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GIS-based Modeling of Environmental Risk Surfaces (ERS) for Conservation Planning in Jamaica

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INTRODUCTION

Identifying and quantifying threats to biodiversity is widely recognized as a critical component of effective conservation assessments (Ervin and Parrish, 2006; Groves, 2003; Margules and Pressey, 2000). This article presents a quantitative method for assessing and incorporating human impact considerations (i.e. threats) into the ecoregional assessment process for terrestrial,

(2010) and marine areas (2012). As of 2007, the Jamaican system of protected areas encompasses nearly 2000 km^2 or over 18% of terrestrial areas and 1800 km^2 of marine area, approximately 15% of the country's archipelagic waters (Figure 1, page 63). However, Jamaica is currently addressing the need to reform the present protected areas system to ensure that all critical biodiversity is adequately represented and supported by viable and well-functioning biological processes. By characterizing human disturbance using GIS-based risk indices in combination with the distribution of biodiversity feature occurrences, the most promising areas to sustain biodiversity to meet national and CBD biodiversity conservation goals can be identified.

METHODOLOGY

GIS-based models called Environmental Risk Surfaces (ERS) were developed using mapped risk elements (e.g. human activities) to examine the spatial relationships between risk elements and biodiversity features. A risk element can be defined as anything identified by experts as having a negative influence on the health of conservation features, such as critical habitats or key species. ERS models were designed to spatially identify habitats within low (intact) and high (threatened or disturbed) risk areas, based on the spatial interaction of nearby risk elements. These models can also serve as input cost models for the popular Marine Spatially Explicit Annealing (Marxan) conservation goal optimization software (Ball and Possingham, 2000; Possingham et al., 2000) which can steer conservation site selection away from high-risk areas where the abatement of pressures on biodiversity seems less likely. The composite or disaggregated individual risk surfaces can also be used to locate specific environmental risks within a landscape that may be degrading the viability of particular conservation feature(s).

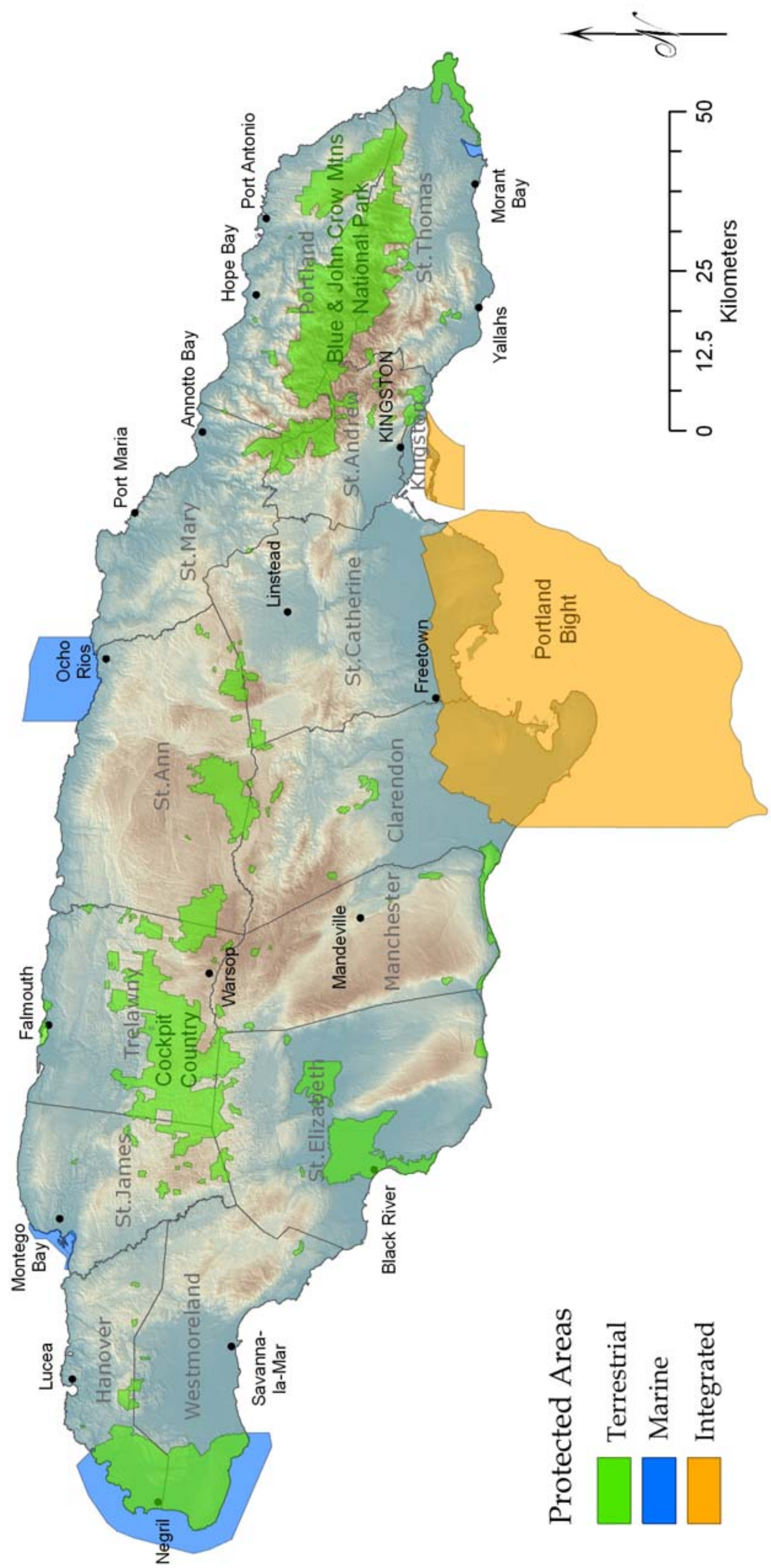
The Environmental Risk Surface tool is a freely available GIS-based tool developed in VisualBasic.NET (ArcObjects) within ArcGIS 9.2 software (ESRI, Redlands, CA) (Schill and Raber, 2008, download at *http://www.gispatools.org*). The first step in creating an ERS model requires assembling a suite of the best available GIS data that spatially represent the risk elements that are most likely to impact the health of terrestrial, freshwater, and/or marine habitats or species. All risk element features must be spatially mapped on the landscape as points, lines, polygons or raster models. Human-induced landscape features such as agricultural and urbanized areas, tourism zones and hotels, roads, industrial areas, and surrogate indicators for human impacts such as population density, are examples of risk elements that can be reviewed by experts and used as input for the ERS model. The combination of risk elements and their assigned risk parameters may vary for each habitat realm in order to account for the different ways that human activities impact biodiversity in each realm.

