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Development of a Landforms Model for Puerto Rico and its Application for Land Cover Change Analysis

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ABSTRACT.—Comprehensive analysis of land morphology is essential to supporting a wide range environmental studies. We developed a landforms model that identifies eleven landform units for Puerto Rico based on parameters of land position and slope. The model is capable of extracting operational information in a simple way and is adaptable to different environments and objectives. The implementation of the landforms model for land cover change analysis represents an advanced step towards understanding the expansion of urban areas and forest cover in Puerto Rico between 1977 and 1994. Expansion of urban areas has typically been associated with low and flat topographies. Forest recovery, on the other hand, has been associated with high elevations and steep slopes. Our study revealed that (1) nearly half of new developments occurred outside the plains, (2) almost all new forests occurred in mountain regions (but not on the steepest slopes), and (3) there are transitional and very dynamic landforms (the side slopes) that experience both important land development and forest recovery. Finally, we present additional examples of the landforms model applications, including vegetation mapping, physiography, and the modeling of vertebrate habitat distributions.

KEYWORDS.—Landforms, land cover change, urban expansion, forest recovery, Puerto Rico, Caribbean

INTRODUCTION

Landforms are features or forms of the Earth's surface. They result from interactions among underlying rock layers, tectonic forces, climate, and human activities. It is notable that landforms also play important roles in defining landscape processes. Consequently, landform significance has been considered, directly or indirectly, in many environmental studies (Moore et al. 1991) with respect to ecosystem classification (Whittaker 1962; Barnes et al. 1982; Host and Pregitzer 1992; Abella et al. 2003), soil erosion (Willgoose et al. 1989; Dikau et al. 1991), identification of watersheds (Band 1986), topoclimates (Geiger 1971), ground water vulnerability (Fels and Matson 1996), and land cover change (Ramos, 2001; Lopez et al. 2001). Additionally, the extensive literature on relationships of vegetation to climate, substrate, and topography makes landforms a useful resource for the study of plant community distribution (Fels 1994, Wondzell et al. 1996; Iverson et al. 1997), assessment of site productivity (McNab 1993), and vegetation mapping efforts (Fels 1994, Dyamond et al. 1995; USFS 1995; Burrough et al. 2001; Manis et al. 2001; Gould et al. 2003).

The rugged topography of Puerto Rico is characterized by elevations up to 1300 meters, a great variety of substrates and vegetation (Holdridge 1967; Ewel and Whitmore 1973), frequent floods and landslides (Brokaw and Walker 1991), and intense human activity. Thus, the development of a landforms model may prove useful in a variety of developmental and/or conservation applications.

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In this paper we develop a base model of landforms for Puerto Rico using parameters derived from a digital elevation model (DEM). We then use the landforms to assess land cover change (LCC) in Puerto Rico between 1977 and 1994; specifically, the expansion of both urban areas and forest cover. Finally, we introduce other current applications of the model, including those of physiographical mapping, plant community mapping, and evaluation of vertebrate habitat distribution.

Classifying land morphology

Several parameters hare typically used to describe the morphology of land surfaces. These include, among others, altitude (Evans 1972), slope (Dole and Jordan 1978, Papo and Gelman 1984), relief (Elghazali and Hassan 1986), land position (LPOS) (Fels 1994), and landforms or terrain units (Zevenbergen and Thorne 1987; Skidmore 1990; Irwin et al. 1997; MacMillan et al. 2000), With the advances in Geotechnologies and the increasing accessibility of digital elevation models (DEMs), those variables have been integrated into GIS-based models and thus provide a practical interface for processing and managing spatial data. Examples of these GIS models include Ecological Land Units (ELU) (The Nature Conservancy, unpublished), Ecologically Predictive Landforms Classes (Manis et al. 2001), Arc-Evolve (Boggs et al. 2001), TopoMetrix[1], LANDFORM classifier (Klingseisen 2004), and WILSIM simulator[2].

The descriptive parameter of land position LPOS by Fels (1994), also referred to as topographic position or slope position, has proven useful in a variety of environmental applications (USFS 1995; Fels and Matson 1996, Miller 2005, Topometrix, TNC unpublished). The distinction of LPOS is that it focuses on revealing the location of a map cell relative to the surrounding map cells. For instance, a map cell might be at the ridge top, at the slope bottom, or somewhere in between. In complex topographies, this simple distinction is impossible to make by using only elevation and/or slope. For example, a map cell with elevation = 200m in an area with gentle slope might be near the slope bottom for a high mountain but near the top of smaller hills. In addition, the combination of LPOS with the slope parameter has shown itself to be practical for identifying a great variety of landforms (TNC unpublished).

