Residential Expansion as a Continental Threat to U.S. Coastal Ecosystems

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Spatially extensive analysis of satellite, climate, and census data reveals human-environment interactions of regional or continental concern in the United States. A grid-based principal components analysis of Bureau of Census variables revealed two independent demographic phenomena, *α-settlement* reflecting traditional human settlement patterns and *β-settlement* describing relative population growth correlated with recent construction in non-agricultural areas, notably in coastal, desert, and "recreational" counties and around expanding metropolitan areas. Regression tree analysis showed that β-settlement was differentially associated with five distinct combinations of seasonality, summer heat or cool, intensity of agriculture, and extent of "barren" land. Beta-settlement was greatest in coastal and desert areas, and coincided with national concentrations of threatened and endangered species.

INTRODUCTION

The population dynamics of the United States afford particular opportunities for the study and modeling of population-environment interactions. Unique among industrial countries, the United States simultaneously experiences three strong population trends, namely immigration, natural increase, and residential mobility. These forces have produced considerable

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= −4%) and node D showing high population growth (mean = 38%). Similarly, calendar year of building for structures increased from left to right, with node I supporting relatively old structures (mean = 1956.7) and node D supporting recent development (mean = 1972.6) (Table 3). The relatively narrow range in mean building age across the five nodes is noteworthy, resulting from major post-World War II growth. Node D differs markedly from the other nodes because a large proportion of its growth is very recent i.e. the mean age of building is a poor metric. Agricultural intensity and farm density were highest in node I, moderate in nodes C and H, and low in nodes G and D (Table 3). In contrast, house density, wealth density, and both population density variables showed similar patterns across the five nodes, with scores ranging from high to low sequentially through nodes H, C, D, I and G. These results are, of course, to be expected on the basis of the structure for the β-settlement vector in Table 2 but make explicit the pattern in individual variables.

Local Patterns in Settlement

The high β-settlement scores for node D hexagons warranted further investigation of these sites. These hexagons were associated with desert and coastal dune ecosystems with at least 2 km^2 of contiguous barren land present. In detail the beta scores in node D were bimodal in distribution, with modes at values of 1.75 and 3.25. Since the node contained hexagons from desert and from coastal areas (Figure 3b), the possibility that this bimodality was associated with a desert versus coastal dichotomy was examined. However, the distributions proved to be very similar for desert and for coastal hexagons. Both groups therefore contained a subset of very high β-settlement scores and a subset of lower ones. The largest β-settlement scores were associated with the western desert counties surrounding Las Vegas (Clark, Lincoln, and Nye, Nevada, and Mojave, Arizona) and with the coastal barriers in North Carolina (South Bodie and Hatteras Islands in Dare County). Figure 4 shows the location of those large (≥ 2 km^2) coastal dune ecosystems identified by our analysis. Coastal barrier hexagons with the lower β-settlement values were associated with Northhampton and Accomack Counties in Virginia and Kenedy County in Texas, areas classified into node D because of their abundance of barren land. Table 4 summarizes county-level demographic and photo-interpreted data for the node D sites mapped in Figure 4. With few exceptions (Northhampton County, Virginia and Kenedy County, Texas), each county associated with these hexagons had disproportionately higher population densities along their coastal margins, spatially linking these coastal barriers to county-level population growth trends (CIESIN-SEDAC 1995). Regional differences in the extent of population change at these sites are clearly evident in Table 4. Between 1960 and 1990 Florida counties experienced net growth of from 16 to 781 percent (107 to 781% if the anomalously low rates associated with Cape San Blas for Gulf County are omitted). In contrast, counties associated with the central Atlantic Coast barriers had growth rates of −23 to 300 percent, and Gulf Coast counties associated with coastal barriers in Louisiana and Texas had growth rates of −48 to 155 percent. Associated with these differences were larger counts of building permits (single-unit, multi-unit and hotels alike) in Florida and New Jersey than elsewhere. Charlotte and Lee Counties in Florida each experienced more than 500 percent growth during this period. The rate of population increase for five of the coastal barrier counties in Florida slowed during the 1990s, with Gulf County being the exception (U.S. Bureau of Census 1998a). In North Carolina, Dare County experienced most of its more than 280 percent growth on the narrow coastal barriers of Bodie and Hatteras islands, adding an additional 16 persons/km^2 to this area. Dare County had the highest β-settlement scores of all coastal counties identified and nationally was second only to southeast Nevada.

We sought independent evidence of a relationship between population change and land use for our coastal barriers. We used data (Lins 1980) on changes in the extent of barren land between 1945–1955 and 1972–1975 for this comparison (Table 4). There was a significant negative correlation (Pearson correlation = −0.66, $P = 0.003$) between the relative change in barrier-specific barren land during this period and the concomitant change in county-level population density (Figure 5). The large increase in barren land for Parramore and Gasparilla Islands was due to the high rates of natural sand accretion associated with these barriers (Lins 1980, Dolan et al. 1985). The overall negative relationship in Figure 5, although for a very different time period from ours, provides direct evidence that absolute increase in human density creates development-related land cover change on these coastal barriers, as postulated here from the contemporary national analysis.

Environmental Consequences

To determine potential threats of population growth and new building on natural systems at the national scale, we mapped the separate distributions of threatened and endangered (T&E) terrestrial and semi-aquatic vertebrates and terrestrial plants for the conterminous United States (Figure 6). Several features of these maps are of relevance in light of the pattern of β-

TABLE 4

County-Level Demographics and Barren Landcover Change Statistics for Atlantic and Gulf Coastal Barriers Containing Large Contiguous Blocks (≥ 2 km²) of Barren, Dune Ecosystems and Associated with High Population Growth and New Building During the 1980s, USA. (Ownership status was determined from 7.5 minute topographic maps and US Census TIGER line files.)

		County-Level Demographics		
Coastal Barrier Unit[1]	County/State	% Δ in Pop 1960–1990	Absolute Δ in Pop/km² 1960–1990	# Single-Unit Permits 1970–1989
Barnegat Island	Ocean, NJ	300.2	195.7	84933
Rehoboth Island	Sussex, DE	54.7	16.4	19214
Cedar Island	Accomack, VA	3.5	0.9	3558
Parramore Island	Accomack, VA	3.5	0.9	3558
Smith Island	Northhampton, VA	–23.0	–6.7	1354
Bodie Island	Dare, NC	283.3	16.6	9395
Hatteras Island	Dare, NC	283.3	16.6	9395
Core Banks	Carteret, NC	91.5	18.4	9832
Core Banks	Carteret, NC	91.5	18.4	9832
Bogue Banks	Carteret, NC	91.5	18.4	9832
Cocoa Beach	Brevard, FL	258.0	111.6	62438
Fort Lauderdale	Broward, FL	276.0	293.8	121855
Miami Beach	Dade, FL	107.2	197.9	131391
Captiva Island	Lee, FL	514.4	134.9	60922
North Captiva	Lee, FL	514.4	134.9	60922
Cayo Costa	Lee, FL	514.4	134.9	60922
Gasparilla Island	Lee, FL	514.4	134.9	60922
Little Gasparilla	Charlotte, FL	781.2	55.1	32216
Longboat Key	Manatee, FL	206.1	73.7	23796
Cape San Blas	Gulf, FL	15.8	1.1	1631
Gardner Island	St. Bernard, LA	107.0	27.4	7445
Bastian Island	Plaquemines, LA	13.4	1.1	0
Isles Dernieres	Terrebonne, LA	59.6	10.2	5800
Matagorda Island	Calhoun, TX	14.8	1.8	1304
San Jose Island	Aransas, TX	155.4	15.0	761
Padre Island	Kenedy, TX	–48.0	–0.1	0
Padre Island	Willacy, TX	–11.8	–1.6	770
Padre Island	Cameron, TX	72.2	46.5	16724

[1]Listed geographically from northeast Atlantic Ocean to southwest Gulf of Mexico.
[2]P = private; L = local; S = state; F = federal; NC = nature conservancy; CBRS = coastal barrier resource unit.

TABLE 4 (*Continued*)

County-Level Demographics					
# Multi-Unit Permits 1970–1989	Total # Residential Permits 1970–1989	# Hotel Permits 1970–1989	% Δ Barren, (Δ acres) Lins	(1980)	Ownership Status[2]
22931	107864	105	−15	(195)	P,S
7501	26715	72	+49	(612)	P,S
639	4197	35	+43	(201)	CBRS, NC
639	4197	35	+203	(1572)	NC
176	1530	3	+75	(983)	NC
1656	11051	45	+7	(965)	P, NC, S, F
1656	11051	45	+4	(319)	P, CBRS, F
4652	14484	37	+43	(445)	F
4652	14484	37	+0.2	(8)	F
4652	14484	37	+9	(68)	P, S
34389	96827	75	+32	(214)	P, F
256493	378348	121	−100	(832)	P, S
240564	371955	154	−100	(672)	P
67502	128424	95	−89	(370)	P, CBRS
67502	128424	95	−8	(47)	P, CBRS, S
67502	128424	95	+14	(65)	P, CBRS, L, S
67502	128424	95	+121	(191)	P, L
12593	44809	20	+42	(174)	CBRS
38988	62784	48	−84	(326)	P, CBRS, L
382	2013	16	−3	(46)	P, CBRS, S, F
2947	10392	1	NA	NA	P
0	0	0	NA	NA	CBRS
1831	7631	11	−9	(81)	CBRS
636	1940	8	+1	(66)	CBRS, S
713	1474	8	+7	(795)	CBRS
0	0	0	+7	(1381)	CBRS, F
29	799	12	−3	(246)	P, CBRS, L
11364	28088	107	−3	(246)	P, CBRS, L

