The Forest Types and Ages Cleared for Land Development in Puerto Rico

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The Forest Types and Ages Cleared for Land Development in Puerto Rico

Todd Kennaway
Center for Environmental Management of Military Lands, Colorado State University, Fort Collins, Colorado 80523

E. H. Helmer[1]
International Institute of Tropical Forestry, USDA Forest Service, 1201 Calle Ceiba, Jardín Botánico Sur, Río Piedras, Puerto Rico USA

Abstract: On the Caribbean island of Puerto Rico, forest, urban/built-up, and pasture lands have replaced most formerly cultivated lands. The extent and age distribution of each forest type that undergoes land development, however, is unknown. This study assembles a time series of four land cover maps for Puerto Rico. The time series includes two digitized paper maps of land cover in 1951 and 1978 that are based on photo interpretation. The other two maps are of forest type and land cover and are based on decision tree classification of Landsat image mosaics dated 1991 and 2000. With the map time series we quantify land-cover changes from 1951 to 2000; map forest age classes in 1991 and 2000; and quantify the forest that undergoes land development (urban development or surface mining) from 1991 to 2000 by forest type and age. This step relies on intersecting a map of land development from 1991 to 2000 (from the same satellite imagery) with the forest age and type maps. Land cover changes from 1991 to 2000 that continue prior trends include urban expansion and transition of sugar cane, pineapple, and other lowland agriculture to pasture. Forest recovery continues, but it has slowed. Emergent and forested wetland area increased between 1977 and 2000. Sun coffee cultivation appears to have increased slightly. Most of the forests cleared for land development, 55%, were young (1–13 yr). Only 13% of the developed forest was older (41–55+ yr). However, older forest on rugged karst lands that long ago reforested is vulnerable to land development if it is close to an urban center and unprotected.

INTRODUCTION

Dramatic landscape changes have occurred on the Caribbean island of Puerto Rico during the last 70 years, as its economy shifted from agriculture to industry and services. As a result of this economic shift, intensively cultivated lands have transitioned to hay or intermittently grazed pasture, and if left unmanaged, regenerate to forest. Forests previously cleared for agriculture have increased, from covering six percent of the island in the late 1930s to covering 42% in 1991 (Franco et al. 1997;

[1]Corresponding author, email: ehelmer@fs.fed.us

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Helmer 2004). Forest recovery on previous agricultural lands occurred with increases in non-farm labor, emigration from rural to urban areas, and immigration to the United States mainland. Coffee growers with small land holdings, for example, apparently sought off-farm income (Rudel et al., 2000). Urban area has also increased, increasing by about 32% in Puerto Rico from 1977 to 1991, and by another 7.2% from 1991 to 2000 (Helmer, 2004; Helmer and Ruefenacht, 2005). The Puerto Rican landscape may exemplify how other tropical forest landscapes will evolve (Grau et al., 2003). Old-growth forest clearing for agriculture, which is currently a major change in many tropical landscapes, occurred over most of Puerto Rico before about 1950. Many countries in Asia or South America are considering agricultural development that will clear old-growth tropical forest. The Puerto Rico example gives a picture of how forests might be distributed should agriculture become unprofitable in such previously forested landscapes.

A current concern in Puerto Rico and other Caribbean islands is forest clearing for *land development*, referring to land cover change to buildings, pavement, or non-agricultural bulldozed land. This land development converts land to: (1) urban or suburban residential, industrial, commercial, or transportation uses; (2) bulldozed land undergoing construction for those uses; or (3) surface-mined land. About 5.2% of the island of Puerto Rico is protected. However, forest types differ in their extent of protection. Some forest types of lowland and submontane ecological zones, which represent most of Puerto Rico, are barely represented in the reserves of Puerto Rico, yet the most land development occurs in these zones (Helmer, 2004). Conservation opportunities exist where agriculture or pasture land has reverted to forest in various successional stages. However, in Puerto Rico and elsewhere, little information exists on the characteristics of those forests that undergo clearing for land development (Alig et al., 2004; Stein et al., 2005).

The climatic zones of Puerto Rico are all forest zones (Ewel and Whitmore, 1973), and in pre-Columbian times the island was probably all forested (Wadsworth, 1950). Given the mentioned low of six percent forest cover, most of the forest now on Puerto Rico is secondary forest. This study quantifies these secondary forests and older forest patches by forest type and age class. It then quantifies the forests that undergo clearing for land development in Puerto Rico by type and age class. Understanding how land-cover changes affect the distributions of forest types and ages across landscapes can be critical to conservation planning, urban planning, ecosystem management or restoration, and research on landscape processes. For example, knowing the spatial distributions of forest ages could impact planning that considers species diversity. In Puerto Rico, forests of different types, past land uses, and successional stages differ in species composition, endemism, and diversity, and in the relative importance of non-native species. Tree species diversity of secondary forests, for example, increases with age or basal area (Aide et al., 1996; Chinea and Helmer, 2003). Where secondary forest exists on former agricultural lands, land use planning might consequently emphasize protection of older secondary forest.

With the overall goal of quantifying the ages and types of forests that are undergoing land development in Puerto Rico, the objectives of this study are to: (1) test whether land cover and forest type can be accurately mapped over Puerto Rico with decision tree classification of Landsat image mosaics; (2) characterize trends in land cover change over time; and (3) quantify the age and type distribution of forests that undergo clearing for land development. Although trends in land cover change in Puerto Rico are known generally, a summary that includes recent data as well as most land cover types has not been available. We determined forest types from field visits, aerial photo interpretation, and input from experts.

METHODS

Study Area

The Caribbean islands of Puerto Rico, Vieques and Culebra (17°45' N, 66°15' W) encompass an area of about 8900 km^2. Forest types range from subtropical drought deciduous, semi-deciduous, and seasonal evergreen forests to evergreen forests including cloud forests. The driest forest types are in southern and southwestern Puerto Rico and the outlying islands of Vieques and Culebra. The wettest forest types occur at higher elevations in Puerto Rico. The geology of Puerto Rico consists of alluvial, sedimentary, volcanic, serpentine, and karst strata. Historically, most mixed woody agriculture focused on coffee cultivation in the island's interior. Where present, the alluvial plains likely supported emergent and forested wetlands that were converted to agriculture, mainly for sugar cane cultivation (Lugo and Brown, 1988).

Time Series Dataset of Land Cover and Forest Type

Overview and potential error sources. As an overview of our approach, we first assembled a time series of maps for Puerto Rico for the years 1951, 1977, 1991, and 2000, which included land cover maps based on aerial photo interpretation for 1951 and 1977, maps of forest type and land cover in 1991 and 2000 based on Landsat satellite imagery, and a map of land development from 1991 to 2000 (Helmer and Ruefenacht, 2005). From the time series dataset we summarized total land cover for all map dates, cross-tabulating the land cover maps from 1977 to 1991 and 1991 to 2000, to derive an indication of trends in land cover change between specific classes. We also used the time series and the map of land development to map forest age in 1991 and 2000 and quantify the areas of forest that underwent urban development or surface mining from 1991 to 2000 by forest type and age.

Potential problems with the overall approach in this study include those related to post-classification change detection, integrating these different data types, and using aerial photo interpretation. In post-classification change detection, misclassification errors can accumulate through time. In addition, residual misregistration errors between the maps that bound each time step can be mistaken for land cover change. We did not cross-tabulate change between 1951 and 1977, for example, because misregistration errors around coastlines would probably lead to somewhat large errors in change between specific classes. Change detection between digitally classified satellite imagery and maps from photo interpretation can also cause inconsistencies in the accuracy of detecting various types of changes. For example, manual interpretation of remotely sensed imagery may yield a more detailed classification scheme than digital image classification, and classification of 30 m satellite imagery usually results in scattered pixels that are misclassified. Satellite image–based maps, however, may distinguish some smaller patches that manual interpretation would aggregate into larger patches of a different land cover type. Another limitation with aerial photo interpretation is that differences between photo interpreters are known to result in some inconsistencies both between different mapping efforts and within them. Another problem with our approach is that quantitative information on the accuracy of the maps for 1951 and 1977 is not available. Some of these problems are, however, unavoidable. Satellite image data did not become available until 1959, and we did not have the resources to purchase and manually interpret aerial photos island-wide for four time steps. The analyses in this study assume that none of these potential error sources are large enough to substantially affect our conclusions.

