THE STUDY OF LAND COVER CHANGE IN A CARIBBEAN LANDSCAPE:

What Has Happened in Eastern Puerto Rico During the Last Two Decades?*

— *Tania del Mar López Marrero*

Abstract...

Rapid rates of land cover change and their impacts in natural resources raise a variety of environmental and land-management policy issues. However, research concerning the spatio-temporal patterns of land cover change and their explanations are usually unknown by large sectors of the society. This study elaborated about such a research area, and used Puerto Rico as a case study to describe the spatio-temporal patterns of land cover change in the eastern portion of the Island between 1977 and 1995. Analysis of land cover maps revealed the dynamism of the region's landscape during the period of study. The most dramatic change was a 73% increase in urban land cover change, where urban expansion occurred mostly at the expense of pasture/agriculture land and to a lesser extent at the expense of woody vegetation. The underlying social, economic, political and environmental drivers of land cover change were discussed. These included, among other factors,

* This study was conducted as a part of the author's Master Thesis in Geography from the Pennsylvania State University, and of a research project in conjunction with the United States Department of Agriculture, Forest Service – International Institute of Tropical Forestry in Puerto Rico.

accessibility, population dynamics, economic and political interests, personal preferences, land ownership, and in some instances, topographic conditions and their different associated environments. Quantifying the spatio-temporal changes in land cover, as well as understanding the causes and consequences of change is essential for adequate land management practices in the region.

Keywords: *land cover change, urban growth, spatial analysis, GIS, Puerto Rico, Caribbean.*

Sinopsis

Altas tasas de cambio en la cobertura de terreno y su impacto en los recursos naturales es un tópico de debate en temas relacionados al medioambiente y al uso y manejo del terreno. Sin embargo, el tipo de investigación en el cual se analizan los patrones espaciales y temporales de cambio en la cobertura de terreno y sus posibles causas es usualmente desconocido por parte de la población. Este trabajo elabora dicha área de estudio y utiliza el caso de Puerto Rico para describir el patrón espacial y temporal en el cambio de la cobertura de terreno en la región este de la isla entre 1977 y 1995. El análisis de mapas de cobertura de terreno reveló el alto grado de cambio del paisaje de la región durante el período del estudio. El cambio más dramático fue un 73% de aumento en cobertura de terreno urbana, que en su mayoría ocurrió a expensas de áreas de pasto/agricultura y en menor proporción a expensas de vegetación leñosa. Los factores que influenciaron estos cambios fueron discutidos. Éstos incluyen, entre otros, accesibilidad, dinámicas poblacionales, intereses económicos y políticos, preferencias personales, tenencia del terreno, y en algunos casos, condiciones topográficas y ambientes relacionados. Es esencial cuantificar el cambio espacial y temporal en cobertura de terreno, y entender las causas y consecuencias de estos cambios para desarollar prácticas adecuadas de manejo del terreno en la región.

Palabras clave: *cambios en la cobertura del terreno, crecimiento urbano, análisis espacial, GIS, Puerto Rico, Caribe.*

Résumé

Des pourcentages élevés de changement dans la couverture spatiale et l'impacte sur les ressources naturelles est un sujet de débat dans des thèmes mis en rapport avec l'environnement et l'usage et manège du terrain. Cependant le type de recherche dans lequel on analyse les patrons spatiaux et temporels de changement dans les couvertures spatiales et ses possibles causes est normalement méconnu par la population. Ce travail examine ce domaine de recherche et se sert du cas de Porto Rico pour décrire le patron spatial et temporel dans le changement de la couverture spatiale dans la région est de l'île entre 1977 et 1995. L'analyse des cartes de couverture spatiale a révélé un haut dégrée de changement du paysage de la région, pendant la période de l'étude. Le changement le plus dramatique a été d'un 73% d'augmentation dans la couverture spatiale urbaine, qui dans la plupart, a eu lieu au détriment des aires de pâturage/agriculture et dans une moindre mesure au détriment de bois. Les facteurs qui ont influencé ces changements ont été discutés. Ceux-ci comprennent, entre autres, l'accessibilité, les dynamiques des populations, les intérêts économiques et politiques, les préférences personnelles, la possession du terrain, et dans certains cas, les conditions topographiques et ses environnements. Il est essentiel de quantifier le changement spatial et temporel en couverture spatiale et de comprendre les causes et les conséquences de ces changements à fin de développer des pratiques adéquates de manège du terrain dans la région.

Keywords: *changement dans la couverture spatiale, développement urbain, analyse spatiale, GIS, Porto Rico, Caraïbe.*

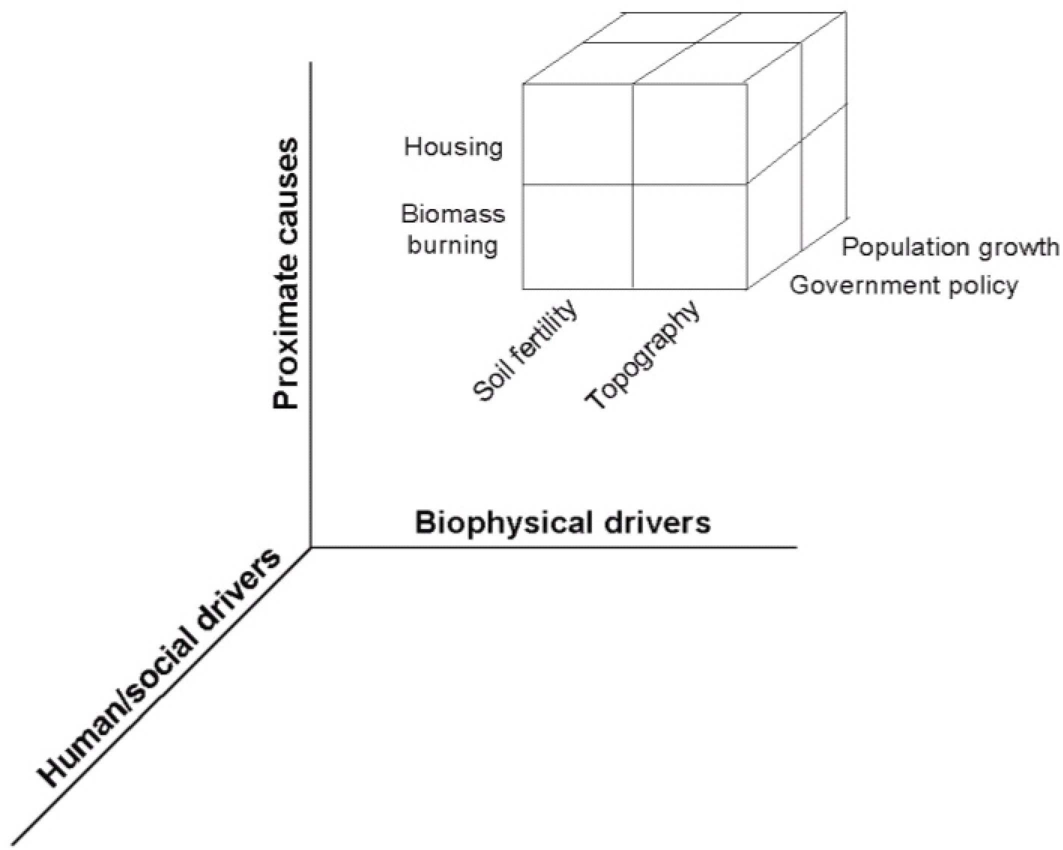
Received: 17 June 2003. Revision received: 17 November 2003. Accepted: 19 November 2003.

Anthropogenic modifications of the Earth's environment can be traced back to the earliest humans. However, the magnitudes, rates, and scales of these modifications have increased dramatically during the past 300 years (Turner *et al.* 1997). One way in which humans are modifying the Earth's environment is by changing its land cover – the biophysical state of the Earth surface and its immediate subsurface. As a result, land cover change (LCC) has become a topic of tremendous interest within the human dimensions of the environmental change research community (BioScience 1994; Meyer and Turner 1996). Different human activities (e.g., agriculture, deforestation, urbanization) are related to a variety of environmental changes including changes in climate; atmospheric and soil composition; alteration of water, nutrients and sediment budgets and flows; habitat fragmentation; and loss of biodiversity (Vitousek *et al.* 1997). Consequently, quantifying and understanding the extent and spatial distribution of LCC is of crucial importance to the study of environmental change at various scales (Ojima, Galvin and Turner 1994). Moreover, this type of analysis provides a valuable tool to increase the efficiency of land use and cover, and to diminish the negative environmental and societal impacts related to LCC.

