



Cuban land use and conservation, from rainforests to coral reefs

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ABSTRACT.—Cuba is an ecological rarity in Latin America and the Caribbean region. Its complex political and economic history shows limited disturbances, extinctions, pollution, and resource depletion by legal or de facto measures. Vast mangroves, wetlands, and forests play key roles in protecting biodiversity and reducing risks of hazards caused or aggravated by climate change. Cuba boasts coral reefs with some of the region's greatest fish biomass and coral cover. Although it has set aside major protected areas that safeguard a host of endemic species, Cuba's environment is by no means pristine. Through much of its early history, deforestation and intensive agricultural production under colonial then neocolonial powers was the norm. Using remote sensing, we find Cuba's land today is 45% devoted to agricultural, pasturage, and crop production. Roughly 77% of Cuba's potential mangrove zone is presently in mangrove cover, much of it outside legal protection; this is likely the most intact Caribbean mangrove ecosystem and an important resource for coastal protection, fish nurseries, and wildlife habitat. Even the largest watersheds with the most agricultural land uses have a strong presence of forests, mangroves, and wetlands to buffer and filter runoff. This landscape could change with Cuba's gradual reopening to foreign investment and growing popularity among tourists—trends that have devastated natural ecosystems throughout the Caribbean. Cuba is uniquely positioned to avoid and reverse ecosystem collapse if discontinuities between geopolitical and ecosystem functional units are addressed, if protection and conservation of endemic species and ecosystems services accompany new development, and if a sound ecological-restoration plan is enacted.

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Cuba's natural environment has played many roles in its history and development. Forests dominated the pre-Columbian landscape, but most were cleared for sugarcane and coffee cultivation, staple food crops, and pastures by the late 18th century. Sugarcane and cattle production intensified in the early 19th century; by 1958 only 14% of forests remained (Funes Monzote 2008). Soil erosion was commonplace where poor agricultural practices in mountainous areas led to land degradation. Mangroves were harvested for firewood and charcoal. Largely as a result of US foreign policy, the country has experienced semi-isolation from international trade flows and foreign direct investments since the 1959 Cuban Revolution, although countries in the Soviet bloc continued trade with Cuba throughout the early decades, and in recent years there has been increased trade and investment from Spain, Canada, China, Brazil, and Venezuela. The Cuban state controlled large tracts of farmland cultivated with mechanization and chemical inputs (1959–1990s). During this time, Cuba imported oil, pesticides, fertilizers, and machinery for food production. But after the fall of the Soviet Union, agricultural production fell 54% (1989–1994), with major losses in cash crops (ERS 1998). In the 1980s, human daily caloric intake was 2908 kcal d⁻¹, dropping to 1863 kcal d⁻¹ in 1993, and rising to >3400 kcal today (FAOSTAT 2017). The circumstances during this “Special Period,” as it was named, forced agricultural practices toward integrated management and agroecological approaches, with changes in land tenure to reinvigorate rural development and an increased focus on environmental protection policies.

Cuba's market isolation, coupled with the Special Period's hard years, led to industrialization with less exploitation and devastation of natural resources than in other socialist countries, and a greater conservation of the richness of Cuba's ecosystems (Díaz-Briquets and Pérez-López 1998). Softening of the US embargo and internal policy changes may lead to further opening of Cuba to international investments. This will have impacts on development and the environment that are uncertain. Yet with good stewardship and an eye to habitat connectivities, Cuba's protected areas could ensure a future for its remarkable endemic flora and fauna, on land and sea (Perera Valderrama et al. 2018). It could also heighten Cuba's importance as a propagule source for native species in other parts of the Caribbean region and the Americas (e.g., Paris et al. 2005).

Cuba's conservation outlook is better than the rest of the Caribbean Sea, but the situation is nonetheless dire for many species and habitats. Cuba's remarking features are its ecological characteristics and the several endogenous opportunities it offers to maintain it.

Caribbean countries are among the most exposed to climate change in the world (World Bank 2014). The array of climate change hazards includes sea-level rise, violent cyclonic storms, ocean acidification, extreme temperatures, droughts, floods, and landslides. These hazards can be exacerbated by warm sea surface temperatures associated with certain phases of El Niño–Southern Oscillation and North Atlantic Oscillation (Giannini et al. 2000). Cuba already experiences more frequent floods, storms, and severe droughts (Bueno et al. 2008), which threaten coastal integrity, soil conditions, food availability, and water quality (Alonso and Clark 2015).

Here, we assess the status of Cuba's ecosystems and endemic species and the extent of legal and de facto protection. We developed a land cover and land use map to understand the extent of Cuba's terrestrial ecosystems and their potential connections

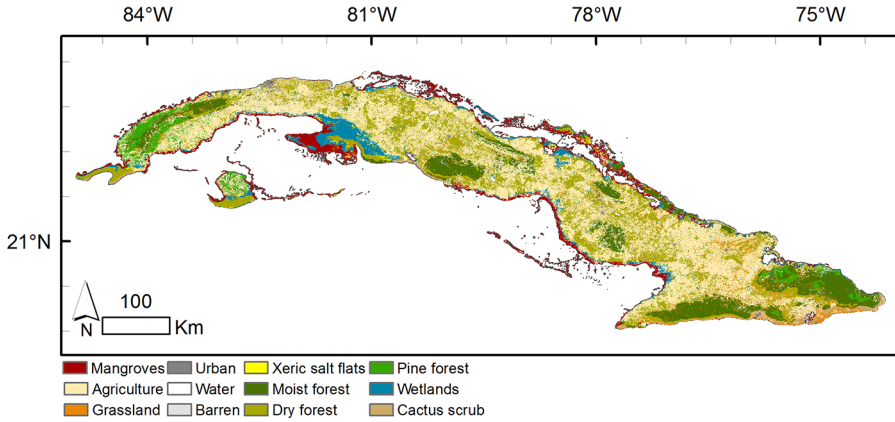


Figure 1. Land covers and land uses in Cuba derived from 2015 Landsat mosaic. *See Methods* for details on data sources.

to the coastal zone. We examined current and future risks to ecosystem function and species' status under the current political and investment climate. We then consider the prospects for Cuban development to benefit ecosystems and humans.