Assigning Intensities and Influence Distances

After assembling all risk element data, each element is reviewed, classified, and ranked based on the degree that each is considered to be a threat to the habitat or species in question. Information from existing literature and expert consultations are used to assign each risk element an *intensity value* and an *influence distance* based on factors such as the likely extent, severity, and reversibility of the impact of the risk element. In addition to vector models, raster models with intensities assigned on a cell-by-cell basis (e.g. population density) can also be used as risk element layers in the ERS tool.

The *intensity value* represents the relative level of threat that the risk element poses to the habitat or species. Separate intensity values can be assigned to the same risk element to capture the different relative levels of impact on different biodiversity features. Users often divide risk elements into major classes (*e.g.* agriculture, roads, mining, urbanization, and industry) which can then be further divided into subclasses. This hierarchical process helps to establish a clear set of quantitative values which are then normalized to a relative scale (*e.g.* 0-100) so that all risk elements are comparable within

FIGURE 1 Declared Jamaican Protected Areas divided into terrestrial (green), marine (blue), and integrated terrestrial and marine (orange) categories. These categories include one national park (Blue and John Crow Mountains) and several forestry reserves, game reserves/sanctuaries, and fish sanctuaries.



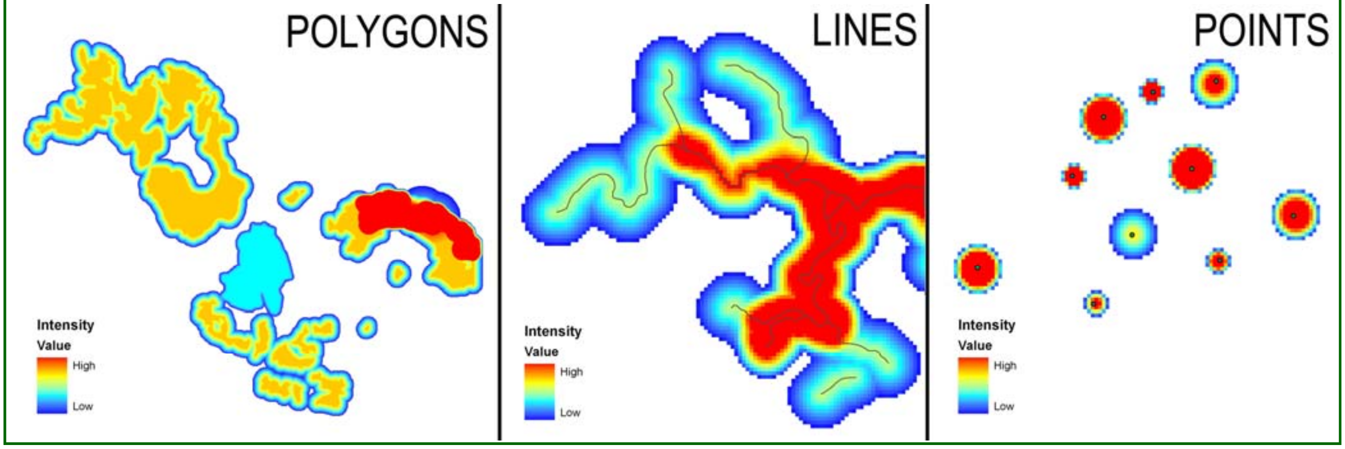
each class and subclass. It is important to note that the final normalized intensity scores generated through this process do not represent an absolute measure of the impact on biodiversity features but rather the relative degree to which the biodiversity feature in question is more likely to survive in one place over another based on the presence of one risk element in comparison to another.