Recent land cover change in Puerto Rico

During the second half of the 20th century, the Puerto Rican land cover has experienced intensive change. In the late 1940s, the Puerto Rican economy changed from one of agriculture to one of industry (Dietz 1986). The rural population, originally distributed all over the island and associated with agricultural practices, abandoned the lands and concentrated in the coastal lowlands, where industrial activities take place. As a result, the following three tendencies of LCC occurred on the island: 1) decrease of agricultural lands, 2) increase of forest cover over abandoned lands, and 3) rapid expansion of urban areas. The total island forest cover increased from less than 10% in the 1940s (Franco et al. 1997) to 41% in 1991 (Helmer et al. 2002). These new forests recovered over abandoned pastures, coffee plantations, and other agricultural lands. This was especially the case at high elevations, on steep slopes, within reserves, away from roads, and in small farm areas located near preexisting forests (Franco et al. 1997; Rudel et al. 2000; Ramos Gonzalez 2001; Helmer 2004, Lugo and Helmer 2004). On the other hand, urban areas have expanded rapidly at lower elevations, on flat topography, and closer to existing urban areas and roads (Thomlinson et al. 1996; Thomlinson and Rivera 2000; Lopez et al. 2001; Helmer 2004). Land cover change in Puerto Rico has been typically evaluated through overlaying land cover maps from different years. Although LCC has been related to topography, those analyses were generalized associations with elevation or slope (Lopez et al. 2001, Ramos Gonzales 2001). We believe the identification of land-

[1] http://www.undersys.com/topometrix.html
[2] http://www.graphics.cs.niu.edu/projects/wilsim.html

form units might improve the understanding of the spatial trends in land cover change.

In this study we develop a landform base-model for Puerto Rico by integrating parameters of land position (Fels 1994) and slope. We subsequently use landforms for evaluating the expansion of urban areas and forest land-cover between 1977 and 1994. Ultimately, we use the obtained data to answer the following three questions: 1) how have the plains been transformed?, 2) did the forest expand equally under different topographic situations?, and 3) what are most dynamic landscapes in terms of land conversion?

MATERIALS AND METHODS

(1) Development of the landform model

LPOS is an index that uses a digital elevation model to calculate elevation differences between two points within a specific radius (Fels 1994). The resulting LPOS value for any pixel is a number (positive, negative, or cero) without units. Positives LPOS imply lower topographic positions (i.e. proximal to streams) and negatives LPOS values imply higher landscape positions (i.e. ridges, summits), while values approaching zero indicate both mid-slope position and areas with minimal relief (Fig. 1). LPOS is calculated by the formula:

LPOS = [∑1, n (En-E0)/d]/n, where

E0 = elevation of the model point under evaluation

En = elevation of a surrounding model point

d = horizontal distance between the two model points

n = the total number of surrounding points employed in the evaluation.

The parameter "d", or radius of search, depends on the study area and should be equal to one-half of the fractal dimensions of the landscape (i.e. one half of the mean ridge-to-stream distance) (Fels, 1994).

We based our application in a 30-meter pixel DEM from the USGS for Puerto Rico and its satellite islands (Culebra, Vieques, Mona, Monito, and Desecheo). Estimation of the parameter "d" was done by superimposing the hydrology layer (from the Puerto Rico Planning Board) over the shaded relief (from the DEM), which helped visualize and calculate the distance between the ridge and stream for different locations. The mean of these measurements was equal to 11 pixels (or 336 meters).

Landforms were identified by combining LPOS and slope in a crosswalk table that uses the TNC approach as base schema (Fig. 2a) and is modified to best fit the local landscape. Ranges of LPOS were established by natural breaks (as in the original document) and adjusted in an attempt to maintain similar distance to the 0 value. Additionally, four (instead of three) breaks in the slope were established based on expert opinion. In total, eleven landforms were identified (Fig. 2b). ArcView GIS 3.2 Spatial Analysis Extension was used to develop the landform model.

(2) Analysis of land cover change

In this step we evaluated the total extent of changes in urban areas and forests between 1977 and 1992-94 for each landform. We present the results from the following two complementary perspectives: (1) analysis of how the extent of urban and

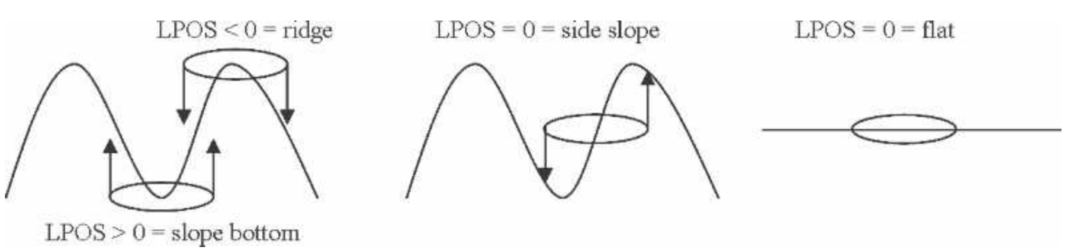

FIG. 1. Land position value (LPOS) for different situations along a slope (Source: TNC unpublished).