METHODS

We created a contemporary map of land uses and land cover at 30-m resolution for Cuba representing 2014–2015 (Fig. 1, Online Appendix 1). This method required compositing a cloud-free input data set and creating, training, and validating a machine-learning classification algorithm done via cloud computing with the Google Earth Engine Code Editor “Playground” (Gorelick et al. 2017). Cloud-free imagery was composited from Landsat sensors over the 2014–2015 dry season and corrected using quality control flags. The resulting 7-band imagery, containing 95,129 km² of land, was input with slope 1 (Farr et al. 2007) to a 100-tree random forest supervised classification (Breiman 2001). In total, 12 classes were used: barren (e.g., non-vegetated landscapes), agriculture, open grassland (including pasture and natural grassland), urban (roads, houses and hard surfaces), water, wetlands, mangroves, xeric coastal vegetation, wet forest, dry forest, pine forest, and cactus scrub. Our algorithm first regionalized by ecozones (Olson and Dinerstein 2002), water, and urban, then further classed pixels into land cover or uses. The barren, agriculture, and grassland classes were trained by 13,028 random points assigned a land cover or use through user interpretation of high resolution Google Earth high resolution imagery, a common technique for machine learning (e.g., Spera et al. 2014). Results were validated against a subset of user-interpreted data (4328 points) withheld from the training data set and showed an overall accuracy (Jensen 1996) of 84%. Further details on the mapping methods and results can be found in Online Appendix 1. Field visits to marine, forest, and agricultural areas were conducted by PDG and MF (ongoing), by LK and JR (2015), and JR and GLG (2016).

Table 1. Taxonomic distribution of endemism among several taxa for both the insular Caribbean region (“regional”) and Cuba. Data are from FishBase (<http://www.fishbase.org>).

Taxonomic group	Regional species richness	Regional endemics (%)	Cuban species richness	Cuban endemics (%)
Freshwater fishes	167	65 (39%)	63	23 (37%)
Marine fishes	1,400	630 (45%)	1,104	4 (<1%)
Amphibians	189	189 (100%)	70	63 (90%)
Reptiles	520	494 (95%)	140	132 (94%)
Birds	564	148 (26%)	368	23 (6%)
Mammals	69	51 (74%)	35	24 (69%)
Plants	11,000	7,868 (72%)	7,020	3,500 (50%)

RESULTS AND DISCUSSION

CUBA’S ENVIRONMENT AND BIODIVERSITY ARE AT STAKE

The Caribbean Sea constitutes one of the world’s great biodiversity hotspots, with Cuba at the heart (Myers et al. 2000). The Cuban archipelago encompasses nearly half the land area in the insular Caribbean region (110,860 km²) and supports extraordinary levels of endemism, including the greatest number of invertebrates and mammal species in the region (Borroto-Páez and Mancina 2017). Cuba’s ecosystems benefit from strong environmental policies (e.g., Environmental Law 81), a large network of protected areas (*see* Cuban Protected Areas), a commitment to the environment (e.g., mangrove reforestation projects), and relative isolation from development pressures (Roman and Kraska 2016). However, our knowledge of its biodiversity remains incomplete, particularly for invertebrates, plants, fungi, and microbes. Alpha diversity (species numbers in one place) is not exceptional as compared to the continent, but Cuba hosts a wealth of species with very small ranges and high vulnerability to extinction, a process that is well underway as 24 of the 59 native mammalian species are extinct (Borroto-Páez and Mancina 2017).

Cuba’s endemic species (Table 1) exhibit three distinct, sometimes overlapping, biological patterns: (1) species or semispecies in clades (a group of organisms from a common ancestor) found elsewhere in the Greater Antilles, (2) unusual species representing relict or highly derived clades, and (3) species from clades unique within Cuba. Twenty-five endemic Cuban bird species exhibit the first pattern, though many, such as the Cuban Trogon (*Priotelus temnurus*, *see* Online Appendix 2 for species authorities) and Cuban Tody (*Todus multicolor*) are remarkable members of their group. The critically endangered Cuban Ivory-Billed Woodpecker (*Campephilus principalis bairdii*) last had a confirmed spotting in 1987 and likely persists only in southeastern Cuba, if at all. There is a tendency toward sympatry of paired widespread and endemic forms: e.g., *Gramma loreto*–*Gramma dejongi* among coral reef fishes, the killifishes *Rivulus cylindraceus*–*Rivulus berovidesi*, and cichlids *Nandopsis tetracanthus*–*Nandopsis ramsdeni* in fresh water. Celebrated among the archaic forms unique to Cuba are the Cuban solenodon (*Solenodon cubanus*) and Cuban gar (*Atractosteus tristoechus*). Extreme forms include the bee hummingbird (*Mellisuga helenae*), perhaps the most charismatic endemic and the world’s smallest bird. Extraordinary radiations include those of the rodent hutias (Capromyidae, 10 of the world’s 13 species, all Caribbean insular endemics), the anole lizards (64 of

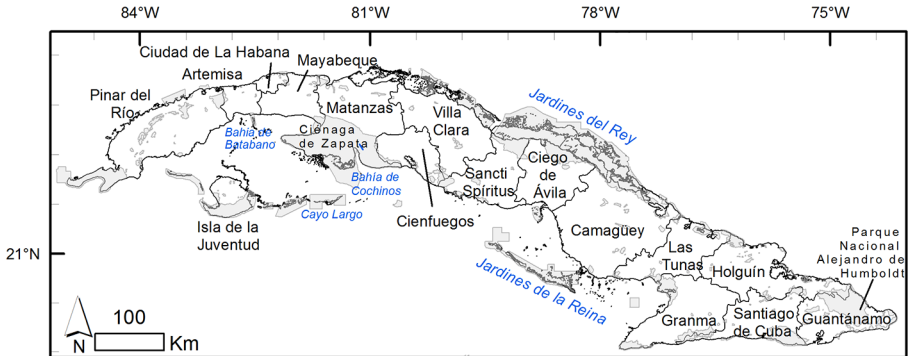


Figure 2. Geographical features of Cuba including provinces, protected areas, and coastal zones.

the 157 insular Caribbean species of *Anolis*), and dwarf geckoes (22 of the 86 insular Caribbean species of *Sphaerodactylus*). The marine biota is typical of the Caribbean region, but there are a few endemics, including the spectacularly colored, recently discovered coral reef sea bass, *Gramma dejongi* (Victor and Randall 2010).

Cuba is an epicenter for evolution, dispersion, and endemism shaped by the maritime influences of its geography, carbonate and tectonic geological history (Iturralde-Vinent et al. 2016), and climate (modified Köppen Aw climate averaging 20.7–30.5 °C; Online Appendix 3). There are five terrestrial ecozones: moist and dry broadleaf forests, coniferous forests, flooded grasslands, xeric or cactus shrublands, and mangroves (Online Appendix 1). The Cuban archipelago consists of the main island, Isla de la Juventud, and more than 1600 islands and cays. The 3735 km of shoreline and adjacent marine zones are home to reefs, seagrass beds, and mangrove forests.

