Caribbean Journal of Science, Vol. 38, No. 3-4, 165–183, 2002

Mapping the Forest Type and Land Cover of Puerto Rico, a Component of the Caribbean Biodiversity Hotspot

E. H. HELMER, O. RAMOS, T. DEL M. LÓPEZ, M. QUIÑONES, AND W. DIAZ

International Institute of Tropical Forestry, USDA Forest Service, P.O. Box 25000, Río Piedras, Puerto Rico 00928, USA. ehelmer@fs.fed.us

ABSTRACT.—**The Caribbean is one of the world's centers of biodiversity and endemism. As in similar regions, many of its islands have complex topography, climate and soils, and ecological zones change over small areas. A segmented, supervised classification approach using Landsat TM imagery enabled us to develop the most detailed island-wide map of Puerto Rico's extremely complex natural vegetation cover. Many Caribbean forest formations that are not spectrally distinct had distributions approximately separable using climatic zone, geology, elevation, and rainfall. Classification accuracy of 26 land cover and woody vegetation classes was 71 % overall and 83 % after combining forest successional stages within image mapping zones. In 1991-92, Puerto Rico had about 364,000 ha of closed forest, which covered 41.6 % of the main island. Unlike previous island-wide mapping, this map better identifies the spatial distributions of forest formations where certain groups of endemic species occur. Approximately 5 % of Puerto Rico's forest area is under protection, but the reserve system grossly underrepresents lowland moist, seasonal evergreen forests.**

INTRODUCTION

Mapping the distributions of vegetation types and human land uses provides critical information for managing landscapes to sustain their biodiversity and the structure and function of their ecosystems. Because vegetation type can link to species composition or habitat types, vegetation maps provide crucial information for biodiversity conservation planning. Spatially explicit inventories of vegetation types and land cover permit comparisons between particular vegetation distributions and distributions of land cover, land-cover change, expected climate changes, and protected areas. Although the interpretation of satellite imagery is useful for mapping vegetation type (Scott et al., 1993, Muchoney et al., 2000), it poses important challenges to mapping vegetation in regions with complex topography and climate.

This study focuses on satellite-image based mapping and related challenges for the complex Caribbean island of Puerto Rico. The subject requires attention because tropical areas with complex topography are particularly important for biodiversity conservation. Such tropical mountainous areas comprised 11 of 25 "biodiversity hotspots" identified by Myers et al. (2000) after evaluating species endemism and habitat loss caused by human disturbance. Seven hotspots included or consisted of complex tropical islands. In fact, "almost all tropical islands fall into one or another hotspot" (Myers et al., 2000), because high species endemism combines with proportionally extensive habitat loss. The Caribbean region is one of the "hottest hotspots," where 11.3 % of the region's original primary vegetation contains 2.3 and 2.9 % of the world's endemic plants and vertebrates, respectively (Myers et al., 2000). Unfortunately, "lack of species and ecosystem inventory data currently hinders development of biodiversity conservation strategies, which are needed at a time of intense development pressures" (Oldfield and Sheppard, 1997). Addressing this problem requires overcoming the remote sensing and mapping challenges that occur in the Carribbean, where diverse biotic, climatic, and topographic conditions combine to produce a landscape with varied vegetation communities.

Mapping natural vegetation and land

use with satellite imagery in complex tropical areas is difficult. First, ecological zones and illumination angles change over small areas, leading to spectral confusion in which varied vegetation communities have similar spectral signatures. Second, the ranges of forest successional stages produced by human disturbance compound spectral confusion (Helmer et al., 2000), but their distinction is important for evaluating ecosystem processes. Third, persistent cloud cover often requires combining satellite images from different dates, thus further complicating image-based mapping.

A final challenge to mapping tropical island vegetation is that spatial scale and class resolution become critical. The spatial and class resolutions of recent global and sub-continental ecoregion and land-cover maps (e.g. Dinnerstein et al., 1995; Hansen et al., 2000; Loveland et al., 2000) are too coarse for biodiversity conservation on tropical islands. For example, while mapping ecological zones of Latin America and the Caribbean, Dinnerstein et al. (1995) grouped over 10 major Puerto Rican ecological zones into two: moist and dry forests. In Puerto Rico, generalizing forest types extends the apparent distribution of endemic species with narrow distributions. For example, the vegetation of serpentine soils includes many endemic species (e.g,. Garcia, 1991; Cedeño-Maldonado and Breckon, 1996). Existing global- or subcontinental-scale maps of Caribbean vegetation zones or land cover do not recognize these areas as distinct.

The most recent land-cover map of Puerto Rico is based on aerial photos taken in 1977 and 1978 (Ramos and Lugo, 1994). The map includes mangrove forests plus four cover-based woody vegetation classes. The U.S. National Atlas map of forest cover types (USDA and USGS, 2001) used this data set for Puerto Rico and groups those cover classes into just one: tropical broadleaf evergreen forest.

Previous maps for the island have not depicted land cover in conjunction with forest type beyond cover-based classes. However, ecological zonation systems have defined potential distributions of vegetation type. Published diagrams of zonation systems include Puerto Rico Forest Regions (Little and Wadsworth, 1964) and Vegetation Zones (Dansereau, 1966). Published maps of ecological zones available in a geographic information system (GIS) include Holdridge life zones (Holdridge 1967; Ewel and Whitmore, 1973) and Holdridge life zones superimposed on generalized geology (Figueroa Colón, 1996). In addition, Areces-Mallea et al. (1999) categorized insular Caribbean vegetation types for conservation efforts based on US Federal Geographic Data Committee (FGDC, 1997) standards. In this hierarchical system, life form and percent cover define vegetation classes, leaf phenology defines subclasses, and leaf morphology defines groups within subclasses. Groups contain formations, and within formations there are floristically defined levels of alliance and association. Although some physiognomic factors may define vegetation formations, most formations are groups of vegetation units broadly defined by environmental factors, including disturbance (FGDC, 1997).

The objectives of our study were to 1) develop and evaluate a practical approach to satellite-image based mapping of forest type and land cover for Puerto Rico, in a way that simultaneously addresses forest succession, and 2) illustrate the usefulness of the resulting map through comparing the island-wide protected extents of the forest formations mapped.

Materials and Methods

Study area

Puerto Rico's land area is approximately 8900 km^2. From northeast to southwest, in the direction of the trade winds, coastal semi-deciduous forests occur in bands and patches along the north and east coasts. As three major cordilleras force moisture-carrying trade winds to higher altitudes, moist, submontane and lower montane wet and rain forests occur, including cloud forest formations. In the southern and westerly directions, rainfall decreases in the rain shadow of major cordilleras, resulting in moist followed by increasingly drier forest formations. The largest climatic zone includes moist broadleaf evergreen forest. Forests have developed over alluvial, sedimentary, volcanic, limestone, and serpentine substrates.

Summary of Approach

We used the vegetation type classification given by Areces-Mallea et al (1999). First, we hierarchically related its woody vegetation types to environmental factor-based ecological zones and rainfall. This step enabled us to identify satellite-image mapping zones that corresponded with groups of woody formations and land cover and that were necessary for mapping forest successional stages (Helmer et al., 2000). Reference observations of these woody vegetation formations and land cover provided data for building separate discriminant function models that classified satellite imagery from each mapping zone. This approach limited labeling of woody vegetation to one of a pre-determined group of 2 to 5 formations within the boundaries imposed by the ancillary data for each image mapping zone. Because forest formations were usually distinguishable in aerial photos, however, a randomized accuracy assessment permitted estimation of errors including those that this limitation introduced. A summary of protected extents of forest formations also evaluated whether the image segmentation approach usefully mapped the complex vegetation formations on the island.

Vegetation classification system

In seeking a vegetation classification system appropriate to the island-wide scale of our analysis, and that would use Landsat imagery, we adapted the hierarchical vegetation classification system of Areces-Mallea et al. (1999). Since resources were inadequate to collect sufficient field-derived reference observations to map floristically-defined vegetation types, we sought to map woody vegetation to its formation level. Aerial photos could support reference data for formation-level mapping. Environmental factors, including disturbance, largely define these formations, and most defining environmental factors were directly or indirectly identifiable in aerial photos and often in satellite imagery. The formations in Areces-Mallea et al. (1999) related hierarchically to a simplification of Figueroa Colon's (1996) GIS overlay of life zone (Holdridge, 1967; Ewel and Whitmore, 1973) and generalized geology (Krushensky, 1995) (Table 1). Aggregating the geoclimatic zones within a GIS resulted in the satellite-image mapping zones in Figure 1, which would help overcome the mapping challenge of spectral confusion between vegetation formations and land covers with similar spectral signatures. Mapping to the formation level also allowed us to add environmentally-defined formations that Areces-Mallea et al. (1999) did not include, such as serpentine formations and two forest successional stages for several geoclimatic conditions. Moreover, its hierarchical structure permitted later assignment of each class to the more general classification systems used in the global Forest Resources Assessment (FRA) (FAO, 1996, 1998) and Global Observation of Forest Cover (GOFC) programs (GOFC Design Team, 1999).