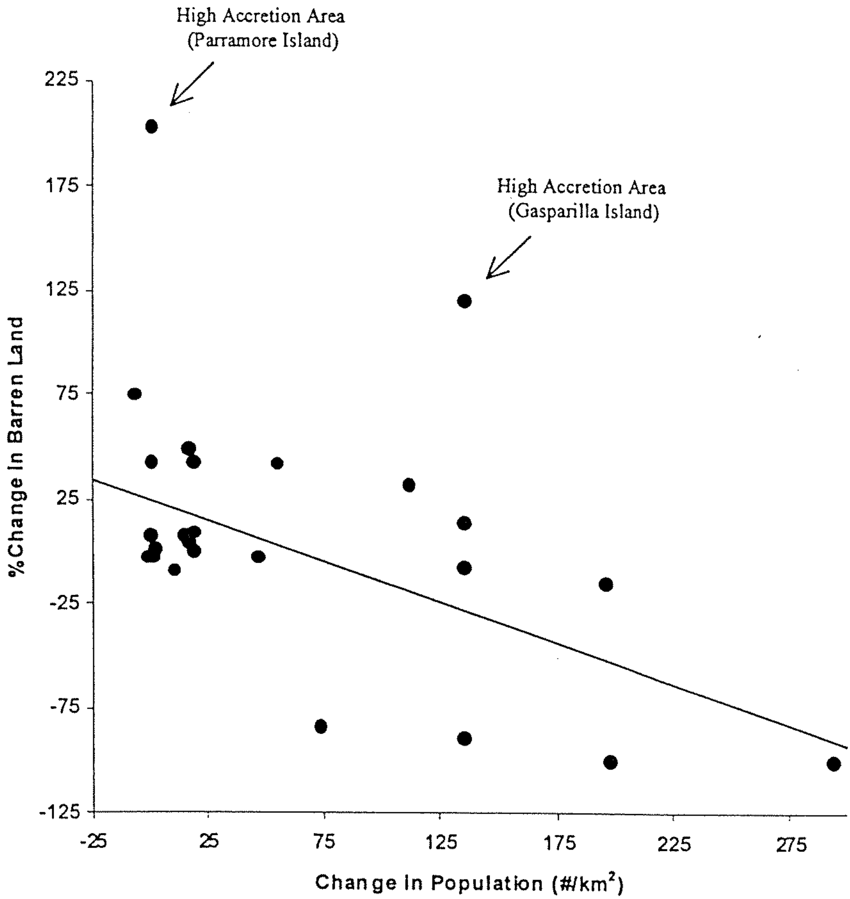

FIGURE 5. Relationship between per cent change in barren land and change in population per km^2 for coastal barriers (Pearson correlation, $r = -0.66$, $P = 0.003$). These barriers contain large blocks of contiguous ($\geq 2\ km^2$) barren land and were associated with high population growth and new building (β-settlement) at the continental scale during the 1980s. Note that sand accretion is common on some islands as a result of tide, wave, and current conditions. The data points for Parramore Island, Virginia and Gasparilla Island, Florida were outliers associated with regions of unusually high sand accretion and were omitted from the correlation and regression calculations.

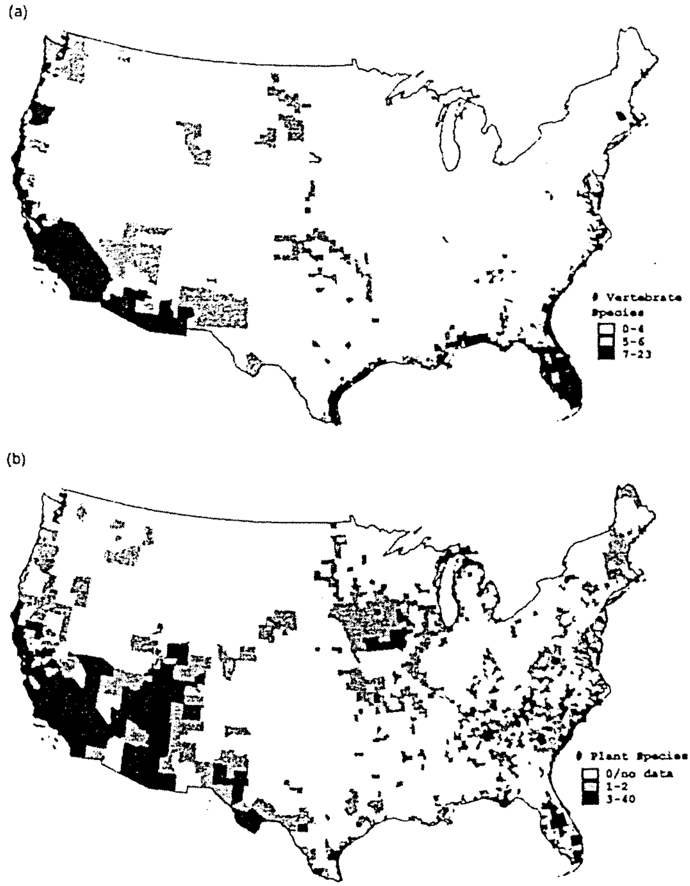

FIGURE 6. County-level distribution of endangered terrestrial and semi-aquatic vertebrates (a) and terrestrial plants (b) for the conterminous United States. Note the high concentrations of endangered vertebrates along coastal margins and the high concentrations of endangered plants in the desert West.

settlement in Figure 2 and its association with coastal and desert lands (Figure 3a). First, the predominantly coastal concentration of T&E vertebrates closely parallels the distribution of high β-settlement, persisting inland in the southwest deserts (Figure 6a). Regionally, California, Arizona, and Florida have major overlaps of both T&E groups with high β-settlement, but for T&E plants (Figure 6b) regional parallels also occur in Colorado, the

TABLE 5

Threatened and Endangered Terrestrial and Semi-Aquatic Vertebrates and Terrestrial Plants Occurring in Coastal Counties Associated with High β-Settlement and Large Blocks (≥ 2 km^2) of Contiguous Barren Dune Ecosystems[1]

Common Name	Scientific Name	Taxonomic Group	Priority Status
AMARANTH, SEABEACH	*Amaranthus pumilus*	plant	T
BEAKED-RUSH, KNIESKERN'S	*Rhynchospora knieskernii*	plant	T
BIRDS-IN-A-NEST, WHITE	*Macbridea alba*	plant	T
BUTTERWORT, GODFREY'S	*Pinguicula ionantha*	plant	T
JACQUEMONTIA, BEACH	*Jacquemontia reclinata*	plant	E
LEAD-PLANT, CRENULATE	*Amorpha crenulata*	plant	E
LOOSESTRIFE, ROUGH-LEAVED	*Lysimachia asperilaefolia*	plant	E
MILKPEA, SMALL'S	*Galactia smallii*	plant	E
PAWPAW, BEAUTIFUL	*Deeringothamus pulchellus*	plant	E
PINK, SWAMP	*Helonias bullata*	plant	T
PINKROOT, GENTIAN	*Spigelia gentianoides*	plant	E
POLYGALA, TINY	*Polygala smallii*	plant	E
RHODODENDRON, CHAPMAN	*Rhododendron chapmanii*	plant	E
SPURGE, DELTOID	*Euphorbia deltoidea ssp. deltoidea*	plant	E
SPURGE, GARBER'S	*Euphorbia garberi*	plant	T
SPURGE, TELEPHUS	*Euphorbia telephioides*	plant	T
CROCODILE, AMERICAN	*Crocodylus acutus*	reptile	E
SNAKE, ATLANTIC SALT MARSH	*Nerodia fasciata taeniata*	reptile	T
SNAKE, EASTERN INDIGO	*Drymarchon corais couperi*	reptile	T
TURTLE, BOG	*Clemmys muhlenbergii*	reptile	T
TURTLE, GREEN SEA	*Chelonia mydas*	reptile	E,T
TURTLE, HAWKSBILL SEA	*Eretmochelys imbricata*	reptile	E

TURTLE, KEMP'S (ATLANTIC) RIDLEY SEA	*Lepidochelys kempii*	reptile	E
TURTLE, LEATHERBACK SEA	*Dermochelys coriacea*	reptile	E
TURTLE, LOGGERHEAD SEA	*Caretta caretta*	reptile	T
CARACARA, AUDUBON'S CRESTED	*Caracara cheriway audubonii*	bird	T
CRANE, WHOOPING	*Grus americana*	bird	E
CURLEW, ESKIMO	*Numenius borealis*	bird	E
EAGLE, BALD	*Haliaeetus leucocephalus*	bird	T
FALCON, ARCTIC PEREGRINE	*Falco peregrinus tundrius*	bird	T
FALCON, NORTHERN APLOMADO	*Falco femoralis septentrionalis*	bird	E
FALCON, PEREGRINE	*Falco peregrinus*	bird	E
JAY, FLORIDA SCRUB	*Aphelocoma coerulescens coerulescens*	bird	T
KITE, EVERGLADE SNAIL	*Rostrhamus sociabilis plumbeus*	bird	E
PELICAN, BROWN	*Pelicanus occidentalis*	bird	E
PLOVER, PIPING	*Charadrius melodus*	bird	E,T
PRAIRIE-CHICKEN, ATTWATER'S GREATER	*Tympanuchus cupido attwateri*	bird	E
PYGMY-OWL, CACTUS FERRUGINOUS	*Glaucidiumbrasilianum cactorum*	bird	E
SPARROW, CAPE SABLE SEASIDE	*Ammodramus maritimus mirabilis*	bird	E
SPARROW, FLORIDA GRASSHOPPER	*Ammodramus savannarum floridanus*	bird	E
STORK, WOOD	*Mycteria americana*	bird	E
TERN, ROSEATE	*Sterna dougalli dougalli*	bird	E,T
WOODPECKER, RED-COCKADED	*Picoides borealis*	bird	E
BEAR, LOUISIANA BLACK	*Ursus americanus luteolus*	mammal	T
COUGAR, EASTERN	*Felis concolor couguar*	mammal	E
JAGUARUNDI	*Felis yagouaroundi tolteca*	mammal	E
MANATEE, WEST INDIAN (FLORIDA)	*Trichechus manatus*	mammal	E
MOUSE, SOUTHEASTERN BEACH	*Peromyscus polionotus niveiventris*	mammal	T
OCELOT	*Felis pardalis*	mammal	E
PANTHER, FLORIDA	*Felis conconcolor coryi*	mammal	E
SQUIRREL, DELMARVA PENINSULA FOX	*Sciurus niger cinereus*	mammal	E
WOLF, RED	*Canis rufus*	mammal	E

[1]T = threatened; E = endangered.

upper Michigan Peninsula, and in mountainous North Carolina where these concentrations are associated with high population growth in the retirement and recreation sector: all ten North Carolina counties in the southwest corner of the state are designated 'retirement and recreation' counties by the Census Bureau (U.S. Bureau of Census 1992). Table 5 lists all T&E species occurring in the high β-settlement coastal counties of our analysis: birds and plants dominate the list, though many mammal and reptile species occur in these areas as well. Each of the 21 coastal counties highlighted in this study have at least five T&E species and 86 percent of those counties have at least nine T&E species. In contrast to β-settlement, overlap of the distributions of T&E species with high α-settlement areas (Figure 1) are more limited, mostly to large metropolitan areas in Massachusetts, Florida, and California.