Coral Reefs.—Much has been written about the high status of Cuba’s coral reefs, as if the island were a Caribbean lost world. The reality is more complicated (González-Díaz et al. 2018) and reefs may be changing with climate and other stressors (Duran et al. 2018). Cuba’s many islands, barrier sub-archipelagoes, and the substantial island shelf form a vast tract with highly variable local conditions. The result is a broad range of coral reef habitat types, some highly degraded, others close to pristine. Heterogeneity in depth and exposure may have promoted extremes in local adaptation by hermatypic corals and other reef organisms. We observed (LK and JR, August 2015) devastating coral mortality and extensive bleaching at the southwest tip of Isla de la Juventud (Figs. 2, 3), but there were large vibrant patches of mature elkhorn coral (*Acropora palmata*), intact, apparently healthy, and bathed in dangerously warm water of the Bay of Pigs near Playa Girón. Fish biomass is highly variable, ranging from startling concentrations of grouper and sharks in parts of the Jardines de la Reina, to Punta Francés, where reefs present the ghost town look of few living corals and low fish biomass now familiar across broad swaths of overfished, highly degraded reefs of the tropical west Atlantic Ocean (Pina-Amargós et al. 2014, Navarro Martínez 2015).

The heterogeneity of Cuba’s coral reefs makes them a natural laboratory for understanding how reefs could be impacted by climate change, and to what extent they might adapt. Although there are no known endemic reef-building corals, Cuba’s reefs are visibly distinctive. Due to their patchy condition, variability in structure

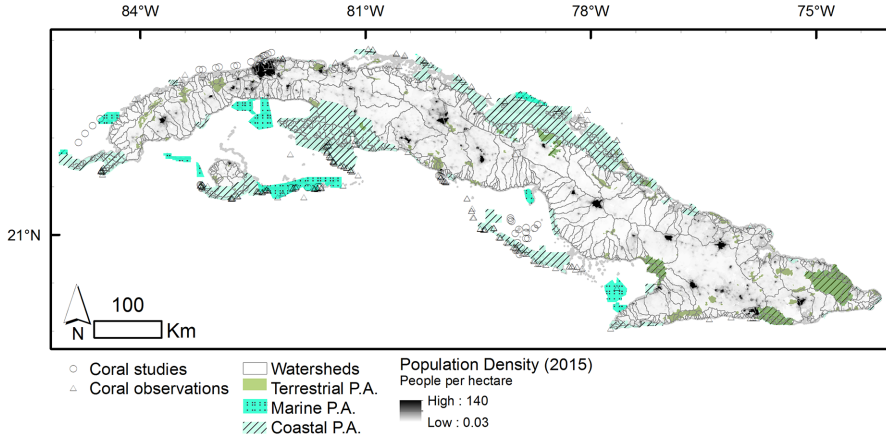


Figure 3. Coral reefs (studied by González-Díaz et al. 2018, and noted by Reefbase 2016) with watersheds (Lehner and Grill 2013) shaded by population density (Sorichetta et al. 2015).

in response to local conditions and subtle variations in the abundance and natural history of particular reef organisms. For example, *Porites branneri* is a finger coral found throughout much of the Caribbean, but normally only at very small sizes, rarely seen and recognized. In Cuba, beautiful blue-violet colonies of *P. branneri* (a highly unusual color for Atlantic reef corals) achieve a large size with conspicuous, elaborate branching. Atlantic pillar coral (*Dendrogyra cylindrus*) is quite rare over much of its range, but is a highly visible reef component in some parts of Cuba. Its coral reef estate makes Cuba one of the richest Caribbean nations, comparable to Belize and its Mesoamerican Reef system.

Cuba's coral reefs may be essential to the survival of reefs in foreign waters, such as the Florida coral reef tract that marks the northern periphery of the coral reef domain. Florida reef organisms are subject to mass mortality from periodic cold water intrusions, interspersed with catastrophic bleaching events when ocean temperatures become too warm. As climate change elevates environmental volatility, Florida's reefs will become increasingly dependent upon outside larval sources. Efforts are underway to propagate and outplant endangered coral species, with a particular focus on the acroporids (elkhorn and staghorn coral, and their hybrid). Given the fact that there is already some degree of genetic connectivity between Cuba and Florida (Hemond and Vollmer 2010), there is a basis to consider adaptive translocation of corals from Cuba to Florida for restoration. Cuba's coral reef domain, vast and varied, may contain a wider array of adaptive genetic variants than can currently be found on the reefs of south Florida.

The future of Cuba's coral reefs rests largely on the links between what is happening on land and in Cuba's coastal seas. Benthic habitat heterogeneity is an obvious feature of Cuba's island shelf. Coral reefs can exist in isolation from other shelf habitats, such as seagrass meadows and mangrove forests, but productivity, diversity, and possibly resilience are elevated by proximity to these sister systems. The relatively good health of Cuba's reefs may rest in part on their proximity to extensive mangrove and seagrass habitats.

Coral reefs are normally discontinuous across the mouths of bays and inlets, where growth is suppressed due to stream runoff and sediment/pollutant loads from the

adjacent watersheds. Coral reefs can persist in proximity to well-forested watersheds, but not denuded ones suffering large volumes of sediment-laden or polluted runoff. It is not surprising, then, that Cuba's healthiest reefs are widely removed from the outfalls of urban and industrial regions (*see* Land Covers and Uses).

Our land use and land cover map illustrates the risks to coral reefs based on population density by watersheds as a proxy for pollution and development pressures (Fig. 3). Reefs in northwestern margins have little protection and have freshwater inputs largely from agricultural areas. Reefs near Havana are already in decline due to industrial waste streams, urban wastewaters, and other pollutants, although coral cover increases away from this urban area (Duran et al. 2018). The most resilient areas may be on the southeast coast where the reef is deeper and a steep drop-off brings in cool waters. That zone excepted, climate change puts all Cuban reefs at risk with warmer waters and sea level rise particularly damaging for shallow systems. The country's coral reef estate could plunge from regional hope to national disaster if preventative stewardship practices are not soon adopted.