After the intensity values have been assigned, the next step is to determine the *influence distance* of each risk element. The influence distance is the spatial extent or footprint of the activity on the landscape and represents the maximum distance at which the feature has a negative impact on biodiversity (Theobald, 2003; Araújo et al., 2002). The influence distance is used to attribute an intensity value to risk elements outside of the immediate area of direct impact. As the distance of the buffer increases away from the center of the area (point, line or polygon) where the risk element is taking place, the intensity values of the cells within the buffers diminish progressively (*i.e.* distance decay) and the risk to the habitat is gradually lessened until the maximum distance is reached and the risk element is no longer considered to pose a risk to the conservation features. Some risk elements may represent risk for large geographic distances while others represent a risk only to areas in close proximity to the habitat or species occurrence. The ERS tool permits users to specify the type of distance decay (linear, concave, convex, or constant) and how to spatially aggregate overlapping risk elements.

Risk tables are developed to indicate the intensity and influence distance of each risk element and are assigned independently to each class and subclass based on the perceived threat level to terrestrial, freshwater or marine biodiversity. These values are then assigned within the GIS attribute table of each risk element for use in the development of the ERS model. Figure 2 demonstrates how individual polygon, line, and point risk elements translate into modeled risk surfaces with varying intensity values that diminish within the range of influence distances.

Expert opinion was critical for identifying key threats and developing the intensity and influence distance values incorporated into the models. All final decisions regarding intensity values and influence distances were made by the small core teams of experts responsible for developing the ERS for each habitat realm. When possible, their decisions were substantiated through literature reviews and consultations with other outside experts. Finally, once completed, the freshwater, marine and terrestrial ERS models including all relevant values were verified in workshops of outside experts.

FIGURE 2 Examples of intensity distance decay in Environmental Risk Surface models based on one risk element for polygon, line, and point features. Red shades indicate higher levels of intensity values in near proximity to the risk element, and shades of yellow to blue indicate varying degrees of intensity decay based on the user-specified influence distance from the risk element (Schill and Raber 2008).



JAMAICA ERS RISK ELEMENTS

The risk elements incorporated into the Jamaica ERS models include mapped representations of development activities (*e.g.* agricultural areas, industrial areas, tourism zones and hotels), infrastructure (*e.g.* roads, ports, airports, dams, sewage outfalls), and surrogate variables for measuring impact (*e.g.* population density, urban areas). The mapped risk elements correspond to IUCN threat types and sub-types as presented in Table 1, page 66. In addition to socio-economic data, natural event data for events such as hurricanes, volcanic activity, and climate change may also be used in the creation of an ERS, although it may be difficult to rank and assign these values due to the extreme unpredictability and complexity of these events. ERS models are the aggregation of all risk elements into a single surface which can then be summed into planning units, such as hexagons, and used as cost values for Marxan analysis.

Agriculture

Agriculture continues to be a primary contributor to the degradation of terrestrial, freshwater, and marine biodiversity of Jamaica despite a persistent downward overall trend in the production of traditional export and domestic crops since the 1960s (JSDN, undated). The agricultural sector remains structurally divided into large farming enterprises and small-scale family farms of two hectares or less. The large-scale farms that produce crops for the export market (primarily sugarcane, banana, and coffee), rely heavily on the use of energy-driven equipment, irrigation, and agrochemicals. These farms occupy fertile lands of the coastal plains and the interior valleys of Jamaica. In contrast, the small-scale farms are concentrated on marginal, less-fertile lands in the upland areas of the central parishes and the hilly areas of the coastal parishes. Livestock also remains an important industry and pasture for the production of meat and dairy for the domestic market covers approximately 1/5th of Jamaica's land (Weis, 2000).

Jamaica is particularly susceptible to watershed degradation because approximately 80% of the country is hilly or mountainous (USAID, 1996). Approximately 9% of the total land area contains topographic relief that exceed 30% slope. The clearing of land for planting crops and other farming related activities--the use of agrochemicals, unregulated burning, and the cutting of timber in forested areas for various uses--have been cited as the principal activities that contribute to the degradation of the watersheds (JSDN, undated). These activities result in the loss and fragmentation of habitat, high rates of soil loss, and sedimentation and contamination of freshwater resources. These processes have dried out rivers, blocked watercourses and negatively impacted marine ecosystems and fisheries (Weis, 2000).