Land-cover maps based on aerial photo interpretation. The two maps based on photo interpretation included the ones from 1951 and 1977. For the map from 1951 (Fig. 1), we vectorized a 1:150,000-scale paper map of land cover in 1951 (Brockman, 1952). The resulting Geographic Information System (GIS) coverage consists of ~17,000 polygons of over 20 different classes. The Rural Land Classification Program of Puerto Rico assembled the intermediate scale paper map from land cover maps that it developed from 1:20,000-scale black and white aerial photos, dated 1951, through manual photo interpretation of stereo pairs. For the map from 1977, we assembled an island-wide map from 1:20,000-scale digitized land cover maps that the U.S. Geological Survey and the Puerto Rico Department of Natural and Environmental Resources generated from photo interpretations of 1:20,000-scale color aerial photos dated 1977–1978 (also via manual photo interpretation of stereo pairs). With the more powerful computers available now, this new assembly of these data for 1977 maintains the native, more detailed classification scheme. However, the same underlying data were used in Ramos and Lugo (1994) and subsequent studies (del Mar López et al., 2001; Ramos, 2001; Helmer, 2004). The data from both 1951 and 1977 were co-registered to the Landsat image mosaic from about the year 2000, which is described below, and then converted to raster format with a pixel size of 30 m.

Satellite image–based maps of land cover and forest types. The satellite image–based maps for 1991–1992 and 2000 came from separately classifying two Landsat image mosaics; one mosaic was from imagery dated around the years 1991–1992, and one was from imagery dated around the year 2000. The image mosaics used the regression tree method of Helmer and Ruefenacht (2005) to fill cloudy areas in Landsat TM and ETM+ imagery from other image dates, and they were the same two mosaics developed in that study. The regression tree method begins with a base or *reference* image for each mosaic, which is usually the clearest one available for the season of interest. The *subject* images for each mosaic are other image dates that are cloud free where the reference image is cloudy. The method then develops regression tree models from the mutually clear parts of each reference-subject image pair. These models predict the pixel values underneath clouds and cloud shadows from corresponding subject image pixels. The normalization minimizes atmospheric, phenological, and illumination differences among the various image dates that form each mosaic (Helmer and Ruefenacht, in press). As the new subject image data are calibrated to the reference image for each mosaic with regression tree models, they more seamlessly fill cloudy areas in the reference image.

To classify the Landsat image mosaics for 1991–1992 and 2000 into forest types and land cover, we completed a supervised classification based on classification models developed with the decision tree software See5 (www.rulequest.com).[2] Training data for the image classifications consisted of 50–150 multi-pixel patches distributed throughout the extent of each class. As a result, the number of training pixels for each class was in the thousands. In mountainous areas, sunlit and shadowed versions of major land-cover types were treated as separate classes and then later combined (Helmer et al., 2000). Island-wide reconnaissance surveys in 1999–2000 and 2003, including airborne reconnaissance in 2003, supported aerial photo interpretation for training data collection.

The field surveys and consultation with experts on Puerto Rico vegetation enabled us to discern land cover and forest type on 1:33,000-scale color infrared aerial photos dated 1991 and 1:38,000-scale color photos dated 1999. Land cover and forest type interpreted in aerial photos and field surveys were then identified in the satellite imagery and used to create classification training data. Digital layers of ancillary geographic data were then co-registered to and stacked with Landsat image bands 1–5, 7, and two-band indices to create a multi-band image for each image mosaic. We selected the ancillary data and spectral bands based on our knowledge of the land cover and vegetation of Puerto Rico and from previous experience mapping Puerto Rico with Landsat imagery (Helmer et al., 2002). The band indices included the normalized difference vegetation index (NDVI) and the band 4/5 ratio, which are useful indictors of vegetation greenness or forest structure (Strahler, 1981; Fiorella and Ripple, 1993; Helmer et al., 2000). Ancillary data included elevation, slope, aspect, and topographic shadow derived from the 30 m National Elevation Dataset (Gesch et al. 2002); annual precipitation, mean temperature, and potential evapotranspiration-to-precipitation ratio (Daly et al., 2003); and distance to roads, road density, and geology (Krushensky, 1995). The decision trees models are complex, and an analysis of variable contributions to the classification was beyond the scope of this study. In related work in Puerto Rico and the Lesser Antilles (Blackard et al., unpubl. data; Helmer et al., unpubl. data), the decision tree models use nearly all of the spectral and ancillary variables that we used here. The models appear to first spectrally segment the images and then use the ancillary variables to separate spectrally similar classes. However, in the classification models for two different but similar landscapes, different variables from a set of correlated variables might predominate. Landsat band 1 might appear repeatedly in one classification, but Landsat band 2 might repeatedly appear in another. Consequently, ancillary data can and perhaps should include correlated variables.

The maps for 1991 and 2000 identify forest types down to the formation level. Forest formations (*sensu* FGDC, 1997) are forest types that environmental factors, like climate, broadly determine. Consequently, forest formations are defined by factors like leaf form and leaf longevity rather than species composition. The formations are based on the hierarchical classification system that Helmer et al. (2002) adapted for Landsat image classification from Areces-Mallea et al. (1999). Forest includes lands with >25% cover of trees or trees that co-dominate with shrubs. Drought deciduous woodland includes lands with 25–60% (open) or >60% (dense) canopy cover dominated by drought deciduous leguminous shrubs and a relatively clear understory that indicates grazing and that may include herbaceous vegetation. Pasture and grass

[2]In See5, we used the default settings for pruning and included boosting with 10 trials.