Seagrass.—Seagrasses cover about 50% of the Cuban shelf, which is wide, shallow, and favorable for marine angiosperms (Martínez-Daranas and Suárez 2018). The dominant species is *Thalassia testudinum*, and five other species have been identified in typical Caribbean seagrass communities (Martínez-Daranas and Suárez 2018). Threats to seagrasses include low seawater transparency caused by eutrophication and erosion, and high salinity related to inputs from land use. Together with coral reefs, seagrasses are essential for Cuban fish and fisheries.

One of the most iconic and beloved associates of Caribbean seagrass meadows is the West Indian manatee (*Trichechus manatus*). Cuba harbors a wide expanse of potential manatee habitat, but illegal hunting persists despite national protection efforts (Álvarez-Alemán et al. 2018). One encouraging discovery is the movement of a manatee from Florida to Cuba, suggesting population exchanges might occur (Álvarez-Alemán et al. 2010).

Mangroves.—Mangroves provide critical habitat, biodiversity protection, and ecosystem services such as nurseries for commercially important fishes, flood control, honey production, and carbon storage. Zapata Swamp, known for its extensive mangrove cover, provides important cultural services including bird watching and fly fishing, as well as national identity for its role in the Bay of Pigs invasion. Strong national legislation, including Environmental Law 81 and Coastal Management Decree Law 212 enacted in 2000, limits development in coastal zones with exceptions for some activities, such as ports, after environmental review and licensing; this includes all areas with mangroves present.

From our land cover and land use analysis, we find that mangroves cover 5% (5979 km²) of Cuba's land area, representing 11% of its forests. We find that mangroves currently occupy 77% of their potential habitat (Olson and Dinerstein 2002), which suggests a high degree of preservation (*see* Land Covers and Uses). Notably, 37% of mangroves are outside protected areas and more than 85% exist in areas outside the 30 m legal shoreline protection zone.

Typical of the northern Caribbean, Cuba's mangroves are dominated by four species along an ecomorphological gradient, with *Rhizophora mangle* (red mangrove) at the leading, permanently inundated edge, to greater amounts of black mangrove (*Avicennia germinans*), and then, at higher elevation, white mangrove (*Laguncularia*

racemosa), and finally, buttonwood (*Conocarpus erectus*) on high ground. Landward, the more freshwater upstream margins may be fringed by *Tabebuia angustata* (roble), *Annona glabra* (pond apple), and other swamp forest dominants. Where this margin has been levelled, there may be species of hibiscus (*Thespesia*, *Talipariti*). Mangroves may also border littoral forest (*Lysiloma latisiliquum*, *Bursera simaruba*) as on the Zapata Peninsula (Suman 2013).

Hutias are one of the most distinctive inhabitants of Cuba's mangrove forests. Desmarest's hutia, *Capromys pilorides*, is an abundant endemic rodent commonly found on the mainland (e.g., Guantánamo province), Isla de la Juventud, Sabana and Dolce Laquinas archipelagos, and various cays. The endemic large-eared hutia (*Mesocapromys auritus*) is endangered due to hunting and limited distribution. It is mostly restricted to Cayo Fragoso (Sabana archipelago), home to 2500 individuals, representing 95% of the species population; the population is considered stable due to its protection in the Lanzanillo-Pajonal-Fragoso Wildlife Refuge (Soy and Silva 2008).

Flooded Grasslands.—Our analysis shows there are 5065 km² of flooded grasslands in Cuba today. The vast majority of Cuba's flooded grasslands, or wetlands, are under tidal influence (Borhidi 1991). They provide habitat for manatees, crocodiles, fishes, and turtles, in addition to migratory birds and endangered endemic fishes and birds. Vegetation ranges from aquatic to xeromorphic with microtopography that affects water inundation, phases of succession, and degrees of disturbance (Borhidi 1991).

The jewel of the Antilles's wetlands is the Zapata Swamp, the largest wetland in the region (>1,100,000 ha), with more than 17 of Cuba's 20 endemic bird species. The swamp is home to roughly half of Cuba's 346 bird species. Zapata is also one of the most important locations for Cuba's plant diversity—150 of the 900 plant species found in Zapata are endemics, five of which are locally endemic (Davis et al. 1997). Approximately 18% of the 212 recorded invertebrates are endemic to Cuba. Zapata is not entirely pristine; legal and illegal extractive activities occur in the park, and invasive species are taking a toll on local ecosystems (*see* Tourism).

Land Covers and Uses.—Natural ecosystems cover 53% of Cuba: the area is dominated by dry forests (23%, 21,649 km²) and wet forests (13%, 12,660 km²), with wetlands (5%), pine forests (3%), cactus scrub (1%), and xeric vegetation (1%) found in small but ecologically important areas.

Agriculture occupies 40% (37,776 km²) of the landscape, with grasslands covering 5% (4820 km²). Agricultural land uses range from central pivot fields, to smallholder cultivation, to mixed commercial systems. Urban areas (Pesaresi et al. 2014) cover 733 km², while inland water bodies, largely reservoirs, account for 1172 km² (Lehner and Grill 2013). Barren lands void of vegetation but not included in urban or water categories cover <0.2% of the land.

The majority (78%) of Cuban agriculture falls in the dry-forest ecozone, and more than half of Cuban dry forests have been converted to agricultural use. A third of the pine-forest ecozone is agricultural, a limited area that represents 5% of agricultural lands. Wet forests host 10% of all agriculture on 21% of the ecozone. Cuba's mangroves remain the least disrupted ecozone, with 77% still in mangrove cover. Wetlands are 70% natural land cover with some (23%) playing a minor role in agriculture (2%). Agricultural lands comprise 541,560 ha of Camagüey (40%), which hosts 14% of the nation's agricultural lands. The provinces of Ciego de Ávila, Granma,

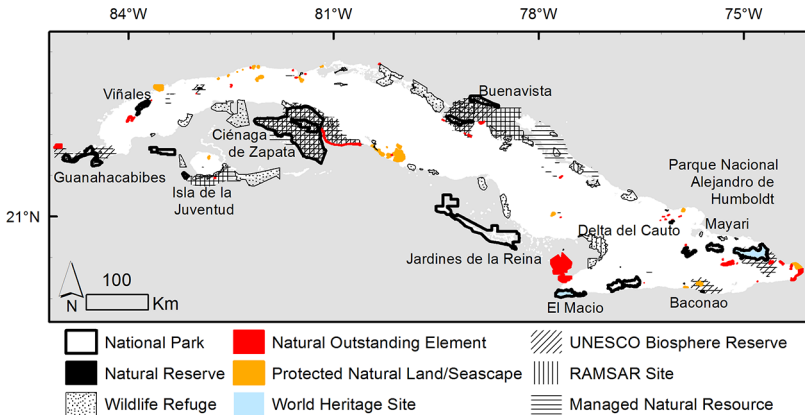


Figure 4. Protected areas of Cuba (SNAP 2017).