Energy inputs by crop type provide a measure of agricultural intensity. According to Redclift (1992), economic development has historically been linked to a progressive increase in energy consumption. This is nowhere more apparent than in the case of agricultural development. Agricultural systems are ecosystems that are artificial in the sense that they are sustained only through human manipulation. Whereas the productivity of natural ecosystems relies on naturally-given energy inputs and processes (gravity, sun, soil nutrient cycles, bacteria, fire, and wind), the productivity of agricultural 'eco'-systems relies on introduced energy inputs not intrinsic to the natural system, as well as controlling and harnessing natural energy inputs. From this perspective, agricultural systems can be organized along an intensity continuum based on the amount of energy inputs into the system. On one end of the continuum are relatively low-yield traditional agricultural systems that rely heavily on natural energy inputs (sun, rain and soil nutrients), human labor, animal power, and induced fires. They require minimal alteration of landscape structures and often use rotating and multi-cropping systems that tend to mimic natural ecosystem processes (Redclift, 1992). On the other end, high-intensity modern agricultural methods produce much higher yields but also rely on much heavier energy inputs per unit of land through the consumption of fossil fuels for machinery use and chemical fertilizers and

TABLE 1 Mapped Risk Elements used in the JERP Environmental Risk Surface Models

Threat types (IUCN)	Sub-Type	Mapped Risk Elements	Impact realms
Habitat loss/ degradation	Dams	Hydroelectric dams Irrigation dams	Freshwater
	Extraction (water abstraction)	Water abstraction	Freshwater
	Infrastructure development (Transport land-air)	Roads	Terrestrial
Habitat loss / degradation and Pollution	Agriculture (Shifting Agriculture; Small-holder Agriculture; Agroindustry; Farming) Water pollution Land pollution	Banana and plantains Sugar cane plantations, Small scale ag. and grasslands, Tree crops (coffee, citrus) and agroforestry	Terrestrial Freshwater Marine (using flow accumulation model)
	Extraction (Mining and Fisheries) Water pollution Land pollution	Limestone quarries Bauxite mines Sand mining Fishing Pressure Model	Terrestrial Freshwater Marine (using flow accumulation model)
	Infrastructure development (Human settlement) Land pollution Water pollution	Urban areas	Terrestrial Marine Freshwater
	Infrastructure development (Transport land-air) Water pollution	Major airports	Terrestrial Marine
	Infrastructure development (Tourism/ recreation) Water pollution	Tourism/resort zones	Terrestrial Marine
	Infrastructure development (Industry) Water pollution	Industrial zones	Marine
	Infrastructure development (Transport/Water) Water pollution	Commercial/Industrial Ports	Marine
	Infrastructure development (Transport/Water) Water pollution	Cruise ship ports	Marine
	Infrastructure development (Transport/Water) Water pollution	Marinas	Marine
	Surrogate for numerous subtypes related to human settlement and pollution	Population density of enumeration districts	Terrestrial Marine
Pollution	Water pollution (Sewage)	Sewage outfalls	Freshwater Marine
	Water pollution (Domestic)	Sewage seepage from latrines	Freshwater
	Water pollution (Sediment; Agriculture; Domestic)	Freshwater accumulation model outfalls	Marine
Invasive Alien Species	Competitors	Bamboo Perna viridis	Freshwater Marine

Source: The IUCN Redlist of Threatened Species: Database Search: http://www.redlist.org/search/search-basic.html. Accessed November, 2005.

pesticides production. In addition, there may be an alteration of the natural landscape by plowing, contouring, terracing, and the rechanneling of water sources for irrigation. As such, these high input systems constitute a much greater departure from the ecological systems that sustain natural biodiversity than low energy systems and demonstrate greater potential to generate secondary environmental impacts, such as altered hydrological regimes and sedimentation patterns, reduced water quality and soil productivity that significantly alter ecological processes beyond the agricultural fields.

The calculation of energy inputs by crop type and system were based primarily on the work of D. Pimentel (1980) and involved the development of a standardized method for calculating energy use values in kcals for inputs into the crop production process that included human labor hours, gas per liter, machinery use, irrigation and inputs such as lime and fungicide and fertilizers. Normalization of the agricultural intensity values, expressed in kcals/crop type and system, took into account the idea that the relationship between agricultural intensity and environmental impact is not linear. An S-curve was therefore developed to reflect the hypothesized relationship between intensity and impact and a logistic function generated to fit intensity values along the curve (Figure 3). Intensities were divided into eight classes corresponding to the normalized impact/intensity values generated by the function to facilitate incorporation into the combined surface which is listed in Table 2.

