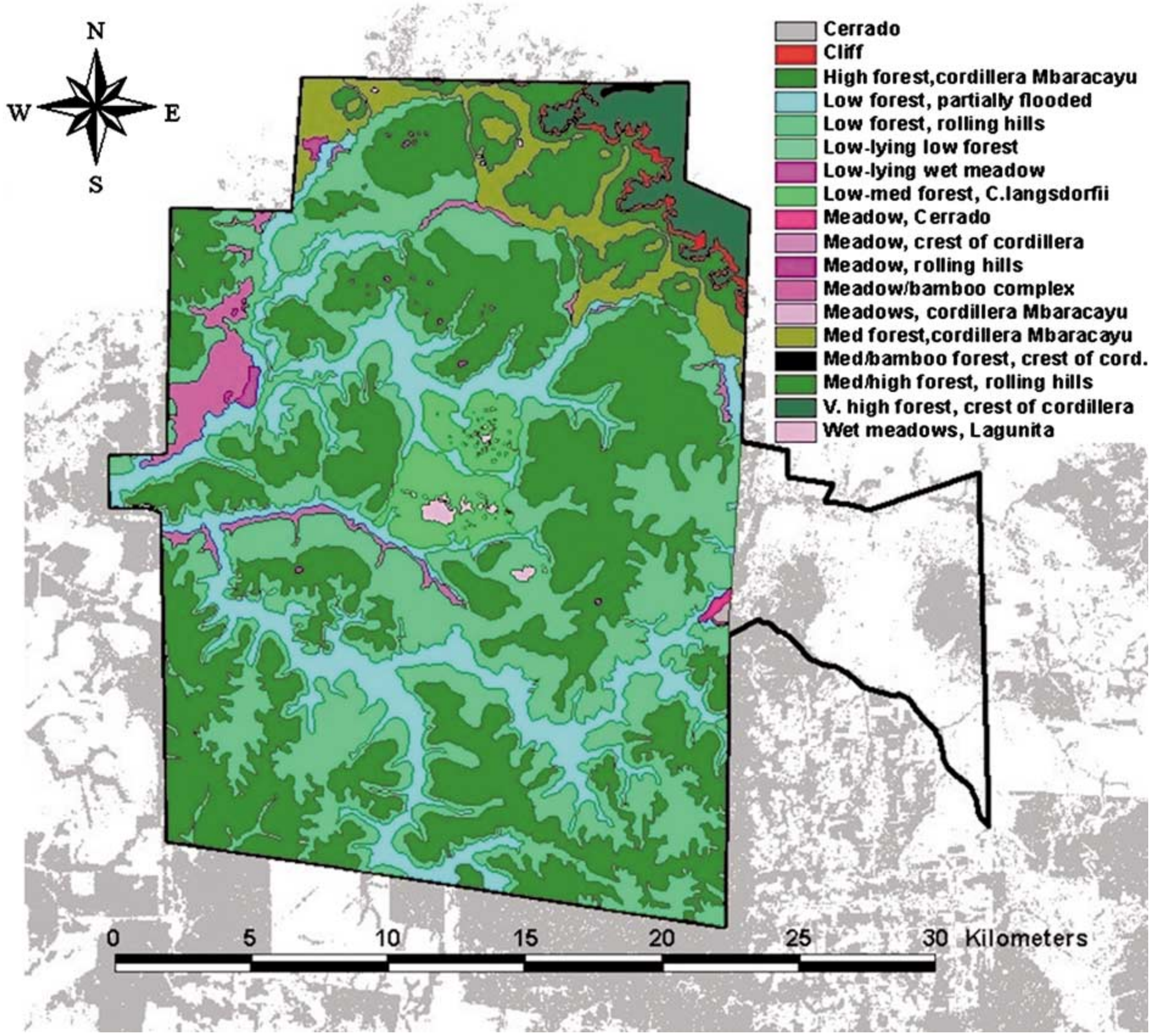

Figure 2. Vegetation map of Mbaracayu Forest Reserve, Paraguay, modified from Burgos and Rodas (2001).