Holguín, Las Tunas, Matanzas, Mayabeque, Pinar del Río, and Villa Clara each have about 8%–9% of the nation's agricultural lands (Online Appendix 3).

Cuba's eight largest watersheds (2125–9056 km²) have vast expanses of agriculture (37%–60% of the watersheds) balanced with forests, wetlands, and mangroves. The surface waters of three agricultural watersheds, all roughly 2150 km² (Negro, Hanabana, Jatibonico del Norte rivers) flow through large bodies of intact wetlands and mangroves, ranging from 13% to 42%, before entering the sea. The other four large basins (Cauto, Zaza, Arimao, and Sagua la Grande rivers) have 2%–5% wetlands or mangrove cover, but total natural cover is 37%–50% of the watersheds' landscapes. Smaller watersheds (e.g., southern-flowing basins of Pinar del Río) also have notable stretches of wetlands and mangroves downstream of agricultural areas. These landscape configurations (either upstream agricultural areas flowing into wetlands and mangroves, or upland mosaics of significant forests and natural cover) may be crucial in filtering sediment and nutrients from agricultural runoff, providing clean fresh water to the coastal margins. Increased sediment loading through forest, wetland, or mangrove removal, or through intensified agricultural/urban systems, would have undesirable impacts on coastal vegetation; areas now hospitable to coral reefs could shrink if agriculture is intensified and unprotected forests are denuded under a newly spirited economy.

CUBA'S PROTECTED AREAS

Nearly a quarter of Cuba's land area (4,330,800 ha) is encompassed within 211 protected areas (SNAP 2017, Fig. 4). Cuba boasts six UNESCO Biosphere Reserves, six Ramsar wetlands of international importance (Zapata and Buenavista fall into both groups), and two UNESCO World Heritage Sites (National Parks Desembarco del Granma and Alejandro de Humboldt). The protected areas are managed in a variety of ways, from strict protection (e.g., IUCN categories I and II) to managed resources (IUCN category VI). In some cases, protection seems to be working. Cuba was recently noted as one of the few countries without significant loss of large, intact forest areas (Potapov et al. 2017). The majority of these protected areas remain forested or in their natural vegetation, although not necessarily pristine. Incursions for charcoal production and mineral extraction threaten the forests of Alejandro de Humboldt National Park, which includes the three most important centers of plant diversity

and endemism in Cuba (Davis et al. 1997). Improved management, enforcement, and compliance incentives are needed to ensure the persistence of intact habitat and the endangered species they support (Hedges and Diaz 2004).

Cuba has proposed or legally declared 106 marine protected areas, covering 25% of the insular shelf, including 30% of coral reefs, 35% of mangroves, and 24% of seagrass beds. González-Díaz et al. (2018) found that the status of Cuba's coral reefs reflects nearby human activities, such as agriculture and fisheries extraction. Areas around the protected Bahía de Cochinos and the Jardines de la Reina continue to exhibit high fish biomass and coral cover, while other areas, including those with protected status, suffer from threats such as illegal fishing and lack of financing for management and enforcement (Whittle and Rey Santos 2006, Perera Valderrama et al. 2018).

Many of Cuba's protected areas are located in more remote regions with low population densities. So, did protection halt development? Or was development pressure low, elevating the likelihood of being gazetted as a park with legal protection? We find examples of both. The Zapata Peninsula was protected in 1936, a time when uses for the swamp were few and its undesirable characteristics were many (e.g., abundant insects, resistance to cultivation) so population centers and roads remained outside Zapata. Alejandro del Humboldt National Park (established in 1997) had been relatively undisturbed except for its role in providing refuge to fugitive slaves and, later, pre-Cuban Revolution foreign investments in extractive logging and mining. Its remote nature and sometimes punishing topography were unsuitable for development (SNAP 2017), giving it passive protection before legal protection was enacted.

RISKS TO BIODIVERSITY AND TO HUMAN WELL-BEING

The fundamental causes of Cuban biodiversity loss are the transformation, fragmentation, or destruction of habitats (Planos et al. 2013). This is mainly due to deforestation and land use change, destructive fishing and harvesting practices, and preparation of soils for agriculture. Invasive species that replace or affect the functioning of ecosystems and native species are a major concern (*see* Invasive Species) (UNDP 2010). Regulatory and control mechanisms face challenges in enforcement to prevent and punish illicit poaching and fishing, as well as trade in threatened species (Gerhartz-Muro et al. 2018). Climate change intensifies periods of drought, hurricanes and heavy rains, rising temperatures, and salt water intrusion. Fires in rural areas also stress ecosystems and humans (Planos et al. 2013).

Climate and Water.—Long-term climate change is already affecting Cuba. Caribbean downscaled climate models estimate a 21st-century mean sea level rise ranging from 2 to 6 mm yr⁻¹ (lower and upper bounds), increases in rainfall variability, and mean temperature rises (Simpson et al. 2012, Rhiney 2015). Sea level rise has been observed by satellite at approximately 3 to 5 mm yr⁻¹ in the Caribbean region (Simpson et al. 2010), suggesting future rates may approach the upper bounds. Settlements with poor drainage along riverbanks are most at risk of sudden flooding or coastal storm surges. An estimated 1.5 million people (excluding the city of Havana) live in 262 settlements threatened by flooding. In the central and eastern regions of Cuba, intense and prolonged drought is already commonplace (Planos et al. 2013), a concern for potable water resources and for species sustained by the wet forests, such as the critically endangered *Eleutherodactylus iberia*, the Northern

Hemisphere's smallest frog found in a small patch of Cuban forest (approximately 100 km²; Hedges and Diaz 2004).

Cuba's mountains parallel its east-west orientation, so water travels short distances from mountaintop to river mouth with few natural water reservoirs, creating challenges for potable water access. Cuba has invested heavily in increasing surface reservoirs, but shortages have been exacerbated by prolonged droughts and variation in seasonality, compounded by other anthropogenic impacts, such as saline intrusion and pollution (Planos et al. 2013). Salinity issues are common because of overuse of groundwater from limestone (karst) aquifers. As a consequence, strategic water resource planning is focused on understanding drought and conducting hydrological assessments. One promising strategy is rainwater harvest to cope with drought (Planos et al. 2013).