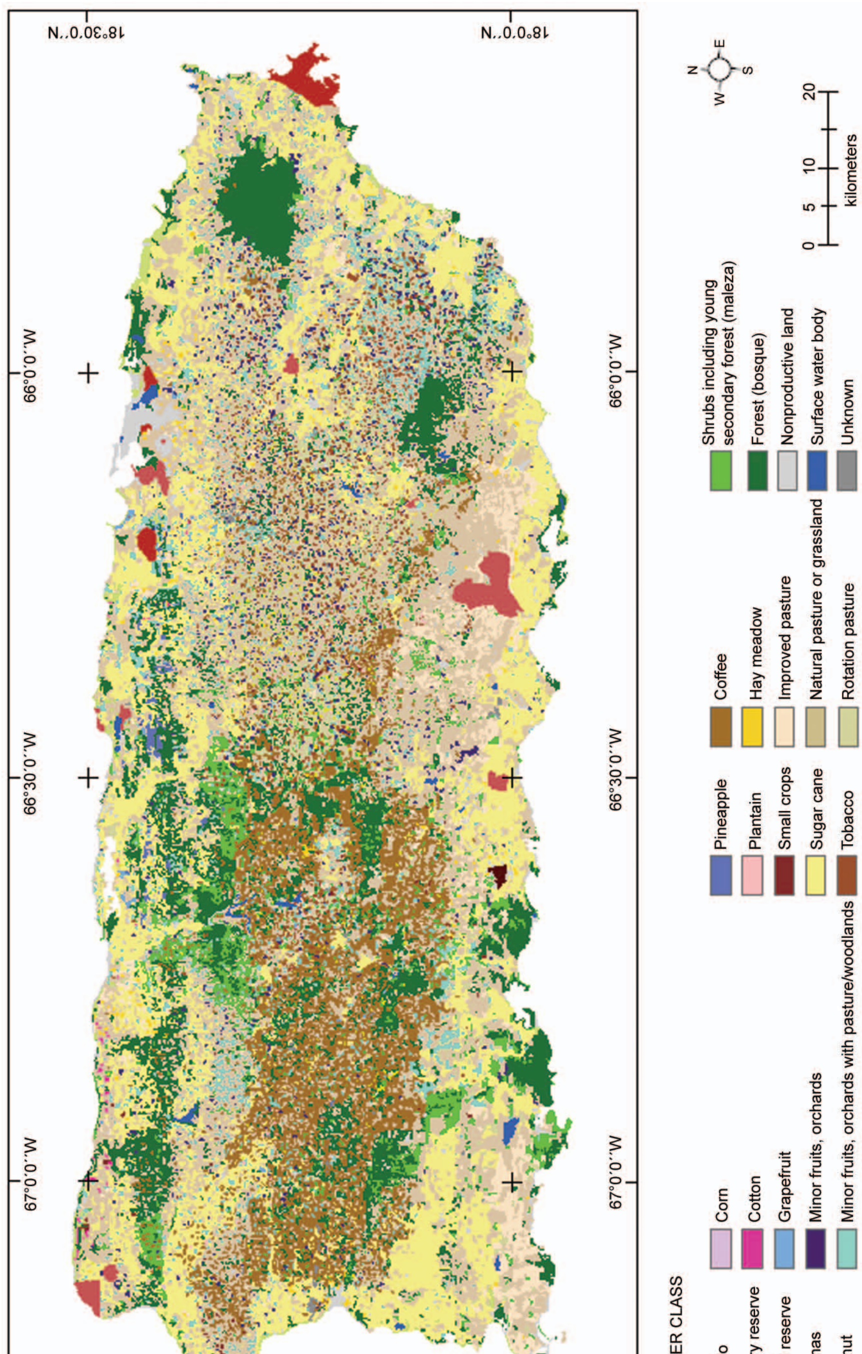

Fig. 1. Puerto Rico land cover map for 1951.

may have up to 25% woody vegetation cover. Cloud forest includes elfin, palm, and tall cloud forests, as well as forests that are transitional to cloud forests. Low to medium density urban and developed areas included lands with as little as 10–15% manmade covers. Consequently, they include some forest or grassland. High density urban lands had >80% cover of man-made structures.

Manual editing of the image-based maps was required to correct for confusion between urban, bare, and senescent pasture lands. We also manually delineated agriculture, inactive agricultural land, and hay/improved pasture in alluvial lowlands for the 2000 classification date. Some confusion between sun coffee and pasture was also manually edited in both dates. We applied the 1991 agricultural delineations from Helmer et al. (2002) for the 1991 time step. We also manually edited the boundary between semi-deciduous and evergreen forest in one part of the island. Finally, seasonally flooded savannas and woodlands were manually delineated in seasonally inundated areas, mainly along the southern coast. The manually interpreted area was 3.2% in 2000, and 5.8% in 1991, of the total area mapped. For both classification dates, a stratified random sample generated about 50 validation points for each land cover class. The validation points for the 1991 classification came from Helmer et al. (2002). The aerial photographs for 1991 and 1999 served as reference data for identifying the class of each validation point in 1991 and 2000, respectively. The aerial photography eliminated restrictions on point locations, permitting us to include points that would otherwise not be accessible because of topography, remoteness, or property ownership.

Summaries of land cover changes and land development by forest type and age. Generalizing the classification scheme of each map in the time series to one common scheme allowed us to summarize land cover change from 1951–2000 and map forest age in the years 1991 and 2000. Agricultural classes in the maps from 1951 and 1977 became either herbaceous (cotton, sugar cane, pineapple, tobacco, corn, and small or specialized crops) or mixed and woody agriculture (coffee, coconut, minor fruits and orchards, plantain, bananas, citrus, mangos). Inactive agriculture in transition to pasture, open drought deciduous woodlands, and other grassy areas became pasture/grass. Urban/developed classes collapsed to a single urban/developed class in all maps, excluding "urban vegetation" in the map from 1977 that consisted of larger patches of forest in larger cities. The 1977 urban areas that collapsed into one class included low-density residential lands that are comparable to the low-density urban class in the classifications for 1991 and 2000. The two to four classes of forest canopy cover in the maps from 1951 and 1977, respectively, were collapsed into one forest class. Forest, dense woodlands, and mixed forest or shrublands in the maps from 1991 and 2000 were also collapsed to the forest class.

To map forest age in 1991, we overlaid the maps from 1951, 1977, and 1991, assigning three age classes (1–13, 14–40 and ≥41–55+ yr) based on forest presence for the three map dates. For example, if forest was present in all three map dates, it was assigned to the oldest age class. To map forest age in 2000, we overlaid the maps from 1951, 1977, 1991, and 2000, assigning four age classes (1–9, 10–22, 23–49, and 50–64+ yr). The upper end of the age range for the oldest age class assumes that lands mapped as dense forest in 1951 were at least 15 years old at that time. In estimating forest ages, we assumed that all woody vegetation classes grew older during the interval between two successive map dates, including open drought deciduous woodlands—i.e., we assumed that pixels did not undergo clearing and regrowth between successive map dates. In addition, we assumed mangrove was in the oldest age class because slight misregistration around coastlines could cause some mangrove areas to map as younger forest.[3] To the extent that forest clearing and regrowth occurred between the map dates, the forest age map undoubtedly has some error. This assumption, however, allowed us to assign a less abstract label to the forest classes (i.e. forest age classes) even though the classes actually represent the sequential persistence of forest cover in the four map dates. Integrating field measurements of forest age with satellite imagery, and then developing a remote sensing classification model that accurately predicts forest age from the imagery (e.g., Jensen et al., 1999) would be preferable. However, we did not have such *in situ* data available on forest stand age.

To quantify the age and type distribution of forests cleared for land development, we used the map of land development from 1991–2000 that Helmer and Ruefenacht (2005) developed from the same two image mosaics that we used to map land cover and forest types in this study. We used the 1991–2000 land development map, instead of the land-cover maps from 1991 and 2000, because it came from merging the two image mosaics into multidate imagery to detect and map patches of land development at least 1 ha in size. Change detection with multidate imagery minimizes the misclassification errors mentioned earlier that accumulate from post-classification change detection. In this case, it minimized errors that could accumulate from misclassification of low-density urban lands in the land cover maps from 1991 and 2000. Helmer and Ruefenacht (2005) validated the 1991–2000 land development map with aerial photos from both dates. It accurately detects land development, including new commercial, industrial, and residential developments, new development within urban centers, bulldozed lands under construction, and newly surfaced mined areas. These classes are the major types of land development in Puerto Rico.

RESULTS

Land Cover and Forest Type Classification for 1991 and 2000

The accuracy assessment for the 1991 and 2000 image classifications yielded Kappa coefficients of agreement of 0.69 ± 0.02 and 0.81 ± 0.02, respectively, and the producer's and user's accuracies for most classes were greater than 75% (Appendices A and B). Overall accuracies for the classifications from 1991 and 2000 were 72% and 82%, respectively. Note that both error estimates combine developed lands of low to medium with high to medium density, because they were not accurately distinguished from each other in either date. In addition, the Kappa coefficient of agreement and overall accuracy for 1991 was computed after combining semi-deciduous forest with drought deciduous woodlands, and active with inactive herbaceous agriculture, because the reference data from Helmer et al (2002) did not distinguish between them. Classifying mosaic imagery with decision trees successfully mapped the remaining land-cover classes and 15 forest types in Puerto Rico, Vieques, and Culebra for the years 1991 and 2000 (Fig. 2). Overlaying these maps with those from

[3]This assumption did not substantially affect results.