The purpose of this paper is twofold. First, a framework used to study LCC is introduced, where changes are explained in terms of three broad aspects – the physical environment,

Figure 1

The dimensions of the driving force of LCC. Examples for each of the drivers are provided (adapted from Turner *et al.*, 1995).



human drivers, and proximate causes. Second, Puerto Rico is presented as a case study, where patterns of LCC in eastern Puerto Rico between 1977 and 1995 are mapped, quantified and explained in terms of their physical and human drivers.

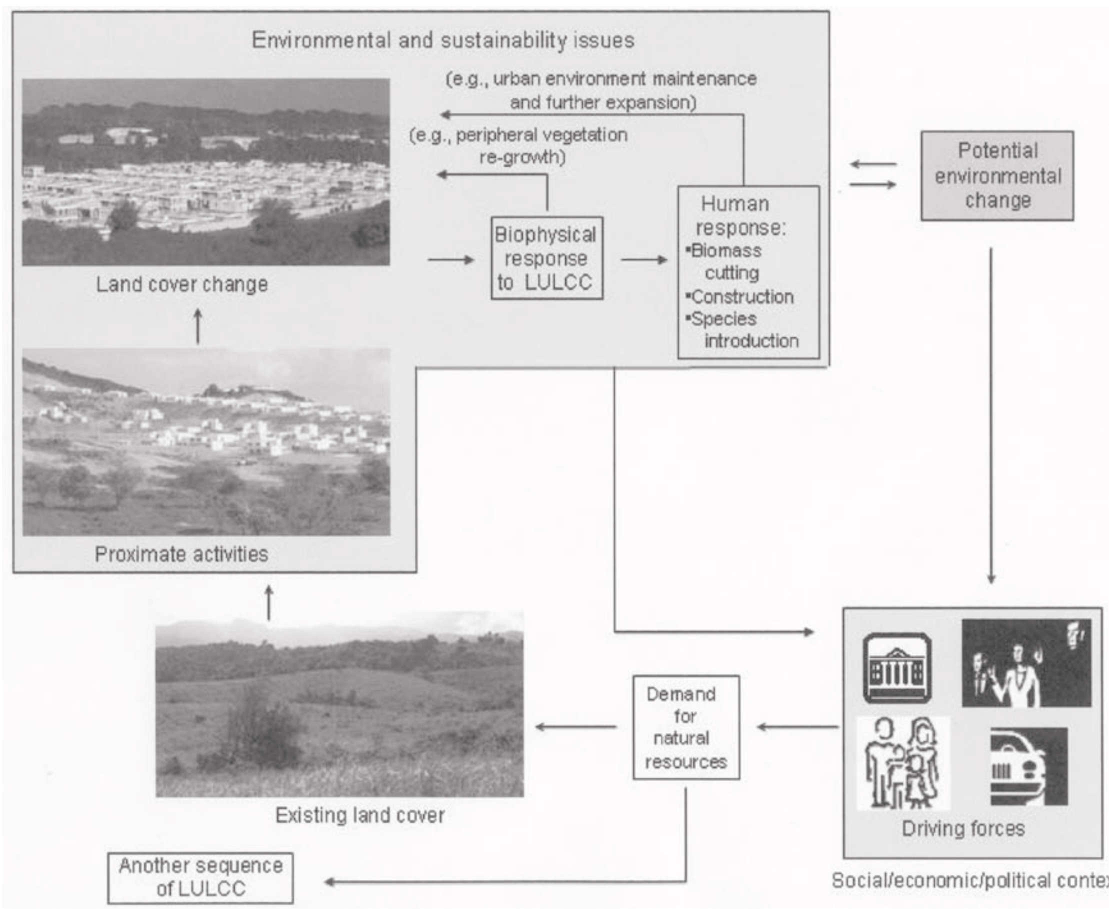
The study of Land Cover Change

One framework proposed by the scientific community studying LCC specifies the analysis in terms of three broad dimensions: biophysical drivers, human/social drivers, and proximate causes (Figure 1; Turner, Moss and Skole 1993; Turner *et al.* 1995). This conceptual framework states that LCC can occur in multiple ways, ranging from the simplest changes that result from independent variations in one of the drivers (e.g., to ecosystems brought on by climate), to more complex changes that result from different interactions of human activities with the biophysical world (e.g., tropical deforestation driven by economic opportunities, related to various social, political, and infrastructural transformations). This complexity is exacerbated as different biophysical and human factors interact at various spatial and temporal scales, and as different feedbacks between biophysical and human factors emerge during the process of LCC (Figure 2).

Although there is no question that biophysical factors interact to influence land cover patterns (Swanson *et al.* 1988),

Figure 2

Land cover dynamics: the linkages among driving forces.



In this example, vegetative land covers were transformed into urban cover. Human driving forces (e.g., population growth), mediated by social/economic/political setting lead to an intended land use (e.g., housing) of an existing land cover (e.g., grassland) resulting in a new land cover (urban). This land cover change may induce environmental changes (e.g., changes in micro-climates, nutrient reallocation, changes in sediment loads) which in turn require social/political institutions to diminish their negative environmental and societal impacts (adapted from Turner *et al.*, 1995).

the literature on LCC demonstrate that human activities are overriding the natural processes of change over the past hundred years (Turner *et al.* 1997). Consequently, increasing attention is given to two of the dimensions mentioned above: proximate causes and the human/social drivers of change (Lambin 1999; Turner, Moss and Skole 1993; Turner *et al.* 1995). Proximate causes are defined as the most immediate human activities or actions that directly alter the physical environment (Turner *et al.* 1990). Often, changes in land cover are driven by changes in land uses – the purpose for which the land is used. Changes in land use in turn are driven by proximate causes. Proximate causes can take the form of either modification, intensification or conversion. Modification results in a change of conditions within a land cover type (e.g., unmanaged to managed forest), whereas conversion implies a change from one land cover to another (e.g., forest to cropland). Proximate causes are in turn shaped by human driving forces – the range of social, economic, political, and cultural attributes and rationales that define the direction and intensity of LCC (Meyer and Turner 1991).

The literature on LCC has identified five broad variables of human drivers of LCC, which operates at different scales of study (Meyer and Turner 1991). These are population growth, level of affluence, technological changes, political and economic institutions and organizations, and attitudes/beliefs of individuals and groups. The first three categories are viewed as global scale drivers, and suggest that LCC is directly related to increases in each one of them. The larger the population, the more consumption of resources. In terms of level of affluence, rising incomes augment the demand for good and services, which are accessed often through changes in land cover (Sage 1991). Finally, advances in technology (e.g., in transportation systems, machinery, fertilizers) increase the ability to extract and process resources, and thus alter the land (Grübler 1991).

These three variables are questioned when applied to understanding patterns of LCC, particularly when going from global to regional/local scales, or when driving forces expand geographic frontiers causing changes elsewhere (Lambin, *et al.* 2001). For example, deforestation is commonly associated with global increases in population, levels of affluence and consumption. However, several regions of the world (for example, Western Europe, Japan, and parts of North America) that have had population and income increases, have experienced increase in forest cover during the past century (Williams 1991). In those cases, economic and political factors ranging from the local to the global are major factors influencing LCC. Consequently, the inclusion of just these three variables (population, affluence, and technology) may obscure underlying processes influencing patterns of LCC at regional or local levels. At finer scales of study (e.g., regional and local), governmental policies, political, social, and economic structures, and attitudes of people toward resources may interact differently to produce different patterns of LCC (Krummer and Turner 1994; Lambin *et al.* 2001; Skole *et al.* 1994). As a result, the inclusion of the remaining two variables – political/economic institutions and attitudes/belief of people – becomes important in the study of LCC.