By 2100, Cuba's surface air temperature is expected to increase more rapidly in the rainy summer months (up to 4.2 °C) than in the dry winter season (2.6–3.6 °C) (Planos et al. 2013). Rainy season precipitation is expected to decrease 10%–20% in some parts (Planos et al. 2013). These changes are particularly problematic in marine and coastal systems vulnerable to temperature and freshwater inputs. For example, the endangered elkhorn coral, the vanguard shallow-water coral for shoreline protection in the Caribbean Sea, has suffered greatly from temperature-induced coral bleaching.

Since 2000, the Cuban government has developed policies and practices for adapting to climate change, particularly hurricanes. Government policies are designed to resettle people from extremely fragile areas and restrict new construction in areas at risk of sea level rise and storm surges (Alonso and Clark 2015). Yet, low disposable incomes, low government fiscal space, and high sovereign debt are driving suboptimal investments in new infrastructure and housing (Bueno et al. 2008).

Land Use and Land Cover Change.—Changes in land use have been affected by exogenous forces (e.g., strict US embargo, Soviet Union collapse) and endogenous controls. These controls include planned or restricted development that directly affect or protect areas, as well as indirect factors such as strict regulation of boats that may have slowed the decline or damage to marine systems. The struggle between basic human needs and habitat conservation is a challenge not unique to Cuba and is critically important for sustainable development policy and management.

Soil degradation in agricultural areas is one of Cuba's greatest challenges. It includes acidification (3.4 million ha), salinization and sodication (1 million ha), compaction (2.5 million ha), and drainage issues (2.7 million ha) (Planos et al. 2013). These challenges are exacerbated by climate variability and produce yield gaps; the average performance of 29 common crops is only 65% of their potential. Floods cause extensive erosion, carrying nutrients into waterways and coastal margins. Rehabilitation of agricultural soils is economically constrained, as the knowledge base exists for significant soil conservation measures.

Given the challenges of climate change, current forest cover may help local recycling of water (e.g., Spera et al. 2016). Coastal dry forests and mangroves (Fig. 1) are particularly important in local recycling and filtration of water. One limitation is a widespread absence of riparian forest to regulate water along rivers and reservoirs, as restoration has remained elusive due to problems with production and quality

of seeds. Forest quality degradation is a major problem stemming from inadequate management and past exploitation (Planos et al. 2013).

Fisheries.—Nearshore and small-scale fisheries play an important role in the culture and economy of Cuba, but they have been in decline in recent years (Puga et al. 2018). Currently, 20% of Cuba's fisheries are fully exploited, 74% are overexploited, and 5% have collapsed (Baisre 2018). The most valuable fishery, spiny lobster (*Panulirus argus*), has declined since the 1980s though it has recently shown signs of stabilizing (Alzugaray et al. 2018). There have been several pressures on this species, including tropical cyclones, coastal habitat degradation, and illegal fishing (Puga et al. 2013). Despite attempts at sustainable management and controls, spiny lobster legal harvests have declined since peaking in the 1980s (12,000 t) to about 4,500 t in current official reports, with an additional 810 t of illegal catch (Alzugaray et al. 2018). In the face of declining fisheries, efforts have been made to increase aquacultural productivity. At present, freshwater tilapia and cyprinids represent 96% of national commercial production, with shrimp considered an emerging market (FAOSTAT 2017).

Energy.—The vast majority (96%) of Cuba's electric grid is powered by fossil fuels, primarily crude oil. There is a high rate of electrification, 95% of households have access to electricity (Planos et al. 2013), but per capita electricity consumption is low (1440 kWh) compared to 2600 kWh in Brazil or 13,000 kWh in the United States (IEA 2016). Cuba reduced residential electrical consumption by 3%–4% by replacing inefficient electrical appliances and incandescent bulbs with energy-saving models (Seifred 2013). Access to electricity has likely reduced pressures on forests for fuel-wood although fossil fuel combustion may contribute to pollution loads.

Large blackouts after hurricanes prompted efforts to decentralize the nation's grid, leading to greater resilience and fewer outages (Cherni and Hill 2009). Although renewable energy comprises just 4% of Cuba's total power grid (6 GW), Cuba has set a target of 24% renewables by 2030, including 14% of total generation from sugarcane residue (bagasse) (Estrada 2009). About 12,000 people rely on biogas mainly from manure for cooking and electricity with aims to add an additional 1000 units each year until 2020 (González 2015, Björkman 2016). Shifts to renewables could put fallow lands into production, such as expanding sugarcane. According to one study, wind could provide up to 2 GW and solar up to 14 GW of generating capacity (Suárez et al. 2012).

Tourism.—Tourism is Cuba's second largest employer and is expected to grow, prompting concerns over how to absorb a greater influx of foreign travelers (ONEI 2016). Ecological tourism accounts for nearly half of Cuba's tourist income, followed by beach tourism at 35% (ONEI 2016). Tourist visits have rapidly increased in recent years, with a record four million visitors in 2016 (Gonzales 2016). By 2030, the government anticipates annual visits of up to 10 million tourists by air and five million by cruise ships (Feinberg and Newfarmer 2016). Ocean-based travel is placing new pressures on fragile coastal ecosystems and is rapidly increasing—yacht visits tripled between 2015 and 2016, while cruise ship visits to Cuban ports are expected to double from 2016 to 2017 (Gonzales 2016).

Cuba's expanding tourism sector will need capital expenditures estimated at \$33 billion (Feinberg and Newfarmer 2016). The question becomes, what is the model of development? One option is high-rise resorts following the model of Cancún,

Mexico. Another option could favor smaller, more eco-friendly destinations that rely on locally-sourced food and furnishings. Costa Rica, for example, offers a national audit-based Certificate of Sustainable Tourism (Feinberg and Newfarmer 2016).

Invasive Species.—Invasive alien species (IAS) are drivers of biodiversity loss worldwide, with significant impact in Cuba, which has few native competitors and predators. In Cuba, 43 IAS are direct predators of native species, competing for resources, destroying habitat, and interfering with ecosystem services. Many economic sectors, including agriculture, fisheries, water, and tourism, are directly or indirectly affected by IAS (UNDP 2010, Kairo et al. 2003).