2%. Ache vegetation categories appeared to be broadly correlated with topographical features (Table 2). Swamps, low forest, and meadows/grasslands were found at low elevations, vine undergrowth and big bamboo forests at high elevation, and high forest and bamboo understory forest at intermediate elevations. We used Tukey's HSD to test the significance of all pairwise combinations of vegetation classes for each of the three topographical variables in Table 2, and found that of 20 pairwise comparisons, only the elevation difference between meadows/grasslands and low forest was not statistically significant (i.e., the 95% confidence interval overlapped 0). A similar situation existed for differences in slope (17 of 21 differences were statistically significant) and distance from rivers (20 of 21 differences significant). Although the results strongly point to segregation of classes along these topographical variables, the statistical significance tests should nevertheless be interpreted with caution, because spatial autocorrelation and multiple comparison effects were not explicitly accounted for, and because the unit of observation is semiarbitrary.

The overlap analysis for our vegetation map and that of Burgos and Rodas (2001) showed that certain categories in both classifications appeared to be representing the same vegetation feature (Figure 4). For example, almost two thirds of our high forest cells were also classified as a type of high forest in the

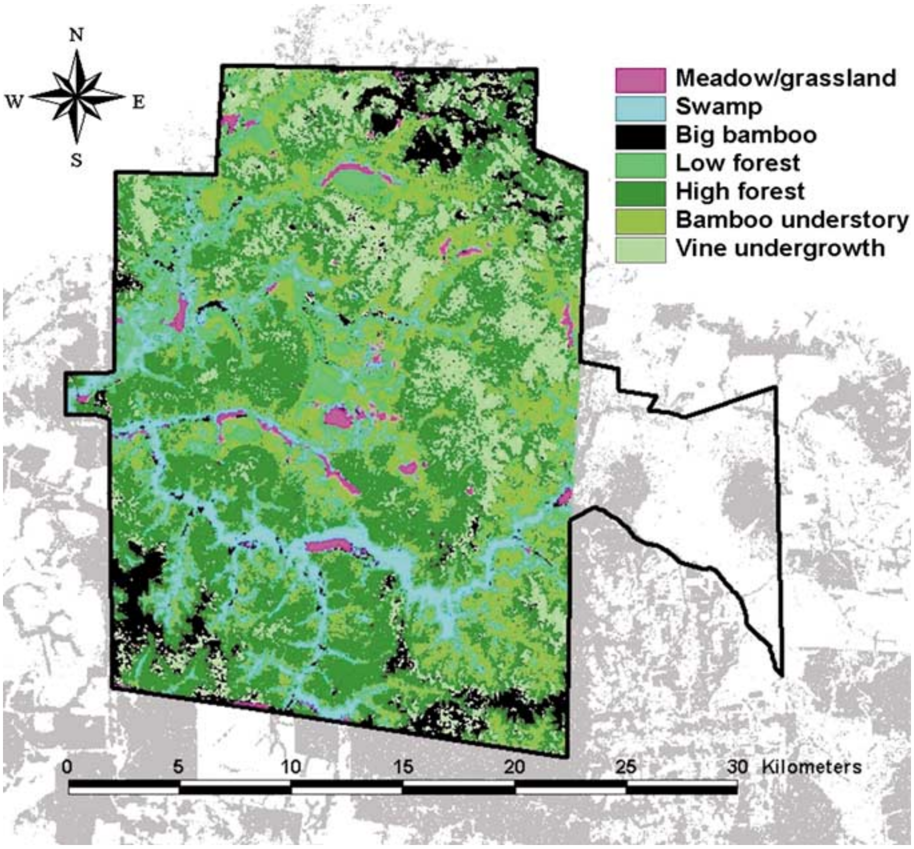

Figure 3. Results of supervised classification of vegetation at Mbaracayu Forest Reserve, Paraguay, using categorizations of the Ache tribe.