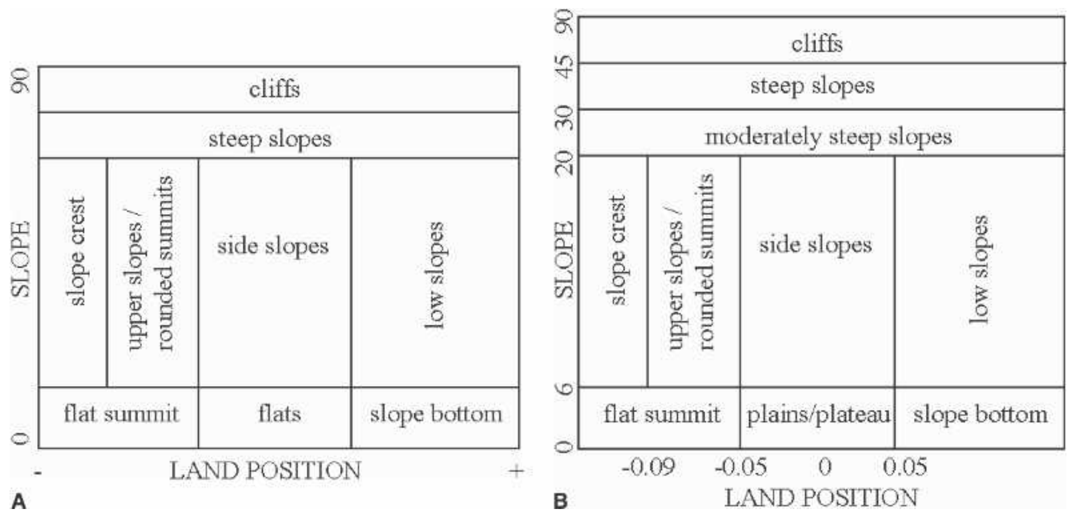

FIG. 2. Relationship between land position and slope parameters for the identification of landform units. 2a) TNC's base approach. 2b) Resulting relationships for Puerto Rico.

forest areas has changed across the landforms, and (2) analysis of how the landforms have changed as a result of the land cover.

For the purpose of this study we first simplified the analysis through classifying landforms as belonging to one of 6 major categories by combining some of the original classes but while also maintaining a detailed description of the landscape.

Urban areas from 1977 and 1994 were extracted from López et al. (2001). They were mapped by visual interpretation of Spot satellite imagery and aerial photography. The forest cover from 1977 and 1992 were extracted from Ramos and Lugo (1994) and Helmer et al. (2002) respectively. The forest cover includes all classes dominated by forest and shrubland excluding those that are part of the agricultural lands such as coffee plantations. Contrary to the urban areas, forests were mapped using different methods. Forests from 1977 were mapped by visual interpretation of aerial photography while those from 1991 were mapped by semiautomatic classification of Landsat imagery. Although these layers were obtained through different techniques, their quality was still accurate for purposes of comparison. Moreover, as we did not overlay them, the potential problems due to differences in methodology were avoided. The land cover change analysis was conducted only for the main island of Puerto Rico due to the absence of land cover data for the other islands. We used ERDAS IMAGINE 8.7 software to to obtain these data.

RESULTS

The LPOS model used in conjunction with slope parameter made it possible to identify eleven different landforms in Puerto Rico, including the plains, 6 slope types (slope bottoms, low slopes, side slopes, moderately steep slopes, steep slopes, upper slopes/rounded summit, slope crests, cliffs, and flat summits. The plateau, an exclusive landform of Mona Island (Kaye, 1959), was separated manually from the plains (Fig. 2b and Fig. 3).

The group of "slopes" covers 63.4% of Puerto Rico. The most abundant slope types are the side and moderately steep forms. Plains cover 31.6% of the island. Consequently, from a total of eleven landforms, three of these (i.e., side slopes, moderately steep slopes, and plains) comprise almost three quarters of the island's area (Fig. 4).

The landforms map provides a detailed classification of the land surface that helps

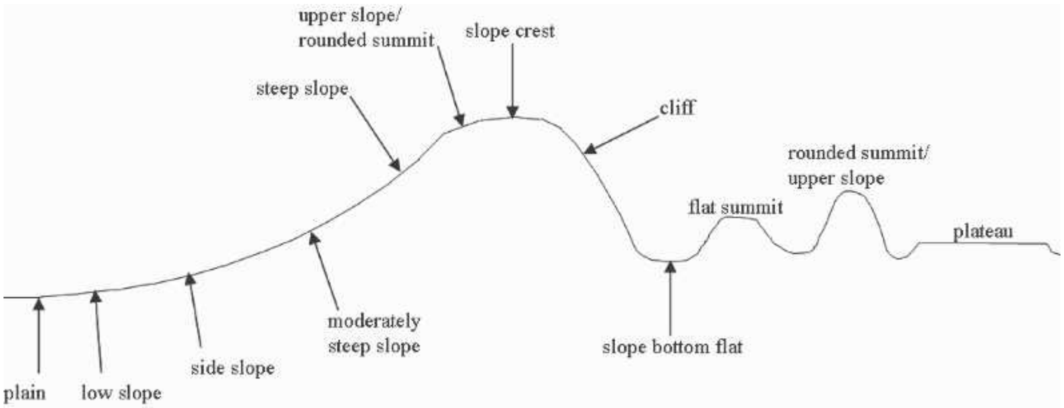

FIG. 3. Location of the different landforms across the landscape. Slope values are in real scale (adapted from TNC).