DISCUSSION

Meyer and Turner (1992) suggest that to identify the key elements of global land-use/cover change, researchers must *"seek a middle scale between the global and the local at which to address driving-force change relationships. The identification of a set of world-regional situations, defined by both socioeconomic and environmental variables, may make possible generalizations that cannot be made at the global scale."* Turner et al. (1995) further suggested that these world-regional situations permit *"spatial and temporal fine-tuning of the overall modelling effort as well as providing the local and regional understanding that is vital for climate impact and sustainability research."* The scale of analysis afforded by our EMAP hexagon grid was ideal in meeting these criteria. Our use of a spatially hierarchical modeling algorithm combined with an extensive suite of demographic and environmental variables then allowed us to measure the *interaction* of humans with land use, land cover and climate. This is evidenced by CART's capacities to handle two-way patterns of interaction between population and environment at regional scales (i.e. that climate may constrain human activity while human activity may determine subsequent land use and thereby influence climate [Salati and Vose 1984]) and to identify complex, nonlinear contingencies and constraints of environment on population at relevant spatial scales. In this article, we used a continental-scale analysis to identify major regional patterns of interaction between population growth and environment and then focused our efforts on a particular regional pattern—population growth and new development in and around coastal barriers—to reveal patterns of local population growth that stress these fragile ecosystems. Coastal dune ecosystems are rich in ecological diversity but are considered fragile because they are extremely vulnerable to human impacts (Marsh 1965, Dolan et al. 1973, Liddle and Greig-Smith 1975a, Clark 1976, McAtte and Drawe 1981, USDOI 1987, Dean 1988).

Why β-settlement?

One of the challenging, yet exciting, aspects of population-environment interaction in the continental United States is the ever dynamic state of the nation's population geography. It has long been known that the pressure of humans on their environment is a function of population density (Meyer and Turner 1992, Terborgh 1989) but the past three decades have witnessed sharp and unanticipated shifts in patterns of residential distribution and mobility that yield a somewhat complex picture of these impacts. Although the overall trend of population distribution through 1980–90 was one of overall metropolitan gain, the decade actually displays two patterns. The early 1980s were years when growth outside the metropolitan areas slowed considerably as these regions were affected disproportionately by the recession, with population eventually declining in many areas (Fuguitt and Beale 1996). Migration balance thus once again favored metropolitan areas. By 1986–87, however, non-metropolitan America had recovered and was attracting and retaining people, and this trend, which appears to be continuing, has renewed discussions about de-concentration in the U.S. population. This de-concentration is largely attributed to innovations in transportation and communication and in economic organization, coupled with preference for living and working in low density settings (Fuguitt and Brown 1990).

Although these broad trends are important it is necessary to recognize that neither metropolitan nor nonmetropolitan U.S. have been homogeneous in their experience of residential mobility. One distinctive form of regionalized growth in rural areas during the 1980s has been in exurban counties, adjacent to metropolitan areas and connected to them by commuting (Frey 1995). This phenomenon is linked to the growth of "edge cities" at the periphery of large metropolises. The term "edge city" was coined by Garreau (1991) to describe a suburban center that transformed from residential, rural, or mixed-use territory into an area that is a center for jobs, shopping and entertainment—whether or not the area is a distinct place defined by political boundaries (Frey 1995).

A second source of inhomogeneity in mobility has been in relation to retirement, especially towards coastal areas. In the South, for example, small metropolitan areas in the interior grew negligibly between 1985 and

1990 whereas coastal Sunbelt areas fared much better (Frey 1995). Similarly, many of the (non-metropolitan) counties classed as retirement counties by the USDA Economic Research Service had led the way in growth during the "turnaround" period of the 1970s and have continued to experience growth throughout the eighties (Fuguitt and Beale 1996). Although adversely affected by economic conditions in the early 1980s, they managed to register positive net migration and they grew at a more rapid pace than other areas. After 1984–85 the net migration rate for retirement counties increased each year, and that trend continued into the 1990s, registering a net migration rate of 1.7 percent by 1993–94 (Fuguitt and Beale 1996). This growth in retirement migration (not all of which has been in coastal areas) has been accompanied by a general trend in internal migration of movement away from the cold weather states toward the coasts, especially along the Atlantic, south from the Chesapeake Bay, along the Gulf Coast and along the Pacific rim (Farley 1996).

The concept of two separate and distinct patterns of settlement which we term α-and β-settlement allows a more refined analysis—particularly in quantified analysis—of the impact of human population on the environment than does use of simple population density. The composition of our α-settlement index (Table 2) clearly parallels that component of population growth associated with gross metro-centric expansion. Population densities a decade apart, housing density, and wealth index all contributed to this index and its distribution over space is essentially what one expected from a knowledge of population distribution across the U.S., even to identifying the exurban growth centers discussed by Frey (1995). However, this index only accounted for just over half the variance in our nine-variable data set, indicating that there existed major contributions of other sorts to the variation in the underlying demography. Our β-settlement vector picked up more than half of the remaining variance and had a very different spatial distribution than had α-settlement (compare Figures 1 and 2), as necessitated by the orthogonal nature of their axes. Our β-settlement index appears to parallel the coastal and Sun-belt concentration described above (Farley 1996). In this index, decadal population change was the major contributor (compare the top left and bottom maps in Figure 2) but β-settlement was more than population change: notice how the β-patterns are more distinct than apparent in the population change in such states as Maine, Michigan, Wisconsin, Minnesota, and Wyoming *inter alia*. Population densities can rise or fall if occupancy rates of extant buildings change, and such patterns impact the environment less directly, through the general activity of masses of people. The β-settlement measure, however, requires new building in parallel with population increase and additionally involves a non-farmland focus. Whether the avoidance of farming is solely a complement of α-settlement consumption of prime farmland (USDA 1996) or whether some other issue is involved remains unknown. As presently constructed, our β-settlement metric conceptualizes and indexes a particularly damaging form of sprawl, of green-field building away from agricultural lands. In an environmental impact context, if traditional settlement essentially results in major destruction of Nature, then β-settlement indices herald developing impacts. Its spatial and temporal patterning therefore provide valuable aid to environmental policy analysis. As noted earlier, alpha and beta settlement focus on nine demographic variables, but these models could be complemented by adding explicit measures of exosomatic evolution outlined in the IPAT (Ehrlich and Holdren 1971, Commoner 1972) and POET (Duncan 1964) models (e.g., per capita increase in automobiles or computers) which may better reflect patterns of energy consumption and subsequent environmental impact (Sterrer 1993).

Our conceptualization of the first and second principal component axes as α-and β-settlement asserts that reification (Blackith and Reyment 1971) of the PCA linear equations of variable values is useful. The underlying equations *may*—but do not necessarily have to – be mere mathematical artifacts: they may instead reflect a real phenomenon. As an example from a different field, the first principal component of multiple morphometric measurements on organisms typically yields equal positive loadings on all variables, unequivocally indexing the real phenomenon of size: a smaller organism is smaller on all measures, and conversely, and the first PCA axis reflects this reality (Blackith and Reyment 1971). Our working hypothesis here is that α-and β-settlement do indeed reflect reality rather than merely mathematical out-turn, a view supported by the high variance accounted for (78% against the random expectation of 2/9 = 22.2%) by the two principal components. Our discussion above further treated α-and β-settlement as independent phenomena on the basis of their orthogonality within the principal component analysis conducted. In essence this orthogonality asserts that there exist two clusters of variables within each of which the variable values co-vary spatially whilst at the same time remaining independent of the values of the variables in the other cluster. This orthogonality does not assert anything about the pattern of *temporal* co-variation over time. Should future research show that the component structures found here are evident in analysis of each past decade's variables, then α-and β-settlement constitute temporally invariant structures of great value in conceptualizing settlement patterns. If, on the other hand, variable loadings change over time, the α-and β-settlement concepts are best regarded as indices of evolving settlement patterns whose changing loadings provide clues as to the causal processes involved. In either case the α-and β-metrics transcend the corresponding univariate metrics.