Agricultural categories for Jamaica were extracted from the 1998 land use/land cover map (Forestry Department, 1998) which classifies agriculture in Jamaica into four broad categories: 1) bananas; 2) sugarcane plantations; 3) small scale agriculture and grasslands (pasture); and 4) tree crops and agroforestry. Intensity values were applied to each agriculture polygon based on the energy inputs associated with each crop category, then normalized according to the corresponding intensity

FIGURE 3 The S-curve used to reflect the hypothesized relationship between energy input intensity and impact for agriculture. The logistic agricultural function that was generated to fit intensity values along the curve is 0.8348/ (1+24.457*EXP(-0.1037*raw cost)).

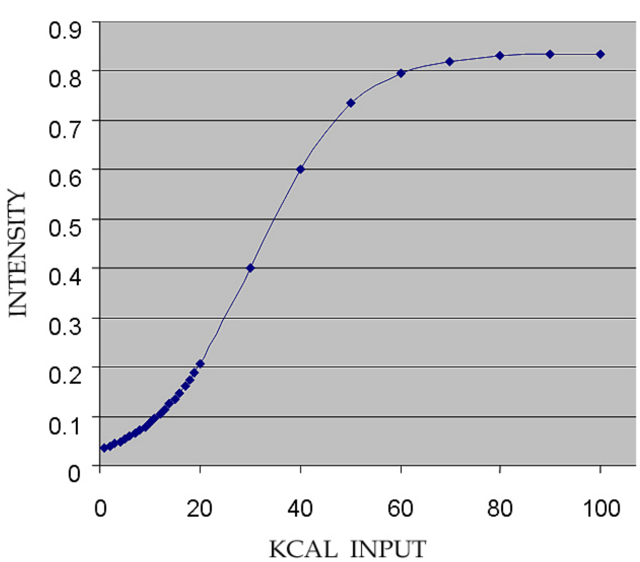


TABLE 2 Agriculture Impact Classes

Kcal Equivalent	Normalized Values
1-3	0.05
4-7	0.11
8-11	0.17
12-17	0.25
18-21	0.5
22-32	0.75
33-39	0.87
40+	0.95

scale. Finally, an influence distance was estimated for each category based on the potential of dispersal of impacts due primarily to the level of pesticide use. Although we did not vary the intensity values for agriculture used for the terrestrial and freshwater ERS models, we assigned larger influence distances for the freshwater model due to the higher projected dispersion of pesticides and sediments along drainage networks. The final intensity values and influence distances for agriculture are listed in Table 3. The resulting ERS agriculture model intensity surfaces for the terrestrial and freshwater habitat realms are shown in Figure 4, page 69. The marine ERS model incorporates agricultural intensity as part of the flow accumulation model that is explained in the freshwater section.