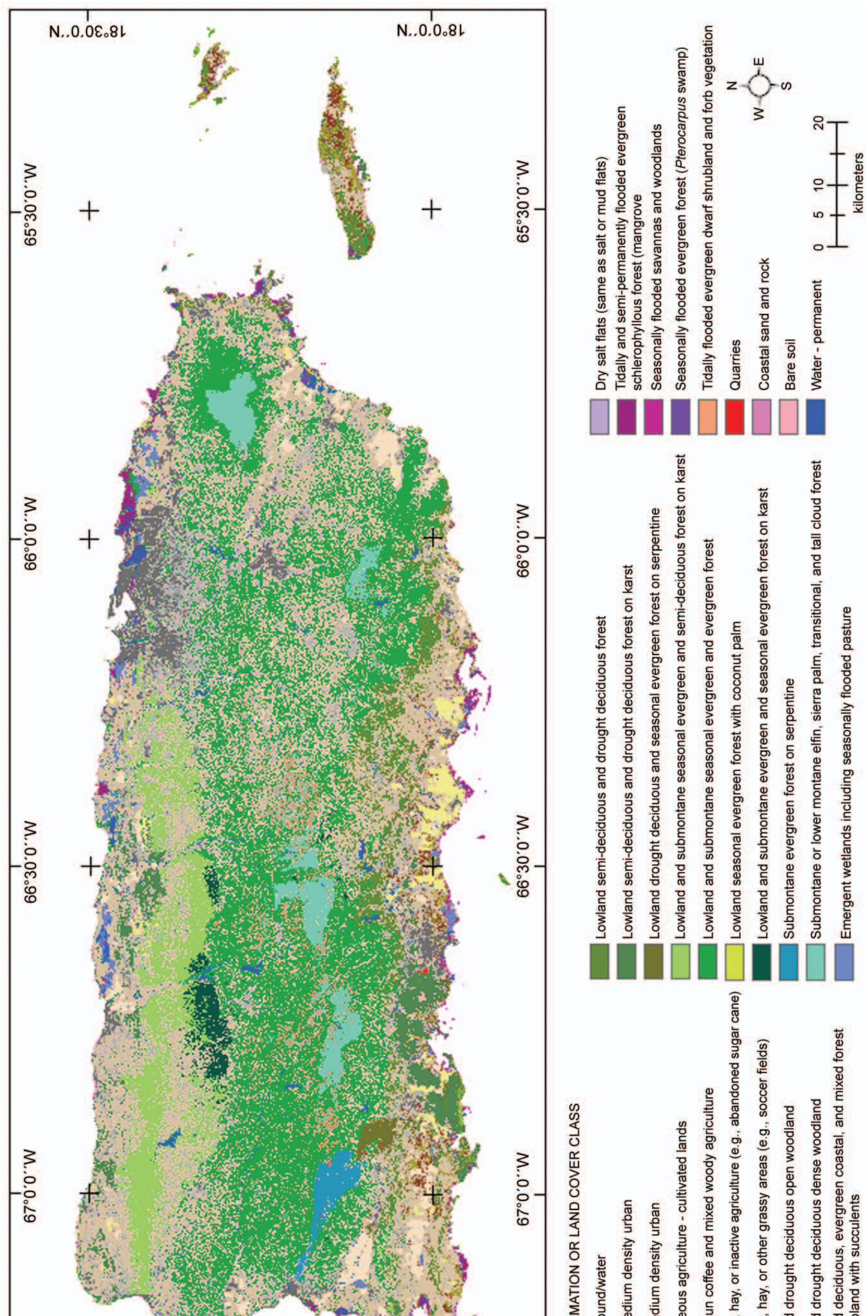

Fig. 2. Puerto Rico, Vieques, and Culebra land cover and forest type classification for 2000.

1951 and 1977 resulted in maps of forest age that included three age classes in 1991 and four age classes in 2000 (Fig. 3). Several studies have joined similar time series datasets with modeling to predict land-cover changes, including to map forest vulnerability to urban growth (Theobald and Hobbs, 1998; Kline et al., 2001; Pontius et al., 2001; Theobald, 2005). The time series dataset here, together with earlier urban change datasets (del Mar López et al., 2001; Helmer and Ruefenacht, 2005) may also support such modeling.

Trends in Land Cover Change, 1951–2000

Agriculture declined 95% from 1951 to 2000 (Table 1). Non-wetland forest area increased from covering 17.8% of the island in 1951 to covering 33.6% in 1977, 43.3% in 1991 (377,563 ha minus about 3800 ha of shade coffee), and 44.8% in 2000. From 1991 to 2000, areas of dominant forest types primarily or partly on karst substrates appear to have slightly increased, while the dominant forest types on volcanic and alluvial soils changed less on a percentage basis. Area of seasonal evergreen and evergreen forest, however, appears to have slightly decreased from 1991 to 2000 (Appendix A). Urban and developed land progressively increased from 1951 to 2000, from 1.7% of Puerto Rico in 1951 to 15.4% in 2000. The estimates of urban and developed land area for 1991 and 2000 are larger than previous estimates (Helmer et al., 2002; Helmer and Ruefenacht, 2005) because they include lands with as little as 10–15% developed surfaces. Total pasture area remained constant from 1951 to 2000, covering about one-third of Puerto Rico.

As we discuss in more detail later, however, the estimates of land cover change between specific classes suggest that the distribution of pasture over the landscape was dynamic (Tables 2–3). While herbaceous agriculture transitioned to pasture, hay, or inactive agriculture, pasture reverted to forest or underwent land development. Some pasture that had reverted to forest was re-cleared, but total forest area increased because more pasture reverted to forest than was re-cleared. Emergent wetlands increased from about 4,500 ha in 1977 to over 7,000 ha in 1991 and 2000. Forested wetland area appears to have increased slightly from 1977 to 2000. Forested wetlands were mapped as forest in 1951, but visually inspecting the maps from 1951 and 1977, along with the DEM, suggested that various areas of forested wetland underwent clearing between 1951 and 1977. Coffee with mixed and woody agriculture declined from 1951 to 1991. In 1951 and 1977, most of this class was *shade coffee*, in which shade trees are planted among coffee plants. From 1977 to 1991, the area of shade coffee continued to decline, but some portion of the coffee cultivation in the map from 1977 was probably inactive shade coffee/secondary forest (Helmer 2004). About 38,100 ha of inactive shade coffee was present in 1980 (Birdsey and Weaver, 1983). This amount helps to quantify what portion of the decrease in coffee cultivation (and forest increase) is not due to actual change. Forest inventory data from 1980 and 1990 also suggest a large transition of shade coffee to forest during that time (Franco et al., 1997). In contrast, by 2000 the decline in mixed and woody agriculture had reversed. The increase in coffee with mixed and woody agriculture from 1991 to 2000 was due to an increase in *sun coffee* cultivation, which does not use shade trees, but some of the increase could stem from slight differences between the classifications.