Our β-settlement is therefore a powerful new tool for identifying continental and regional-scale anthropogenic stress on the environment. This is because β-settlement identifies population growth and new development in areas *away from* traditional population centers and does so independently of α-settlement. Increasing α-settlement in an area may intensify anthropogenic stress on its remaining natural resources such as wildlife but area-sensitive species such as forest-interior birds (Terborgh 1989, Witham and Hunter 1992) are likely to have been already lost in the earlier stages of development associated with road expansion and infrastructure development adjacent to existing population centers. Areas of high β-settlement are therefore potentially more likely to experience natural resource degradation in the forms of biodiversity loss and ecosystem simplification because of the lack of prior anthropogenic stress on their resources. In fact, in coastal dune environments, even minimal human impacts such as foot traffic decrease total plant cover and plant diversity (Liddle and Greig-Smith 1975a, Boorman and Fuller 1977, Hylgaard and Liddle 1981, McAtte and Drawe 1981), impact invertebrate populations (Bayfield 1979), and alter soil characteristics (Liddle and Greig-Smith 1975b). Thus our finding of a spatial link between high values of our β-settlement index and landscape features of special management concern has implications for conservation and policy development since these areas may still contain relatively intact ecosystems in the early stages of human development. This finding is paralleled by research in developing countries that indicates that once gross settlement reaches a certain threshold (100 persons/km^2), drastic environmental deterioration occurs (Terborgh 1989). In the U.S. a particular threat arises since the high β-settlement areas along the Atlantic, eastern Gulf, and Pacific Coasts are strongly associated with high concentrations of endangered terrestrial vertebrates, and high β-settlement areas in the desert southwest and along the Pacific Coast are also areas where concentrations of endangered plants occur (Figure 6). Dobson et al. (1997) concluded that a relatively limited set of protected reserves chosen to be mutually complementary could protect the majority of the threatened and endangered species of the United States. However, as most of their sites are located in areas we identify here as likely to experience intensified new construction and higher population density, there must be major doubts about the long-term viability of such a strategy.

In our study, β-settlement was highest in the counties surrounding Las Vegas, Nevada. Nevada has been the fastest growing state in the country for twelve consecutive years from 1985–1997 (U.S. Bureau of Census

1998c), and between 1990 and 1996 Las Vegas and its suburban neighbor Henderson were the fastest growing metropolitan area and city, respectively, in the country (U.S. Bureau of Census 1998b). Our study shows that the highest concentrations of people in the area surrounding Las Vegas are in close proximity to barren, desert ecosystems. Since population expansion in these water-poor areas is spatially linked to existing infrastructure where population density is relatively high (McKibben 1998), future population growth, urban expansion, and concomitant diversion of resources, such as water, are likely forms of imminent anthropogenic stress on these fragile barren environments. This problem, although sharing the characteristics of a nationally noteworthy impact on a fragile ecosystem, is sufficiently different from the coastal issues not to be pursued here.

Coastal Barrier Development

The coast of the United States, like many other countries around the world, has a long history of human development pressure (Walker 1990). Coastal zones comprise 8 percent of earth's land area, yet two-thirds of the world's population and 53 percent of the U.S. population live in the zone (Culliton et al. 1990). Barrier beaches comprise 13–15 percent of the world's coastline and the U.S. coastline from Maine to Texas, containing approximately 2700 linear miles of barrier islands (USDOI 1982), is the *"longest and best evolved chain of barrier islands in the world"* (Godfrey and Leatherman 1979). In addition to sheer population growth, other development trends on and around coastal barriers, such as pressure to reclassify CBRS lands and recreational pressure on natural shoreline communities, can herald potential risks to geological and ecosystem integrity. Any reclassification of CBRS lands involves restoring federal subsidies for infrastructure development and flood insurance and has major implications for conservation since these areas make up 29 percent (183,700 ha) of all Atlantic and Gulf Coast barrier beach acreage. Despite much research, however, it has proven difficult to quantify human-induced coastal change because of the dynamic character of natural processes acting on the coast and because of the equally dynamic response of humans to these phenomena (Walker 1990). Thus our coastal barriers exhibited much demographic variation (e.g. from uninhabited Bastian Island, Louisiana to Miami Beach, with a population of 70,700) and much variability of ownership (e.g. from single-owner barriers such as Smith Island to multi-owner barriers such as Cape San Blas). Our national analysis nevertheless indicates an important commonality across all of these barriers, the large blocks (≥ 2 km^2) of barren land they contain. These large dune ecosystems provide critical habitat for many candidate and listed endangered species (Figure 6), and they are the largest contiguous blocks of dune or barren habitat remaining along the central and south Atlantic, and Gulf Coasts (Loveland et al. 1991). Our analysis in Figure 5 shows that within this group of nationally distinctive barriers (Figure 3) any increase in population density has historically been correlated with the loss of these ecosystems.

Our hierarchical regression tree analysis spatially links the occurrence of high beta settlement to fragile dune and desert ecosystems, providing for the first time a national context for this class of environmental threat. Application of our model to policy analysis and formulation will need to proceed along three lines. First, our model's major contribution is to identify emergent patterns of human settlement—separate and distinct spatial patterns in α-settlement and β-settlement which transcend simple metrics of anthropogenic stress such as generic population density. Second, although the environmental correlates of β-settlement established here—July temperatures, seasonality—are of little practical predictive value short of climate change, the regionalization of β-settlement levels associated with the intersection of environmental and land cover constraints provides a regional cast to the issues, stimulating a search for regional drivers of beta settlement which are amenable to state or local control. Finally, our modeling approach can be re-scaled to exploit higher resolution land cover data, such as Thematic Mapper 30m pixels, and census data such as block or tract level records. Thus, while our existing model with its spatially coarse resolution provides a national overview and context, its methodology promises equivalent quantification of human-environment interactions within a local context. It is important to remember that our beta settlement model is a first approximation of potential human-environment interactions. Analysis of large-scale patterns by correlation is prone to statistical artifacts that do not reflect causal mechanisms, and our use of regression trees is no exception. However, the end partitions identified by our regression tree model imply that the regionalizations are real enough to warrant use in formulating hypotheses for further study, and our *post hoc* perturbation analyses ensured that our predictors were not confounded with others in the very large suite of variables considered as candidate predictors. Other factors not in the candidate predictors considered here may be confounding variables but if so, their action is necessarily limited to a spatial domain already approximated here by an end node contingent on the confounding variable. Thus the present analysis limits the scope for potential mis-interpretation and provides us with "experimental" and "control" domains within which any potential confounding variable must display appropriate effects. Ultimately, the greatest value of our modeling approach may be its ability to provide a perspective on human-environment interactions that is common both to policy analysis of the local actions that are foundational to global trends (Kates 1998, Hinrichsen 1998) and to policy analysis of the emerging properties of global and continental systems (Turner et al. 1995).

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population growth, with resulting pressure on the environment. First, between 1980 and 1990 the U.S. population grew by 9.8 percent and since 1990 has continued to grow by an average of 1.0 percent per year (De Vita 1996). During the same period approximately 1.2 million immigrants arrived in the country annually, though most of this immigration was concentrated into just seven states and fourteen metropolises (Farley 1996). Second, industrial restructuring and internal migration (spurred by the search for amenities, recreation, and retirement opportunities) resulted in major shifts in population away from the North and East to the South and West (De Vita 1996). Third, a continuing major trend has been the continued growth of "edge cities," with population moving away from the older central areas (Garreau 1994). Nelson and Dueker (1990) estimated that one-third of the population growth between 1960 and 1985 has been of this "exurban" character. Growth in certain states and cities has been particularly dramatic. During the last decade, the states of Nevada, Arizona and Florida grew by 50.4, 34.9 and 32.8 percent respectively and between 1990 and 1997 Nevada, Arizona, Idaho and Utah recorded average annual growth rates of 4.6, 3.0 and 2.5 percent, respectively (De Vita 1996). These particularly rapid rates of growth—faster than many developing countries—are in large measure the result of dramatic and fast-paced distribution dynamics consequent upon industrial restructuring and changing migration patterns.

A second pattern of impact has been coastal, reflecting growth rates in coastal areas that are triple the national average (Clark 1996). In 1998 population density in coastal counties was, at 341 people per square mile, more than four times the national average, and this trend was expected to result in nearly 75 percent of all Americans living in coastal areas by 2025 (Hinrichsen 1998). Growth was particularly high in the 1980s in Alaska and in Florida (36 and 31 percent respectively), with California not far behind (26 percent) (*ibid.*).

These changes, accompanied by such shifts in demographic patterns as increases in income and in leisure time and the aging of the population, have placed considerable strain on the environment. They result in increased demand both for resources (Shafik 1994) and for retirement and recreational opportunities in non-urban areas (Culliton et al. 1992). It is well known that contemporary changes in land cover are largely human-induced (Allen and Barnes 1985, Whitby 1992) and that habitat loss is the critical component of anthropogenic stress on the environment. This is apparent even at the landscape scale in the U.S. where cumulative effects of land cover change by individual landowners create changes that impact ecological processes (Forman and Godron 1986). Rather little research effort, however, has focused on understanding population-environment linkages in the U.S., despite widespread availability of reliable demographic and environmental databases (Davis and Bernstam 1991, Population Resource Center 1992, Stycos 1993, Jolly 1994), and the development of innovative tools for assessing environmental quality at the landscape-scale (see review by O'Neill et al. 1997). In fact, a literature review by Myers (1991) concluded *"There has been all too little assessment of the multiple linkages between population factors and environmental degradation with a view to evaluating their dynamic interactions."* Coarse resolution (1 km^2 or greater) remotely sensed data for mapping land cover characteristics are considered ideal for this type of analysis (Turner et al. 1995) but efforts to develop relevant theory have been hindered by lack of empirical research linking ecologically relevant landscape metrics and measures of human activity (Jolly 1994). Much of the research conducted to date has focused on individual sites or small regions (e.g., Wear and Bolstad 1998, White et al. 1996) or on individual ecosystems (O'Connor and Ehler 1991). Global reviews that have been undertaken, often within internationally coordinated programs (IGBP 1990, WCED 1987), have necessarily been at rather coarse resolution and with considerable data uncertainty (Clark et al. 1986, Houghton 1994, Turner et al. 1995). Orians and Skumanich (1997) therefore call for increased environmental analysis of methodological issues related to demographic analyses and greater interdisciplinary research on population-environment linkages within the U.S.