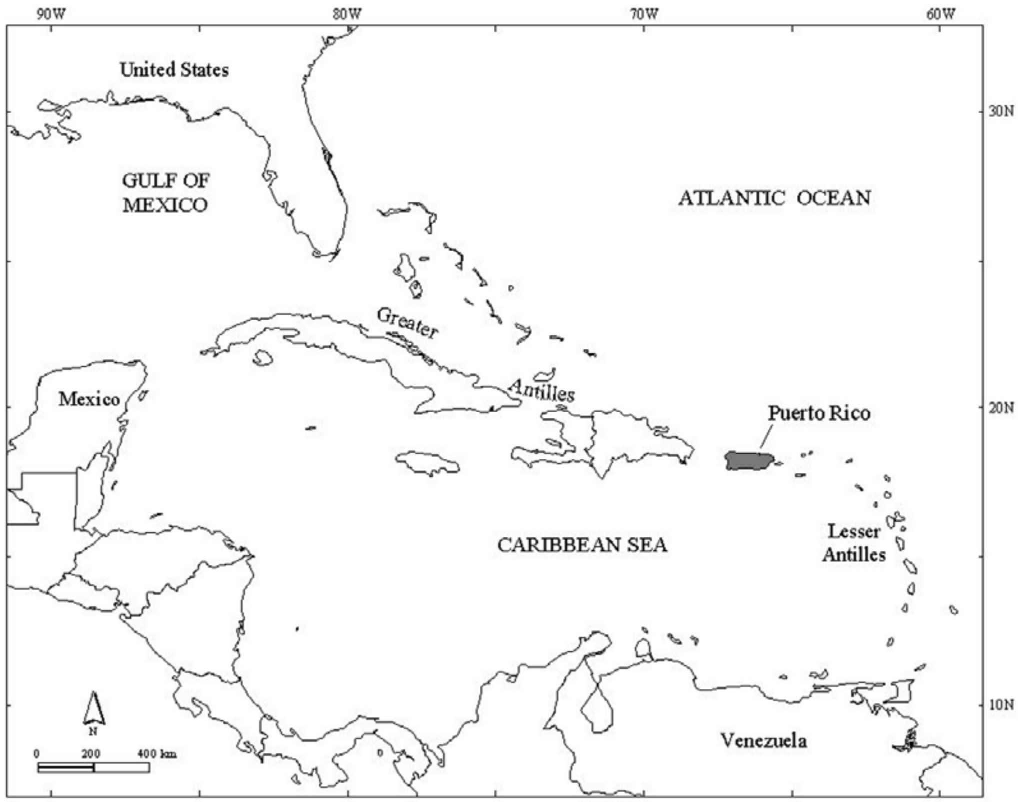
Puerto Rico as a case study of Land Cover Change

The Caribbean island of Puerto Rico (Figure 3) possesses a rich and varied physiography, is exposed to frequent natural hazards, and has undergone major socioeconomic changes during the second half of the 20th century. Together, these factors make the Island an interesting case study in terms of patterns of LCC.

Across the approximately 8,900 km^2 of land area, one finds three main geomorphologic areas: the central interior mountain region, the coastal plains, and the karst region (Monroe 1977). Steep topographic and climatic gradients are common[1] (Lugo, Figueroa-Colón and Scatena 2000). The island's soils are also diverse[2]. Exposure to natural hazards is another factor that characterizes the island's environment: hurricanes, high rainfall, landslides, and droughts have been major natural disturbances on the island (Larsen and Torres-Sánchez 1998; Lugo, Figueroa-Colón and Scatena 2000; Biotropica 1991).

Figure 3

Location of Puerto Rico in the Caribbean Basin.



The intensity of human activity has also been a major component influencing the island's changes in land cover. Factors related to human drivers have included both local and foreign social, economic and political dynamics. For example, agriculture dominated Puerto Rico's economy during the first half of the 20th century (Dietz 1996; Dietz 1986; Irizarry-Mora 2001). The almost complete deforestation of Puerto Rico at the beginning of the 20th century resulted in part because of the political and economic influences of the United States (US). During this period, Puerto Rico was one of the principal suppliers of sugar cane to the US, resulting in the conversion of thousands of acres of forests to sugar cane production. Tobacco, although to a lesser extent, was another agricultural product for which the land was used, and was also exported. Conversely, US policies also contributed to the protection and conservation of land and biodiversity mostly in the Luquillo mountains in eastern Puerto Rico. The incorporation of adjacent plots of lands into the Caribbean National Forest protected and expanded the forested area (Domínguez-Cristóbal 2000). By the middle of the century, and again due to socioeconomic and political changes influenced by the relationship of the island with the US, industry – specifically manufacturing and construction – replaced agriculture as the main economic activity and, as in the case of the sector it replaced, industry had a foreign orientation (Dietz 1996). By mid-century, raw materials were imported to the island and exported as industrial products to the US.

The 20th century economic transition of the island was also accompanied by dramatic changes in population, when the island experienced more than a threefold increase (Rivera-Batiz and Santiago 1996). Moreover, Puerto Rico's average population density increased from approximately 107 persons per km^2 in 1899 to about 428 in 2000. This positioned the island as one of the most densely populated countries in the world (Atlas of World Geography 2000). Another important demographic change involved rapid urbanization. The economic transformation promoted the movement of the island's population to the urban centers in the coastal plains, where most of the industrial centers were located. In 1990, the island's urban population was estimated to be 71%, compared to 40.5% in 1950 and 15% in 1899 (Cruz-Báez and Boswell 1997).

The human factors described above, in conjunction with the islands' physical characteristics, have shaped the Puerto Rican landscape over time. The transition to an industrial economy resulted not only in the movement of the island's population to urban centers, but also in the abandonment of agricultural land. As a result, agricultural land diminished while the area of forest cover increased[3]. This increase in forest cover resulted mostly from natural succession on abandoned lands, especially on steep slopes and at higher elevations. Simultaneously, reforestation on the island has been accompanied by an important land cover change - the rapid increase in urban land cover and built-up areas (López, Aide and Thomlinson 2001a; Ramos-González 2001; Thomlinson and Rivera 2000; Thomlinson *et al.* 1996)[4].

In summary, Puerto Rico's land cover history is punctuated by alternating periods of intensive use and subsequent land recovery. Forest cover increases stands in stark contrast to general deforestation trends occurring throughout of the tropics (Koop and Tole 1997; Rudel, Pérez-Lugo and Zichal 2000). Although today the island possesses large areas of secondary forest compared to other Caribbean and tropical countries (Franco, Weaver and McIntosh 1997; Rudel, Pérez-Lugo and Zichal 2000), the view of Puerto Rico as an example of reforestation in the tropics could start to be questioned as the rate of change in urban land cover may be overwhelming forest recovery processes (Ramos-González 2001; Thomlinson and Rivera 2000). This study presents data that supports this tendency by assessing recent changes in land cover in the eastern portion of Puerto Rico.

Study area

The study area covers about 71,500 ha, which represents 8.2 % of the total area of Puerto Rico (Figure 4). It is composed of eight municipalities in eastern Puerto Rico – Canóvanas, Río Grande, Luquillo, Fajardo, Ceiba, Naguabo, Las Piedras, and Juncos[5].

A variety of physiographic and socioeconomic characteristics distinguish the region as important for the Island in both environmental/ecological and economic terms. Various ecosystems provide different services such as water resources, flora, fauna, air quality, and recreation. It also possesses a variety of natural areas including mangroves, wetlands, and forested ecosystems. Of particular interest is the Caribbean National Forest (CNF), locally known as *El Yunque*. This forest possesses several distinctions (Lugo 1994). The CNF is the only tropical forest in the US National Forest system. In 1976, it was designated a United Nations Educational, Scientific, and Cultural Organization (UNESCO) Biosphere Reserve. And, because some sectors of the forest have been under protection since 1876, the CNF is one of the oldest legally protected forest

Figure 4

Location of the study area in eastern Puerto Rico.

reserves in the western hemisphere. Besides these characteristics, the CNF provides the region with several services. The area is source of nine major rivers, which provide water for approximately 20% of the island's population (Naumann 1994). The forest contains a high number of endemic plant and animal species, and provides habitat for rare and endangered species. Moreover, the CNF is considered the only forest within Puerto Rico and the US Virgin Islands containing remnants of primary forest (Lugo 1994). It also serves as a research site, and is considered one of the most important tourist attractions in the island.