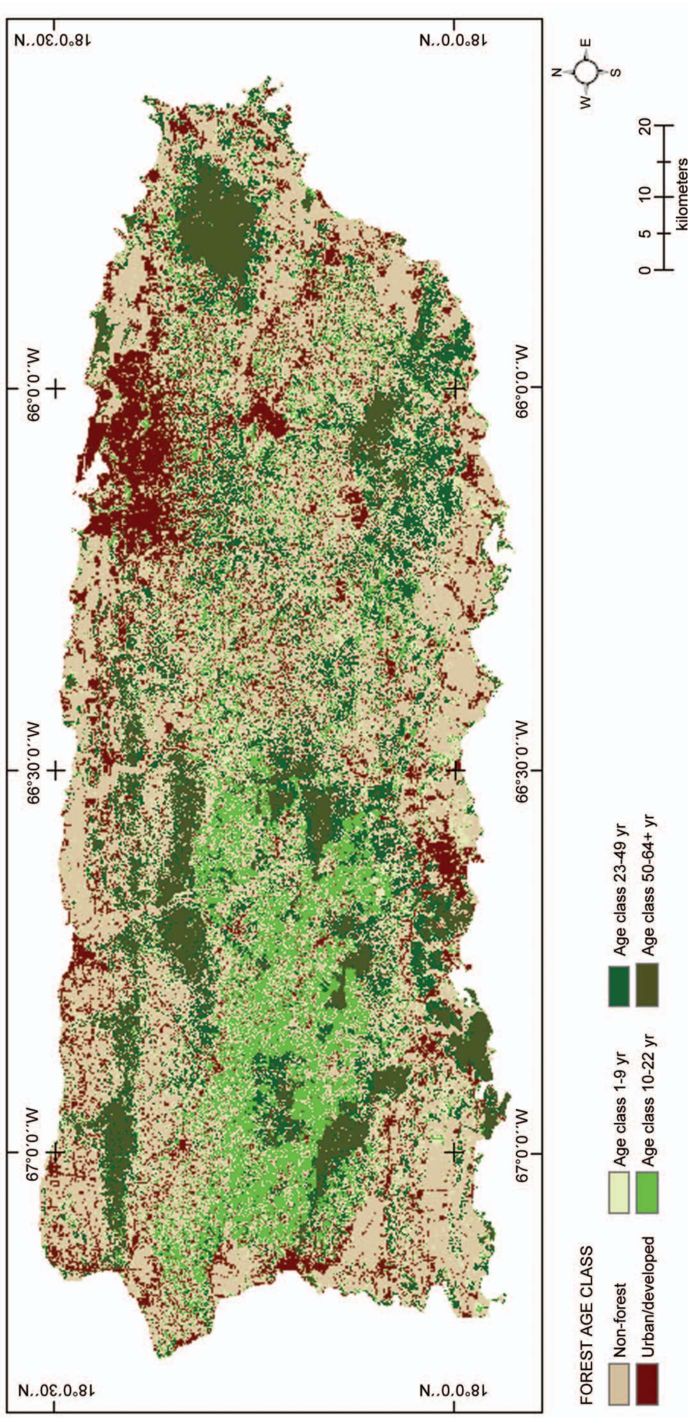

Fig. 3. Puerto Rico closed woody vegetation age classification for 2000.

Table 1. Puerto Rico Land Cover Area Summary for the Years 1951, 1977, 1991, and 2000, in hectares[a]

Year	Urban/ developed[b]	%	Herbaceous agriculture	%	Coffee/mixed and woody agriculture[c]	%	Pasture/ Grass	%	Forest/ woodland/ shrubland[d]	%	Non-forested wetland	%	Forested wetland[e]	%	Other[f]	Total hectares per land cover period
1951	14,991	1.7	199,717	22.9	161,961	18.6	319,715	36.7	154,585	17.8	1,836	0.2	n.a.[g]	na	18,044	870,849
1977	86,231	9.8	77,644	8.9	109,392	12.6	274,624	31.5	292,548	33.6	4,502	0.5	7,456	0.9	18,387	870,785
1991	124,812	14.3	29,377	3.4	14,063	1.6	302,807	34.7	377,563	43.3	7,124	0.8	7,656	0.9	8,493	871,908
2000	134,218	15.4	9,684	1.1	19,199	2.2	302,632	34.7	381,613	44.8	7,135	0.8	7,939	0.9	9,814	872,248
Overall change from 1951 to 2000																
Hectares	119,227		−190,033		−142,762		−17,083		227,028		5,299		n.a.		−8,230	
Percent	795		−95		−88		−5		147		289					

[a]Excludes Vieques, Culebra, Icacos, Piñero, Palominos, Caja De Muertos, Mona, and surrounding islets.

[b] For 1951, urban/developed is high density and includes coastal sand/rock. In 1977, 1991, and 2000, urban/developed includes bulldozed land, quarries, and low-density residential lands (with as little as 10–15% human-made structures).

[c]Coffee is mainly shade coffee in 1951 and 1977 and sun coffee in 1991 and 2000. Coffee in 1977 probably includes up to 38,100 ha of abandoned shade coffee (estimated in 1980; Birdsey and Weaver, 1983).

[d]Excludes drought deciduous open woodland, which is included with pasture/grass. Forest area in 1991 includes an estimated 3,800 ha (Helmer et al,, 2002) to 13,800 ha (Franco et al., 1997) of active shade coffee in 1991.

[e]Forested wetlands were included with other forested lands in the 1951 map.

[f]Other includes rivers, reservoirs, and coastal sand/rock for 1977, 1991, and 2000. Other also includes military/naval reserves and unknown in 1951. Military areas in the map from 1977 were filled with land cover data from the 1991 map.

[g]n.a. = forested wetlands were not differentiated from forest in the map from 1951.

Table 2. Land Cover Change Summary Matrix for the Island of Puerto Rico, 1977—1991[a]

	Area 1991, ha								
Area in 1977, ha	Urban/ developed[b]	Herbaceous agriculture	Coffee/mixed and woody agriculture[c]	Pasture /grass	Forest/ woodland/ shrubland[d]	Non-forested wetland	Forested wetland	Other[e]	Total in 1977
Urban/developed	85,433	0	0	0	0	0	0	0	85,433
Herbaceous agriculture	5,266	25,054	139	40,560	5,517	537	88	477	77,639
Coffee/mixed woody agriculture	4,280	520	5,706	18,715	79,365	109	228	372	109,294[ii]
Pasture/grass	20,008	2,711	4,676	171,632	71,318	2,638	579	995	274,555
Forest/woodland/shrubland	5,729	666	3,436	64,295	216,441	658	389	772	292,385
Non-forested wetland	28.35	38	0	1,375	317	2,333	228	166	4,486
Forested wetland	0	29	0	533	735	333	5,069	391	7,088
Other	2,115	342	106	5,457	3,713	490	658	4,743	17,624
Total in 1991	122,859	29,361	14,063	302,566	377,405	7,096	7,238	7,916	868,503
Change 1977 to 1991 (ha)	37,426	–48,278	–95,231	28,011	85,020	2,611	149	–9,708	
Change 1977 to 1991 (%)	44	–62	–87	10	29	58	2.1	–55	

[a]The urban/developed class includes barren lands bulldozed for development or surface mining. Totals differ slightly from those in Table 1 because of slight misregistration between maps from different years. The matrix also includes adjustments that assume that any lands that changed from urban/developed to other cover types resulted from slight misregistration or misclassification errors. Areas for detailed land cover and forest types for Puerto Rico, Vieques, and Culebra in 1991 and 2000 are shown in Appendices A–B. Icacos, Piñero, Palominos, Caja de Muertos, and surrounding islets are included with areas for Puerto Rico in Appendices A–B. Data from aerial photos or the 1991 map were used to fill areas mapped as military areas in 1977.
[b]In 1977 and 1991, urban/developed includes bulldozed land, quarries and low-density residential lands (with as little as 10–15% human-made structures). The estimate of urban/built-up land in 1977 is smaller than that in Helmer (2004) because this assembly of the dataset excludes primarily vegetated areas within urban centers from the total urban/developed area.
[c]Coffee in this class is mainly shade coffee in 1977 and sun coffee in 1991, but the shade coffee in 1977 may include up to 38,100 ha of abandoned shade coffee (Birdsey and Weaver, 1983).
[d]Excludes drought deciduous open woodland, which is included with pasture/grass. Forest area in 1991 includes an estimated 3,800 ha (Helmer et al., 2002) to 13,800 ha (Franco et al., 1997) of active shade coffee in 1991.
[e]Other includes rivers, reservoirs, and coastal sand/rock. Rivers were larger in the 1977 map than in the satellite image–based map. Military areas were filled with 1991 data.