We aggregated Figueroa Colon's geoclimatic zones, as detailed in Table 1, if they contained the same group of forest formations and land covers. For example, sedimentary-moist, intrusive-volcanic, and extrusive-volcanic moist zones formed one image mapping zone because they contained mainly seasonal evergreen forest formations and similar land uses. We also aggregated wet, rain, and lower montane wet and rain forest zones on alluvial, sedimentary, and volcanic substrate under the assumption that satellite imagery plus digital elevation data could more precisely delineate the distributions of cloud forest formations. Modifications to the geoclimatic zones included subsetting by rainfall (using Calvesbert, 1970) the moist zone on karst substrate in the northwest. Most of the northern karst vegetation falls in the moist life zone, but forest vegetation gradually dries toward the coast to the point where semi-deciduous forest dominates karst substrates instead of the semi-deciduous and seasonal evergreen mosaic of more humid

TABLE 1. Satellite image mapping zones for Puerto Rico and associated woody vegetation formations.

Satellite image mapping zone[1,2]	Woody vegetation formations[2]
Dry forest—Alluvial	Lowland dry semi-deciduous forest or woodland/shrubland
	Tidally and semi-permanently flooded evergreen sclerophyllous forest
Dry forest[3]—Volcanic, Sedimentary, Limestone	Lowland dry semi-deciduous forest or woodland/shrubland
	Lowland dry mixed evergreen drought-deciduous shrubland with succulents
Dry and moist forest—Serpentine	Lowland dry and moist, mixed seasonal evergreen sclerophyllous forest with succulents
Moist forest—Alluvial	Lowland moist evergreen hemi-sclerophyllous shrubland
	Lowland moist seasonal evergreen forest or forest/shrub
	Lowland moist coconut palm forest
	Seasonally flooded evergreen forest
	Tidally and semi-permanently flooded evergreen sclerophyllous forest
Moist forest—Volcanic and Sedimentary	Lowland moist seasonal evergreen forest or forest/shrub
	Lowland moist semi deciduous forest[4]
Moist forest with rainfall <1500 mm yr^{-1}—Northern Limestone[5]	Lowland moist semi-deciduous forest or forest/shrub
Moist forest with rainfall >1500 mm yr^{-1}—Northern Limestone[5]	Lowland moist and wet, seasonal evergreen and semi-deciduous forest or forest/shrub
Wet and lower montane wet forest—Serpentine	Submontane and lower montane wet evergreen sclerophyllous forest or forest/shrub[6]
Wet and rain forest, lower montane wet and rain forest—Volcanic, Sedimentary and Alluvial	Submontane wet evergreen forest
	Active sun/shade coffee, submontane/lower montane wet evergreen forest/shrub, other agriculture
	Submontane/lower montane wet evergreen forest/shrub, active/abandoned shade coffee
	Lower montane wet evergreen forest[7]—tall cloud forest
	Lower montane wet evergreen forest[7]—palm and elfin cloud forest
	Lower montane wet evergreen forest—elfin cloud forest

[1]Aggregated from Geoclimatic Zones in Figueoa Colón (1996), which overlay Holdridge life zones (Ewel and Whitmore 1973) onto generalized geology (Krushensky, unpubl.). Volcanic refers to intrusive/plutonic and extrusive/volcanoclastic geology.

[2]Forests are subtropical *sensu* Holdridge (1967) and broadleaf unless otherwise indicated; lowland refers to forests from 0 to 400 m elevation. Both forest/shrub and woodland/shrubland refer to stands with a) 25-60% cover of trees with distinct canopies and an under story of shrubs, seedlings or saplings, or b) dense shrubs, seedlings or saplings, as indicated by a matrix of woody vegetation or a smooth canopy.

[3]The Dry-Volcanic/Sedimentary/Limestone Zone included southern limestone areas in the drier part of the moist forest zone.

[4]Coastal areas in southeastern Puerto Rico.

[5]Northern Limestone refers to limestone areas north of the Central Cordillera with well-developed karst topography and areas at the Cordillera's southern edge.

[6]Includes forest in the rain forest zone *sensu* Holdridge (1967).

[7]Includes forest in the lower montane rain forest zone *sensu* Holdridge (1967).

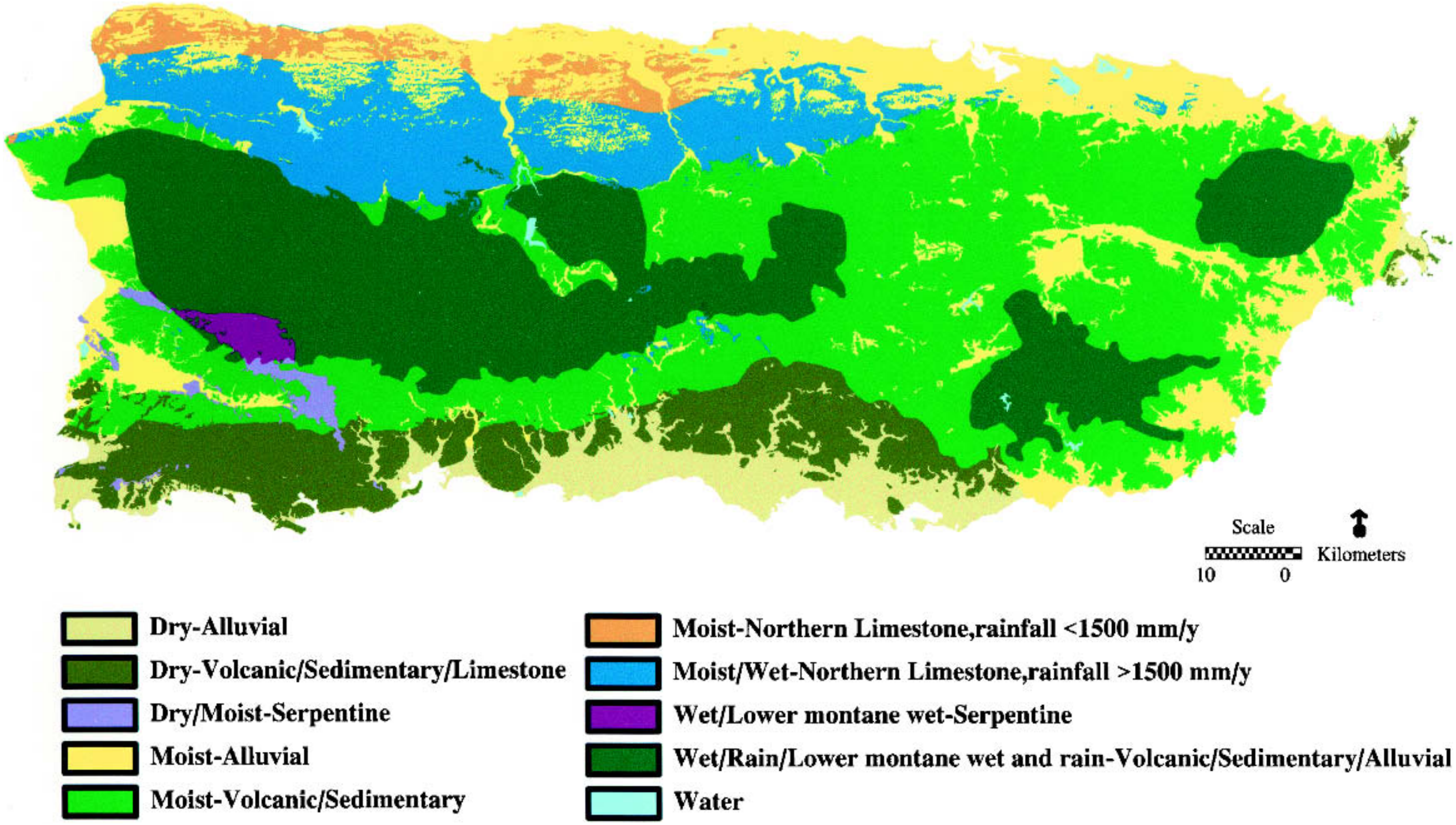

FIG. 1. Satellite image mapping zones used for segmenting classification.

TABLE 2. Relationships between woody vegetation formations mapped in this study, formations in Areces-Mallea et al. (1999), forest zones in Dansereau (1966), and forest regions in Little and Wadsworth (1964).