Among the different economic sectors present in the region, manufacturing and services are two major activities, followed by commerce and public administration (US Census of

Population 1980 and 1990; PRPB 2000). Some of the employment generated by these two major economic sectors in the study area is strongly related to tourism, both for the government and private sectors. The presence of a variety of natural resources (e.g., forests, beaches, mangroves) has served as focal points for tourism, particularly in the municipalities of Río Grande, Luquillo, and Fajardo where land use devoted to tourism activities has increased during the past years (PRPB 2000).

In terms of the region's population dynamics, 277,820 inhabitants were reported for the year 2000 (US Census of Population 2000). This represents 7.3% of the total population of Puerto Rico. Río Grande and Las Piedras are the most populated municipalities, whereas Luquillo and Ceiba possess lesser inhabitants. During the last two decades, rates of population change have been higher for the study area compared to the whole island (Table 1). During the period from 1980 to 1990, the study area experienced a population increase of 19.9% compared to 10.2% for the Island. Within the study

Table 1
Population within the study area, 1980 to 2000.

Municipality	Population			% Change	
	1980	1990	2000	1980-1990	1990-2000
Canó vanas	31,880	36,816	43,335	15.5	17.7
Río Grande	34,283	45,648	52,362	33.2	14.7
Luquillo	14,895	18,100	19,817	21.5	9.5
Fajardo	32,087	36,882	40,712	14.9	10.4
Ceiba	14,944	17,145	18,004	14.7	5.0
Naguabo	20,617	22,620	23,753	9.7	5.0
Las Piedras	22,412	27,896	43,385	24.5	23.6
Juncos	25,397	30,612	36,452	20.5	19.1
Region	196,515	235,719	277,820	19.9	14.1
Puerto Rico	3,196,500	3,522,037	3,808,610	10.2	8.1

Source: US Census of Population (1980-2000).

area, the municipality of Río Grande experienced the greatest change in population, with a 33.2 % increase. The next largest increase occurred in Las Piedras, with 24.5%. During the period from 1990 to 2000, the population of the study area increased by 14.1%, which was also much higher than the island wide rate (8.1%). During this period, contrary to the previous 1980 to 1990 period, the municipality of Las Piedras experienced the highest increase in population (23.6%), followed by the municipality of Juncos (19.1%). For both periods, the municipality of Naguabo registered the lowest growth in the region.

Methodological approach

Land cover maps were used to quantify the spatio-temporal patterns of land cover change in Eastern Puerto Rico between 1977 and 1995. These maps were derived from existing land cover maps based on the interpretation of aerial photographs[6] (López *et al.* manuscript in preparation; Ramos and Lugo 1994, Velez-Rodríguez 2001). The original maps consisted of different categories of land cover, which were reclassified into six categories for the purpose of this study: pasture and agriculture, woody vegetation, water, wetlands and mangroves, urban/built–up, and other (for a description of each land cover category, refer to table 2). The maps were digitally stored in geographic information system (GIS) for analysis. A GIS is a computer system for managing geographically referenced information which allows us to conduct spatially explicit analysis. In a GIS, data is stored as coverages, where elements in the real world are represented as a set of geographic features and contains both spatial and attribute data describing the features. The GIS programs Arc View 3.2 and ArcInfo were used to perform the analysis of land cover change (ESRI 2001, 1999).

To describe the study area landscape composition in 1977 and 1995, the areal percentage of each land cover was determined from both land cover maps. To determine land cover changes between 1977 and 1995, an overlay coverage was created by digitally combining the 1977 and 1995 land cover

Table2
Description of the land covers categories used in this study

Land cover category	Description
Pasture and Agriculture	Included areas of natural and/or managed pastures, and areas of agricultural production.
Woody Vegetation	Included areas of open and closed canopy forest, as well as shrub lands.
Wetlands	Included non-forested and forested wetlands (mangroves).
Urban/Built-up	Included areas with high percentage (30% or greater) of constructed materials (e.g., buildings, asphalt, concrete).
Water	Water bodies.
Other	Includes areas of bare and exposed soils, quarries, and sandy areas within beaches.

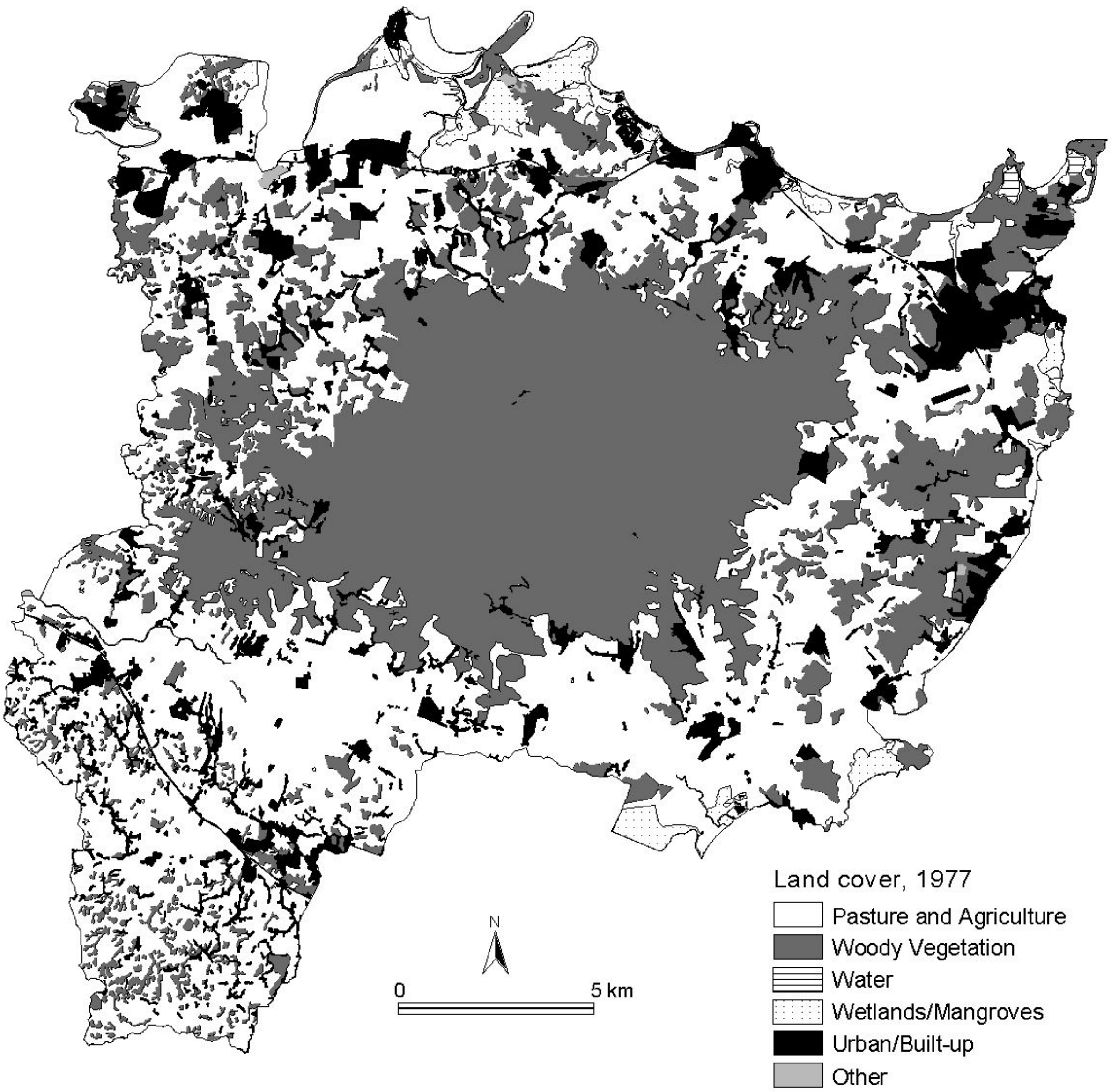
maps. To characterize and summarize these changes (i.e., the trajectory and amount of change between different land cover categories), a transition matrix expressing area for each land cover change from 1977 to 1995 was constructed.