Machlis and Forester (1996) have proposed a three-component modeling strategy for understanding human-environment interactions: (1) a theoretical framework for identification of variables of potential importance in linking population and environment; (2) a conceptual model of correlation and path analysis among population and environmental variables; and (3) a predictive model using a parsimonious set of variables that identifies the established patterns of interaction to support predictions of future outcomes. Our study primarily addresses Machlis and Forester's (1996) first two modeling levels, currently addressing the third component only through statistical (rather than causal) predictions as to response to future change. Our theoretical framework is based on *a priori* selection of relevant demographic, socioeconomic, climate, land cover and pattern metric variables. Our conceptual model then captures the interaction of humans with the environment by linking ecologically-relevant climate and landscape metrics with measures of human activity at relevant spatial scales, leading to identification of patterns of regional collinearity or covariation between component variables. We also incorporate the two-way nature of population-environment interactions. Human activity can itself determine land use and thus modify environmental conditions on regional scales defined by critical thresholds. Such critical thresholds and positive feedback mechanisms have been demonstrated empirically for complex natural systems (Grover and Musick 1990, Schlesinger et al. 1990). Finally, although not developed extensively here, our model can be extended to predict future changes in the intensity and distribution of human-environment interaction under continuing demographic change and provide input appropriate to policy analysis and development. Thus while the present article treats the human-environment relationships established as static, the use of the model results in future policy acknowledges the anticipatory nature of humans (e.g. the capacity to change our present state by envisioning future modeled states and implementing appropriate policy) as a critical but indirect link in the longer term model development process.

Important considerations in modeling human-environment relationships are: (1) the presence of multiple scales within the local, regional, and global dynamics of these interactions; (2) the need to disentangle the complex nonlinear interactions commonly found in these relationships; and (3) the need to provide a local context within which the implications of continental-scale patterns can influence local policies and goals. Multi-scale model development was addressed by Turner et al. (1995) who stated "*the relationship between scales of organization (cross-scale dynamics) is unknown but important to determining scale boundaries and the influences of key variables on emerging properties at different scales.*" These scales of organization may be particularly important since natural systems are hierarchically organized (Allen and Starr 1982, O'Neill et al. 1991) but our knowledge of the links between these scales is currently poor (Allen and Hoekstra 1992). The need to disentangle the complexity of non-linear interactions has been emphasized by Geoghegan et al. (1998) who write "*. . . most cases of land-use and land-cover change . . . are the result of multiple actors and structures combining in complex, synergistic ways. Moreover, critical exogenous forces, especially international and national policy decisions, . . . can be seen as shocks to the existing land management system that fundamentally alter the pathways and trajectories of change . . . .*" These authors also emphasize that a linked land-use and land-cover system may exhibit its own dynamics, independent of driving forces, through path dependencies of the system originating in either self-reinforcement (where returns increase with scale or agglomeration) or in investment rigidities (where sunk costs or infrastructure development constrain and shape future development). Finally, the importance of local context within continental-scale and global patterns was addressed by Kates (1998) who stated: "*we need to analyze local actions as the foundation for* *global trends . . . it is at the local level that we can most readily examine the interaction of global environmental change with the other profound changes of economic restructuring and population growth and migration currently underway."*

In the present article we present an innovative hierarchical analysis relating human activity to climate and remotely sensed land cover data characterizing the environmental geography of the conterminous United States. Our approach allowed us to identify and quantify broad demographic patterns linked to the natural and anthropogenic environment and to demonstrate at a continental scale the intensity and distribution of human impact on particular ecosystems, notably coastal and desert ones.

MATERIALS AND METHODS

Our general approach was first to determine the values of demographic and environmental variables across a regular spatial grid, then to identify independent patterns of variation among the demographic variables by means of principal components analysis (PCA), and finally to correlate these patterns with environmental attributes of each location by use of regression tree analysis. The spatially explicit correlates were then used to identify regional patterns of human-environment impact.

Spatial Grid

Our spatial grid was the hexagonal grid developed for the U.S. Environmental Protection Agency (EPA) for use in the Environmental Monitoring and Assessment Program (EMAP) (White et al. 1992). Each hexagon was approximately 640 km^2 in area and approximately 12,600 hexagons cover the conterminous U.S. A hexagonal grid, unlike a square grid, has a constant center-to-center distance between adjacent grid cells (here 27 km).

Demographic Data

We extracted nine variables from the county-level census files of the U.S. Bureau of Census for 1990 (U.S. Bureau of Census 1990a). The variables chosen—population densities in 1980 and 1990, change in population density over 1980–1990, mean age of built structures, metropolitan or non-metropolitan status, total number of farms present in 1987, total acreage in farms in 1987, total number of housing units in 1990, and per capita income in 1989—were those thought *a priori* likely to reflect human influence (through population density and anthropogenic stress) on the environment. Population density and its derivatives are a driving force of global environmental change due to their correlation with resource demand (Meyer and Turner 1992). The other demographic variables we used were thought likely to capture key aspects of anthropogenic stress in the U.S. (Kiester et al. 1993, Wickham et al. 1997). The high rate of redistribution of people in the U.S. (1 in 5 per year) warranted the inclusion of a population change variable (Orians and Skumanich 1997). Our mean age of structure and per capita income variables captured aspects of timing of settlement and intensity of consumption, respectively, these being variables also considered important by Orians and Skumanich (1997). These two variables may also be surrogates of leisure income and of regional socioeconomic patterns, in effect tracking seasonal population demands for recreational and retirement opportunities and consequential building of second homes (Culliton et al. 1992). Although household income is arguably a better index of consumption pressures, we found that per capita income and household wealth were correlated across counties, such that the latter variable need not be computed for our hexagons. It is also possible to argue for cross-walking variables such as income or wealth from county to hexagon on a basis other than relative area of county-hexagon overlap, an approach of particular value if a spatially explicit model of the underlying socio-economics were available (Costanza et al. 1993). Absent such a model at this early stage, we adopted area-weighting . Then in order to area-weight our county-level per capita income variable to the EMAP hexagon grid, it was converted to the wealth density index used here. Wealth density may be an index of affluence paralleling several theoretical concepts outlined in the IPAT model (Ehrlich and Holdren 1971). Land cover conversion to agriculture is a major global concern (Meyer and Turner 1992) but in the U.S. it is agricultural conversion to urban land that matters since two-thirds of domestic agricultural production revenues are generated in or adjacent to metropolitan counties (USDA 1996). Our farm density and farmland proportion variables, coupled with census data on population change rates and degree of urbanization, were intended to reflect regional farmland conversion to suburban development and population growth in sparsely-populated areas still containing remnants of intact natural ecosystems (Ricketts et al. 1997). These nine variables only approximately capture the human dimensions of the environment. Theoretical models of human-environment interaction such as IPAT (Ehrlich and Holdren 1971, Commoner 1972) and POET (Duncan 1964) suggest that measures of affluence, energy flow, and technology would better reflect human impacts on the environment by indexing patterns of exosomatic evolution. Even without these, the suite of nine variables used here yielded just two principal component axes that between them captured 78% of the variance (see below). Hence incorporation of other variables is less likely to provide additional predictive power than to provide greater insight into the processes underlying the phenomena described here. Further research is necessary to address these issues.

We mapped the county-based census variables to the regular EMAP grid by overlaying a digital county-level boundary file onto the digital hexagon grid in a GIS (ARC/INFO 1996, ESRI Inc., Redlands, CA) and calculating weighted values for each census variable in each hexagon from the intersected coverage polygons (Table 1). All census variables were appropriately normalized prior to analysis.

The nine variables we chose were cross-correlated to various degree and therefore did not constitute independent measures of human activity. We used a principal components analysis (PCA) of the correlation matrix of transformed variables to identify independent patterns of covariation and thus reduce the dimensionality of the study (Mageean and Bartlett 1998). Scores on each of the principal component axes of interest were then computed for each hexagon for use as dependent variables in analysis here.

TABLE 1

County-Level Census Variables from the 1990 Bureau of Census and Their Hexagon-Weighted Equivalents for the Conterminous United States

County-level Census Variable	Hexagon-Level Equivalent
Total Population—1980	Population Density / km^2 (1980)
Total Population—1990	Population Density / km^2 (1990)
Per Capita Income (1989)	Wealth (income) Density / km^2
Total Number of Houses (1990)	House Density / km^2
not applicable	% Change in Population / Hexagon (1980–1990)[1]
Total Number of Farms (1987)	Farm Density / km^2
Acres of Farmland (1987)	Proportion of Hexagon in Agriculture
Mean Calendar Year of Building for Structures (1990)	Mean Calendar Year of Building / Hexagon
Metropolitan Status	Proportion of Hexagon Classified as Metropolitan

[1]Computed as: [(population in hexagon in 1990 – population in hexagon in 1980) / (population in hexagon in 1980)].

The derivation of hexagon-weighted values from county-level census data depended on GIS overlay from fewer (ca. 3,111 counties) to more (ca. 12,600 hexagons) spatial units, raising issues of true sample size. We therefore computed a PCA from the 3,111 county-based values to ensure that additional cases created by the hexagon grid analysis were not generating spurious structure. The change from county to hexagon spatial units could have affected the results in either or both of two ways. First, the proportional allocation assumes that each county population is distributed uniformly over the county. If, however, the population of a county intersected by four hexagons were actually concentrated locally within the county, our population estimate for the hexagon at that location would be too low and the estimates for the other three too high. This process, assessed over all counties, would introduce error variance tending to obscure the true result. Second, the increase in sample size from ca. 3,000 counties to ca. 12,000 hexagons would approximately halve all standard errors, allowing effects statistically insignificant with county data appear significant with hexagon data. The two principal component analyses yielded virtually identical coefficients, indicating that the assumption of uniform distribution across counties was adequately approximated by the data and that the results were also well away from the marginal significance associated with large (N = 3,000) sample sizes. We therefore accepted the direct computation of hexagon scores.