Woody vegetation formation, this study	Woody vegetation formation, Areces-Mallea et al. (1999)[1]	Vegetation zone[2] Dansereau (1966)	Forest region[3] Little and Wadsworth (1964)
Forest and shrubland—Dry and Dry/Moist			
Lowland dry semi-deciduous forest or woodland/shrubland[4]	Lowland semi-deciduous woodland; Lowland and Lowland/submontane drought-deciduous woodland	SDF	DCF, DLF
Lowland dry mixed evergreen drough-deciduous shrubland with succulents[4]	Mixed evergreen drought-deciduous shrubland with succulents	SDF	DLF
Lowland dry and moist, mixed seasonal evergreen sclerophyllous forest with succulents[5]	—	SDF	LCF
Forest and shrubland—Moist and Moist/Wet			
Lowland moist seasonal evergreen forest or forest/shrub[6]	Lowland seasonal evergreen forest	RF	MCF, (low elev. LCF, LLF)
Lowland moist semi-deciduous forest or forest/shrub	Lowland semi-deciduous forest; Evergreen shrubland	SEF, HSC, LRF	MLF, MCF
Lowland moist coconut palm forest	Lowland seasonal evergreen forest developed from *Cocos nucifera* woodland plantation	RF	MCF
Lowland moist evergreen hemi-sclerophyllous shrubland	Evergreen hemi-sclerophyllous shrubland	LIT	MCF
Lowland moist and wet, seasonal evergreen and semi-deciduous forest or forest/shrub[7]	Lowland semi-deciduous forest; Lowland seasonal evergreen forest; Evergreen shrubland	SDF, HSC	MLF
Forest—Wet, Rain, Lower montane Wet/Rain			
Submontane and lower montane wet evergreen sclerophyllous forest with succulents[8]	—	LMRF, MF	LCF

[1]Formations based in part on Dansereau (1966), and all are broadleaved unless otherwise indicated. Forest/shrub formations would be termed as disturbed (Areces-Mallea, pers. comm.). Dash (—) indicates formations not in Areces-Mallea et al. (1999).

[2]LIT—Littoral, RF—Lowland rainforest, SEF—Seasonal evergreen forest, HSC—Hill scrub, SDF—Semi-deciduous forest, LMRF—Lower montane rainforest, MF—Montane forest, MSC—Montane scrub.

[3]MCF—Moist coastal forest, MLF—Moist limestone forest, DCF—Dry coastal forest, DLF—Dry limestone forest, LCF—Lower cordillera forest, UCF—Upper cordillera forest, LLF—Lower Luquillo forest, ULF—Upper Luquillo forest.

[4]Also see Murphy et al. (1995).

[5]Also see Garcia (1991) and Ewel and Whitmore (1973).

[6]Also see Aide et al. (1996), and Chinea (2002).

[7]Also see Chinea (1980), and Rivera and Aide (1998).

[8]Also see Caminero Rodriguez (1991), Cedeño-Maldonado (1997), Cedeño-Maldonado and Breckon (1996), and Ewel and Whitmore (1973).

[9]Also see Ewel and Whitmore (1973), Scatena and Lugo (1995).

[10]Also see Weaver (1995).

TABLE 2. Continued.

Woody vegetation formation, this study	Woody vegetation formation, Areces-Mallea et al. (1999)[1]	Vegetation zone[2] Dansereau (1966)	Forest region[3] Little and Wadsworth (1964)
Submontane evergreen wet and rain forest[9]	Submontane rainforest	LMRF	LLF, LCF
Active/abandoned sun and shade coffee; submontane/ lower montane wet forest/ shrub; other agriculture[9]	*Inga vera-Erythrina poeppigiana/ Cafea arabica* forest; commercial plantations	LMRF, MF	LLF, ULF LCF, UCF
Lower montane wet evergreen forest—tall cloud forest[10]	Montane rainforest	MF	ULF, UCF
Lower montane wet evergreen forest—palm and elfin cloud forest[10]	Montane rainforest (palm); Cloud forest (elfin); Evergreen shrubland (highest peaks)	MF, MSC	ULF, UCF
Forest—Flooded			
Tidally and semi-permanently flooded evergreen sclerophyllous forest (Mangrove)	Tidally (Mangrove) and semi-permanently flooded evergreen sclerophyllous forest	LIT	DCF, MCF
Seasonally flooded evergreen forest (*Pterocarpus officinalis*)	Seasonally flooded rainforest (*Pterocarpus officinalis*)	LIT	MCF

[1]Formations based in part on Dansereau (1966), and all are broadleaved unless otherwise indicated. Forest/shrub formations would be termed as disturbed (Areces-Mallea, pers. comm.). Dash (—) indicates formations not in Areces-Mallea et al. (1999).

[2]LIT—Littoral, RF—Lowland rainforest, SEF—Seasonal evergreen forest, HSC—Hill scrub, SDF—Semi-deciduous forest, LMRF—Lower montane rainforest, MF—Montane forest, MSC—Montane scrub.

[3]MCF—Moist coastal forest, MLF—Moist limestone forest, DCF—Dry coastal forest, DLF—Dry limestone forest, LCF—Lower cordillera forest, UCF—Upper cordillera forest, LLF—Lower Luquillo forest, ULF—Upper Luquillo forest.

[4]Also see Murphy et al. (1995).

[5]Also see Garcia (1991) and Ewel and Whitmore (1973).

[6]Also see Aide et al. (1996), and Chinea (2002).

[7]Also see Chinea (1980), and Rivera and Aide (1998).

[8]Also see Caminero Rodriguez (1991), Cedeño-Maldonado (1997), Cedeño-Maldonado and Breckon (1996), and Ewel and Whitmore (1973).

[9]Also see Ewel and Whitmore (1973), Scatena and Lugo (1995).

[10]Also see Weaver (1995).

regions. We have seen no attempt to map this feature of the landscape. A second modification was extending the dry semi-deciduous zone in the southeast to include areas east of Guyama (based on Little and Wadsworth, 1964).

As mentioned above, we added five woody vegetation formations that structurally defined a second, younger forest successional stage, within all but the dry/ moist serpentine and alluvial satellite-image mapping zones. Disturbance timing and intensity drive these younger formations. We defined these stands as having either 25-60 % cover of trees with crowns visibly distinct in aerial photos that co-dominate with shorter woody vegetation, or young, dense stands of shrubs, seedlings or saplings (as indicated by a continuous but smooth canopy with more than approximately 40 % cover). Different stand structures within this range are difficult to distinguish in satellite imagery because their spectral signatures are often similar (Foody et al., 1996; Steininger, 1996; Helmer et al., 2000). We used the term forest/shrub (or woodland/shrubland within the dry mapping zones) to identify these formations. For example, we termed younger stands in moist zones as lowland moist seasonal evergreen forest/shrub. By contrast, stands with more than 60 % cover of trees with canopies distinct in aerial photos were termed lowland moist seasonal evergreen forest. Although the FGDC system classifies woody vegetation with 25-60 % tree canopy cover as woodland, we used the term forest/shrub for younger stands in humid zones because 1) shrub species can co-dominate with tree species, and 2) most stands will develop closed canopies. For dry forests we used the term woodland/shrubland for stands with structures similar to those described for forest/shrub; we felt that this term described more appropriately the structural range of younger stands in the dry region because grazing or burning can maintain the zone's woody vegetation in a relatively open or shrub-dominated state.

We added Holdridge life zones to formation names because they played an important role in defining woody vegetation formations. Following Areces-Mallea et al. (1999), we also added the term lowland to formations occurring in the Holdridge basal altitudinal zone (basal is not usually included in life zone names), and we added the term submontane to formations occurring in wet life zones. To facilitate interpretation of the woody vegetation formations listed in Table 1, we related them to those in Areces-Mallea et al. (1999) and to two ecologial zonation systems for the island (Table 2). For floristic information on these formations, readers should consult Areces-Mallea et al. (1999) and the bibliography they used to build their classification. In addition, Little and Wadsworth (1964) compare Upper Cordillera with Upper Luquillo forest (Table 2). Floristic information for the formations that we added, which Areces-Mallea et al. (1999) do not describe, is available from Chinea (1980), Aide et al. (1996), Rivera and Aide (1998), and Chinea (2002) for moist and wet secondary forests over limestone and volcanic substrates. Garcia (1991), Caminero-Rodriguez (1991), Cedeño-Maldonado and Breckon (1996), Cedeño-Maldonado (1997), and Ewel and Whitmore (1973) contain additional information on forests developed over serpentine substrates.