Population Density

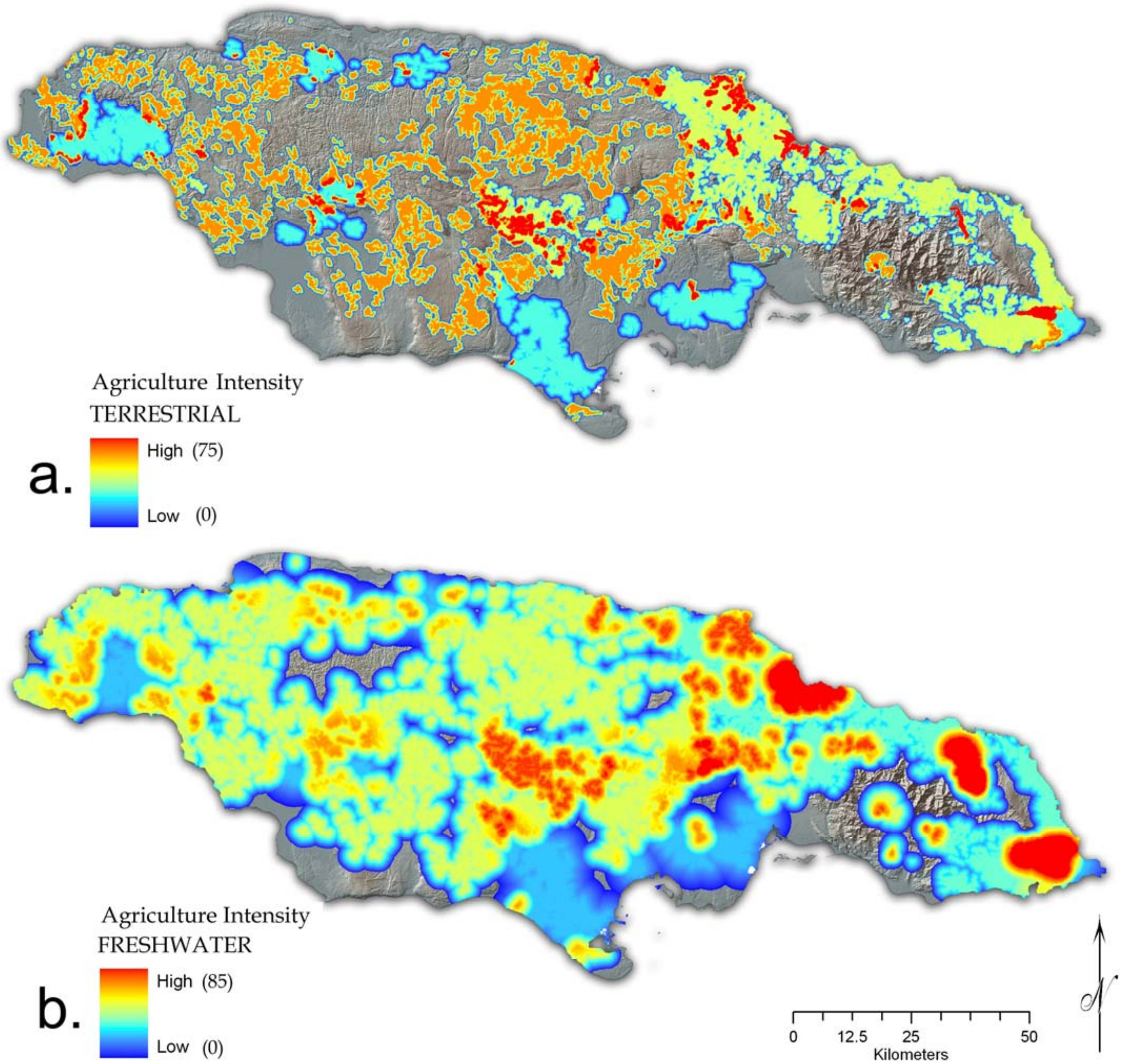
The Jamaican population is currently growing at a relatively slow rate of less than 1% per year (CIA, 2005). The rural population remains stagnant and may even be decreasing as people are concentrating along the coast and urban areas, especially in Kingston, which holds approximately 40% of the total population of the island. Whereas the 1991 census reported 49.6% of the population as urban, in the most recent census (2001) urban residents represented 55% of the population.

Population is the variable that is most commonly correlated with resource scarcity and biodiversity degradation (Cohen, 1995; Cincotta and Engelman, 2000). The environmental impact of a given population is not correlated directly with size but also influenced by settlement patterns, technology use, affluence and consumption levels, practices and policies, and the resilience of the occupied ecosystem (Holdren and Ehrlich, 1974; Meadows et al., 1992). Nevertheless, the assumption used in generating normalized intensity values for population density was that areas of higher population density are generally less attractive for biodiversity conservation than areas of lower population density. This is due to the fact that higher population represents a higher probability of the presence of activities that modify natural systems, including landscape disturbances from human settlement, infrastructure development and other local resource uses related to survival and subsistence (Theobald, 2003; Holdren, 2000; Harrison and Pearce, 2000).

TABLE 3 Final Agricultural Intensity Values and Influence Distances

Crop type	Intensity (kcal)	Normalized Value	Influence Distance Terrestrial (meters)	Influence Distance Freshwater (meters)
Banana	20	0.5	2000	5000
Sugarcane plantations	4	0.11	1000	5000
Small scale ag. and grasslands	13	0.25	500	3000
Tree crops and agroforestry (includes coffee)	8	0.17	500	2000

FIGURE 4 Environmental Risk Surfaces depicting agriculture-based activities and corresponding aggregation of intensities for terrestrial (a) and freshwater (b) habitat realms. Each realm exhibits variation based on the intensity and influence distances specified by experts.



The average population density per km^2 within each Jamaican enumeration district was used as the intensity value. These raw intensities were then normalized using the logistic function shown in Figure 5 and then divided into nine categories to facilitate incorporation into the combined terrestrial ERS model (Table 4). Figure 6a, page 71, shows the results of the final population density (km^2) ERS model.

FIGURE 5 S-Curve used to reflect the hypothesized relationship between risk intensity and impact from population density. The logistic population function for normalized intensity of population density used the population function: =0.9217/ (1 +22.6614*EXP(-0.0114*raw cost)).