Land Cover Data

Turner et al. (1995) recommended using coarse resolution remotely sensed data (1 km^2 or greater) to map land cover conversion at the continental scale. Loveland et al. (1991) used Advanced Very High Resolution Radiometry (AVHRR) meteorological satellite images to derive prototype maps of land cover types for the conterminous U.S. at 1.1 km^2 sensor resolution. We aggregated these data, with an urban class from the Digital Chart of the World (Danko 1992) added, to derive our environmental correlates (O'Connor et al. 1996). The resulting 160 land cover classes were aggregated here to 14 coarser classes (Anderson et al. 1976)—cropland/pasture, grassland/cropland, woodland/cropland, grass-dominated, shrub-dominated rangeland, mixed grass/shrub rangeland, deciduous forest, coniferous forest, mixed deciduous/coniferous forest, water bodies, coastal wetlands, barren or sparsely vegetated land, alpine tundra, and urban areas. The representation of each of these 14 cover classes was summarized by hexagon across the 1.1 km^2 pixels within each hexagon and landscape metrics such as patch size distributions, shape complexity, contagion and dominance, fractal dimension, types and frequencies of habitat edges, road abundance, and total length of riparian systems were determined for each hexagon (Hunsaker et al. 1994, O'Connor et al. 1996).

Other Environmental Data

We incorporated several climatic variables—annual precipitation, mean January and mean July temperatures, and annual temperature variation (seasonality)—in the form of long-term climate averages from the Historical Climate Network (Quinlan et al. 1987, HCN 1996). The data were modeled with 1 km resolution (except that precipitation was modeled to 10 km and then resampled to 1 km) and were then summarized within each hexagon as average, minimum and maximum values. Other variables included in the environmental data set were ownership (federal or non-federal), road density (separately for major and minor roads), and stream density. All were expressed as within-hexagon averages and corresponding extrema (O'Connor et al. 1996).

Local-Scale Analysis

County-level census data (U.S. Bureau of Census 1990a) and building permit data for coastal areas (NOAA 1998) were used to track growth patterns in those local areas identified as of interest from our large extent analysis. Census tract-level (U.S. Bureau of Census 1990b, 1990c) and block-level (CIESIN-SEDAC 1995) information was also extracted for such areas to identify demographic characteristics for very local sites, mostly inhabited barrier islands.

Land ownership characteristics for coastal barrier islands that proved of interest (see Results) were assessed to determine protection status. Each coastal barrier was evaluated for the presence of local, state, or federally owned land (USDOI 1979, 1982, 1983, 1985) or Coastal Barrier Resources System (CBRS) units (USDOI 1985, 1988). CBRS units are designated in undeveloped and unprotected areas by the Coastal Barrier Resources Act of 1982 and are ineligible for direct or indirect federal financial assistance for flood insurance or infrastructure development.

Threatened and Endangered Species Data

County-level data on the distribution of threatened and endangered (T&E) species of terrestrial vertebrates and plants for the U.S. (USEPA 1997) were used to identify areas where T&E species concentrations paralleled areas of high population density and high population growth and new building. We included species actually listed, species proposed for listing, and species proposed for delisting, following Dobson et al. (1997).

Statistical Analysis and Modeling

We used classification and regression tree (CART) modeling (Sonquist et al. 1973, Breiman et al. 1984) to identify significant, nonlinear, regionalized relationships between our response variables (two significant PCA vectors) and the land use, pattern metric, and climate covariates. Traditional linear regression and correlation techniques assume that each independent variable entering the regression model has a common effect across the entire sample, and this is not true in the face of regional effects. Moreover, we lacked prior knowledge of the form of likely interactions, precluding explicit specification of interaction terms. We used the S-PLUS (MathSoft Inc. 1995, Seattle, WA) implementation of CART (Clark and Pregibon 1992, Venables and Ripley 1994) to partition our response variables recursively with respect to a set of selected covariates.

At each node the independent variable that best discriminated the response variable was determined and used in the tree as the splitting variable for that node. Discrimination was maximized by trying all possible splitting thresholds for all possible prediction variables and choosing the variable and threshold to maximize the differences in the response variable (maximum between-group diversity) before splitting the dataset into two subsets. The process was then repeated independently and recursively on each increasingly-homogenous subgroup until a stopping criterion was satisfied. This tree was then pruned back using a ten-fold cross-validation strategy (Clark and Pregibon 1992). This strategy reduced the propensity of CART models to over-fit the data, though the optimum strategy for doing so is currently the subject of debate among statisticians (e.g. Miller 1994; J. Sifneos, D. White, and N.S. Urquhart *personal communication*). We therefore further randomly perturbed the response variable by 5 and 10 percent, in turn, and re-ran the model to check for overall consistency in tree structure. We also evaluated the robustness of the regression trees by deriving versions of them from randomly chosen subsets of the data and using these to predict the response variables on the remaining test cases. CART models are especially vulnerable to the normal collinearity problem—of non-independent variables in the suite of explanatory variables—in linear multiple regression (Longley 1967) because collinearity may be influential within particular subsets of the data rather than globally. Since we wished to interpret the role of predictors, and not merely obtain robust but uninterpretable models, we controlled for collinearity problems by randomly perturbing each independent variable in the pruned model by up to 5 percent and re-running the analysis to check for inclusion or omission of the variable in the tree. Variables stable in the face of such perturbation could not be markedly collinear with any other variable in the dataset. The models presented here passed all these checks.

Local Geographic Analysis

Our eventual analysis drew attention to particular land cover classes and areas. To study these further we overlaid our modified (160 land cover class) Loveland et al. (1991) land class map onto high resolution county boundary maps of the United States and isolated the remotely sensed pixels of interest within each hexagon. Correct identification of these sites (primarily barrier islands and coastal sites) was then confirmed by reviewing United States Geological Survey (USGS) 7.5 minute topographic maps (USDOI 1988) and high resolution census TIGER line maps (U.S. Bureau of Census 1995). To track urban growth rates, barren land class conversion rates, and coastal erosion and accretion rates for specific coastal barrier islands, we incorporated information from photo-interpreted maps (Lins 1980) and annual shoreline change data (Dolan et al. 1985). Lins (1980) was particularly useful since the land cover interpretation therein was designed specifically for use with remotely sensed data and was based on the Anderson et al. (1976) land classification scheme used here.

RESULTS

Continental Patterns of Settlement

The principal components analysis of the demographic data yielded two significant vectors that indexed interpretable demographic phenomena (Table 2). The first axis had relatively large positive loadings on four density-related variables—1980 and 1990 population densities, our wealth density index, and housing density—and had smaller positive loadings on farm density and proportion of metropolitan land; agricultural intensity and building age were negligible in loading. Position on this axis was therefore taken to be an index of human settlement (HSI) (Mageean and Bartlett 1998) with large positive values in historical population centers and low values in historically low-population areas (Figure 1). We will term this type of settlement *alpha settlement* (α-settlement), to distinguish it from a further

TABLE 2

Component Loadings for Significant PCA Vectors of Hexagon-Weighted Census Data for the Conterminous United States (Axis 1 is an index of human settlement [α-settlement], comprised of population density variables and its correlates. Axis 2 is an index of density-independent population growth and new building in nonagricultural areas [β-settlement]. Bold text denotes significant loadings.)

Hexagon-Weighted Census Variable	Axis 1	Axis 2
Population Density / km^2 (1980)	**0.4467**	−0.0527
Population Density / km^2 (1990)	**0.4493**	0.0007
Wealth (income) Density / km^2	**0.4486**	0.0223
House Density / km^2	**0.4476**	0.0068
Percent Change in Population / Hexagon (1980–1990)	0.0848	**0.5588**
Farm Density / km^2	0.3121	**−0.3613**
Proportion of Hexagon in Agriculture	−0.0573	**−0.4583**
Mean Calendar Year of Building for Structures / Hexagon	0.0316	**0.5769**
Proportion of Hexagon Classified as Metropolitan	0.2971	0.1047
	$R^2 = 54.0\%$	$R^2 = 24.0\%$

type (below). The map of these values closely resembles a map of national population density, reflecting the dominant importance of population density in characterizing gross demographic pattern. Within the PCA this axis accounted for 54 percent of the overall variance in the nine-variable dataset.

The second principal component axis—by definition orthogonal to (and therefore independent of) the first—had a very different structure (Table 2). The largest positive loadings were on the year of construction for buildings and for the magnitude of population change over 1980–90: areas experiencing large relative population increase accompanied by recent building activity therefore scored highest in this axis. However, the axis also had substantial negative loadings on agricultural intensity within the hexagon and on the density of farms in the hexagon, indicating that this combination of population increase and building construction was differentially located away from farmland. (This is in contrast with the traditional settlement pattern of urban expansion encroaching onto prime farmland