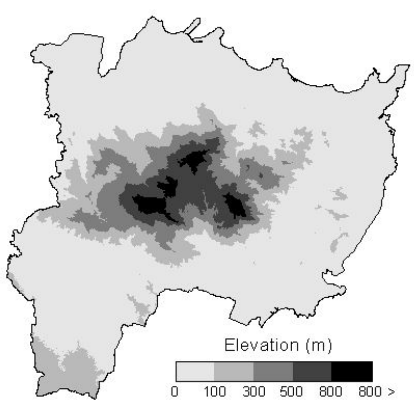
Land cover trends in Eastern Puerto Rico

In 1977, pasture/agriculture was the dominant land cover in eastern Puerto Rico (Figure 5, Table 3). This category covered 49% of the study area, and occurred mostly at lower elevations. Woody vegetation was also prominent – occupying 39% of the area – and tended to occur at higher elevations. Some continuous patches of woody vegetation occurred at lower elevations, mostly in the eastern portion of the study area. The largest continuous patch classified as woody vegetation was the Caribbean National Forest and its vicinity. Urban land cover occupied 10% of the study area. The town centers of each municipality were the largest continuous urban patches in 1977. However, other prominent areas classified as urban

Figure 5

Study area land covers, 1977.





An elevation map for the study area is presented to the left for comparison purposes of the spatial distribution of land covers and its relation to elevation (refer to text for further details).

Table 3

Total area covered by each major land cover category and percentage change between 1977 and 1995

Land cover	Area, ha (%)		% Change
	1977	1995	
Pasture/Agriculture	34,776.3 (48.6)	29,358.6 (41.1)	-15.6
Woody Vegetation	27,599.6(38.6)	27,352.0 (38.2)	-0.9
Urban/Built-up	7,165.6 (10.0)	12,368.9 (17.3)	72.6
Wetlands	1,589.5 (2.2)	1,644.5 (2.3)	3.5

included recreational and medium density housing development, and where mostly located in the northern portion of the study area. Wetlands accounted for 2% of the study area, and predominated in the lowland-coastal plains. A minute portion of the study area in 1977 (0.5%) was classified as either “water” or “other” categories.

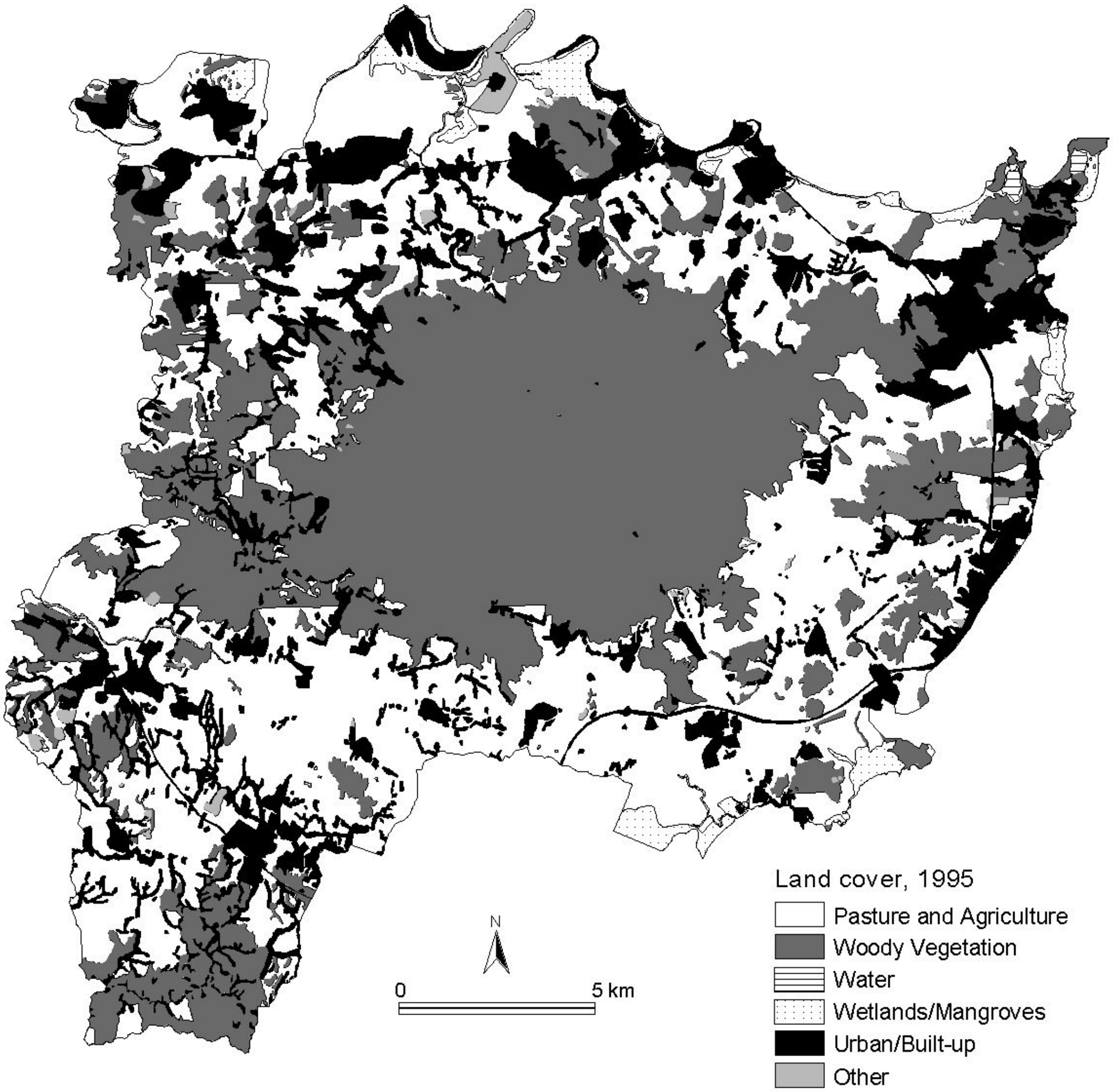
Although decreasing in area by 1995, pasture/agriculture remained the dominant land cover, occupying 41% of the study area (Figure 6, Table 3). The percentage covered by woody vegetation (38%) in 1995 remained about the same as in 1977. Urban lands covered approximately 17% of the area, with a noticeable expansion from urban patches that existed in 1977. In addition, the construction of a new major highway was observed in the eastern portion of the study area. Wetland cover (2%) remained unchanged in 1995. Approximately 1% was classified as either “water” or “other” categories.

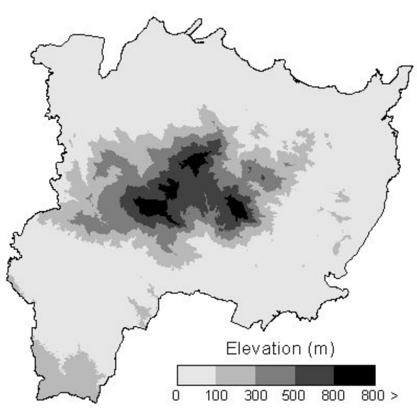
By 1995 one of the most evident changes was the increase in urban land cover. Urban land increased by approximately 73% (Table 3). In contrast, pasture/agriculture decreased by 15%. The areal extent of woody vegetation and wetlands remained fairly constant.

The results presented above focused on the total area in the primary land cover categories. However, approximately 26% (18,726 ha) of the study area experienced some type of land cover change during the study period (Table 4). Of the 34,776

Figure 6

Study area land covers, 1995.





An elevation map for the study area is presented to the left for comparison purposes of the spatial distribution of land covers and its relation to elevation (refer to text for further details).

Table 4

Land cover transition matrix from 1977 to 1995.