Lionfish (*Pterois volitans*, *Pterois miles*) first arrived in 2007 and rapidly dispersed to all coastal zones, where they prey on native marine fishes (Chevalier et al. 2008, Schofield 2009). The African walking catfish (*Claria gariepinus*) is an aggressive and adaptable omnivore that was imported for freshwater aquaculture and either escaped or was intentionally released in the 1990s and 2000s (P Tilapia, University of Havana, pers comm). This air-breathing catfish can leave the water to feed on small birds and nestlings, which may have contributed to the near extinction of the endemic, critically endangered Zapata Rail (*Cyanolimnus cerverae*). The Asian green mussel (*Perna viridis*) was unintentionally introduced either through ship ballast water or hull fouling near Cienfuegos; it has the potential to take over the root systems of mangroves (UNDP 2010). On land, predatory mammals, such as the mongoose (*Herpestes javanicus auropunctatus*), wild dogs and cats, and rats (Borrotta-Páez 2009) have reduced the levels of recruitment of important endemic species (Kairo et al. 2003, UNDP 2010).

The Australian tree, *Melaleuca quinquenervia*, is transforming portions of Zapata wetland into monoculture forests, displacing endemic species, reducing native habitat, and altering hydrology through high rates of transpiration (Kairo et al. 2003, UNDP 2010). The invasive Southeast Asian fruit tree, pomarrosa (*Syzygium jambos*), was introduced in 1875 and has since invaded natural forests across Cuba, where it dominates tree stands and alters water flow. Particularly abundant in the Pinar del Rio province, pomarrosa has likely contributed to the extirpation of 45 other species (UNDP 2010).

Important IAS are present in agricultural landscapes throughout Cuba, such as the herb malva de caballo (*Sida acuta*) and the crop pest, blue tobacco mold (*Peronospora hyoscyami*). The small leguminous marabú (*Dichrostachys cinerea*) and the aroma acacia tree (*Vachellia farnesiana*) invaded much of Cuba's uncultivated arable lands during the Special Period. Marabú is a thorny tree, easily spread by birds or dung, unpalatable to ruminants, and it is difficult to clear. This remains an obstacle to landscape reformation for ecological restoration or agricultural redevelopment. However, marabú is emerging as a popular charcoal source for wood-fired ovens and grills in Havana. In 2017, marabú charcoal became the first legal export from Cuba to the United States in more than 50 yrs.

DEVELOPMENT TO EMBRACE AND BENEFIT FROM CUBA'S NATURAL WEALTH

Food Security and the Environment.—Sustainably feeding a growing population while maintaining ecosystem services and addressing climate change, poverty, and biodiversity loss is a pressing global challenge. Agroecology, applying ecological principles from traditional and scientific knowledge in managing agricultural systems, could play a central role in transitioning toward a sustainable global food system

(IAASTD 2009, Altieri et al. 2011). Cuba has quietly become a leader in sustainable agriculture through the challenges of the Special Period. Strategic partnerships developed between farmers, scientists, and government, along with restructuring of land tenure and distribution, transformed Cuba's former large-scale, high external input, and capital intensive system of agriculture to small-scale, low external input, knowledge intensive, diversified systems. Many of Cuba's on-farm practices to build and maintain soils or manage pests, including biological pest controls, crop rotations, and locally adapted seeds, also provide resilience to climate and economic changes.

Prior to the Special Period, 83% of agricultural land was state controlled large, industrialized farms. Restructuring in 1993 turned more than half of state farms into private cooperatives [Basic Units of Cooperative Production, or UBPC (Unidad Básica de Producción Agropecuaria)] owned and managed by its members. In 2015, state managed farms controlled only 17% of agricultural lands, whereas UBPC's represented 23%. Small farmer cooperative systems formed in the early days of the Cuban Revolution steadily increased from 12% before the Special Period to 60% in 2015 (Nova in press). The government further incentivized land redistribution with the 2008 Decree Laws 259 and 300 that allows any willing individual to farm up to 68 ha of previously abandoned farmlands. Over 200,000 families have used this law to recultivate 1.7 million ha (Nova in press). Cuba is also a world leader in urban agriculture with 383,000 farms covering 50,000 ha that produce >1.5 million t of vegetables in cities like Havana and Villa Clara (Altieri et al. 2011). Agroecological systems for urban agriculture and small farmer cooperatives were key to surviving the food crisis of the 1990s, but crops such as tobacco, sugarcane, citrus, coffee, and grains are generally still managed as monocultures with classic technological packages of synthetic fertilizers and pesticides.

With normalizing of relations, US agribusinesses interests raise concerns over how a corporate value-chain may affect gains in agroecology, impacts to the environment, and status of Cuban food security and livelihoods. There might be easier access to pesticides and fertilizers, as well as land exploitation and acquisition by international agrifood companies. This scenario could include crops such as sugarcane, which requires the addition of synthetic fertilizers, heavy machinery, large swaths of flat land, and abundant water. An alternative trajectory would be toward small, intensive horticultural crops (e.g., cucumbers, flowers) for rapid delivery to US markets, akin to the strategy developed in Kenya of producing for European markets. However, these systems can also require large amounts of fertilizer and pesticides that affect local water bodies, and often negatively affect social and economic systems as well. Cuba is well poised as a global example of a nation developing agriculture that is ecologically sound, socially just, economically fair, and best suited to resiliency in a changing climate.

Tourism and Coastal Development.—Roughly two-thirds of Cuba's 326 resorts are located in coastal areas (e.g., Havana, Varadero, Holguin, Santiago de Cuba) (ONEI 2015). Increasing visitation to these regions is expected but some beach destinations may be unsuitable in the future. Varadero has billions invested in hotel infrastructure, but is extremely vulnerable to water scarcity and is expected to have a 25% decline in precipitation over the next century (Planos et al. 2013). The Varadero Peninsula will be largely submerged once sea level has risen 50 cm, a likely occurrence within a few decades (Planos et al. 2013). Conversely, ecotourism in Cuba may

rely heavily on small, locally-owned operations such as *casas particulares* (private in-home bed and breakfasts). New areas of attraction may develop, such as coastal towns with near-shore access to reefs.