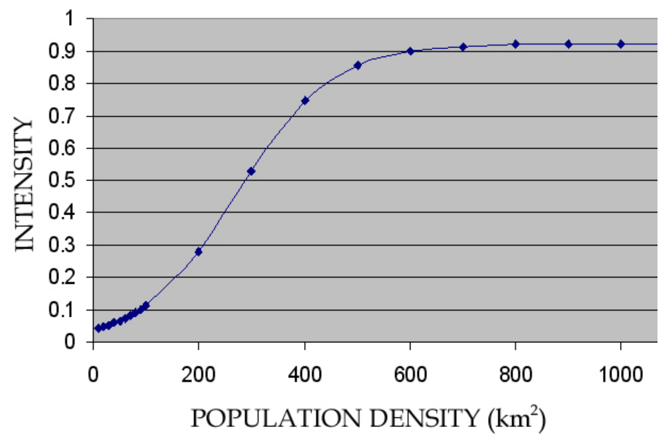
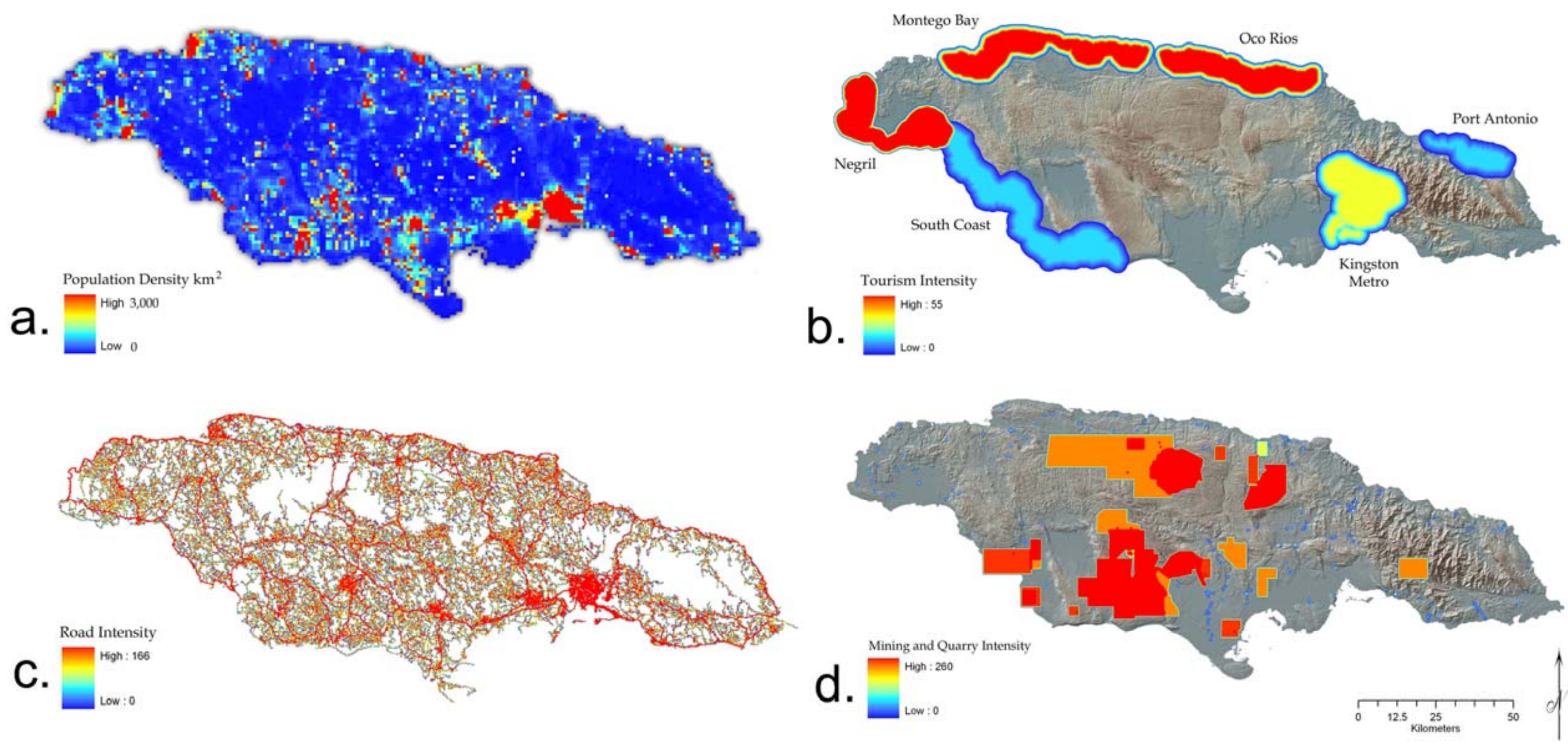


TABLE 4 Population Density Normalized Intensity Scale Categories for Terrestrial and Marine ERS Models

Pop Density (Terrestrial)	0-1 Scale of Normalized Values (Terrestrial)	Terrestrial Influence Distance (m) [1]	Population Density Scale (Marine)	0-1 Scale Normalized Values (Marine)	Marine Influence Distance for Direct Impact (m)	Marine Influence Distance for Indirect Impact (m)
1	0.05	30	1-99	1	500	4000
10	0.11	30	100-299	2	1000	5000
30	0.17	30	300-599	3	1000	5000
50	0.25	30	600-999	4	1000	5000
100	0.5	30	1000-1999	5	1500	5000
200	0.75	30	2000-3499	6	1500	5000
500	0.87	30	3500-5499	7	1500	5000
1000	0.95	30	5500-7999	8	1500	5000
20000+	1	30	8000 +	9	1500	5000

[1] The Influence Distance is one cell size, in this case a grid with 30 meter cells was used to run the surface.