LC 1995

LC 1977	**None**	**Pa/Ag**	**Woody**	**Water**	**Wetlands**	**Urban**	**Other**	**Total**
None		10.6	2.6	4.5	11.6	2.8	0.2	32.4
Pa/Ag	1.1	23,841.0	5,544.1	44.8	219.0	4,793.4	260.9	34,776.3
Woody	0.3	4,511.5	21,461.9	5.8	162.1	1,248.4	209.5	27,599.6
Water	6.5	35.0	10.5	148.6	32.7	16.3	7.2	256.7
Wetlands	7.5	302.4	26.6	13.2	1,118.0	51.0	70.8	1,589.5
Urban	0.8	614.5	305.0	1.0	14.5	6,221.8	76.9	7,165.6
Other	0.5	43.5	1.3	1.7	14.6	35.2	16.8	113.6
Total	**16.8**	**29,358.6**	**27,352.0**	**219.5**	**1,644.5**	**12,368.9**	**573.4**	**71,533.6**

Values in the table represent the area in hectares for each land cover type in 1995 (columns) and in 1977 (rows). Column totals represent 1995 land covers, row totals represent 1977 land covers, and individual entries (different from diagonal entires) represent land cover conversion between years. Pa/Ag is an abbreviation for the land cover category Pasture/ Agriculture. Values under the «None» category represent areas that did not match exactly when the overlay analysis between the two coverages was performed.

ha of pasture/agriculture in 1977, 23,841 ha (69%) remained as pasture/agriculture in 1995. The main change in this category was conversion to woody vegetation and urban land cover. Approximately 5,544 ha (16%) of pasture/agriculture in 1977 was converted to woody vegetation by 1995. These changes from pasture/agriculture to woody vegetation occurred mostly at higher elevations, mainly in the southern and western portions of the study area. In addition, 4,793 ha (14%) of pasture/agriculture in 1977 were converted to urban uses by 1995. This figure underscores the importance of urban expansion onto agricultural lands. In addition, pasture/agricultural areas are not only threatened by loss of total land area, but also by its fragmentation. Fragmentation of pasture/agricultural lands may result in land units that are not optimal for production, limiting thus the region's potential agricultural production. Changes from pasture/agriculture to urban land cover occurred mostly at lower elevations, and compared to the spatial distribution of pasture/agriculture to woody vegetation, conversion to urban land cover tended to occur more evenly distributed throughout the study area.

Most of the changes in the woody vegetation category were related to conversion to pasture/agriculture. Of the 27,600 ha of woody vegetation in 1977, 4,512 ha (16.3%) were converted to pasture/agriculture. These changes tended to occur at lower elevations, mainly in the northeastern and eastern portions of the study area. In addition to those changes, 1,248 ha (5%) of woody vegetation were converted to urban land cover.

About 302 ha (19%) of the wetlands in 1977 became pasture/agriculture by 1995, whereas a small portion – 51 ha (3%) – became urban. Draining wetlands is a practice used to support agricultural activities, which may account for the conversion of some of the wetland to agriculture/pasture. However, the wetland category used in this study included both forested and non-forested wetlands. Non-forested wetlands in this region are seasonal wetlands, and different activities (e.g., cattle raising) are sustained during the dry season (Ramos-González, personal communication). Consequently, the reported result of wetland to pasture/agriculture may be a case of seasonal variation, not one of conversion. Additionally, it may also be a result of artifacts in photo-interpretation. Non-forested wetlands, especially during the dry season, have very similar appearance to pastures. If this is the case, and if non-forested wetlands were classified as pastures in 1995, changes from the wetland category to pasture/agriculture could be overestimated.

Of the 7,166 ha of lands classified as urban in 1977, 615 ha (8%) and 305 ha (4%) showed as being converted back to pasture/agriculture and woody vegetation, respectively, by 1995. Reversion of urban land cover to other uses is not common. Two main reasons may account for this unexpected result. The first reason could be differences in photo-interpretation techniques and classification criteria used in the two study periods (mainly in areas of rural, low density urban uses). The results reporting reversion to woody vegetation could also be related to artifacts in the interpretation of the aerial photographs. It may be possible that forest canopy increased in the photographs used to generate the 1995 land use coverage, causing urban uses (particularly scattered, isolated urban patches) to be disguised.

Drivers of land cover change in Eastern Puerto Rico

The landscape of Eastern Puerto Rico has been dynamic in the last two decades, with approximately 26% of the area experiencing land cover change. The mix of driving forces of LCC in the region varied in time and across scales.

In terms of biophysical drivers, elevation proved to be an important consideration for most of the changes documented in this study. Land conversion, mainly of woody vegetation to either pasture/agriculture or urban land cover and from pasture/agriculture to urban, often took place at lower elevations and, in some instances, at lesser slope angles. Lower elevations and slope are more favorable for conversion from woody vegetation to pasture/agriculture because soils tend to be more suitable to agricultural activities (e.g., because of the rich nutrient contents). Also, active pastures found at lower elevations serve for raising cattle and horses. Additionally, lowlands are more accessible to public services and existing infrastructure, which present fewer obstacles to land manipulations. Similar trends of land conversion have been documented for other areas. In the US, similar changes to those of eastern Puerto Rico have been reported for areas where forest dominated, where lowlands were converted to agricultural and urban uses more rapidly than in the steepest terrain (LaGro and DeGloria 1992). The similarity in trends is striking because of the tremendous difference in land area, and similar trends in urban expansion between the two countries.

Areas that experienced increase in woody vegetation or forest regeneration in the region tended to occur at higher elevations and on steeper slopes. Usually, these topographic conditions are not considered as productive or attractive for other uses, or as accessible to different services as the lower elevation land. This condition often results in less human activity, land abandonment and subsequent forest regeneration. Furthermore, some of the forest regeneration tended to occur near the boundary of the CNF, which suggests the importance of forested patches as triggers (e.g., by their importance as seed-source pools) for further forest regeneration (Thomlinson *et al.* 1996). It is important to mention that, although the percentage of woody vegetation cover did not change, the spatial distribution of some forest areas did. This finding demonstrates that the forested landscape of the study area, with the exception of the CNF, is characterized by ongoing modifications and heterogeneity. This situation could inhibit progression of regenerated forested areas towards a mature stage. In such case, the potential services associated with more mature forests could be reduced.

Changes in pasture/agriculture land in the study area resulted in similar levels of conversions to woody vegetation and urban cover (specifically, 16% and 14% of pasture/agriculture in 1977 were converted to woody vegetation and urban, respectively). As discussed above, these changes may be driven by physical factors such as topographic conditions and soils characteristics. However, agricultural land abandonment may also be driven by socioeconomic factors.

The economic base of the study area is highly dependent on the industrial, commercial, and tourism sectors, whereas agriculture is nearly nonexistent (PRPB 2000). The industrial, commercial, and tourism sectors, consequently, offer higher wages and stimulate population migration to more profitable employment than agriculture. Salaries resulting from agricultural activities are not as attractive as those from other economic activities. For instance, this situation has been cited as a primary reason for abandonment of coffee plantations and conversion to other uses during the last two decades in the municipality of Utuado, in the central-western part of the island (Marcano-Vega, personal communication).

Although urban land cover accounted for a lower percentage of the total study area than pasture/agriculture and woody vegetation, it increased greatly during the study period. The majority of new urban areas occurred at the expense of pasture/agriculture and woody vegetation. Most of the pasture/agriculture conversion occurred on the coastal plains at lower elevations and at lesser slope angles, whereas the conversion from woody vegetation tended to occur at higher elevation and the steepest slopes. In fact, a quantitative analysis determined that the spatial distribution of new urban areas was statistically related to these biophysical variables. The analysis showed that new urban areas tended to be located at lower elevations and at lower slope angles; while areas of no change tended to occur at higher elevation and on steeper slopes (López 2002). The pattern of urban land cover change observed in the study area is complex and challenging to explain, as many factors may have influenced this expansion.

Increases in population density have been directly related to increases in urban land cover (Jenerette and Wu 2001; López *et al.* 2001b). In this study, the pattern is especially evident for municipalities such as Las Piedras and Juncos. Both municipalities experienced high rates of urban land cover change between 1977 and 1995 (100% and 82% increase for Las Piedras and Juncos, respectively), and much of the change was related to residential development. These two municipalities also experienced the highest degree of population change in the region during the past two decades. However, a statistical analysis conducted for two periods – 1977 to 1985 and 1985 to 1995 – where regional urban land cover expansion was related to different independent variables suggested that population was a major driver of urban land cover change in the first period, but not in the second (López 2002). This finding may be explained by the type of development and the diversification of urban activities (e.g., commercial, recreational, and transportation) occurring in the region during this period. This suggests that in the latter period, population was not a major driver of LCC, but rather socioeconomic factors.