Image data

We used Landsat TM imagery dated 7 February 1991, 24 December 1991 (both Path 4/Rows 47-48), and 19 August 1992 (Path 5/Rows 47-48). Georeferencing included terrain correction and pixel resampling to 30 m resolution. Transforming all images to the TM Tasseled Cap brightness, greenness, and wetness indices (Crist et al., 1986) enhanced visual interpretation of the imagery because these bands have ecologically meaningful interpretations, can be viewed in three-dimensional color space, and minimize topographic effects (Cohen et al., 1995). They derive from a guided principle components analysis that condenses the six visible bands in Landsat TM imagery into three bands. Furthermore, Helmer et al. (2000) showed that the TM wetness band enhances distinction of tropical forest successional stage in complex tropical regions. Reference data derived from photo-interpreting NASA high definition Aerochrome-IR photos (scale 1:32,000; dated January and February of 1991) and from field visits made in 1999 and 2000.

Segmented approach to image interpretation

Geographic data ancillary to satellite imagery alleviates spectral confusion when mapping natural vegetation types (Strahler, 1981; Skidmore, 1989; Ma et al., 2001), land cover (Vogelmann et al., 1998), or forest successional stage (Helmer, 2000). We chose a segmented approach to image interpretation to help overcome the challenge of similar spectral signatures among different vegetation formations and land cover. In addition, work in montane Costa Rica had indicated that information on ecological zones would benefit efforts to address forest successional stages. After collecting reference observations for each image mapping zone, we segmented Landsat TM scenes into the image mapping zones in Fig. 1, and we separately built and applied within each mapping zone a discriminant function model that assigned a woody vegetation formation or land cover to each of the satellite image pixels within that zone (commonly referred to as a supervised maximum likelihood classification). This approach limited labeling of woody vegetation formation within each zone to one of the major formations within that zone

(Table 1). Digital elevation data with 30-m resolution (Gesh et al., 2002) served as a fourth data band in the image mapping zone combining submontane with lower montane zones.

We made many reconnaissance surveys during 1999-2000, before the development of reference observations (i.e., training data for building satellite image classification models). These surveys and extensive consultation with experts on Puerto Rico's forest vegetation (John Francis, J. Danilo Chinea, Juan Ramirez, Julio Figueroa-Colón, Sandra Molina, Ariel Lugo, and Fred Scatena) enabled us to recognize various forest formations in the aerial photos. Forest formations were usually clearly distinguishable in the photos, and often also in the satellite imagery, because their geology, canopy texture, color tone, and other attributes were recognizable. Exceptions occurred in transitional areas between lowland moist seasonal evergreen forest and submontane wet evergreen forest, and in transitional areas between lowland dry/moist semi-deciduous forest and lowland moist seasonal evergreen forest. Field surveys frequently focused on these transitional areas.

Training data for building satellite image classification models derived from aerial photos and from our reconnaissance surveys. They consisted of 70-100 aerial photo-derived point observations for woody vegetation formation and land cover within each zone. Training data included high-density urban areas, sunlit greened-up pasture, sunlit senescent pasture, shadowed pasture, and sunlit and shadowed woody vegetation formations within each zone. For example, in the higher elevation image mapping zone, we collected separate sets of reference data for submontane wet evergreen forest, three classes of lower montane wet (cloud) forest, and two spectral classes that represented mixtures of coffee cultivation (*Coffea* sp.) and submontane and lower montane wet forest/shrub. We did not include training data for coffee cultivation in moist areas because currently it is not extensive there. Another example is the moist alluvial zone, in which training data distinguished between lowland moist seasonal evergreen forest, mangrove, seasonally flooded forest dominated by swamp bloodwood (*Pterocarpus officinallis*), and abandoned closed-forest coconut palm plantations. Except for dry zones, pastures included urban grasslands and could have up to 25 % tree cover or about 40 % shrub cover as long as they were apparently active (as indicated by a matrix of grass). Grass-dominated lands with up to about 25 % tree cover are generally difficult to reliably distinguish in satellite imagery from grass-dominated areas with no trees. In the dry zones, pastures with up to 60 % woody vegetation cover can still be active but are indistinct in aerial photos and satellite imagery from recovering vegetation. Consequently, the forest formation of lowland dry semi-deciduous woodland/shrubland includes pastures, which still likely undergo grazing, that have 25-60 % woody vegetation cover (Table 1).

Manual editing and interpretation

Another challenge in mapping complex tropical areas is that the spectral signatures of several agriculture classes are often similar to forest or urban areas. This occurred in Puerto Rico even after segmenting the imagery. Consequently, we manually interpreted the satellite imagery (using aerial photos as a guide) for sugar cane, plantain, banana, mango, and citrus plantations. Similar manual interpretation included recently burned and bare agricultural fields, which were spectrally similar to urban and bulldozed areas; emergent wetlands, which had highly variable spectral signatures; coconut palm plantations; and pineapple plantations. Manual recoding was also necessary for scattered moist semi-deciduous forest stands along the southeast coast and for confusion between urban and pasture areas. In the dry forest zone, we manually corrected for confusion between pasture with less than 25 % tree or shrub cover and mixed drought-deciduous shrubland with succulents. Finally, we manually interpreted the few stands of lowland moist hemi-sclerophyllous shrubland that were large enough to be clearly visible in the imagery. The manually interpreted agriculture formed less than 6 % of the total area mapped, while all other manually interpreted or recoded areas combined formed 1.6 % of the total mapped area.

Cloudy areas

Clouds cause difficulties in satellite-image based mapping of complex tropical areas. We used unsupervised clustering to separate clouds, cloud shadows, and water from the remainder of each Landsat TM scene. Successive reclustering of confused classes, followed by combining subclasses of these elements, produced contiguous areas of clouds and cloud shadows. We then filtered contiguous groups of less than 11 pixels, which usually did not represent cloud elements or water (ERDAS, 1999). Adding a 5-pixel buffer around the remaining contiguous cloud elements allowed masking of cloud and cloud shadow edges that remained confused with non-cloud elements.

Following separate classifications of the image mapping zones in each eastern Puerto Rico scene, cloud-free portions of the classified February scene replaced cloud-covered areas in the December scene. Subsequent mosaics of image mapping zones and scenes resulted in an island-wide map. For remaining areas of cloud elements in the imagery (less than 5 % of the total map area), we overlaid data from the 1977-78 land-cover map (Ramos and Lugo, 1994) that we reclassified to the land-cover and natural vegetation classes mapped for 1991-92. Reclassification by the geoclimatic zones that we used to segment the image classification enabled us to translate into forest formations the forest and shrub classes from the 1977-78 data. High- and medium-density canopy forests were reclassified to forest, while forest with low-density canopy cover and shrub were reclassified to forest/shrub or woodland/shrubland. Agriculture in the wet image mapping zone in the west became the mixed class that included coffee, wet evergreen forest/shrub, and other agriculture (the data did not distinguish between different types of coffee cultivation).

Accuracy Assessment

The 1991 NASA aerial photos were most suitable for accuracy assessment because the large study area relative to staff resources made reliance on field data impractical (Zhu et al. 2000). Another advantage of using aerial photos was that accessibility would not affect the probability of an observation's selection. Finally, the satellite imagery was dated 1991-92 and the project took place between 1999 and 2001. Consequently, field-based accuracy assessment was problematic for estimating accuracy of land cover, because some land-cover changes could have occurred.

A random sample of over 250 9-pixel clusters (3 by 3 pixel groups), stratified by the class of each cluster's center pixel, provided data for accuracy assessment. The accuracy assessment included manually interpreted or recoded classes. Locating clusters in the original satellite imagery facilitated their identification in aerial photos. We photo-interpreted the woody vegetation formation or land-cover class of each pixel within each cluster, recording the predominant as well as other classes that mixed pixels apparently reflected. Using these observations, we estimated the overall percentage of correctly classified observations, the user's and producer's accuracy for forest formations and land cover, and the Kappa coefficient (Landis and Koch, 1977), which measures accuracy that accounts for chance agreement between classes in an error matrix. Producer's accuracy is the proportion of correctly-classified accuracy assessment observations, while user's accuracy estimates the proportional assignment of pixels to a correct class.

Forest formation was not always distinct in aerial photos of transitional areas between, for example, moist seasonal evergreen and wet evergreen forest. Where photo interpretation or our knowledge of transitional areas was insufficient to identify forest formation, we recorded the most likely forest formation and noted the transition type. Staff resources were insufficient to field-check the 5 % of accuracy assessment observations located in transitional areas between forest formations.

Global forest cover classification systems

To facilitate using the data in global-scale forest cover evaluations, we identified the class of each forest formation for two classification systems used in global forest monitoring efforts: the GOFC (GOFC Design Team, 1999) and FRA systems (FAO, 1996, 1998) (Table 3). The GOFC system classifies upland forest according to four variables: leaf type (needle leaf, broadleaf, mixed), leaf longevity (evergreen, deciduous, mixed), canopy cover (10-25 %, 25-40 %, 40-60 %, 60-100 %), and canopy height (0-1 m low shrub, 1-2 m tall shrub, >2 m trees). This system recognizes flooded forest as a separate class.