Table 3. Land Cover Change Summary Matrix for the Island of Puerto Rico, 1991–2000[a]

	Area in 2000, ha								
Area in 1991, ha	Urban/ developed[a]	Herbaceous agriculture	Coffee/ mixed and woody agriculture[b]	Pasture /grass	Forest/ woodland/ shrubland[c]	Non-forested wetland	Forested wetland	Other[d]	Total in 1991
Urban/developed	124,014	0	0	0	0	0	0	0	124,014
Herbaceous Agriculture	1,259	5,530	1	21,314	1,057	65	18	133	29,377
Coffee/Mixed Woody Agriculture	0	0	7,535	2,665	3,911	0	0	18	14,129
Pasture/grass	2,390	3,889	2,512	226,764	62,408	2,453	710	1,627	302,753
Forest/Woodland/Shrubland	5,457	229	9,097	48,697	312,543	213	337	998	377,570
Non-forested Wetland	240	5	1	1,787	385	3,822	339	506	7,085
Forested Wetland	0	8	1	529	712	432	5,800	203	7,685
Other	62	20	52	912	573	170	540	5,912	8,241
Total in 2000	133,422	9,681	19,199	302,668	381,588	7,155	7,745	9,397	870,855
Change 1991 to 2000, ha	9,408	–19,696	5,070	-85	4,017	70	60	1,155	
Change 1991 to 2000, %	8	–67	36	0	1.1	1.0	0.8	14	

[a]The urban/developed class includes barren lands bulldozed for development or surface mining. Totals differ slightly from those in Table 1 because of slight misregistration between maps from different years. The matrix also includes adjustments that assume any lands that changed from urban/developed to other cover types resulted from slight misregistration or misclassification errors. Areas for detailed land cover and forest types for Puerto Rico, Vieques, and Culebra in 1991 and 2000 are shown in Appendices A–B. Icacos, Piñero, Palominos, Caja de Muertos, and surrounding islets are included with areas for Puerto Rico in Appendices A–B.

[b]In 1991 and 2000, urban/developed includes bulldozed land, quarries, and low density residential lands (with as little as 10–15% human-made structures).

[c]Coffee in this class is mainly sun coffee in 1991 and 2000. Most shade coffee in 1991 is included with forest.

[d]Excludes drought deciduous open woodland, which is included with pasture/grass. Forest area in 1991 includes an estimated 3,800 ha (Helmer et al., 2002) to 13,800 ha (Franco et al., 1997) of active shade coffee in 1991.

[e]Other includes rivers, reservoirs, and coastal sand/rock.

Forest Types and Ages Cleared for Land Development

Sixty-four percent of the forest cleared for land development was seasonal evergreen and evergreen forest, which was followed by semi-deciduous and drought deciduous forest on karst (14%), seasonal evergreen and semi-deciduous forest on karst (6%), semi-deciduous and drought deciduous forest (6%), and open or dense drought deciduous woodlands (5% and 2%, respectively) (Table 4). The proportion of forest cleared for land development that was old (40–55+ yr in 1991) was small for non-wetland forest types on alluvial or volcanic substrates. For example, this proportion was only 2% for seasonal evergreen and evergreen forest and 1% for semi-deciduous and drought deciduous forest. Only 1% to 5% of the total area of these latter forest types was old in 1991, which is smaller than most of the other forest types. In contrast, the proportion of urbanized forest that was old was much larger for forest types entirely on karst substrate, including semi-deciduous and drought deciduous forest on karst (52%), evergreen and seasonal evergreen forest on karst (38%), and seasonal evergreen and semi-deciduous forest on karst (24%). Larger proportions of old forest were also urbanized for forest types partially or mostly on karst substrate, including open or dense drought deciduous woodland (14% and 35%, respectively), and the class deciduous, evergreen coastal and mixed forest or shrubland, with or without succulents (20%). Forest types that were largely protected were also mostly old and underwent little urbanization, including forests on serpentine substrate, mangroves, *Pterocarpus* swamp, and cloud forests.

DISCUSSION

Decision Tree Classification of Landsat Imagery in Complex Tropical Landscapes

Quantifying forest clearing for land development in Puerto Rico by type and age class required maps of the many forest types present. Although decision tree classification is well established in remote sensing, it has rarely been applied in a tropical island setting to classify image mosaics to many different forest types that are spectrally similar. Consequently, the outcome of the classification was uncertain. We have since used the approach to map forest types on two other Caribbean islands (Helmer et al., unpubl. data), but these latter islands did not include all of the land cover classes and forest types in Puerto Rico.

Decision tree classification of Landsat image mosaics appears to be a viable alternative for mapping land cover and forest types in complex tropical landscapes like those of Puerto Rico. We chose decision tree classification for two main reasons. First, decision tree classifiers accommodate spectrally heterogeneous classes. As long as training data represent class spectral variability, decision trees can accommodate some of the class spectral variability that comes from the different image dates that compose an image mosaic (Friedl and Brodley, 1997; Woodcock et al., 2001). Image mosaics or composites are necessary for cloud-free coverage in many persistently cloudy tropical landscapes. Secondly, decision trees can handle many discrete and continuous predictor variables, separating spectrally similar forest types with variables like rainfall or geology (Strahler, 1981; Skidmore, 1989). They quickly identify complex relationships between variables and apply them in a classification model.

When using decision trees to classify stacks of image bands and ancillary data, the decision tree software determines which of several image bands and ancillary layers most accurately predict classes. The models that result are often complex. But complex models are acceptable when the goal of a classification is accuracy rather than characterizing the relationships between the classes and the spectral or ancillary data. With decision tree classification, the training data locations define the spatial distributions of different forest types by parameterizing the decision tree classification model. Decision tree classification consequently avoids assigning forest type based only on ecological zone maps that may be inaccurate. Although the spectral signatures of the different forest types in Puerto Rico overlap (Helmer et al. 2002), the decision tree classification that incorporated ancillary data mapped these types without ecological zone maps. Consequently, the classification eliminated sharp boundaries between types, which is an improvement over previous work (Helmer et al. 2002).

Trends in Land Cover Change

In summary, in 1951, agriculture was the primary economic base in Puerto Rico (del Mar López et al. 2001). Land cover changes between 1951, 1977, 1991, and 2000 reflect shifts in the economy from agriculture to industry and services, because farmland area decreased. The results are consistent with previous studies for parts of the island or other time steps (Thomlinson et al., 1996; Ramos, 2001; Helmer, 2004). In lowland areas, intensively cultivated lands have transitioned mainly to pasture or other grassland, although some have also converted directly to urban/built-up land. From 1991 to 2000, forest area on karst lands appears to have increased slightly, but the area of evergreen and seasonal evergreen forest on volcanic and alluvial soils may have decreased. Drought deciduous woodland area has also increased slightly, and open woodlands transitioned to dense ones. In addition, areas of emergent wetlands increased from 1977 to 1991, as drainage systems were removed from former agricultural lands in new conservation reserves (Helmer, 2004).[4] Although some forested wetland was cleared from 1951 to 1977, the area of forested wetlands appears to have slightly increased from 1977 to 2000, as woody vegetation recovered on some alluvial or coastal lands previously cleared for agriculture.

At intermediate to higher elevations, pasture has tended to reforest. With pasture area decreasing at intermediate to higher elevations, but increasing at lower elevations, island-wide pasture area has remained at about one-third of Puerto Rico's land cover since 1951. The large decline in area of coffee cultivation from 1951 to 1991 is consistent with results of forest inventories showing extensive reversion of shade coffee to forest (Franco et al. 1997). That trend reversed, however, from 1991 to 2000, when mixed and woody agriculture increased by 36%. The increase was mainly because new areas of sun coffee cultivation replaced forest or former shade coffee. The new areas of sun coffee cultivation do not use shade trees. This finding confirms field observations in the region, and the trend probably decreases the amount and

[4]Note that new emergent wetlands mapped as agriculture in 1977 were also agriculture in 1951.