Landform type		Ha	%	
plains		282077	31.6	
slopes	slope bottoms	16258	63.4	1.8
	low slopes	71869		8.0
	side slopes	241016		27.0
	upper slopes	40802		4.6
	moderately steep slopes	151245		16.9
	steep slopes	45445		5.1
slope crests		28433	3.2	
cliffs		1233	0.1	
flat summits		10416	1.2	
plateau		4831	0.5	
Total		893624	100.0	

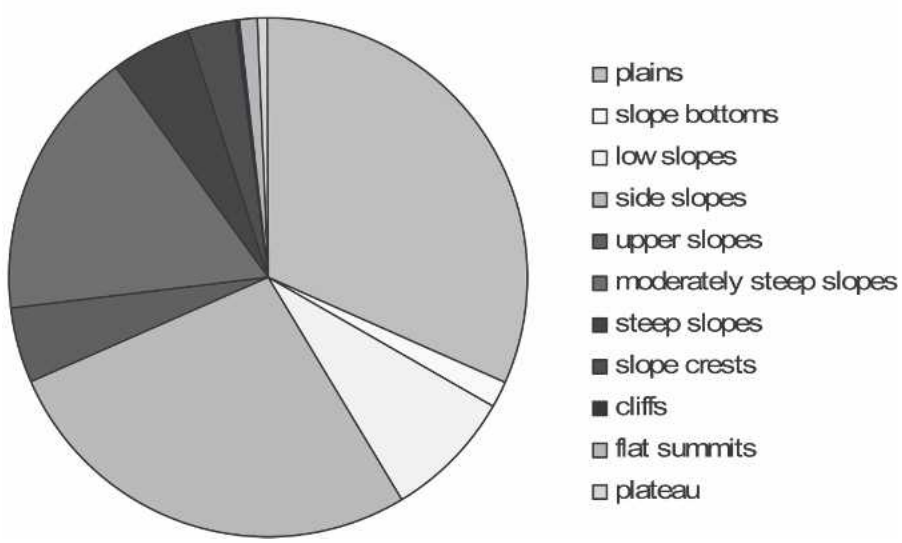

FIG. 4. Extent and proportion of the landforms in Puerto Rico.

identify and visualize fine topographic features. Even small changes in topography are reflected in the landforms. For example, in the northern limestone, the mogotes (i.e., steep-side hills rising out of the surrounding plains (Monroe 1980b)) appear as individual units in the map, separated from the plains. The different parts of the mogotes, the top, side, and valley, are also discernible. The limit between the limestone belt and the central mountains is easy to identify as it reflects a significant change in geology. The model is not only able to distinguish among large, visible physiographic units such as the Luquillo Mountains, Sierra de Panduras, the karst region, but it can also identify smaller units, such as Sierra Bermeja or single mogotes. It therefore captures the distinctive group of landforms occurring in an area and makes it possible to separate those units from the surroundings. In this way, for example, it is possible to visualize internal features such as valleys, different types of slopes, peaks, and lineaments (Fig. 5).

Analysis of LCC (Table 1)

Changes in forest cover.—Between 1977 and 1992 the forest cover increased in 20%, or 60,000 ha, from nearly 306,000 ha to 366,000 ha. This expansion affects all landforms. The greatest increases occurred in mountains, on side slopes (19,000 ha), and on moderately steep slopes (near 17,000 ha). Conversely, the smallest increases occurred in the coastal plains and in the steepest lands (3000 ha each). The rate of forest expansion followed similar trends, with lower rates observed in plains and steep slopes (8% and 11% respectively) and higher ones noted in other mountainous landforms (21% to 26%).

Changes in urban cover.—Between 1977 and 1994 the urban areas increased in 27%, or 27,000 ha, from 98,000 ha to nearly 125,000 ha. Among these, nearly half of the new developments (i.e., 14,000 ha) occurred in the plains while the remaining 13,000 ha occurred in non-plain landforms, particularly side slopes (8,000 ha). The rate of urban expansion in the plains was 23%, but this was lower than observed for any mountain landform (30% to 37%).

Changes per landform unit.—Changes in forest and urban land cover affected between 6.1% and 13.6% of each landform. The majority of these changes occurred in side slopes (31.4% of the total), moderately steep slopes (21.1%), and plains (19.3%).

In the plains, changes were primarily related to the expansion of urban areas. Fifty two percent of the new developments occur in the plains while only 5% of the new forests occur in this landform. As a result, 6.1% of the coastal plains were transformed during the 1977-1994 period. At the same time, the plains reported the lowest rates of urban growth and forest expansion when compared to other landforms.