For the GOFC system, we classified Puerto Rico's moist and dry broadleaf semi-deciduous forests as broadleaf mixed forests. We distinguished semi-deciduous forest from the mosaic of semi-deciduous and evergreen forests that occur in the karst area. We also grouped each forest/shrub class with its corresponding forest formation because the forest/shrub areas generally have over 60 % total woody vegetation cover.

In the FAO (1998) system, natural closed forest has tree cover in the various understories and under growth of over 40 % and does not have a continuous dense grass layer. Although our forest/shrub had tree cover of 25-60 %, it does not have a continuous grass layer and its canopy could reach at least 5 m on maturity, so it is classifiable as closed forest. Most forest/shrub is not forest fallow because shifting cultivation is not significant in Puerto Rico. Because the woodland/shrubland formation includes some open forest or tree/shrub mixtures with a grass layer, we disaggregated it to 70 % closed forest, 10 % open forest, and 20 % shrubs ("other wooded land"). Using our accuracy assessment data, we disaggregated the two forest/shrub/coffee classes to 40 % agriculture (active sun/shade coffee and other agriculture) and 60 % closed forest (formerly forest/shrub) for the first class, and 80 % closed forest (forest/shrub, abandoned shade coffee and forest) with 20 % agriculture (active coffee shade) for the second class. We based our estimates of total closed forest and coffee agriculture areas on these disaggregation percentages.

Summary of protected woody vegetation by formation

To illustrate the usefulness of the forest formation and land-cover map that resulted from satellite image interpretation, we quantified island-wide protected extent of each forest formation. A simple GIS summary (ERDAS, 1999), which overlaid forest formation with a digital map of protected areas (Dragoni, 2002), output the aerial extent of each forest formation within Federal, Commonwealth, or private reserve land.

RESULTS

Mapping forest type and land cover in Puerto Rico

We mapped 21 forest formations plus land cover (Fig. 2) and estimate that Puerto Rico (plus the islands of Icacos and Piñero) had about 364,000 ha of closed forest in 1991-92, which composed 41.6 % of its land area (Table 3). The second most abundant land cover was pasture and grassland (36.7 % of the land). Agriculture and coffee agriculture composed 5.9 % and 2.4 % of the area, respectively, and 10.5 % of the land reflected urban and developed land cover. Remaining land covers each compose <1 % of the island area.

The spatial resolution of Landsat TM was generally adequate for mapping Carribbean-island woody vegetation formations. Exceptions included some upland coastal formations too narrow to be distinct in the imagery. The Puerto Rico map includes only a few stands of one coastal shrubland formation that we manually interpreted because it mainly occurs in narrow, coastal bands. The spatial resolution of Landsat TM also contributed to difficulty resolving elfin from palm cloud forests where patches were no more than a few

TABLE 3. Forest type, land cover, protected areas and proportions, and forest class for two global classification schemes (GOFC and FAO) for the islands of Puerto Rico, Icacos and Piñero. Numbers identify classes in Appendix A. Total area of closed forest was about 363,650 ha, or 41.6% of the main island's area. Total shrubland area (OW) was 5,734 ha.

No. in Apdx A	Formation and Land Cover	Area (ha)	Protected (ha)	Protected (%)[7]	GOFC[1]	FAO[2]
	Forest and shrubland—Dry and Dry/Moist					
1	Lowland dry semi-deciduous forest[3]	16,342	1,248	7.6	4	CF
2	Lowland dry semi-deciduous woodland/shrubland[3]	22,957	2,044	8.9	3	Mix[4]
3	Lowland dry mixed evergreen drought-deciduous shrubland with succulents	1,052	250	23.8	6	OW
4	Lowland dry and moist, mixed seasonal evergreen sclerophyllous forest with succulents	3,535	1,527	43.2	1	CF
	Forest and shrubland—Moist and Moist/Wet					
—	Lowland moist evergreen hemisclerophyllous shrubland	90	45	49.8	2	OW
5	Lowland moist seasonal evergreen forest	55,383	1,093	2.0	6	CF
6	Lowland moist seasonal evergreen forest/shrub	68,348	393	0.6	6	CF
7	Lowland moist coconut palm forest	448	77	17.2	6	CF
8	Lowland moist semi-deciduous forest	5,130	423	8.2	4	CF
9	Lowland moist semi-deciduous forest/shrub	2,081	99	4.8	4	CF
10	Lowland moist and wet, seasonal evergreen and semi-deciduous forest	25,872	2,933	11.3	5	CF
11	Lowland moist and wet, seasonal evergreen and semi-deciduous forest/shrub	26,411	857	3.2	5	CF
	Forest—Wet, Rain, Lower montane Wet/Rain					
12	Submontane and lower montane wet evergreen sclerophyllous forest	3,064	2.453	80.1	6	CF
13	Submontane and lower montane wet evergreen sclerophyllous forest/shrub	1,956	1,109	56.7	6	CF
14	Submontane wet evergreen forest	49,790	6,027	12.1	6	CF
15	Active sun and shade coffee, submontane and lower montane wet forest/shrub, agriculture	26,879	521	1.9	6	Mix[5]
15	Submontane and lower montane wet evergreen forest/shrub, active/abandoned shade coffee	51,926	1,173	2.3	6	Mix[6]
16	Lower montane wet evergreen forest—tall cloud forest	21,299	9,530	44.7	6	CF
17	Lower montane wet evergreen forest—palm and elfin cloud forest	3,051	2,082	68.2	6	CF
17	Lower montane wet evergreen forest—elfin cloud forest	1,104	626	56.7	6	CF
	Forest—Flooded					
18	Tidally/semi-permanently flooded evergreen sclerophyllous forest[3]	6,838	2,709	39.6	7	CF
19	Seasonally flooded rainforest	319	202	63.3	7	CF

[1]GOFC classes: 1) Broadleaf evergreen tall shrub, 10-40%; 2) Broadleaf evergreen tall shrub, 60-100%; 3) Broadleaf mixed tree, 25-40%; 4) Broadleaf mixed tree, 60-100%; 5) Broadleaf evergreen and mixed mosaic tree, 60-100%; 6) Broadleaf evergreen tree, 60-100%; 7) Flooded forest.

[2]FAO classes: OW—Other wooded land (shrubs); OF—Open forest; CF—Closed forest; AG—Cultivated land.

[3]Includes Icacos island, which contains 44 ha of class 1, and 5 ha of class 21, and Piñero Island, which contains 49 ha of class 1, 11 ha of class 2, 45 ha of class 18, and 14 ha of class 22.

[4]Disaggregate: 70% CF, 10% OF, 20% OW.

[5]Disaggregate: 40% AG, 60% CF (16,127 ha), based on proportions of sub-types in accuracy data: 17% active sun coffee, 17% and 7% active and abandoned shade coffee, 48% forest/shrub).

[6]Disaggregate: 20% AG, 80% CF (41,541 ha), based on proportions of sub-types in accuracy data: 2% active sun coffee, 13% and 9% active and abandoned shade coffee, 49% forest/shrub, 20% forest).

[7]Percent protected for combining classes 1 and 2-18.4%, classes 5 and 6-1.2%, classes 8 and 9-7.2%, classes 10 and 11-7.2%, classes 12 and 13-63%, and classes 14 and 15-6.0%.

TABLE 3. Continued.

No. in Apdx A	Formation and Land Cover	Area (ha)	Protected (ha)	Protected (%)[7]	GOFC[1]	FAO[2]
	Emergent Wetlands, Agriculture and Non-vegetated					
20	Tidally flooded evergreen dwarf-shrubland and forb vegetation	52	0	0.9	—	—
21	Other emergent wetlands (includes seasonally flooded pasture)	5,798	1,187	20.5	—	—
26	Salt and mud flats	533	276	51.9		
22	Pasture/grass	321,011	3,451	—	—	—
23	Agriculture/hay/pasture	51,607	703	—	—	—
24	Urban and bare	91,799	1,013	—	—	—
25	Sand and rock	2,422	366	15.1	—	—
26	Quarries and salt mining	249	44	—	—	—
—	Water	6,348	1,379	21.7		

[1]GOFC classes: 1) Broadleaf evergreen tall shrub, 10-40%; 2) Broadleaf evergreen tall shrub, 60-100%; 3) Broadleaf mixed tree, 25-40%; 4) Broadleaf mixed tree, 60-100%; 5) Broadleaf evergreen and mixed mosaic tree, 60-100%; 6) Broadleaf evergreen tree, 60-100%; 7) Flooded forest.

[2]FAO classes: OW—Other wooded land (shrubs); OF—Open forest; CF—Closed forest; AG—Cultivated land.