Table 1. Accuracy assessment of supervised classification of vegetation types at Mbaracayu Forest Reserve, Paraguay, using vegetation categories of the Ache (stratified random sampling design with given inclusion probabilities per stratum)

	Reference class									
Map class	Meadow / grassland	Swamp	Big bamboo	Low forest	High forest	Bamboo understory	Vine undergrowth	Total	Inclusion probabilities	User's accuracy
Meadow/grassland	75	0	0	14	2	1	1	93	1.00	83.8
Swamp	1	72	0	10	3	4	0	90	1.00	86.1
Big bamboo	1	6	51	1	3	4	3	69	0.56	74.9
Low forest	16	11	0	63	7	0	3	100	1.00	69.1
High forest	2	3	30	0	52	29	35	151	0.05	6.3
Bamboo understory	4	8	0	12	29	54	4	111	0.13	20.9
Vine undergrowth	1	0	19	0	4	8	54	86	0.29	55.4
Total	100	100	100	100	100	100	100			
Producer's accuracy	75.0	72.0	51.0	63.0	52.0	54.0	54.0			

Overall % accuracy = 60.1, kappa statistic = 0.53.

Burgos–Rodas vegetation map, whereas more than half of the swamps cells were classified as partially flooded low forest. Habitat descriptions (Hill and others 2003; Yanosky 2004) confirm that the latter two classes do represent the same type of vegetation community, although in each case a sizable minority of cells were also categorized as low forest on rolling hills.

For the other categories, however, less overlap was recorded. In the case of the meadow/grassland and low forest classes, no one category from the Burgos–Rodas classification was observed to overlap substantially. Over half the cells in our bamboo understory class were categorized in the Burgos–Rodas map as low forest on rolling hills vegetation. Finally, big bamboo

Table 2. Area and percent cover of Ache vegetation categories at Mbaracayu Forest Reserve, Paraguay, with mean levels of associated topographical features

Class	Area (ha)	Percent cover	Mean elevation (m)	Mean slope (°)	Mean dist. rivers (m)
High forest	19,037	32.7	234	3.41	566
Bamboo understory	15,079	25.9	210	3.24	408
Vine undergrowth	9,118	15.7	267	3.28	724
Swamp	5,600	9.6	181	2.55	232
Big bamboo	4,956	8.5	260	4.12	578
Low forest	3,370	5.8	198	2.76	448
Meadow/grassland	1,019	1.8	198	2.52	519
	Totals >>>		Average >>>		
	58,179	100	221	3.1	496

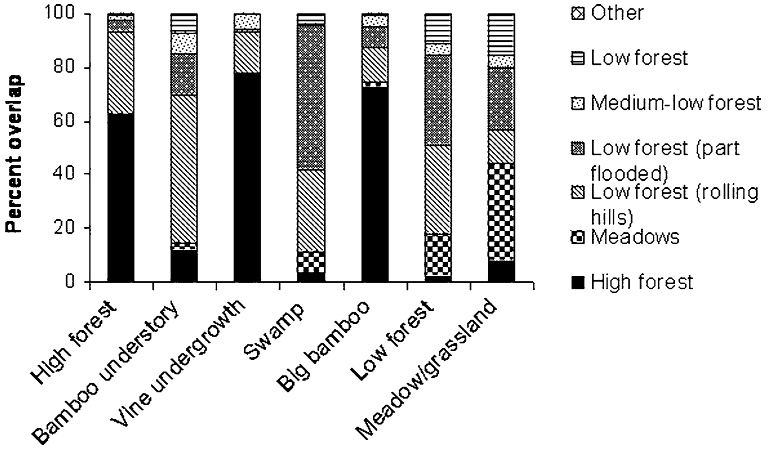

Figure 4. Percent overlap of categories of a vegetation map modified from Burgos and Rodas (2001) with Ache forest categories, for the Mbaracayu Forest Reserve, Paraguay. Ache categories on X-axis, Burgos–Rodas categories represented in bars.

and vine undergrowth forests were not explicitly represented in the Burgos–Rodas classification, and most of these areas were simply lumped as high forest (72.4% and 77.1%, respectively).