The mountainous landforms made up 95% of the new forests and 48% of the new developments. The side slopes were the only landforms with significant increases in both forests and urban areas. As a result, 11.7% of their area was transformed due to changes in land cover. In the other mountainous landforms the percentage of change ranged from 7.7% to 13.6% and was primarily determined by forest recovery.

Additional uses of the landform model[3]

(1) Mapping the physiography of Puerto Rico

The landforms information was combined with elevation data, geologic maps, and expert opinion in order to develop a new physiographical map for Puerto Rico. Three major physiographic units where identified, including 1) plains (corresponding to the landform with the same name), 2) hills (groups of non-plain landforms that form a distinguishable unit or feature with elevation below 400 meters), and 3) mountains (groups of non-plain landforms that form a distinguishable unit or feature with elevation above 400 meters). At the same time, minor units within plains, hills, and mountains were named according to the bibliography and expert opinion.

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[3] These applications are part of the current research by the Puerto Rico Gap Analysis Project. For more information please contact the authors of the paper.

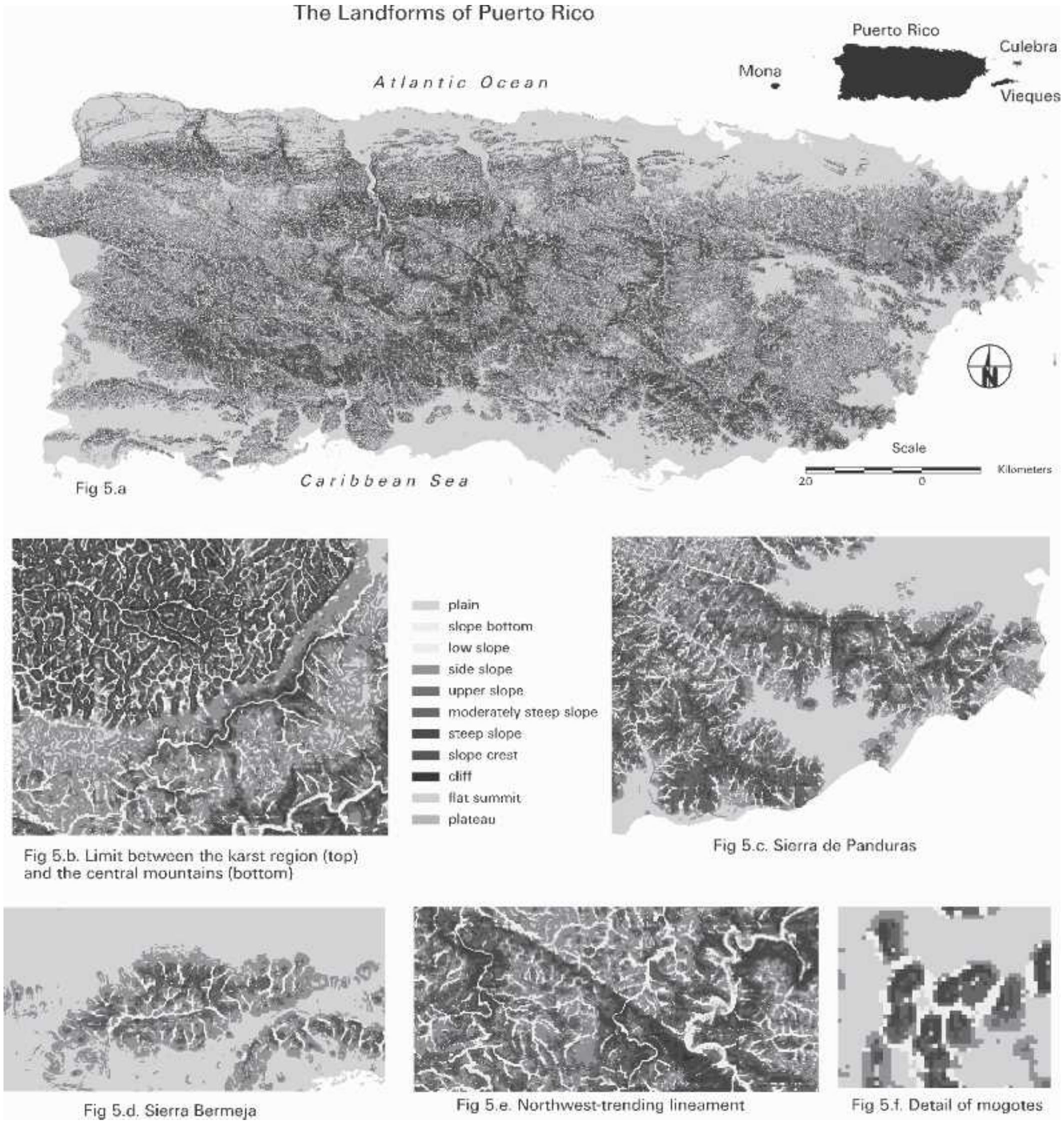

FIG. 5. View of the landform units in different regions of the island.