Table 4. Area of Forest That Underwent Land Development[a] from 1991 to 2000 by Type and Age Class, Percent of Total Area of Each Forest Type in Oldest Age Class in 1991, and Percent of Each Forest Type Protected in 1991[b]

Forest type	Total forest area developed, ha	Area of Age 3 forest developed (41–55+ yr) ha (% of type)	Area of Age 2 forest developed (14–40 yr) ha (% of type)	Area of Age 1 forest developed (1–13 yr) ha (% of type)	Percent of all forest types in Age 3 in 1991	Percent of all forest types protected in 1991	Percent of all forest developed
Low- to intermed.-elevation forests on alluvial or volcanic geology[c]							
Seasonal evergreen and evergreen forest	919	22 (2.4)	297 (32)	601 (65)	10	3.5	64
Semi-deciduous and drought deciduous forest	91	1.3 (1.4)	33 (37)	56 (62)	7.3	1.8	6.3
Seasonal evergreen forest with coconut palm	10	1.0 (10)	0.5 (4.3)	8.9 (86)	5.6	14	0.7
Forests on alluvial, volcanic, or karst geology with gentler slopes							
Drought deciduous open woodland	73	11 (15)	19 (26)	43 (59)	9.2	3.7	5.1
Drought deciduous dense woodland	23	7.9 (35)	6 (27)	8.7 (38)	19	3.1	1.6
Forests entirely or primarily on rugged karst geology							
Semi-deciduous and drought deciduous Forest on karst	206[d]	108 (52)	63 (31)	35 (17)	47	14	14
Seasonal evergreen and semi-deciduous forest on karst	94	23 (24)	39 (42)	32 (34)	49	5.5	6.5
Evergreen and seasonal evergreen forest on karst	3.1	1.2 (38)	0.9 (29)	1 (32)	58	20	0.2
Deciduous, evergreen coastal and mixed forest or shrubland with or without succulents	0.9	0 (20)	0 (0)	0.7 (80)	72	80	0.1
Forests on serpentine geology							
Semi-deciduous and seasonal evergreen forest on serpentine	3.9	0 (0)	3.4 (88)	0.5 (12)	68	51	0.3
Evergreen forest on serpentine	0	0 (0)	0 (0)	0 (0)	66	62	0

Cloud forests							
Elfin, sierra palm, transitional, and tall cloud forest	0.4	0 (0)	0 (0)	0.4 (100)	63	55	0.0
Forested wetlands							
Mangrove	6.1	6.1 (100)	0 (0)	0 (0)	100	40	0.4
Seasonally flooded savannas and woodlands	2.3	0 (0)	1.5 (65)	0.8 (35)	10	12	0.2
Pterocarpus swamp	0	0 (0)	0 (100)	0 (0)	62	77	0
Total	1,433	180 (13)	464 (32)	789 (55)	23	10	100

[a]Change to manmade structures, land under construction, or surface-mined lands; excludes Vieques and Culebra.
[b]Of a total 38,338 ha protected.
[c]Excluding forested wetlands.
[d]Of this total, 39 ha was new surface-mined land (quarry land).

quality of habitat available for some species, like Nearctic migrant birds (Wunderle and Latta, 1998). A cautionary note is that the sun coffee increase from 1991 to 2000 could stem in part from differences between the classifications, because in both dates there was some confusion between sun coffee, forest, pasture, and low-density urban lands.

Forest Types and Ages Cleared for Land Development and Management Implications

Low- to intermediate-elevation forests on accessible, arable lands. A new finding in this study is that forests on the most accessible and arable lands, which tend to undergo the most land development, also tend to be younger. The forest types on the most accessible and arable lands in Puerto Rico are mainly those on volcanic or alluvial substrates at low to intermediate elevations, where most of the major urban centers also occur. The non-wetland forests on these lands, including seasonal evergreen and evergreen forest, and semi-deciduous and drought deciduous forest, underwent more than 70% of the land development from 1991 to 2000 and tend to be young. This result is consistent with other studies on the patterns of tropical forest recovery after clearing for agriculture. Forest on more accessible land tends to be younger (Helmer, 2000; Rudel et al., 2000; Endress and Chinea, 2001; Etter et al., 2005). Meanwhile, land development in Puerto Rico is typical of other temperate and tropical landscapes. Closer proximity to existing urban areas or roads, larger size of nearby urban areas, lower elevations, gentler slopes, and more surrounding pasture are among the most important factors that predict the locations of land development (Helmer, 2004). Seasonal evergreen and evergreen forest by far undergoes the most clearing for land development, and the area of this forest type appears to have decreased slightly from 1991 to 2000. An explanation for this result is that this forest type surrounds the largest urban center as well most of the other major cities. Of the seasonal evergreen and evergreen forest, most of the forest cleared within this class is lowland seasonal evergreen forest, because it is at lower elevations, has gentler slopes, and is closer to the major urban centers than is evergreen forest. Only 0.5% of the Puerto Rico land area where lowland seasonal evergreen forest may occur is protected (Helmer et al., 2002; Helmer, 2004).

As for semi-deciduous and drought deciduous forest, it also undergoes substantial development, and only 1.8% of this forest type is protected. In addition, drought deciduous woodlands occur both on alluvial and volcanic substrates as well as on limestone substrates, but they are mainly on flat lands and gentle slopes. They also experienced substantial clearing for development (6.6% of all forest developed), but their total areas appear to have increased slightly from 1991 to 2000. While some wildlife species are more abundant in more mesic forests (J. Wunderle, pers. comm.), semi-deciduous and drought deciduous forests in Puerto Rico, and to some extent drought deciduous woodlands, provide important habitat for many wildlife species (Nellis, 1999; Faaborg et al., 2000).

Cloud forests, forested wetlands and serpentine forests. Mangroves, *Pterocarpus* swamp, cloud forests, and forests on serpentine geology are on lands that are among the least suitable for agricultural use. These forest types have the largest proportions of old forest, with 62 to 100% of their area in the oldest age class (55–64+

yr) in the year 2000 (Appendix A). These forests also tend to have the largest proportions of their area protected, and they underwent little or no urban development. Although only about 40% of mangroves on the main island of Puerto Rico are in reserve land, laws and regulations protect them, and little mangrove underwent development from 1991 to 2000. The critical importance of mangrove ecosystems to many aquatic and terrestrial species is well-known (e.g., Mumby et al., 2004; Hunt et al., 2005). Many large areas of mangrove forests are near urban centers and may still be under some development pressure, but total area of forested wetlands appears to have increased.

Forests on karst geology. Forests primarily on rugged karst geology underwent over 20% of the land development from 1991 to 2000. This result probably stems from the fact that unprotected forest on karst is adjacent to and within the two largest cities in Puerto Rico. In addition, karst lands undergo surface mining, and about 13% of the land development on karst forest lands was surface mining. Nevertheless, forest area on karst lands appears to have increased. In this study, we found that the karst forests are distinct from the other forests. They undergo substantial land development, but tend to be older. Forests on karst encompass much of the oldest forest on the island that is not protected. Forty percent or more of their area was relatively old forest, both in 1991 and in 2000. Only the driest of the karst forests, drought deciduous and mixed forest and shrublands (with or without succulents), has more than 50% of its area protected. In Hispaniola, this forest type provides important stopover habitat for Nearctic migrant birds (Latta and Brown, 1999). The other forest types on karst have 5 to 20% of their area protected. Most (62%) of the oldest forest that was cleared for development was drought deciduous and semi-deciduous forest on karst, followed by seasonal evergreen and evergreen forest on karst (13%), and then seasonal evergreen and evergreen forest (12%). Even though the karst lands are rugged, Helmer (2004) observed that steep topography appeared to be less inhibiting to land development in and near urban centers. The diversity of tree species in humid secondary forests of Puerto Rico, including those on karst, increases as these forests age (Aide et al. 2000; Chinea and Helmer 2003). Abundance of Nearctic migrant birds also tends to increase with canopy complexity in Caribbean forests (Wunderle and Waide, 1993; Latta et al., 2003). Consequently, older forest could have greater conservation value. Another point is that the most important bat habitat in Puerto Rico is in karst lands (Placer, 1998). In addition to species conservation, karst lands are important to water resources in Puerto Rico (Lugo et al., 2001), which is another reason why their land cover is important.

SUMMARY AND CONCLUSIONS

Decision tree classification of Landsat image mosaics developed with regression trees can result in fairly accurate maps of land cover, including more detailed forest classes than are typically mapped with satellite imagery over a large tropical study area with automated classification. As for land-cover changes in Puerto Rico from 1991–2000, several of the changes continue prior trends. These include urban expansion and transition of sugar cane, pineapple, and other lowland agriculture to pasture. Forest recovery continues, but it has slowed, and the changes in forest area vary between forest types. Forested wetland area appears to have increased slightly. The gains in emergent wetlands that began from 1977 to 1991 have remained, while sun coffee cultivation appears to have increased slightly.