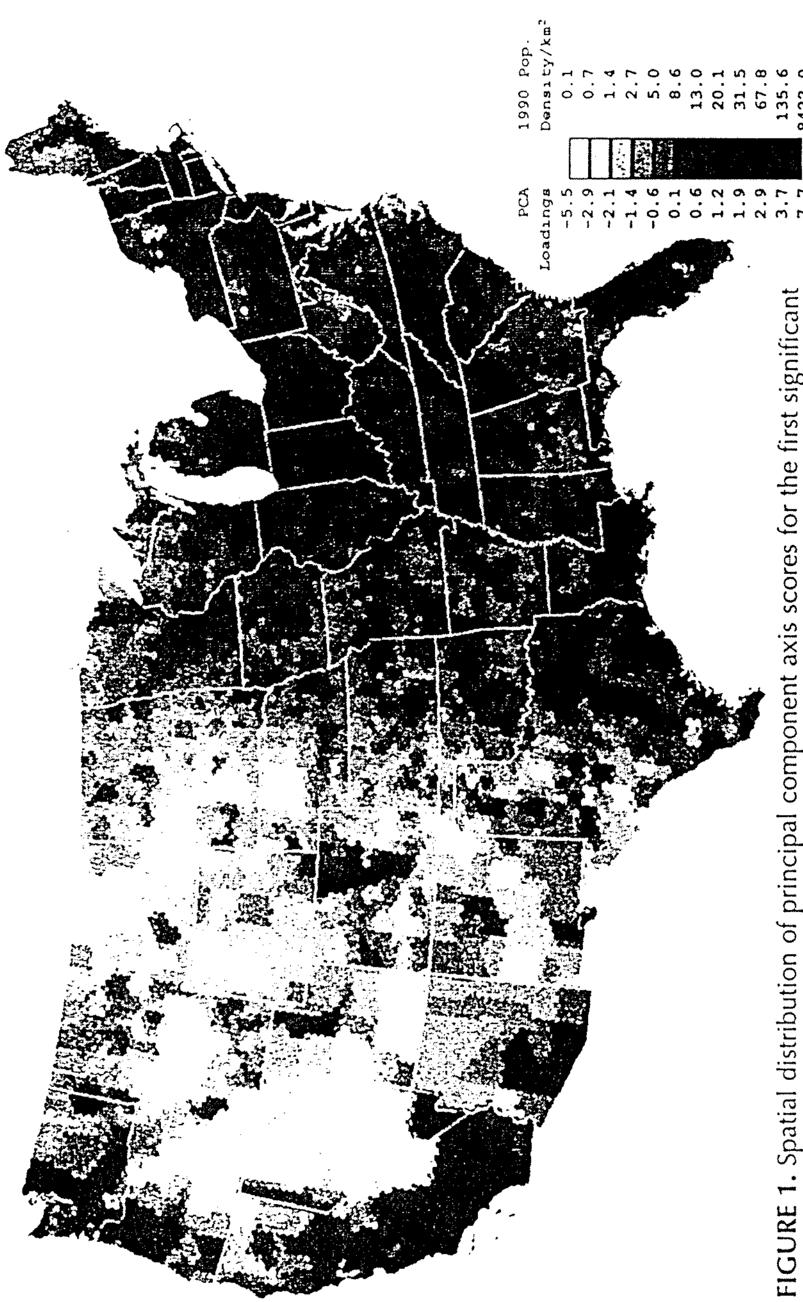

FIGURE 1. Spatial distribution of principal component axis scores for the first significant axis—an index of human settlement (α-settlement)—based on nine variables extracted from the 1990 United States Census.

(USDA 1996).) The other four variables considered had negligible loadings on this axis. Mageean and Bartlett (1998, 1999) termed this vector an index of density-independent growth and settlement (DIGS index) to reflect its independence of the traditional density-associated settlement of the HSI score. From a landscape planner's perspective, the phenomenon might best be termed "de-densification" (C. Steinitz *personal communication*). Here we will term it *beta settlement* (β-settlement) to distinguish it from the traditionally understood pattern of growth from existing centers of population reflected in our first component score (α-settlement). This terminology better captures the idea of independent facets of a common concept of settlement pattern than does the HSI/DIGS language of Mageean and Bartlett (1999). Within the principal component analysis this β-settlement axis explained 24 percent of the overall variance in the nine variable matrix and the two patterns combined explain 78% of total variance.

Comprehension of the β-settlement concept is aided if we visualize the spatial distributions of the four variables dominating its PCA axis by mapping them across the U.S. (Figure 2a): lightly shaded areas represent negative or low values, while darker grays represent hexagons with positive or high values for the variable. The bottom map presents the mapped PCA scores for β-settlement (Figure 2b). Note the high population growth and new building associated with (a) Gulf and mid-Atlantic coastal counties, (b) suburban counties surrounding rapidly expanding urban areas (e.g. Dallas/ Fort Worth, TX; Atlanta, GA; Minneapolis/St. Paul, MN), (c) recreational counties (e.g. in Minnesota and in Wisconsin; the upper peninsula counties in Michigan; the Poconos in Pennsylvania; the Adirondacks in New York; and the Southern Appalachians in North Carolina), and (d) southwestern U.S. counties in New Mexico, Arizona, Nevada, and California. The negative loadings on farm density and agricultural intensity for β-settlement are obvious here as Midwest Cropbelt areas show very low scores for the index, broken only by urban centers of population growth and new building such as Des Moines in Iowa, and Sioux Falls in South Dakota.

Correlates of Beta Settlement

Our vector for beta settlement (the per-hexagon PCA scores for axis 2) was used as the response variable in a regression tree analysis using our suite of environmental covariates as independent variables. The resulting regression tree model incorporated two climate and two land cover variables and resulted in five terminal nodes (rectangular boxes in Figure 3a) with markedly regional distributions (Figure 3a). Each terminal node is viewed as the *set intersection* of the conditions in the branches from that

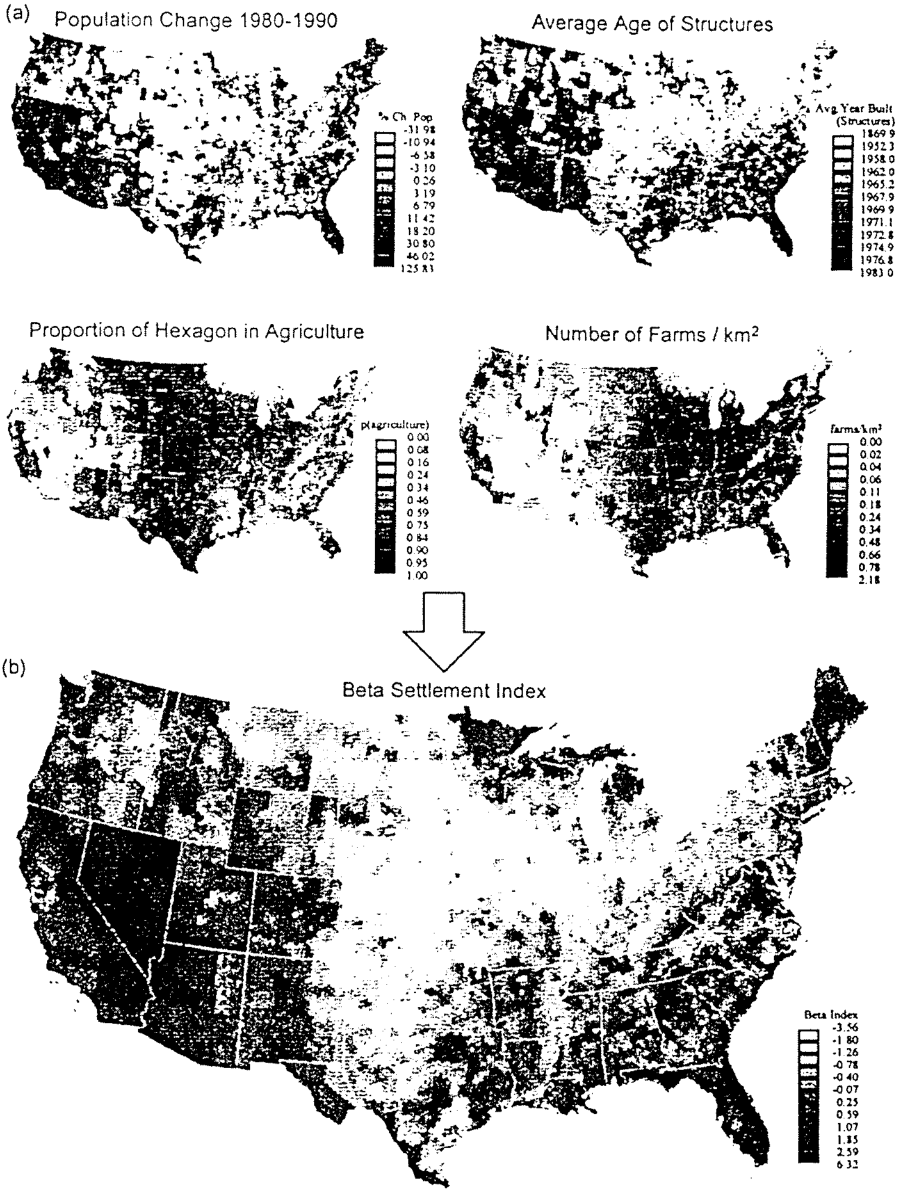

FIGURE 2. (a) Spatial distribution across the conterminous United States of the four dominant census variables in the second principal component of Table 2—an index of density-independent growth and new building away from traditional agricultural areas (β-settlement). (b) The hexagon-level PCA scores for β-settlement are mapped. Note: β-settlement scores increase with increasing population growth and newer structures and decrease with increasing farm density and land proportion in agriculture.