(2) Vertebrate habitat modeling

Modeling the distribution of vertebrate species requires a detailed characterization and mapping of their habitats. The landforms represent a useful layer that can be combined with other environmental variables for better predicting species distribution. For example, in the case of two species of frogs occurring in forested narrow valleys or ridges, the forest cover was intersected with the corresponding landforms, thereby making it possible to obtain accurate maps of their habitat's distribution.

(3) Vegetation mapping

In the northern karst region, characterized by the presence of mogotes, the landforms were used to separate the vegetation of mogote valleys, sides, and tops. In the Guanica dry forest of southern Puerto Rico,

TABLE 1. Summarized land cover change analysis. The six landforms used in the analysis resulted from the combination of some of the original classes as follow: 1 plains (no change), 2 low slopes (low slope + slope bottom flat), 3 side slopes (no change), 4 moderately steep slopes (no change), 5 steep slopes (steep slope + cliff), and 6 ridges (upper slope + slope crest + flat summit).

Forest recovery		Forest land cover 1977		Forest land cover 1992		Change 1977-1992		
Landform		Ha	%	Ha	%	Ha	% of the total change	Rate of forest expansion (in %)
Plains		38464	13	41502	11	3038	5	8
Slopes	Low slopes	38860	13	47815	13	8954	15	23
	Side slopes	80384	26	99315	27	18931	31	24
	Moderately steep slopes	81693	27	98850	27	17157	28	21
	Steep slopes	31587	10	35025	10	3438	6	11
Ridges and upper slopes		34909	11	43813	12	8904	15	26
Total		305897	100	366319	100	60422	100	20

Urban recovery		Urban land cover 1977		Urban land cover 1994		Change 1977-1994		
Landform		Ha	%	Ha	%	Ha	% of the total change	Rate of urban expansion (in %)
Plains		60409	62	74153	59	13744	52	23
Slopes	Low slopes	4394	4	5707	5	1313	5	30
	Side slopes	23977	24	32412	26	8435	32	35
	Moderately steep slopes	3494	4	5051	4	1257	5	33
	Steep slopes	397	0	542	0	145	1	37
Ridges and upper slopes		4996	5	6765	5	1768	7	35
Total		97968	100	124628	100	26661	100	27

Changes per landform				Forest recovery 1977-1992		Urban expansion 1997-1994		Total change		
Landform		Ha	%	Ha	% of the landform	Ha	% of the landform	Ha	% of the landform	% of the total changes
Plains		274077	31	3038	1.1	13744	5.0	16782	6.1	19.3
Slopes	Low slopes	87559	10	8954	10.2	1313	1.5	19267	11.7	11.8
	Side slopes	234498	27	18931	8.1	8435	3.6	27366	11.7	31.4
	Moderately steep slopes	150338	17	17157	11.4	1257	0.8	18414	12.2	21.1
	Steep slopes	46733	5	3438	7.4	145	0.3	3583	7.7	4.1
Ridges and upper slopes		78286	9	8904	11.4	1768	2.3	10672	13.6	12.3
Total		871490	100	60422	6.9	26661	3.1	87083	10.0	100.0

the landforms were used for identifying patches of evergreen forest located in narrow valleys.

DISCUSSION

Comprehensive analysis of surface landforms creates a foundation of information that can assist in a variety of research and planning efforts. Thus, there is an increased demand for topographic and DEMs data combined with an increased demand for improved tools that are capable of extracting operational information in a simple and flexible way.

The development of a landform model using parameters of land position by Fels (1994) and slope represents an advanced step in the characterization of the land surface. This methodology has advantages over generalized characterizations that use only single variables, such as elevation or slope. In landscapes, such as those of Puerto Rico, that are characterized by complex topography, vegetation, and intense human influence, the identification of landform units has proven practical towards obtaining two goals: 1) a better understanding of land cover changes, and 2) environmental assessment, including vegetation mapping, physiography, and modeling of vertebrate habitat distributions.

A key characteristic of the landform model presented in this study is its adaptability. Depending on the objectives and the study area, landform units can be merged, ranges of land position and slope can be adjusted, and final products can be combined with other data (such as geology, climate, soil moisture, etc.). Although we established the parameters with respect to the island of Puerto Rico, the same settings might also function when similarly applied to the remainder of the Antilles.

Relating landforms to land cover change allowed us to better interpret the spatial trends in land transformation related to urban and forest expansion in Puerto Rico during the period 1977-1994. It also provides an innovative mechanism for understanding how humans and nature interact on the island. In addition, these correlations yield useful data for modeling future trends.

The key findings of this study can be summarized as follows:

1) Almost half of the new developments (48%) occurred outside of the plains. The rate of urban expansion for any mountainous landform was higher than in the plains.
2) Ninety-five percent of the new forests occurred in mountainous landforms (mainly in side slopes and moderately steep slopes) while only five percent were in the plains.
3) The most dynamic landforms, in terms of land cover change, were the side slopes areas, characterized by gentle slopes and minimal relief.
4) The steepest areas experienced low rates of forest recovery; probably because these areas were already forested in 1977.