Although forest area has increased 147% in Puerto Rico with the economic shift away from agriculture, unprotected forests near or within urban centers are vulnerable to urban development. When land development clears certain forest areas, it may impact sensitive ecosystems or old forests with specialized biological or water resource conservation value. Despite their ruggedness, for example, karst lands with little agricultural value that have older forests are quite vulnerable to land development.

Puerto Rico is no longer unique in its marked forest recovery, urban expansion and agricultural decline (Kauppi et al., 2006). On several other Caribbean islands, for example, the forest recovery and urban expansion that began just before 1951 in Puerto Rico is now observable (Helmer et al., unpubl. data). More recently, European and local governments have stopped many subsidies or price supports for bananas or sugar cane. Consequently, the trend away from agriculture and towards forest recovery and urban expansion will probably continue on these islands. These results can help us understand and predict the patterns of land development and forest recovery, and their implications for forest management and conservation, in Caribbean and other tropical landscapes.

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Appendix A. Forest Areas by Type in 1991 and 2000, and by Age Class in 2000[a]

Forest type	1991 user's accuracy, %	1991 producer's accuracy, %	2000 user's accuracy, %	2000 producer's accuracy, %	Puerto Rico area in 1991, ha	Puerto Rico area in 2000, ha	Vieques area in 1991, ha	Vieques area in 2000, ha	Culebra area in 1991, ha	Culebra area in 2000, ha	Age class 1 area (1–9 yr) in 2000, ha	Age class 2 area (10–22 yr) in 2000, ha	Age Class 3 area (23–49 yr) in 2000, ha	Age Class 4 area (50–64+ yr) in 2000, ha
Forest, forest/shrub, woodland and shrubland—lowland dry and dry/moist														
Drought deciduous open woodland[b]	83	76	52	89	6,429	5,813	2,079	2,033	705	478	3,894	1,107	581	232
Drought deciduous dense woodland[b]			76	76	3,389	7,202	2,107	2,781	432	575	3,892	1,249	1,291	770
Deciduous, evergreen coastal, and mixed forest or shrubland, with or without succulents	86	70	72	97	1,292	679	137	155	222	255	154	79	100	346
Semi-deciduous and drought deciduous forest on karst/other limestone[d]	83	76	91	75	20,837	23,581	333	318	0	0	3,956	1,834	8,084	9,616
Semi-Deciduous and Drought Deciduous forest[b]			57	65	24,086	27,080	4,341	3,272	842	607	8,794	5,687	10,974	1,626
Semi-deciduous and seasonal evergreen forest on serpentine, sclerophyllous	80	77	94	89	2,517	2,871	0	0	0	0	469	167	538	1,698
Forest and forest/shrub—lowland and submontane, moist and moist/wet														
Seasonal evergreen and evergreen forest	75	76	85	48	242,398	231,615	94	74	0	0	44,811	102,439	63,338	21,027
Seasonal evergreen forest with coconut palm	80	65	98	80	456	499	0	3	0	2	126	292	46	36
Seasonal evergreen and semi-deciduous forest on karst/other limestone[c]	75	91	88	71	45,809	51,195	0	0	0	0	11,785	5,116	13,660	20,633
Evergreen and seasonal evergreenforest on karst/other limestone[c]			72	97	7,512	7,949	0	0	0	0	864	640	2,151	4,294

(*Table continues*)

Appendix A. (*Continued*)

Forest type	1991 user's accuracy, %	1991 producer's accuracy, %	2000 user's accu-racy, %	2000 producer's accuracy, %	Puerto Rico area in 1991, ha	Puerto Rico area in 2000, ha	Vieques area in 1991, ha	Vieques area in 2000, ha	Culebra area in 1991, ha	Culebra area in 2000, ha	Age class 1 area (1–9 yr) in 2000, ha	Age class 2 area (10–22 yr) in 2000, ha	Age Class 3 area (23–49 yr) in 2000, ha	Age Class 4 area (50–64+ yr) in 2000, ha
Forest and forest/shrub–submontane and lower montane, moist/wet/rain														
Evergreen forest on serpentine, sclerophyllous	90	53	84	100	6,276	6,139	0	0	0	0	169	796	1,139	4,034
Elfin, sierra palm, transitional, and tall cloud forest	75	96	73	100	23,294	23,101	0	0	0	0	1,091	3,614	3,867	14,528
Forested wetland														
Mangrove	75	88	82	87	7,100	7,261	286	285	54	64	0	0	0	7,261
Seasonally flooded savannas and woodland[d]	na	na	na	na	581	738	0	0	0	0	404	142	147	45
Seasonally flooded evergreen forest (*Pterocarpus* swamp)	78	90	78	100	254	232	0	0	0	0	19	6	43	164

[a]User's and producer's accuracies for the 1991 and 2000 classifications of Purto Rico, Vieques, and Culebra are also included. Puerto Rico areas include the islands of Icacos, Piñero, Palominos, Caja De Muertos, and other surrounding islets. Shaded accuracies were combined in the accuracy assessment for 1991. Small changes in the area between 1991 and 2000 may stem in part from differences between the classifications.
[b]Drought deciduous open woodland, drought deciduous dense woodland, semi-deciduous, and drought deciduous forest on karst/other limestone, and semi-deciduous and drought deciduous forest land cover classes combined in 1991 accuracy assessment.
[c]Seasonal evergreen and semi-deciduous forest on karst/other limestone, and evergreen and seasonal evergreen forest on karst/other limestone land cover classes combined in 1991 accuracy assessment.
[d]Land cover class manually delineated and not included in accuracy assessment.

Appendix B. Non-forest Classes and Area Totals including User's and Producer's Accuracies, for the 1991 and 2000 Puerto Rico, Vieques, and Culebra Classifications[a]

Non-forest type	1991 user's accuracy, %	1991 producer's accuracy, %	2000 user's accuracy, %	2000 user's accuracy, %	Puerto Rico area in 1991, ha	Puerto Rico area in 2000, ha	Vieques area in 1991, ha	Vieques area in 2000, ha	Culebra area in 1991, ha	Culebra area in 2000, ha
Urban or built-up land										
High-medium and low-medium density urban[b]	80	77	83	72	117,618	127,846	613	693	113	296
Agricultural land										
Herbaceous agriculture—cultivated lands[c]	67	88	98	94	29,377	9,684	0	0	0	0
Coffee and mixed woody agriculture	70	36	51	100	14,063	19,199	0	0	0	0
Pasture, hay, or inactive agriculture (e.g., abandoned sugar cane)[c]	67	88	87	100	21,889	19,481	0	0	0	0
Pasture, hay, or other grassy areas	47	44	83	44	274,500	281,151	2,799	3,252	454	545
Non-forested and wetland										
Emergent wetlands including seasonally flooded pasture and freshwater ponds	78	81	94	87	6,457	6,405	0	0	0	0
Salt or mud flats	82	62	96	96	610	739	133	110	0	0
Tidally flooded evergreen dwarf-shrubland and forb vegetation	82	64	96	100	63	103	0	0	0	0
Quarries	74	52	100	94	295	299	0	0	0	0
Coastal sand and rock[d]	na	na	na	na	1,799	2,032	278	231	122	116
Bare soil (including bulldozed land)	66	70	82	75	6,905	7,280	149	179	19	17
Water (permanent)	78	84	86	94	6,788	8,361	132	117	44	35

[a]Puerto Rico includes Icacos, Piñero, Palominos, Caja De Muertos, and other surrounding islets. Shaded values represent land cover classes combined in accuracy assessment.
[b]High-medium density urban and low-medium density urban land cover classes combined in 1991 and 2000 accuracy assessment.
[c]Herbaceous agriculture–cultivated lands, and pasture hay or inactive agriculture (e.g., abandoned sugar cane) land cover classes combined in 1991 accuracy assessment.
[d]Land cover class manually delineated and not included in accuracy assessment.