[3]Includes Icacos island, which contains 44 ha of class 1, and 5 ha of class 21, and Piñero Island, which contains 49 ha of class 1, 11 ha of class 2, 45 ha of class 18, and 14 ha of class 22.

[4]Disaggregate: 70% CF, 10% OF, 20% OW.

[5]Disaggregate: 40% AG, 60% CF (16,127 ha), based on proportions of sub-types in accuracy data: 17% active sun coffee, 17% and 7% active and abandoned shade coffee, 48% forest/shrub).

[6]Disaggregate: 20% AG, 80% CF (41,541 ha), based on proportions of sub-types in accuracy data: 2% active sun coffee, 13% and 9% active and abandoned shade coffee, 49% forest/shrub, 20% forest).

[7]Percent protected for combining classes 1 and 2-18.4%, classes 5 and 6-12%, classes 8 and 9-7.2%, classes 10 and 11-7.2%, classes 12 and 13-63%, and classes 14 and 15-6.0%.

pixels wide. Also, in more humid parts of the northwest karst zone, semi-deciduous forest occurs on the sides and tops of the steep and narrowly dissected limestone hills (haystack hills, *mogotes*). However, seasonal evergreen forest occurs in the closely spaced valleys between these hills. We called these areas "seasonal evergreen and semi-deciduous forest." While geology distinguished this mosaic of two forest formations, Landsat TM seemed too coarse to resolve the two formations. Additional woody vegetation formations that occurred in patches smaller than a few pixels, and that were impractical to map using Landsat TM imagery, included sinkhole swamp forests, cactus scrub (Areces-Mallea et al., 1999), and gallery forest in the dry/moist serpentine zone.

Accuracy assessment yielded a kappa coefficient of agreement of 0.69 ± 0.01 (Appendix A), which indicates substantial agreement (Landis and Koch, 1977). This kappa value estimates agreement after combining all manually defined agriculture and hay/pasture into one class, called agriculture/hay/pasture, because their separate classification accuracies were low, and considered observations classified to agriculture/hay/pasture when labeled pasture in reference data. We attribute low accuracy estimates for these classes to differences between photo interpreters. Many areas of former sugar cane and pineapple are gradually shifting to hay or pasture, which causes difficulty in interpretation. In addition, for the above kappa estimate we combined the mixed palm and elfin forest class with the elfin forest class. The proportion of correctly-classified reference observations (producer's accuracy) was low for urban/bare areas (Appendix A). We believe the source of this error was mixed pixels, because removing such pixels from a separately calculated error analysis increased producer's accuracy to 79 %. Many mixed urban-green vegetation pixels mapped to pasture.

The major error source in woody vegetation formation derived from confusion be-

Fig. 2 live 4/C

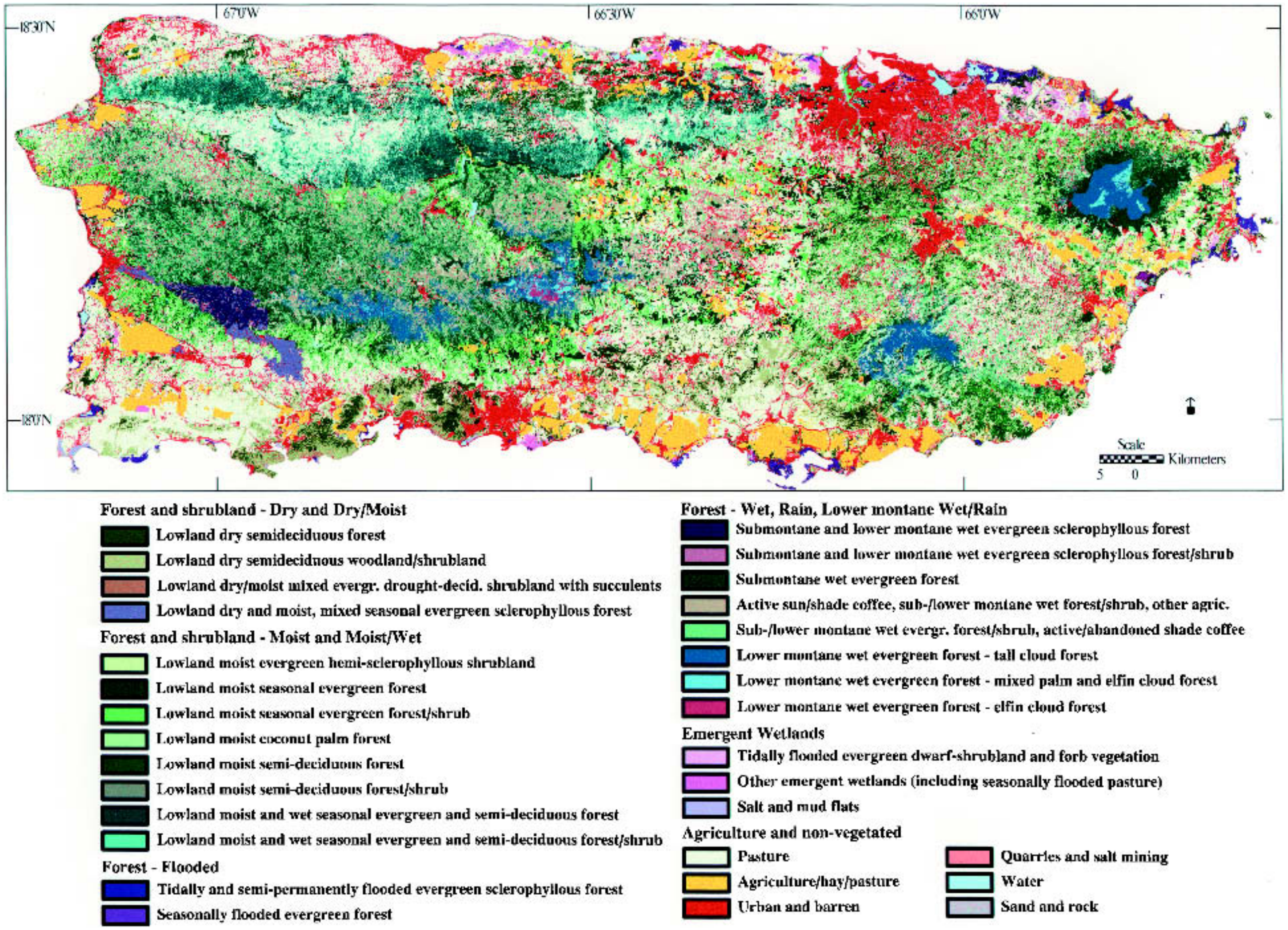

FIG. 2. Map of Puerto Rico natural vegetation and land cover.

tween forest successional stages within the same ecological zone. Combining forest with forest/shrub or woodland/shrubland within each image mapping zone significantly improved agreement to a kappa coefficient of 0.79 ± 0.01; for forest formations, it also yielded user's and producer's accuracies between 62 % and 92 %. Additional error derived from confusion between adjacent forest formations, such as confusion between lowland moist seasonal evergreen and submontane wet evergreen forest, and misclassification as pasture of some recovering or previously little disturbed shrub vegetation on limestone hilltops. Spectral signatures similar to pasture apparently reflected poor soils, where potential biomass accumulation or recovery rates are low. We also noted confusion between pasture and the higher-elevation mixed class that included active sun/shade coffee, submontane/lower montane wet forest/shrub, and other agriculture.

Protection of Puerto Rico's forest formations

Protection of natural vegetation formations ranges from about 0.6-2 % for lowland moist, seasonal evergreen forest formations (not including abandoned coconut palm plantations), to 56.7-80.0 % for submontane and lower montane wet evergreen sclerophyllous forest formations on serpentine substrates. Percentages of protected forest were lowest for moist seasonal evergreen forest formations. The extensive woody vegetation mosaic of active and abandoned shade coffee and forest/shrub has a protected proportion of 1.9-2.3 %. The overall protected proportion of Puerto Rico, Icacos and Piñero is about 5.2 %, including Federal, Commonwealth and private reserve lands.

Discussion

Approach to image interpretation

Our approach to satellite-image based mapping of land cover and forest type addressed several related challenges in complex tropical areas. A major challenge is complex topography and geology, its associated variation in vegetation formations, and the resulting spectral confusion between vegetation types. First, separating reference observations into sunlit vs. shadowed slopes likely improved land cover distinction (Helmer et al., 2000). Second, segmenting the image interpretation helped overcome the problem of spectral confusion among land covers and forest types; for example, the segmented approach allowed distinction between dry semi-deciduous woody formations and young forest or pasture occurring in wetter zones. Incorporating geology into the image mapping zones separated the unique forest formations developed on serpentine and karst substrates. Submontane wet evergreen forests on serpentine, for example, would have otherwise been confused with tidally flooded forested wetlands. Rainfall identified areas where limestone hill vegetation becomes mostly lowland moist semi-deciduous forest or forest/shrub, as opposed to a mosaic with seasonal evergreen forest. Third, adding an elevation band to the submontane-lower montane image mapping zone allowed distinction between cloud forest formations vs. disturbed forest at lower elevations, and dense-canopied submontane vs. lower montane wet cloud forests. The accuracy assessment results helped to validate our segmented approach to mapping forest formation, but they also indicated that mapping of forest successional stages was less reliable. Finally, manually delineating some agriculture relieved its confusion with forest or urban areas.