The expansion of urban areas in Puerto Rico has typically been associated with lower elevations, flat topographies, and proximity to existing developments and roads. Forest recovery, on the other hand, has been associated with high elevations and steep slopes. The incorporation of landforms into the analysis of LCC reflected that there exist transitional areas, the side slopes, which have experienced both important land development and forest recovery over the time period extending from 1977 to 1995. Since these types of areas relate to landscape fragmentation, habitat loss, soil erosion, and introduction of exotic species (Radeloff et al. 2005), identification of these areas represents an additional advance in the analysis of human-environmental conflicts.

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Literature Cited

Abella, S. R., V. B. Shelburne, and N. W. MacDonald. 2003. Multifactor classification of forest landscape ecosystems of Jocassee Gorges, southern Appalachian Mountains, South Carolina. *Can. J. For. Res.* 33:1933-1946.

Band, L. E. 1986. Topographic partitioning of Watersheds with digital elevation models. *Water Resources Res.* 22:15-24.

Barnes, B. V., K. S. Pregitzer, T. A. Spies, and V. H. Spooner. 1982. Ecological forest site classification. *Journal of Forestry.* 80:493-498.

Briere, P. R., and K. M. Scanlon. 2000. Lineaments and lithology derived from a side-looking airborne radar image or Puerto Rico. In *Puerto Rico--marine sediment database, terrestrial and sea-floor imagery and tectonic interpretations*: U.S. Geological Survey Open-File Report 00-006.

Boggs, G. S., K. G. Evans, and C. C. Devonport. 2001. ArcEvolve: A Suite of GIS Tool for Assessing Landforms evolution. *Proceedings of the 6th International Conference on GeoComputation*. University of Queensland, Brisbane, Austria, 24-26 September.

Brackney, E. S., and M. D. Jennings, editors. 2003. Gap

Analysis Bulletin No. 12. USGS/BRD/Gap Analysis Program, Moscow, Idaho.

Brokaw, N. L. V., and L. R. Walker. 1991. Summary of the effects of Caribbean hurricanes on vegetation. *Biotropica* 23:442-447.

Burrough, P. A., P. S. Wilson, P. F. M. van Gaans, and A. J. Hansen. 2001. Fuzzy k-means classification of topo-climate data as an aid to forest mapping in the Greater Yellowstone Area, USA. *Landscape Ecology* 16:523-546.

Dalrymple, J., R. Long, and A. Conacher. 1968. A hypothetical nine-unit land-surface model. *Zeitschrift fur Geomorphologie* 12:60-76.

Dietz, J. L. 1986. *Economic History of Puerto Rico*. Princeton (N.J.): Princeton University Press.

Dikau, R. 1990. Digital relief models in landform analysis. In *GIS: Three Dimensional Applications in Geographic Information Systems*, ed J. Raper 51-57.

Dikau R., E. E. Brabb, and R. M. Mark. 1993. Morphometric landforms analysis of New Mexico. In: Advances in Geomorphometry, Proc of the Walter F Wood memorial symp. 3rd International Conf on Geomorphology, Mc Master University, Hamilton, Ontario, pp 109-126.

Dole, W. E., and N. F. Jordan. 1978. Slope mapping. *The American Association of Petroleum Geologists Bulletin* 62:2427-2440.

Dymond, J. R., R. C. DeRose, and G. R Harmsworth. 1995. Automated mapping of the land component from digital elevation data. *Earth Surface Processes and Landform* 20:131-137.

Elghazali, M. S., and M. M. Hassan. 1986. A simplified terrain relief classification from DEM data using finite differences. *Geo Processing* 3:167-178.

Evans, I. S. 1972. General geomorphometry, derivation of altitude, and descriptive statistics. In *Spatial Analysis in Geomorphology*, ed R. J. Chorley. London: Methuen & Co. Ltd. 17-90.

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.

Fels, J. E. 1994. Modeling and Mapping Potential Vegetation using Digital Terrain Data: Applications in the Ellicott Rock Wilderness of North Carolina, South Carolina and Georgia. Raleigh, NC: North Carolina State University. Ph.D. dissertation.

Fels, J. E., and K. C. Matson. 1996. A cognitively based approach for hydrogeomorphic land classification using digital terrain models. In Proceedings of the 3rd International Conference/Workshop on Integrating GIS and Environmental Modeling, 21-25 January 1996, Santa Fe, NM National Center for Geographic Information and Analysis, Santa Barbara, California. [CD-ROM].

Franco, D. R., P. L. Weaver, and S. Eggen-McIntosh. 1997. Forest resources of Puerto Rico, 1990. Ashvile (N.C.): U.S. Department of Agriculture, Forest Service, Southern Research Station, *Resource Bulletin SRS-22*.

Geiger, R. 1971. *The climate near the ground*. Harvard Univ. Press, Cambridge, 61 pp.

Gould, W. A., M. Raynolds, and D. A. Walker. 2003. Vegetation, plant biomass, and net primary productivity patterns in the Canadian Artic. Journal of Geophysical Research 108:1-14.