It is likely that population dynamics and subsequent urban land cover increase in the study area may be driven by human and socioeconomic factors such as accessibility, job opportunities, commuting distances, housing costs, and preferences for residential locations. In fact, some of these factors were identified as drivers of population redistribution and resulting increases in urban land in the United States during the 70s and 80s (Fuguitt and Brown 1990). In that study, surveys showed that low costs of rural lands, high rural amenity values, and increasing transportation mobility contributed to the movement of population from large urban centers to suburbs, smaller cities, and rural areas. In Puerto Rico, although no empirical studies have been conducted to support this conclusion, these factors have been suggested as driving rapid increases in urban land cover (Cruz-Báez and Boswell 1997; González 1995; McPhaul 1998). Data showing percent employment outside of the region, and housing values suggest the influence of these drivers. The proximity of the study area to the San Juan metropolitan area, and the high accessibility provided by major transportation routes, may influence urban land cover change, especially residential development. Actually, a regression analysis demonstrated that distance from roads was an important variable explaining urban land cover change in the study area (López 2002). The metropolitan area is a major source of employment opportunities for the residents of eastern Puerto Rico. Often, it is economically advantageous to live elsewhere but work in the metropolitan area (e.g., median housing values for San Juan are twice as high than for most of the municipalities in the study area; PRPB 2000). Consequently, approximately 50% of the working population of Río Grande and Canóvanas, which are the closest municipalities in the study area to San Juan, work in San Juan (PRPB 2000). However, further examination of these variables is needed to determine accuracy and strength of these inferences.

Personal preference may be another human driver of urban land cover change, particularly in the case of low density residential development (González 1995; Guilbe 1998). For example, the degree of urban land cover increase in higher-elevation land in the periphery of the CNF suggests the desire to improve quality of life, experience more desired climate conditions, and obtain sought-after scenic views by moving farther from urban concentrations. López (2002) reported that inside the CNF proclamation boundary, the rate of change of urban land cover almost doubled between two different time periods – 1977 to 1985 and 1985 to 1995 (24% versus 45% increase). This percentage change was slightly greater than the percentage change reported for all urban land cover for the whole study area (20% for the 1977-1985 period; 42% for the 1985-1995 period). These findings are of great concern because this area is intended to be a buffer zone – an area intended to protect the forest from human activity – and, therefore, to be of less intensive uses. Another factor that causes land use intensification in the periphery of the CNF, and especially inside its proclamation boundary, is land ownership. Some of these lands are privately owned, and the current zoning laws allow for the subdivision of these privately owned peripheral lands (PRPB, personal communication). Other studies of LCC conducted in the island during the last two decades have suggested personal preferences of housing development in rural environments as influencing urban land cover expansion (Thomlinson and Rivera 2000). The authors suggest this relationship based on the observed spatial distribution of low density residential development. They found that newly urban areas were located at higher elevations, steeper slopes, and away from urban centers.

Political and economic factors may also be driving urban land cover change, especially in the coastal plains. Commercial and tourism development are explicitly expressed as a main governmental objectives for the region (PRPB 2000). Many of eastern Puerto Rico coastal areas are attractive to development because of their high tourism and economic values. In fact, the Puerto Rico Planning Board and the Puerto Rico Tourism Company have developed a strategic plan for the municipalities of Río Grande, Fajardo, and Luquillo to promote their socioeconomic development mainly in terms of tourism activities (PRPB 1998). In this plan, tourism development and all the infrastructure inherent to the activity – including the construction of new roads – is highly promoted.

Industrial development is another example in which politics and economics may be dominant drivers of land use change. Several municipalities of eastern Puerto Rico are high industrial rental zones (Cruz-Báez and Boswell 1997), and many of the lands in these zones have been converted to urban uses. Industrial development is widespread in the municipalities of Canóvanas, Las Piedras, and Juncos. In the same way that the government is promoting tourism in some municipalities, it is also promoting industry, manufacture, and commerce in the municipalities of Juncos and Las Piedras (PRPB 2000).

Concluding Remarks

The results of this study revealed the dynamic character of the eastern Puerto Rico's landscape. Transitions between vegetative land covers (i.e., pasture/agriculture and woody vegetation) were common during the 18-year study period. However, the most significant land cover change experienced in the study area was related to urban development.

It appears that the driving forces of land cover change in eastern Puerto Rico operated interactively to produce the observed pattern. Land cover change may be explained by a variety of factors, which in turn can be influenced or constrained by several other physiographic and socioeconomic drivers.

These drivers and modifying factors vary in relative significance both spatially and temporally. Proximate causes related to housing, industry, commerce, and tourism appeared to be driven by economic and political factors, social and demographic dynamics, personal preferences, land ownership, and in some instances, topographic and environmental conditions.

The observed land cover trends, specially the rapid increase in urban land cover, can impact the region in different ways. For example, urban land development associated with pasture/agricultural land conversion can significantly limit the region's potential agricultural production. This can occur not only because of the loss of potential agricultural land, but also by its fragmentation. The rapid changes in urban land cover also pose threats to forested ecosystems, in this case particularly to the CNF. The close proximity of urban lands to the forest expose the area to negative effects which includes forest fragmentation, flora and fauna habitat reduction, loss of biodiversity, increase of exotic species, and changes in microclimate conditions (Lugo 1994).

The rapid changes in urban land cover, combined with a limited land area may pose threats to open spaces and non-urban ecosystems in general. This pattern can also be reversing the general trend of forest recovery observed during the latter part of the 20th century. The results of this study demonstrate the need to rethink land use management not only for the study area, but for Puerto Rico as a whole. However, this has to be done taking into account the areal constraints and the current trends in population and economic development of the island.

Acknowledgements

I will like to thank William E. Easterling and Brent Yarnal from the Department of Geography at the Pennsylvania State University for advising and helping in the development of my graduate research, which data was used to develop this manuscript. The comments and reviews of Humberto García Muñiz, from the Institute of Caribbean Studies – University of Puerto Rico, Ángel David Cruz Báez from the Department of

Geography – University of Puerto Rico, Olga Ramos and Ariel Lugo from the USDA Forest Service – International Institute of Tropical Forestry, and two anonymous reviewers helped to improve the manuscript. The Geographic Information Systems and Remote Sensing laboratory of the USDA Forest Service – International Institute of Tropical Forestry in Puerto Rico provided some of the database used to conduct the research.

References

Atlas of World Geography. 2000. Skokie, IL: Rand McNally & Company.

BioScience. 1994. "Global impact of land-cover change". *BioScience* 44(5):291-356.

Biotropica. 1991. "Special Issue: Ecosystem, plant, and animal responses to hurricanes in the Caribbean". *Biotropica* 23(4a):313-521.

Birdsey, R.A. and P.L Weaver. 1987. "Forest area trend in Puerto Rico". Research Note SO-331. New Orleans: USDA Forest Service Southern Forest Experimental Station.

Cruz-Báez, A.D. and T.D. Boswell. 1997. *Atlas de Puerto Rico*. Miami: Cuban American National Council.

Dietz, J.L. 1996. "Operation Bootstrap and economic change in Puerto Rico". In *Caribbean freedom: economy and society from emancipation to the present*. Princeton, NJ: Markus Wiener Publishers.

_________. 1989. *Historia económica de Puerto Rico*. Río Piedras, P.R.: Ediciones Huracán.

Domínguez-Cristóbal, C.M. 2000. *Panorama histórico forestal de Puerto Rico*. San Juan, P.R.: Editorial de la Universidad de Puerto Rico.

ESRI. 2001. ArcInfo version 8.1. Redlands, CA: Environmental Systems Research Institute, Inc.

ESRI. 1999. Arc View GIS version 3.2a. Redlands, CA: Environmental Systems Reseach Institute, Inc.

Franco, P.A., P.L. Weaver, and S. Eggen-McIntosh. 1997. "Forest resources of Puerto Rico". Research Station Bulletin SRS-22.

New Orleans: USDA Forest Service Southern Forest Experimental Station.

Fuguitt, G.V. and D.L. Brown. 1990. "Residential preferences and population redistribution: 1972-1988". *Demography* 27(4):589-600.

González G.M. 1995. "Cambio en uso de terrenos agrícolas en Puerto Rico y sus impactos en la agricultura". *Acta Científica* 9:3-14.

Grüber, A. 1991. "Technology". In *Changes in land use and land cover: a global perspective*. Great Britain: Cambridge University Press.

Guilbe, C.J. 1998. "Los espacios conflictivos: urbanización y urbanismo en Puerto Rico". In *Globalization in America: A Geographical Approach*. San Juan, P.R.: Instituto de Estudios del Caribe.