Changes in the US embargo and internal policy may lead to further opening of Cuba to international investments for large-scale development, with potential negative effects on the environment. This has been the cautionary tale from development and investment experiences in recent decades for neighboring Caribbean countries in the absence of comprehensive planning or enforcement of environmental regulations. In particular, preservation of agricultural land in good agro-environmental conditions should be a major focus. The experience of Barbados shows that rapid conversion of agricultural land into infrastructure for tourist facilities and residences leads to serious negative outcomes (Barbados 2010). Agricultural area decreased >30%, production decreased 85%, and agricultural import dependence rose sharply (FAOSTAT 2017), with negative impacts to food costs and security, incomes, and livelihoods. Increased vulnerabilities to hazards emerged as impervious surfaces expanded, intensifying runoff and the potential for floods and coastal erosion (CEPAL 2009, Simpson et al. 2012, ECLAC 2015). Development in Barbados's southwestern coastal areas contributed to declines in mangroves and sand dunes that protected communities from increasingly threatening storm surges, erosion, and sea level rise—all processes further aggravated by climate change (IPCC 2014, Nurse et al. 2014). Preserving conservation land while improving its agro-environmental functions by, for example, introducing climate resilient agricultural practices, will be fundamental to assure food security while protecting soils from erosion and aquifers from pollution.

Protecting and Restoring Ecosystems.—Cuba has been extremely successful in preserving large, intact swaths of forest cover. In 2000, Cuba, Uganda, the Dominican Republic, and Thailand were the only countries that protected >90% of their intact forest landscape (Potapov et al. 2017). Cuba was one of only two nations (the other being Nepal) that has experienced no loss of large intact forest tracks since 2000 (Potapov et al. 2017).

Whether by design or historical happenstance, much of Cuba's legally protected areas and intact vegetation are remote from populated areas (Fig. 4). If population pressures continue, these natural areas may remain undisturbed, except for the impacts of climate change and, perhaps, IAS. On the other hand, even sparsely populated areas can wind up being exploited for extensive resource extraction or intensified agriculture to meet global needs for food, fuel, and timber. To date, socialist programs (e.g., health, education) have not been enough to stem the rural to urban migrations, mostly to Havana. Comparatively stable living conditions and food security have been maintained with little access or pressure from international companies as a result of the embargo and Cuban controls on investment, further sparing forests from extractive exploitation. With a five-fold increase in tourism anticipated, along with the opening of markets and industrial opportunities, the security of natural capital and biodiversity in Cuba can hardly be assured except through concerted efforts to ensure that adequate safeguards are in place. While this obviously requires enhanced management and enforcement of protected areas, it is just as important that basic infrastructure and services such as water supply and waste handling are upgraded sufficiently with visitation and economic opening.

Cuba is ripe to address the demands of development with programs to elevate ecosystem services through good planning and ecological restoration. Within populated areas, restoration of riparian zones could improve water purification, retention, and recycling with other potential co-benefits such as carbon sequestration, pollination habitat, and timber sourcing. The most troublesome areas are high density coastal developments with limited water supply, small watersheds (no dilution of wastewater), and acutely vulnerable nearshore marine ecosystems (e.g., Havana and its coral reefs). These same areas are facing increasing tourism visits that strain the antiquated water and treatment systems, bring more garbage to the area, and are likely to increase impervious surfaces.

CONCLUSIONS

Cuba's natural coastlines and dense mangrove and littoral forests are sites of historical and cultural importance. The relationship of humans and nature has evolved over time; during the early years of the Cuban Revolution, there was a strong sentiment to conquer nature, exemplified by this excerpt from the influential Cuban revolutionary and scientist Antonio Núñez Jiménez, "mountains will be demolished and rocks taken to the depths of the seas to build dikes to transform seas into productive soils; no river . . . will deliver a single drop of potable water to the ocean" (Díaz-Briquets and Pérez-López 2000). Yet today, extensive coastal wetlands and mangroves filter agricultural and urban runoff and may be partly responsible for the quality of Cuba's coral reefs in an era of global degradation. Agroecological practices have minimized or slowed erosion and synthetic nutrient inputs to a level that appears to allow wetlands to serve as a buffer. Keeping the landscape configuration, as mapped here, and associated functions is essential to sustaining fisheries, culture, and tourism, a new approach to Núñez Jiménez's vision of "a culture of nature."

What is not clear is how Cuba can maintain its impressive balance between flows of essential ecosystem services and demands placed on the ecosystems that support them in the face of an opening economy. The opportunity to avoid and indeed reverse ecosystem collapse is virtually unprecedented; there may be no country or region of the world undergoing rapid development that has truly succeeded in doing so. Three approaches could be at the heart of a solution. First, like nearly everywhere else in the world, there is a disconnect between the geographies of ecological function and of geopolitical governance; in Cuba governance units do not generally correspond to watershed-coastal ocean units of ecology. Currently, Cuban policies are biased toward terrestrial ecosystems leaving gaps in marine policy (Gerhartz-Muro et al. 2018), yet our work shows that terrestrial policies can benefit coastal systems. As compared to capitalist nations, with something closer to a free-market economy, Cuba is in a unique position to correct this deep ailment that nearly all modern nations suffer. Second, many of Cuba's endemic species and important functioning ecosystems (e.g., mangroves) are not limited to protected areas and are on the verge of extinction or loss, if not already. Acceleration of economic development should be accompanied by an equivalent and commensurate commitment to protect, manage, and expand or add national protected areas, ensuring adequate habitat for Cuba's natural patrimony. We find extensive mangroves and forests that may reduce sediment and pollution influxes to coastal systems; however, we have not documented the rates of change in forest cover or in freshwater flow from impoundments that pose threats to coastal ecosystems. Third, Cuba would benefit by creating and realizing a national ecological

restoration plan with clear targets for species survival, habitat preservation and restoration, and ecosystem service productivity. The restoration work in Guanacaste National Park, Costa Rica, for example has connected islands of dry tropical forest, reduced the spread of IAS, and engaged Costa Ricans and the international community. Cuba is uniquely equipped to halt extinctions of its unique biota, fight incursions of invasive species, and maximize the benefits made possible by a harmonious coupling between the ecosystem and society. If Cuba were to succeed in these measures, in concert with sensible limits to population size, rates of consumption, and environmental degradation, then it would become a beacon to a troubled world. The forging of a modern society in which every citizen enjoys a rich quality of life that is sustainable across the generations is badly needed. Cuba can look across the Florida Straits to a similar ecosystem with distinctly different patterns of development that have led to environmental stress and degradation (National Research Council 2014).

Cuba can move toward development that nurtures and safeguards ecological integrity. Preserving natural infrastructure, such as mangroves, is challenging as the benefits of ecosystem services are often unseen, unknown, or unfold over time. This is a problem inherent to human nature, not unique to Cuba. What is unique is the magnitude of Cuba's determination to make its own decisions and not be ruled by outside forces. A future that values ecological integrity will help minimize risks and weather shocks from global political, economic, and biophysical changes.

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