With regard to challenges of spatial scale and class resolution, mapping floristically-defined forest communities, remnant old-growth forest, or certain forest types that occur in patches smaller than a few pixels, would require more field surveys and could benefit from imagery with finer spatial resolution than Landsat TM.

The segmented approach permitted mapping forest formations simultaneously with land cover. Unlike previous island-wide mapping, this map better identifies the spatial distributions of forest formations where certain groups of endemic species occur. Previous work has mapped ecological zones or land cover plus cover-based woody vegetation classes and mangrove. Although distinguishing forest successional stages was less successful, the map resulting from the approach presents the most detailed picture to date of Puerto Rico's natural vegetation and land cover. A drawback of our approach is that the image mapping zones not only segmented our classification, but also defined the extents of some formations and therefore could only approximate the boundaries between them. The resulting visible and even boundaries between zones could more realistically depict patchy ecotone shifts in forest formation. The approach also resulted in misclassification of coffee cultivation that extended into moist forest zones (see Appendix A). Integrating spectral data with continuous climate and elevation data using machine-learning algorithms (e.g. Muchoney et al., 2000), along with incorporating more extensive field-derived reference observations from transitional areas, could yield maps that more realistically depict patchy and uneven transitions between forest formations.

Protection of natural vegetation in Puerto Rico

Our detailed vegetation map identified an uneven distribution of reserve areas across forest formations. It indicates that only 1.2 % of lowland moist seasonal evergreen forest or forest/shrub are protected (Table 3). Generally, these forests occur at lower elevations where rates of land-cover conversion to urban and developed lands are highest (López et al., 2001). Some forest types in Puerto Rico are well-protected, including 45 to 68 % of cloud forest types and 43 to 80 % of the sclerophyllous forests that develop on serpentine substrates (Table 3). However, quarries in serpentine areas occur immediately adjacent to reserve areas and therefore require monitoring. Extensive wetland draining and forested wetland clearing has occurred for agriculture or other uses (Lugo and Brown, 1988). Excluding riparian wetlands, about 20 % to 63 % of remaining forested or non-forested wetlands receive protection (Table 3).

Acknowledgments.—This research was funded in part by a U.S. National Aeronautics and Space Administration - Institutional Research Award to the University of Puerto Rico (Grant NAG8-1709, UPR Subcontract 2000-000946). We thank Richard Webb and John Parks, U.S. Geological Survey-Puerto Rico; Carmen Santiago, U.S. Natural Resources Conservation Service-Puerto Rico; NASA Global Observation of Forest Cover program; Alexis Dragoni, DNER; two anonymous reviewers and the editor, and John Francis, Alberto Areces-Mallea, J. Danilo Chinea, Julio Figueroa, Ariel Lugo, Sandra Molina, Juan Ramirez, Fred Scatena, Alberto Rodríguez and Ivan Viscens, for guidance on Puerto Rico's natural vegetation.

Literature Cited

Aide, T. M., J. K. Zimmerman, M. Rosario, and H. Marcano. 1996. Forest recovery in abandoned cattle pastures along an elevational gradient in northeastern Puerto Rico. For. Ecol. Manage. 28: 537-548.

Areces-Mallea, A., et al. 1999 (active January 2002). A guide to Caribbean vegetation types: classification systems and descriptions. N. Panagopoulos (Ed.), The Nature Conservancy International Headquarters, Washington, D.C., 166 pp. http://edcsnw3.cr.usgs.gov/ip/tnc/

Calvesbert, R. J. 1970. Climate of Puerto Rico and the U.S. Virgin Islands. Climatology of the United States No. 60-52. U.S. Department of Commerce, 29 pp.

Caminero-Rodríguez, G. 1991. Estudio de la vegetación en afloraciones de serpentinita en el Bosque Estatal de Maricao, Puerto Rico. M.S. Thesis, University of Puerto Rico, Mayagüez, Puerto Rico. 118 pp.

Cedeño-Maldonado, J. A. 1997. Vascular flora of the Rio Maricao watershed Maricao Commonwealth Forest, Maricao, Puerto Rico. M.S. Thesis, University of Puerto Rico, Mayagüez, Puerto Rico. 157 pp.

Cedeño-Maldonado, J. A. and G. J. Breckon. 1996. Serpentine endemism in the flora of Puerto Rico. Carib. J. Sci. 32:348-356.

Chinea, J. D. 1980. The forest vegetation of limestone hills of northern Puerto Rico. M.S. Thesis Cornell University. Ithaca, New York., 70 pp.

Chinea, J.D. 2002. Tropical forest succession on abandoned farms in the Humacao Municipality of eastern Puerto Rico. For. Ecol. Manage. 167:195-207.

Cohen, W. B., T. A. Spies, and M. Fiorella. 1995. Estimating the age and structure of forests in a multiownership landscape of western Oregon, U.S.A. Int. J. Rem. Sens. 16:721-746.

Crist, E. P., R. Laurin, and R. A. Cicone. 1986. Vegetation and soils information contained in transformed thematic mapper data. Proceedings, IGARSS '86 Symposium, Zürich, Switzerland, 8-11 September 1986, pp. 1465-1470. ESA SP-254, Paris.

Dansereau, P. 1966. Studies on the vegetation of Puerto Rico. 1. Description and integration of the plant-communities. Institute of Caribbean Science, Mayagüez, Puerto Rico, Special Publication 1:1-45.

Dinnerstein, E. D. et al. 1995. A conservation assessment of the terrestrial ecoregions of Latin America and the Caribbean. The World Bank, Washington, D.C. 129 pp.

Dragoni, A. 2002. Digital map of protected areas of Puerto Rico. Puerto Rico Department of Natural and Environmental Resources, San Juan, Puerto Rico.

ERDAS, Inc. 1999. Earth Resource Data Analysis System Field Guide, Fifth Edition. ERDAS, Inc., Atlanta, Georgia, 672 pp.

Ewel, J. J. and J. L. Whitmore. 1973. The ecological life zones of Puerto Rico and the U.S. Virgin Islands. USDA For. Ser. Res. Pap. No. ITF-18, Inst. Trop. For., 72 pp.

FAO. 1996. Forest resources assessment 1990, survey of tropical forest cover and study of change processes. FAO Forestry Paper 130, Rome, Italy, 152 pp.

FAO. 1998. FRA 2000: Guidelines for assessments in tropical and sub-tropical countries. FAO working paper No. 2, Rome, Italy, 45 pp.

FGDC. 1997 (active January 2002). National vegetation classification standard. Vegetation Subcommittee, Federal Geographic Data Committee, FGDC-STD-005, June 1997, U.S. Geological Survey, Reston, Virginia, 58 pp. http://biology.usgs.gov/fgdc.veg/

Figueroa Colón, J. 1996. Geoclimatic regions of Puerto Rico (map). U.S. Dept. Interior Geol. Surv. Water Res. Div. San Juan, Puerto Rico.

Foody, G. M., G. Palubinskas, R. M. Lucas, P. J. Curran, and M. Honzak. 1996. Identifying terrestrial carbon sinks: classification of successional stages in regenerating tropical forest from Landsat TM Data. Remote Sens. Environ. 55:205-216.

Garcia, G. R. 1991. Relaciones taxonómicas entre la flora endémica de serpentina en Susúa, Puerto Rico y Río Piedras, Gaspar Hernández, Repúlica Dominicana. M.S. Thesis, University of Puerto Rico, Mayagüez, Puerto Rico, 137 pp.

Gesch, D. et al. 2002. The national elevation dataset. Photogramm. Eng. Rem. S. 68:5-11.

GOFC Design Team. 1999 (active January 2002). A Strategy for Global Observation of Forest Cover, Draft for comments, Version 1.2, January 4, 1999, http://www.gofc.org/gofc/docs/docs.html

Hansen, M. C., R. S. Defries, J. R. G. Townshend and R. Sohlberg. 2000. Global land cover classification at 1 km spatial resolution using a classification tree approach. Int. J. Rem. Sens. 21:1331-1364.

Helmer, E.H. 2000. The landscape ecology of secondary forest in montane Costa Rica. Ecosystems 3:98-114.