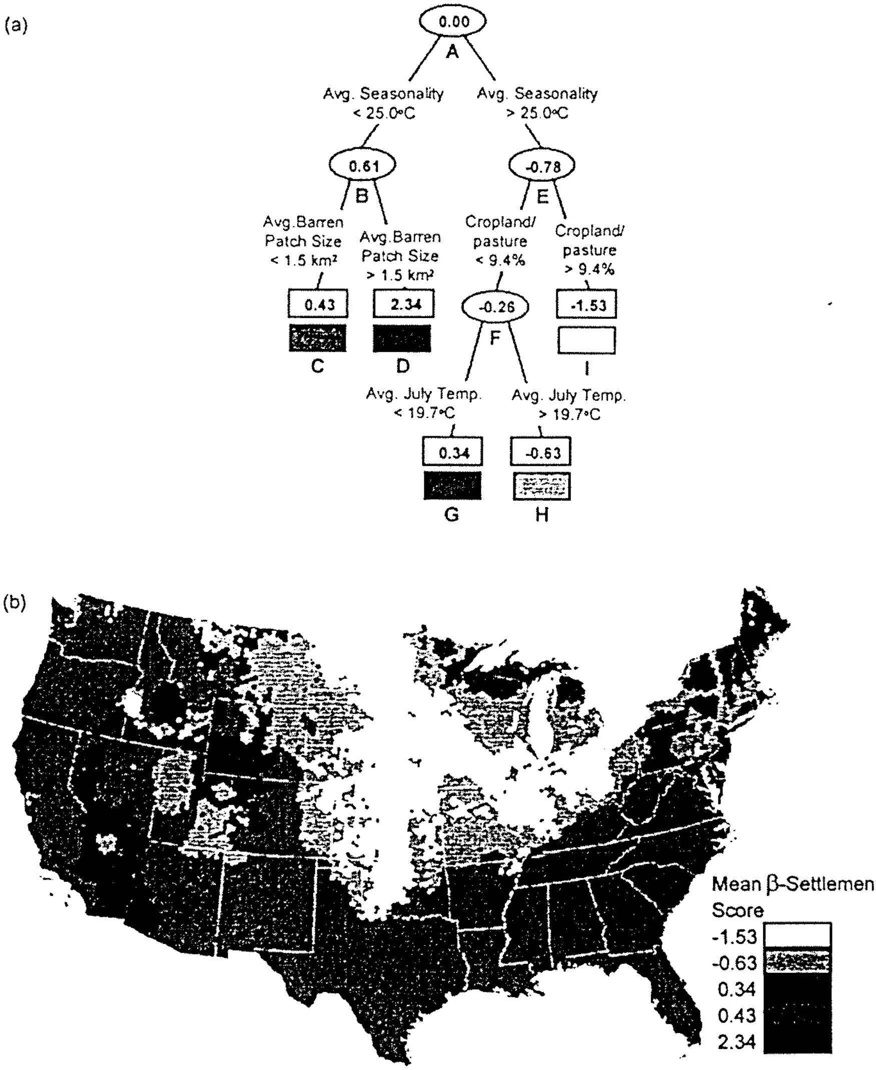

FIGURE 3. (a) Regression tree model for density-independent growth and new building (β-settlement) and its environmental correlates across the conterminous United States. Numbers inside the circle or box denote mean values for β-settlement across all hexagons associated with that branch or end node. The environmental variable that best explains the variation in β-settlement for each recursive hexagon subgroup is shown at each branch and its splitting value is given. (b) Regionalization of environmental correlates for β-settlement predicted by the regression tree analysis. All hexagons of one gray-shade share the same combination of predictor variables, corresponding to a particular end node which is labeled in the tree diagram along with its corresponding gray-shade.

end node back to the root node, i.e. the regionalization of β-settlement identified by each terminal node is the result of the interaction of demographics with a complex of constraints. As a result, similar β-values can occur (even as an average) within the different end nodes but for different reasons (if the correlation-implied causality is genuine). In fact, the distributions of β-settlement values for each end node partially overlapped. Nodes C and G, and to a lesser extent node H, largely overlapped each other but the distributions for the beta values for hexagons in nodes D and I were centered on markedly higher and lower (respectively) positions, with less overlap with nodes C, G, and H. In addition, the distribution of beta values from node D hexagons was noticeably bimodal, with modes at about beta values of 1.75 and 3.25. Node I (Figure 3a) was a statistically distinguishable group of hexagons that had the lowest β-settlement of any in the U.S. and comprised those hexagons that both had more than 9.4 percent of their area in cropland and had high seasonality (above 25°C). Similarly, node H comprised hexagons with high July temperatures (above 19.7°C), low proportions of cropland, and high seasonality (Figure 3a), and these hexagons had the second lowest β-settlement levels. Node G hexagons differed only in having cooler July conditions (Figure 3a) and had intermediate rates of β-settlement. Node C hexagons had less barren land but still had low seasonality (Figure 3a), and had the second highest rates of β-settlement. The greatest β-settlement was observed in the hexagons of node D, characterized by reduced seasonality (under 25°C) and more barren land (Figure 3a).

The geographic distribution of the hexagons of each node is mapped in Figure 3b and shows strongly regional patterns. Beta-settlement was lowest in the very seasonal, agricultural Midwest from the Dakotas south to northwest Oklahoma, and from southwest Minnesota through Iowa, Illinois, Indiana and western Ohio. The hexagons of node H bordered this zone but also extended into New England and into Utah, and were often contiguous with blocks of cooler summer, node G hexagons (Figure 3b). The bulk of the rest of the country was covered by node C hexagons (largely seasonal, with little barren land). Hexagons within node D had the greatest β-settlement but were relatively scarce (about 5.2% of all hexagons) and were spread in small clusters along the Atlantic and Gulf coasts (Figure 4) and in larger clusters in the deserts of the southwest, notably along the border of California with Nevada and Arizona (Figure 3b).

We disaggregated the β-settlement index into its component parts (demographic variables) and summarized in Table 3 the distributions of these variables within each end node. Percent change in population increased from left to right in the table, with node I exhibiting negative growth (mean

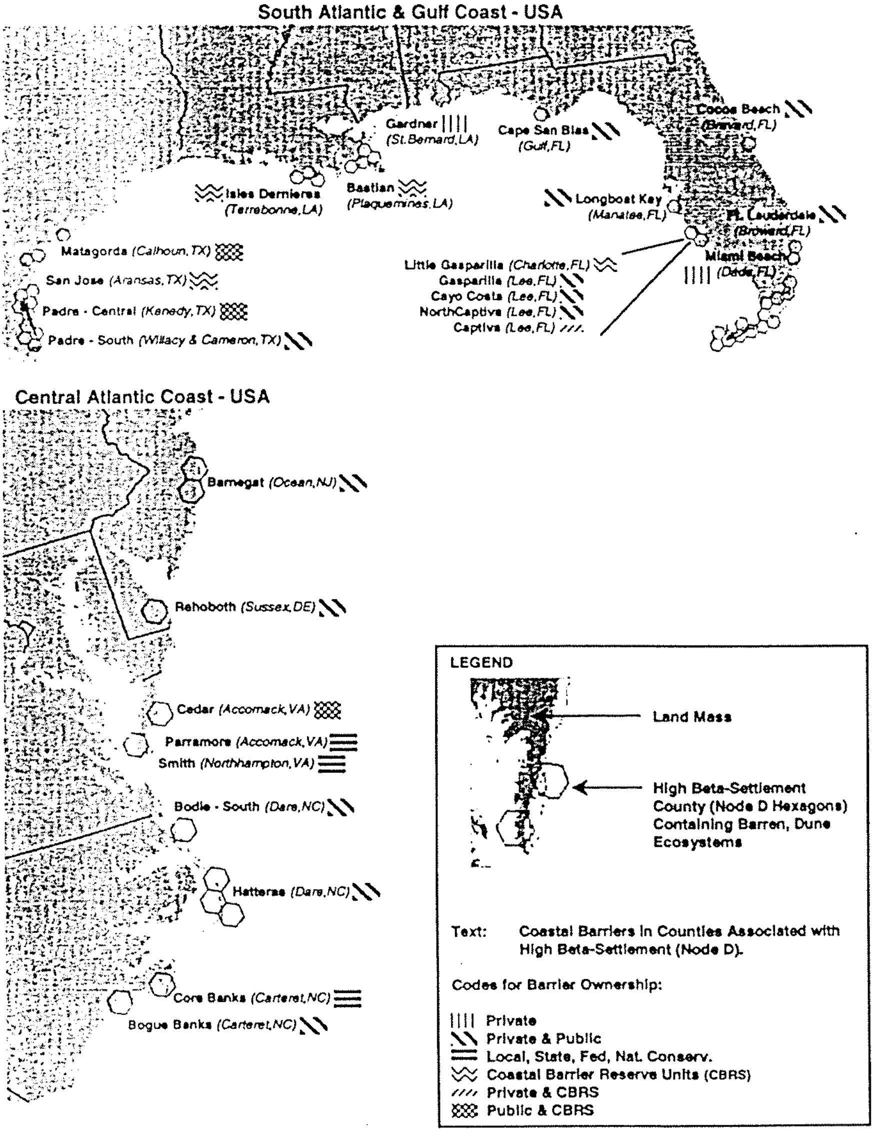

FIGURE 4. Atlantic and Gulf coastal barriers with large blocks (≥ 2 km^2) of contiguous barren land that were associated with nationally high levels of β-settlement during the 1980s. Ownership patterns for each barrier are included. See text for details.

TABLE 3

Summary Statistics for Census Variables Across Regression Tree-Defined End Nodes for Beta-Settlement Index

Census Variable	Node	min	max	mean	s.d.
	I	−30.15	45.97	−4.01	8.97
Percent Change in	H	−31.98	96.52	0.95	12.74
Population (1980–1990)	G	−23.92	94.16	2.79	14.97
	C	−31.98	125.83	11.83	19.34
	D	−15.29	96.52	38.04	27.94
	I	1939.00	1977.30	1956.71	8.72
	H	1939.00	1980.00	1961.95	8.40
Year of Building	G	1939.00	1980.00	1964.97	8.63
for Structures	C	1869.88	1983.00	1969.02	6.23
	D	1949.69	1981.00	1972.62	5.44
	I	0.00	1.00	0.80	0.20
	H	0.01	1.00	0.58	0.30
Proportion of Hexagon	G	0.00	1.00	0.27	0.25
in Agriculture	C	0.00	1.00	0.42	0.27
	D	0.00	1.00	0.19	0.20
	I	0.00	1.92	0.43	0.26
	H	0.00	1.49	0.31	0.29
Farm Density/km^2	G	0.00	0.70	0.10	0.11
	C	0.00	2.18	0.24	0.26
	D	0.00	0.70	0.06	0.09
	I	0.12	642.01	10.28	28.78
	H	0.07	2434.01	18.09	75.70
House Density/km^2	G	0.11	89.03	4.50	7.87
	C	0.06	3389.26	16.96	64.01
	D	0.06	1414.69	15.50	65.85
	I	2.56	25697.68	340.40	1128.96
	H	1.19	105946.04	669.59	3193.49
Wealth Density ($)/$km^2$	G	1.78	3427.11	117.50	268.86
(× 1000)	C	1.15	128431.57	605.14	2666.75
	D	1.15	62485.00	596.87	2902.35
	I	0.27	1664.57	24.76	70.24
	H	0.13	5578.72	43.22	183.04
Population Density/km^2 1980	G	0.18	204.73	9.02	17.81
	C	0.11	8187.78	36.23	151.61
	D	0.08	2939.12	29.82	140.09
	I	0.24	1627.07	25.17	71.51
	H	0.12	5737.34	44.32	184.08
Population Density/km^2 1990	G	0.17	209.55	9.46	18.66
	C	0.13	8422.34	41.06	160.38
	D	0.13	3136.40	37.87	155.61