Discussion

Our study attempted to relate vegetation classifications of the Ache to satellite imagery, so that the resulting vegetation map could be assessed for possible management application. Measured accuracy for the smoothed classification was at the lower end of the range of published forest classifications containing a similar number of classes (Foody and Hill 1996; Hill 1999; Trisurat and others 2000; Roy and Joshi 2002; Powell and others 2004; Tottrup 2004). There was a high degree of variation in the producer's and user's accuracies among classes; meadows and swamps were classified reasonably well, whereas classification accuracies amongst the various types of forest were lower. In particular, a moderate degree of misclassification existed amongst high forest, bamboo understory forest, and vine undergrowth forest. One possible reason for this is that the distinction between these forest types is based primarily on characteristics of the understory, which are usually better distinguished by radar than by optical remote sensors such as Landsat (Saatchi and others 2001). In addition, the large area that a single GPS ground-truth point corresponds to within the methodology of the transect study (Hill and others 1997), the lack of differential correction of points, and the increased positional error that characterizes the use of GPS receivers under forest canopy have likely all contributed to introducing error into the classification analysis. Given these factors, it is arguably quite remarkable that the vegetation classifications used by the Ache have emerged through our remote sensing analysis as accurately as they did. The answer to our first question, "Do indigenous vegetation classifications emerge as spectrally distinct classes when they are used in supervised classification of satellite imagery?," therefore appears to be a qualified yes, with finer-scale sampling of Ache vegetation types (i.e., at scales corresponding to Landsat pixels) necessary to remove this qualification.

The aggregated vegetation classes used by the Ache appeared to be associated with differences in topography. Meadows/grasslands, swamps, and low forests were all found at lower elevations on nearly flat ground, with swamps bordering rivers very closely, and meadows and low forests also nearby. These findings are supported by anecdotal evidence of the same trends by the Ache themselves (Hill and others 1997), and reflect the combination of vegetation and geographic inputs into their forest classification scheme.

Big bamboo forests and vine undergrowth forests were both found at higher elevations, although bamboo forests were generally on steeper slopes and further away from streams or rivers. However, the distribution for bamboo forests was actually bimodal, with some such forests being very close to running water, and others very far away. This is due to the fact that there is often a significant component of bamboo to swamp vegetation, in addition to the bamboo forests associated with higher and drier areas. Both types are composed of *Guadua* species of bamboo (Yanosky 2004). High forest was found at more intermediate levels of elevation, slope, and distance from streams/rivers, and was also the most common forest type in the Reserve, as had previously been noted (Hill and Hurtado 1996).

Our vegetation map using the Ache's traditional vegetation classification system revealed notable differences when compared to the most recent vegetation map of the Reserve. Bamboo understory was the second most-common forest in the Reserve, according to our classification, accounting for 25% of the surface area. This forest type has no analog in previous classifications of the Reserve's vegetation (Burgos and Rodas 2001; Marin and others 1998), and as such represents a significant contribution of the Ache's TEK to our understanding of forest types at Mbaracayu. Vine undergrowth forests are also a "new" forest type, and big bamboo forests, although subsumed under several different forest categories in the modification of the Burgos–Rodas classification, are explicitly recognized and mapped for the first time in our classification. The fact that these classes are reasonably accurate and also correlated with measured game abundance in the Reserve (Hill and others 2003) suggests that our vegetation map may be of use in the management of vertebrate populations in Mbaracayu.

Following on this, the Burgos–Rodas map recognizes many more vegetation categories than our classification, including seven classes of meadows and nine classes of forest. These classes are distinguished amongst one another by differences in soil type and topography, not necessarily by species composition or vegetation structure (Burgos and Rodas 2001). Although we have shown that there is topographical segregation of the Ache vegetation classes, the Ache do not consider soil differences in their classifications, and their classification scheme is directly related to the use of particular forest types for Ache subsistence activities. This contrast in the way in which classes were developed highlights the fact that incorporating the way in which the Ache view the forest can lead to a different perspective on how vegetation cover is defined, classified, and managed. An additional advantage of the integration of Ache TEK with remote sensing techniques is that our use of a classification scheme based on the spectral characteristics of satellite imagery pixels, rather than more coarse-grained visual interpretation and digitizing, better represents the naturally high level of spatial heterogeneity in forest types of the Mbaracayu Forest Reserve (Hill and Padwe 2000). All in all, we argue that in answer to our second question posed in the Introduction, the vegetation map produced by combining Ache TEK and remote sensing techniques does provide additional insight into the structure and composition of Mbaracayu Forest Biosphere Reserve.