Helmer, E. H., W.B. Cohen and S. Brown. 2000. Mapping montane tropical forest successional stage and land use with multi-date Landsat imagery. Int. J. Rem. Sens. 21:2163-2183.

Holdridge, L. R. 1967. Life zone ecology. Tropical Science Center, San Jose, Costa Rica. 206 pp.

Krushensky, R.D. 1995. Generalized geology map of Puerto Rico. U.S. Geol. Sur., San Juan, Puerto Rico.

Landis, J. R. and G. C. Koch. 1977. The measurement of observer agreement for categorical data. Biometrics 33:159-174.

Little, E. L. and F. H. Wadsworth. 1964. Common trees of Puerto Rico and the Virgin Islands. USDA Forest Service Handbook No. 249, Washington, D.C., 548 pp.

López, T. del M., T. M. Aide and J. R. Thomlinson. 2001. Urban expansion and the loss of prime agricultural lands in Puerto Rico. Ambio 30:49-54.

Loveland, T. R., et al. 2000. Development of a global land cover characteristics database and IGBP DISCover from 1 km AVHRR data. Int. J. Rem. Sens. 21:1303-1330.

Lugo, A. E. and S. Brown. 1988. The wetlands of Caribbean islands. Acta Cient. 2:48-61.

Ma, Z., M. M. Hart and R. L. Redmond. 2001. Mapping vegetation across large geographic areas: integration of remote sensing and GIS to classify multisource data. Photogramm. Eng. Rem. S. 67:295-307.

Muchoney, D., et al. 2000. Application of the MODIS global supervised classification model to vegetation and land cover mapping of Central America. Int. J. Rem. Sens. 21:1115-1138.

Murphy, P. G., A. E. Lugo, A. J. Murphy and D. C. Nepstad. 1995. The dry forests of Puerto Rico's south coast. In: A. E. Lugo and C. Lowe, C. (eds.) Tropical forests: management and ecology. Ecol. Stud. 112:178-209.

Myers, N. R. A. Mittermeier, C. G. Mittermeier, G. A. B. da Fonseca, and J. Ke. 2000. Biodiversity hotspots for conservation priorities. Nature 403: 853–858.

Oldfield, S., and C. Sheppard. 1997. Conservation of biodiversity and research needs in the UK dependent territories. J. Appl. Ecol. 34:1111-1121.

Ramos, O. M. and A. E. Lugo. 1994. Mapa de la vegetación de Puerto Rico. Acta Cient. 8:63-66.

Rivera, L.W. and T. M. Aide. 1998. Forest recovery in the karst region of Puerto Rico. For. Ecol. Manage. 108:63-75.

Scatena, S. N. and A. E. Lugo. 1995. Geomorphology, disturbance, and the soil and vegetation of two subtropical wet steepland watersheds of Puerto Rico. Geomorph. 13:199-213.

Scott, J.M., et al. 1993. Gap analysis: a geographic approach to protection of biological diversity. Wild. Monogr. No. 123. Suppl., J. Wildl. Manage. 57:1-41.

Skidmore, A. K. 1989. An expert system classifies eucalypt forest types using thematic mapper data and a digital terrain model. Photogramm. Eng. Rem. S. 55:1449-1464.

Stehman, S. V. and R. L. Czaplewski. 1998. Design and analysis for thematic map accuracy assessment: fundamental principles. Rem. Sens. Environ. 64: 331-344.

Steininger, M. K. 1996. Tropical secondary forest regrowth in the Amazon: age, area and change estimation with Thematic Mapper data. Int. J. Rem. Sens. 17:9-27.

Strahler, A. H. 1981. Stratification of natural vegetation for forest and rangeland inventory using Landsat imagery and collateral data. Int. J. Rem. Sens. 2:15-41.

USDA Forest Service and US Geological Survey. 2001 (active May 2002). Forest cover types of the United States. National Atlas of the United States, http://nationalatlas.gov/atlasftp.html.

Vogelmann, J. E., T. Sohl and S. M. Howard. 1998. Regional characterization of land cover using multiple sources of data. Photogramm. Eng. Rem. S. 64:45-57.

Weaver, P. L. 1995. The colorado and dwarf forests of Puerto Rico's Luquillo Mountains. In A. E. Lugo, and C. Lowe (Eds.) Tropical forests: management and ecology. Ecol. Stud. 112:109-141.

Zhu, Z., L. Yang, S. V. Stehman and R. L. Czaplewski. 2000. Accuracy assessment of the U.S. Geological Survey regional land-cover mapping program: New York and New Jersey region. Photogramm. Eng. Rem. S. 66:1425-1438.

APPENDIX A. Error matrix for 2303 accuracy assessment observations for 26 classes. Observations within the four- to six-cell shaded blocks collapse to one cell for the 19 classes that result from collapsing forest successional stages within 6 classification zones. Overall accuracies (P_o) and kappa coefficients of agreement, respectively, are 71% and 0.69 ± 0.01 for 26 classes and 83% and 0.79 ± 0.01 for 19 classes. The variance estimates for kappa do not account for lack of independence among secondary sampling units within clusters (Stehman and Czaplewski 1998).

	Reference																										User's accuracy %	
																											Number of classes	
Class	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	26	19
1	**41**	7	—	—	—	—	16	—	—	—	—	—	—	—	—	—	—	6	—	—	—	—	—	—	—	—	59	76
2	14	**52**	1	—	—	—	—	—	—	—	—	—	—	—	—	—	—	1	—	—	—	12	—	—	—	—	65	
3	4	7	**32**	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	4	—	6	—	—	60	
4	—	—	—	**40**	—	—	—	—	—	—	—	—	5	—	—	—	—	—	—	—	—	5	—	7	1	—	69	
5	—	—	—	—	**31**	35	1	3	—	—	—	—	—	6	—	—	—	3	1	—	1	5	3	—	—	—	35	70
6	—	—	—	—	3	**41**	—	—	—	—	—	—	—	8	9	—	—	—	—	—	—	4	—	2	—	—	61	
7	—	—	—	—	7	—	**43**	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	1	84	
8	—	—	—	—	—	—	—	**80**	5	1	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	93	98
9	—	—	—	—	—	—	—	16	**26**	—	—	—	—	—	—	—	—	—	—	—	—	1	—	1	—	—	59	
10	—	—	—	—	—	3	—	—	—	**30**	18	—	—	—	5	—	—	—	—	—	—	—	—	—	—	—	54	73
11	—	—	—	—	9	4	—	—	5	17	**28**	—	—	—	4	—	—	—	—	—	—	5	—	—	—	—	39	
12	—	—	—	—	—	—	—	—	—	—	—	**35**	21	—	—	—	—	—	—	—	—	—	—	—	—	—	62	91
13	—	—	—	4	—	—	—	—	—	—	—	11	**20**	—	1	—	—	—	—	—	—	4	—	—	—	—	50	
14	—	—	—	—	2	2	—	—	—	—	—	—	3	**45**	22	—	—	—	—	—	—	4	—	—	—	—	58	92
15	—	—	—	—	2	1	—	—	—	—	—	—	—	22	**156**	—	1	—	—	—	—	5	—	4	—	—	82	
16	—	—	—	—	—	—	—	—	—	—	—	—	—	10	25	**53**	6	—	—	—	—	—	—	—	—	—	56	
17	—	—	—	—	—	—	—	—	—	—	—	—	—	—	10	21	**56**	—	—	—	—	—	—	—	—	—	64	
18	9	—	—	—	4	—	3	—	—	—	—	—	—	—	—	—	—	**41**	—	—	—	—	—	2	—	—	70	
19	—	—	—	—	—	8	—	—	—	—	—	—	—	—	—	—	—	—	**21**	—	—	1	—	—	—	—	70	
20	—	—	—	—	—	—	1	—	—	—	—	—	—	—	—	—	—	—	—	**18**	—	—	—	—	—	—	95	
21	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	2	—	—	**61**	—	—	—	—	5	90	
22	—	13	—	—	2	8	—	4	11	2	1	—	1	2	8	—	—	1	—	1	4	**135**	9	21	—	2	60	
23	—	—	—	—	—	—	—	—	—	1	—	—	—	—	—	—	—	—	—	3	—	—	**338**	12	—	—	95	
24	—	—	3	1	—	—	3	—	—	—	3	—	2	—	1	—	—	9	—	—	—	21	2	**86**	—	—	66	
25	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	1	—	—	—	—	—	2	**56**	—	95	
26	—	—	—	—	—	—	1	—	—	—	—	—	—	—	—	—	—	2	—	—	—	1	1	9	8	**65**	76	
Producers accuracy %	19 classes																											
	19	60	66	89	89	52	40	63	78	55	59	56	76	39	48	65	72	89	62	95	82	92	65	96	57	86	89	**P_o = 71%**
	26 classes	78				68			85		92		89			82												**P_o = 83%**