Hunter, J.M. and S.I. Arbona. 1995. "Paradise lost: and introduction to the geography of water pollution in Puerto Rico". *Social Science and Medicine* 40:1331-1355.

Irizarry-Mora, E. 2001. *Economía de Puerto Rico: evolución y perspectivas*. Mexico: Thomson Learning Press.

Jenerette, G.D. and J. Wu. 2001. "Analysis and simulation of land-use change in the central Arizona-Phoenix region, USA". *Landscape Ecology* 16:611-626.

Koop, G. and L. Tole. 1997. "Measuring differential forest outcomes: A tale of two countries". *World Development* 25(12):2043-2056.

Krummer, D.M. and B.L. Turner. 1994. "The human causes of deforestation in Southern Asia". *BioScience* 44(5):323-328.

LaGro, J.A. and S.D. DeGloria. 1992. "Land use dynamics within an urbanized non-metropolitan county in New York State (USA)". *Landscape Ecology* 7(4):275-289.

Lambin, E.F., B.L. Turner, H.J. Geist, S.A. Agbola, A. Angelsen, J.W. Bruce, O.T. Coomes, R. Dirzo, G. Fischer, C. Folke, P.S. George, K. Homewood, J. Imbernon, R. Leemans, X. Li, E.F. Moran, M. Mortimore, P.S. Ramakrishnan, J.F. Richards, H. Skånes, W. Steffen, G.D. Stone, U. Svedin, T.A. Veldkamp, C. Vogel, and J. Xu. 2001. "The causes of land-use and land-cover change: moving beyond myths". *Global Environmental Change* 11:261-269.

Larsen, M.C. and A.J. Torres-Sánchez. 1998. "The frequency and distribution of recent landslides in three montane tropical regions of Puerto Rico". *Geomorphology* 24:309-331.

López, T. del M. 2002. "Characterization and modelling of land cover change: the case of urban expansion in a Caribbean landscape". MS Thesis. The Pennsylvania State University, University Park, PA.

_____, T.M. Aide, and J.R. Thomlinson. 2001a. "Urban expansion and loss of prime agricultural lands in Puerto Rico". *Ambio* 30:49-54.

López, E., G. Bocco, M. Mendoza, and E. Duhau. 2001b. "Predicting land-cover and land-use change in the urban fringe: A case in Morelia city, Mexico". *Landscape and Urban Planning* 55:271-285.

Lugo, A.E. 1996. "Caribbean island landscapes: indicators of the effect of economic growth on the region". *Environment and Development Economics* 1:128-136.

_____. 1994. "Preservation of primary forests in the Luquillo Mountains, Puerto Rico". *Conservation Biology* 8(4):1122-1131.

_____, J. Figueroa-Colón and F.N. Scatena. 2000. "The Caribbean". In *North American Terrestrial Vegetation*. New York: Cambridge University Press.

Meyer, W.B. and B.L. Turner. 1991. *Changes in land use and land cover: a global perspective*. Great Britain: Cambridge University Press.

McPhaul, J. 1998. "Experts: P.R. suffers from urban sprawl". *The San Juan Star,* October 27, p. 5.

Meyer, W.B. and B.L. Turner. 1996. "Land-use/land-cover change: challenges for geographers". *GeoJournal* 39(3):237-240.

Monroe, W. 1977. "Geomorfología de Puerto Rico". In *Geovisión de Puerto Rico*. San Juan, P.R.: Editorial Universitaria.

Naumann M. 1994. "A Water Use Budget for the Caribbean National Forest of Puerto Rico". European Postgraduate Programme in Environmental Management Thesis, Universitat Trier, Germany.

Ojima, D.S., K.A. Galvin, and B.L. Turner. 1994. "The global impact of land-use change". *BioScience* 44(5):300-304.

Puerto Rico Planning Board (PRPB). 2000. "Planes regionales de Puerto Rico: Región Este". San Juan, PR: Government of Puerto Rico.

Puerto Rico Planning Board (PRPB). 1998. "Plan Territorial 1998: Municipios de Fajardo, Luquillo, Río Grande". San Juan, PR: Government of Puerto Rico.

Puerto Rico Planning Board (PRPB). 1996. Economic Report. San Juan, PR: Government of Puerto Rico.

Ramos-González, O.M. 2001. "Assesing vegetation and land cover changes in northeastern Puerto Rico: 1978 to 1995". *Caribbean Journal of Science* 37(1-2):95-106.

_____, and A.E. Lugo. 1994. "Mapa de vegetación de Puerto Rico". *Acta Científica* 8(1-2):63-66.

Rivera-Batiz, F.L. and C.E. Santiago. 1996. *Island paradox: Puerto Rico in the 1990s*. New York: Russell Sage Foundation.

Rudel, T.K., M. Pérez-Lugo, and H. Zichal. 2000. "When fields revert to forest: development and spontaneous reforestation in post-war Puerto Rico". *Professional Geographer* 52(3):386-397.

Sage, C. 1991. "Population and Income". In *Changes in land use and land cover: a global perspective*. Great Britain: Cambridge University Press.

Skole, D.L., W.H. Chomentowski, W.A. Salas, and A.D. Nobre. 1994. "Physical and human dimensions of deforestation in Amazonia". *BioScience* 44(5):314-321.

Swanson, F.J., T.K. Kratz, N. Caine, and R.G. Woodmansee. 1988. "Landforms effect on ecosystem patterns and processes". *BioScience* 38(2):92-98.

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

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

Turner, B.L. *et al.* 1997. *The Earth as Transformed by Human Actions.* Cambridge, UK: Cambridge University Press.

_____, R.E. Kasperson, W.B. Meyer, K.M. Dow, D. Golding, J.X. Kasperson, R.C. Mitchell, and S.J. Ratick. 1990. "Two types of global environmental change". *Global Environmental Change* 1:14-22.

_____, R.H. Moss, and D.L. Skole. 1993. "Relating land use and global land-cover change: A proposal for an IGBP-HDP Core Project". IGBP Report No. 24, HDP Report No. 5, Stockholm.

_____, D.L. Skole, S. Sanderson, G. Fisher, L. Fresco, and R. Leemans. 1995. Land –use and land-cover change; Science/Research Plan. IGBP Report No. 35, HDP Report No. 7, Stockholm and Geneva.

US Census Bureau. 1960-2000 and 1930. Unites States Census of Population. Puerto Rico. General Characteristics. Washington, DC: US Department of Commerce.

Vélez-Rodríguez, L. 2001. *Final Report of the Research on Land Use Classification of the Caribbean National Forest and Adjacent Municipalities*. Mayagüez, P.R.: University of Puerto Rico, Mayagüez Campus.

Vitousek, P.M., H.A. Mooney, J. Lubchenco and J.M. Melillo. 1997. "Human domination of Earth's Ecosystems". *Science* 277:494-499.

Williams, M. 1991. "Forests and Tree Cover". In *Changes in land use and land cover: a global perspective.* Great Britain: Cambridge University Press.

Notes

[1] Its elevation ranges from sea level to 1300 m, and annual rainfall and mean temperature ranges from 900 to 5000 mm and from 19to 26°C, respectively.

[2] Lugo, Figueroa-Colón and Scatena (2000) reported that nine taxonomic soils orders, 29 suborders, 38 great groups, 82 subgroups, 51 families, and 164 soil series have been identified in the island.

[3] During the 20th century, González (1995) reported a decrease of 1,258,269 *cuerdas* (1 *cuerda* is 0.9712 of an acre) of agricultural land in Puerto Rico. At the same time, the island's total forest area was estimated to have increased from 6% in the late 1940s to more than 30% in 1990 (Birdsey and Weaver 1987; Franco, Weaver and Eggen-McIntosh 1997; Rudel, Pérez-Lugo and Zichal 2000).

[4] For example, Thomlinson et al. (1996) found that urban land cover in the northern municipality of Luquillo increased about 2000% between 1936 and 1988.

[5] Portions of Ceiba and Naguabo municipalities were not included in this study. The excluded area (approximately 43% and 5% of Ceiba and Naguabo municipalities, respectively) is part of a US Naval Base, which possesses different land use dynamics compared to the rest of the study area.

[6] For the 1995 land cover map, different aerial photographs acquired from 1993 to 1999 were used, and the map was denominated as of 1995 for the purpose of the study.