In a more general sense, this analysis highlights some of the potential benefits, in terms of mapping of forest types, that can be gained through the use of indigenous forest knowledge. Forest indigenous groups such as the Ache have lived for generations mostly or entirely off the natural resources that forests provide. The Ache are accustomed to moving through the forest without the aid of trail systems, and by doing so are able to reach many areas that field biologists do not reach, for lack of accessibility. By moving throughout the forest, and not simply in those areas that are accessible through roads and/or trails, members of the Ache tribe have literally seen the vegetation in almost every square meter of Mbaracayu Forest Reserve.

This is in contrast to published studies on the vegetation in the Reserve, where detailed botanical investigations have been conducted over transects that penetrate fewer than a kilometer or two into the forest from a road's edge (Keel and others 1993). Although such studies are of course far more scientifically detailed than the Ache's utilitarian experience with the forest, at issue is the depth of detailed ecological studies versus the breadth of indigenous everyday use. Melding both sources of information can lead to a broader understanding of the forest as a whole, a benefit that has been noted for other ecological and cultural systems (Berkes and others 2000; Forsyth 1996; Robbins 2003). In particular, we expect that combining remote sensing and indigenous vegetation classifications in forested areas where access has historically been restricted to indigenous groups, where resource needs of these groups have resulted in vegetation classifications that capture elements other than those of a Western/scientific classification and where management agencies recognize the need and importance of including TEK in developing management plans for sustainable development, will produce gains from both research and applied perspectives.

These differences in perspective also have implications for the management of forest reserves where indigenous groups live. Although botanical studies of forest community types are typically based on species composition and diversity, vegetation classifications of native groups who have depended on the forest for generations are more likely to reflect the provision of useful ecosystem goods and services (Berkes 2004). For example, major factors associated with Ache vegetation classes are the likelihood of encountering important resources such as wild game and honey, which is defined not only by the inherent capacity of habitats to support such items, but also the ease with which tribe members can move through particular forest types. In terms of sustainably managing forest reserves where traditional use occurs, using indigenous forest classifications may be more directly relevant to the setting of resource extraction and game harvesting limits.

On a related point, the Mbaracayu Forest Reserve is the core protected area of the larger Mbaracayu Forest Biosphere Reserve, a UNESCO-designated landscape of forests and agricultural areas that is supposed to be managed "sustainably." As one aspect of sustainable management (both from an ecological and Ache/cultural viewpoint), maintaining healthy populations of game species in the Biosphere Reserve depends on keeping the core protected area connected to other forests of the region, and thereby halting its increasingly quick progress towards isolation. Most of our knowledge of vertebrate ecology and their habitat requirements in this specific area of Paraguay has come from the traditional knowledge of the Ache and other local peoples (Hill and others 1997, 2003; Zuercher and others 2003). The successful classification of Ache vegetation types using remote sensing methods will now allow us to map forests of the entire Biosphere Reserve into vegetation types that have known associations with various vertebrate species (Hill and others 2003). This will allow predictions of vertebrate distributions across the whole landscape, and along with more detailed information on movement patterns that can be acquired via technical avenues such as radio and GPS collars, could be used to manage at least some aspects of the Biosphere Reserve in a sustainable and quantifiable manner.