Helmer, E. H., O. R. Ramos-Gonzales, T. M. Lopez, M. Quinones, and W. Diaz. 2002. Mapping forest type and land cover for Puerto Rico, a component of the Caribbean biodiversity hotspots. *Caribbean Journal of Science* 38:165-183.

Helmer, E. H. 2004. Forest Conservation and land development in Puerto Rico. *Landscape Ecology* 19:29-40.

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

Host, G. E., and K. S. Pregitzer. 1992. Geomorphic influences on ground-flora and overstory composition in upland forests of northwestern lower Michigan. *Can. J. For. Res.* 18:659-668.

Iverson, L. R., M. E. Dale, C. T. Scott, and A. Prassad. 1997. A GIS-derived integrated moisture index to predict forest composition and productivity of Ohio forests (U.S.A.). *Landscape Ecology* 12:331-348.

Irwin, B. J., S. J. Ventura, and b. K. Slater. 1997. Fuzzy and isodata classification of landform elements from digital terrain data in Pleasant Valley, Wisconsin. *Geoderma* 77:137-154.

Kaye, C. A. 1959. Geology of Isla Mona, Puerto Rico, and notes on the age of the Mona Passage: *U.S. Geological Survey, Professional Paper 317C*: 141-178.

Klingseisen, B. 2004. GIS based generation of topographic attributes for landform classification. Diploma thesis. University of Applied Sciences, School of Geoinformation, Viallch, Austria, 122 pp.

Lopez, 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.

Lugo, A. E., and E. H. Helmer. 2004. Emerging forests on abandoned land: Puerto Rico's new forests. *Forest Ecology and Management* 190:145-161.

MacMillan, R. A, W. W. Pettapiece, S. C. Nolan, and T. W. Goddard. 2000. A generic procedure for automatically segmenting landforms into landforms elements using DEMs, heuristics rules and fuzzy logic. *Fuzzy Sets and Systems* 13(1):81-109.

Manis, G., J. Lowry, and R. D. Ramsey. 2001. Preclassification: An Ecological Predictive Landform Model. *Gap Analysis Bulletin* 10:11-13.

McNab, W. H. 1993. A topographic index to quantify the effect of mesoscale landform on site productivity. *Canadian Journal of Forest Resources* 23:1100-1107.

Miller. J. 2005. Incorporating Spatial Dependence in Predictive Vegetation Models: Residual Interpolation Methods. *The Professional Geographer* 57:169-184.

Moore, I. D., R. B. Glayson, and A. R. Ladson. 1991. Digital terrain modeling: a review of hydrological, geomorphological and biological applications. *Hydrological Processes* 5:3-30.

Papo, H. B., and E. Gelman. 1984. Digital terrain models for slopes and curvatures. *Photogrammetric Engineering and Remote Sensing* 50:695-701.

Radeloff, V. C, Hammer, R. B., Stewart, S. I., Fried, J. S., Holcomb, S. S., and McKeefry, J. F. 2005. The Wildland-Urban interface in the United States. *Ecological Applications* 15(3):799-805.

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

Ramos Gonzales, O. M. 2001. Assessing Vegetation and Land Cover Changes in Northeastern Puerto Rico: 1978-1995. *Caribbean Journal of Sciences* 37(1-2):95-106.

Rudel, T. K., M. Perez-Lugo, and H. Zichal. 2000. When fields revert to forests: Development and spontaneous reforestation in pos-war Puerto Rico. *Professional Geographer* 52:386-397.

Skidmore, A. K. 1990. Terrain position as mapped from gridded digital elevation data. *International Journal of Geographic Information Systems* 4:375-387.

Thomlinson, J. R., M. I. Serrano, T. del M. Lopez, T. M. Aide, and J. K. Zimmerman. 1996. Land-use dynamics in a post agricultural Puerto Rican landscape (1936-1988). *Biotropica* 28:525-536.

Thomlinson, J. R., and L. Rivera. 2000. Suburban growth in Luquillo, Puerto Rico: Some consequences of development on natural and seminatural systems. *Landscape and Urban Planning* 49:15-23.

USFS. 1995. Ecological Classification, Mapping, and Inventory for the Chattooga River Watershed. Atlanta, GA: US Forest Service, Southern Region, Chattooga Ecological Classification Team. *Draft report*.

Willgoose, G. R., R. L. Bras, and I. Rodriguez Iturbe. 1989. A physical based channel network and cathment evolution model. TR 32. Ralph M. Parsons Laboratory, Massachusetts Institute of Technology, Cambridge.

Whittaker, R. H. 1962. Classification of Natural Communities. *Bot. Rev*. 28:1-239.

Wondzell, S. M., G. L. Cunningham, and D. Bachelet. 1996. Relationships between landforms, geomorphic process, and plant communities on a watershed in the northern Chihuahuan Desert. *Landscape Ecology* 11(6):351-362.

Zevenbergen, L. W., and C. R. Thorne. 1987. Quantitative analysis of land surface topography. *Earth Surface Processes and Landforms* 12:47-56.