The use of TEK in scientific research and management has been steadily increasing, but remains somewhat on the outside of conventional techniques in both ecological and conservation-oriented research, and adaptive or community-based management (Goldman 2003; Huntington 2000). We have shown here that forest categorizations by an indigenous group can emerge through a typical remote sensing application using standard principles associated with supervised classifications of satellite imagery. Such an emergence highlights the complementarity of TEK and Western scientific methods, and provides another example that the two approaches may be more compatible than has generally been assumed (Berkes and others 2000; Agrawal 1995). We encourage other researchers and managers to explore the possibility of working with native groups living in forests, because their TEK appears to be an underutilized resource in the scientific investigation and management of forested ecosystems.

Acknowledgments

We are very grateful to Felipe Jakugi, Carlos Bejyvagi, Ambrosio Bepurangi, Tito Tykuarangi, and Roberto Tykuarangi for collecting vegetation data in Mbaracayu, and for teaching KH about the Ache's system of vegetation classification. RN thanks Freddy Ramirez and Sixto Fernandez for help in the field, and the Fundacion Moises Bertoni for logistical support. Comments from Taylor Ricketts, Doug Goodin, and two anonymous reviewers improved earlier versions of the manuscript. RN was supported by a grant from the Social Sciences and Humanities Research Council of Canada, and a World Wildlife Fund Science Fellowship.

Literature Cited

Agrawal, A. 1995. Dismantling the divide between indigenous and scientific knowledge. *Development and Change* 26:413–439.

Berkes, F. 2004. Rethinking community-based conservation. *Conservation Biology* 18:621–630.

Berkes, F., J. Colding, and C. Folke. 2000. Rediscovery of traditional ecological knowledge as adaptive management. *Ecological Applications* 10:1251–1262.

Burgos, S. M., and O. Rodas. 2001. Relaciones suelo-paisaje y mapeamiento geomorfico de la Reserva Natural del Bosque Mbaracayu, Paraguay. Universidad Nacional de Pilar, Asuncion, Paraguay.

Danby, R. K., D. S. Hik, D. S. Slocombe, and A. Williams. 2003. Science and the St. Elias: an evolving framework for sustainability in North America's highest mountains. *Geographical Journal* 169:191–204.

Di Bitetti, M. S., G. Placci, and L. A. Dietz. 2003. A biodiversity vision for the Upper Parana Atlantic Forest ecoregion: designing a biodiversity conservation landscape and setting priorities for conservation action. World Wildlife Fund, Washington, D.C.

Foody, G. M., and R. A. Hill. 1996. Classification of tropical forest classes from Landsat TM data. *International Journal of Remote Sensing* 17:2353–2367.

Forsyth, T. 1996. Science, myth, and knowledge: testing Himalayan environmental degradation in Thailand. *Geoforum* 27:375–392.

Gadgil, M., P. R. Seshagiri Rao, G. Utkarsh, P. Pramod, and A. Chhatre. 2000. New meanings for old knowledge: the people's biodiversity registers program. *Ecological Applications* 10:1307–1317.

Goldman, M. 2003. Partitioned nature, privileged knowledge: community-based conservation in Tanzania. *Development and Change* 34:833–862.

Herlihy, P. H., and G. Knapp. 2003. Maps of, by, and for the peoples of Latin America. *Human Organization* 62:303–314.

Hill, K., and A. M. Hurtado. 1996. Ache life history: the ecology and demography of a foraging people. Aldine de Gruyter, New York.

Hill, K., and J. Padwe. 2000. Sustainability of Ache hunting in the Mbaracayu Reserve, Paraguay. Pages 79–105 *in* J. G. Robinson, E. L. Bennet (eds.), Hunting for sustainability in tropical forests. Columbia University Press, New York.

Hill, K., G. McMillan, and R. Farina. 2003. Hunting-related changes in game encounter rates from 1994 to 2001 in the Mbaracayu Reserve, Paraguay. *Conservation Biology* 17:1312–1323.

Hill, K., J. Padwe, C. Bejyvagi, A. Bepurangi, F. Jakugi, R. Tykuarangi, and T. Tykuarangi. 1997. Impact of hunting on large vertebrates in the Mbaracayu Reserve, Paraguay. *Conservation Biology* 11:1339–1353.

Hill, R. A. 1999. Image segmentation for tropical humid forest classification in Landsat TM data. *International Journal of Remote Sensing* 20:1039–1044.

Huntington, H. P. 2000. Using traditional ecological knowledge in science: methods and applications. *Ecological Applications* 10:1270–1274.

Johannes, R. E. 1998. The case for data-less marine resource management: examples from tropical nearshore fisheries. *Trends in Ecology and Evolution* 13:243–246.

Keel, S., A. H. Gentry, and L. Spinzi. 1993. Using vegetation analysis to facilitate the selection of conservation sites in eastern Paraguay. *Conservation Biology* 7:66–75.

Landgrebe, D., and L. Biehl. 2001. An introduction to Multispec. Purdue Research Foundation, West Lafayette, Indiana.

Marin, G., B. Jimenez, M. Pena-Chocarro, and S. Knapp. 1998. Plantas comunes de Mbaracayu: una guia de las plantas de la Reserva Natural del Bosque Mbaracayu, Paraguay. The Natural History Museum of London, London, UK.

Olson, D. M., and E. Dinerstein. 1998. The Global 200: a representation approach to conserving the earth's most biologically valuable ecoregions. *Conservation Biology* 12:502–515.

Pontius, R. G., and L. Schneider. 2001. Land-cover change model validation by an ROC method for the Ipswich watershed, Massachusetts, USA. *Agriculture, Ecosystems, and Environment* 85:239–248.

Powell, R. L., N. Matzke, C. De Souza, M. Clark, I. Numata, L. Hess, and D. A. Roberts. 2004. Sources of error in accuracy assessment of thematic land-cover maps in the Brazilian Amazon. *Remote Sensing of Environment* 90:221–234.

Redford, K. H., and A. M. Stearman. 1993. Forest-dwelling native Amazonians and the conservation of biodiversity: interests in common or collision. *Conservation Biology* 7:248–255.

Robbins, P. 2003. Beyond ground truth: GIS and the environmental knowledge of herders, professional foresters, and other traditional communities. *Human Ecology* 31:233–253.

Roy, P. S., and P. K. Joshi. 2002. Forest cover assessment in north-east India—the potential of temporal wide swath satellite sensor data (IRS-1C WiFS). *International Journal of Remote Sensing* 23:4881–4896.

Saatchi, S., D. Agosti, K. Alger, J. Delabie, and J. Musinsky. 2001. Examining fragmentation and loss of primary forest in the southern Bahian Atlantic forest of Brazil with radar imagery. *Conservation Biology* 15:867–875.

Schwartzman, S., A. Moreira, and D. Nepstad. 2000. Rethinking tropical forest conservation: perils in parks. *Conservation Biology* 14:1351–1357.

Stehman, S. V., and R. L. Czaplewski. 1998. Design and analysis for thematic map accuracy assessment: fundamental principles. *Remote Sensing of Environment* 64:331–344.

Terborgh, J. 1990. An overview of research at Cocha Cashu Biological Station. Pages 48–59 *in* A. H. Gentry (ed.), Four neotropical rainforests. Yale University Press, New Haven.

Ticktin, T., and T. Johns. 2002. Chinanteco management of Aechmea magdalenae: implications for the use of TEK and TRM in management plans. *Economic Botany* 56:177–191.

Tottrup, C. 2004. Improving tropical forest mapping using multi-date Landsat TM data and pre-classification image smoothing. *International Journal of Remote Sensing* 25:717–730.

Trisurat, Y., A. Eiumnoh, S. Murai, M. Z. Hussain, and R. P. Shrestha. 2000. Improvement of tropical vegetation mapping using a remote sensing technique: a case of Khao Yai National Park, Thailand. *International Journal of Remote Sensing* 21:2031–2042.

Yanosky, A. 2004. Actualizacion de la evaluacion ecologica rapida de la Reserva Natural del Bosque Mbaracayu. Fundacion Moises Bertoni, Asuncion, Paraguay.

Zuercher, G. L., P. S. Gipson, and G. C. Stewart. 2003. Identification of carnivore feces by local peoples and molecular analyses. *Wildlife Society Bulletin* 31:961–970.