FIGURE 6 Jamaica ERS intensity models for a) population density (km^2); b) tourism zones showing calculated tourism intensity values and influence distances based on final average tourism population density per (km^2) and values listed in Table 5; c) road network; and d) mining and quarry activities.



Urban Areas

Urbanized areas are distinctively unattractive for natural biodiversity because they include extensive development of infrastructure, roads, houses and other paved and impervious surfaces, the generation of concentrated levels of sewage and other types of industrial and domestic pollution and are a source of exotic and domestic species. Although assigning intensity to urban areas in addition to population density could be considered double counting (in the case of the terrestrial surface), the purpose of assigning urban areas high intensity values was to deliberately steer conservation feature selection away from highly populated urban areas when used in conservation goal optimization models. Furthermore, population density and existence of urban land uses may be correlated but densities likely vary depending on type/intensity of urban land uses that may or may not be sufficiently distinct in land cover data.

The urban areas were based on the Jamaica Forestry Department (1998) land cover classification and include polygons delineating major populated areas. For the terrestrial ERS models, these polygons were assigned an influence distance of 3 kilometers based on logical rationale to account for impact overlaps. The freshwater ERS models were based on an assigned intensity value of 0.7 and an influence distance of 5 kilometers based on consensus of the core team of experts after consulting relevant literature on urban impacts on freshwater habitat (Miltner et al., 2004; Public Sector Consultants, Inc., undated).

Tourism

Mass tourism in Jamaica originated in the early 1960s and is now the most important sector of the Jamaican economy, directly and indirectly accounting for 31.1% of GDP and 27.4% of total employment in 2007 (WTTC, 2008). The six designated tourist resort areas in Jamaica are Kingston, Ocho Rios, Montego Bay, Negril, Port Antonio, and the South Coast. In 2006, there were 1,678,905 stop over visitors in Jamaica and another 1,336,453 cruise passengers visited the island (JAMPRO, 2007). The country currently has over 25,000 hotel rooms with plans to expand capacity to 30,000 by 2009 (CTO, 2007).

The tourism sector in Jamaica significantly impacts terrestrial, freshwater, and marine resources since tourism facilities tend to be built in environmentally sensitive areas (Dixon et al., 2001). Negative impacts from tourism occur initially when beaches and mangroves are cleared for the building of hotels and resorts. Tourism development and activities can lead to impacts such as soil erosion, increased pollution, discharges into the sea, natural habitat loss, increased pressure on endangered species and heightened vulnerability to forest fires (Gössling et al., 2002; Halcrow, 1998). In order to better understand and identify the areas most highly affected by tourism development within the region, the location of all cruise ship ports, golf courses, hotels, and marina locations were digitized as point and polygon risk features.

Tourism zones were compiled to represent concentrations of tourism activities within the country by creating a buffer of 5 km inland around hotel clusters. This buffer zone represents areas within direct concentrated resource use on land, including waste disposal and direct pressure associated with tourist attractions including hotels and restaurants, beaches, golf courses, and cruise ship ports.

Establishing tourism intensity involves treating the overall annual population of tourists as permanent human populations living within the tourist zones. Individual tourists are transient; however the tourist population as a whole implies persistent resource use patterns, waste emissions and the development of infrastructure for the tourist population. Although the management practices of resorts and hotels are critical determinants of the overall environmental impact of the tourist population, estimates suggest that the average tourist emission of waste and demand for resources such as energy and freshwater resources is at least twice that of the permanent population on a daily basis (Halcrow, 1998; UNEP, 2001; Island Resources Foundation, 1996).

Calculating tourism intensity involves converting the average visitation per tourism zone into a value that is the equivalent of the average daily population density of tourists per km^2 within each tourism zone, including short-term cruise ship visitors. The data came from the hotel layer as well as official visitation figures for 2003 (JTB, 2004). The calculations for determining average visitation density per km^2 are described in Text Box 1. Table 5 shows the final intensity values that were assigned to each tourism zone. Tourist population density was multiplied by two to reflect the greater pressure exerted by tourists than the local population and the values were normalized into intensity scales using the population density logistic function shown in Figure 5, page 70. The same intensity value was then applied to all of the cells within each respective tourism zone.

Finally, for the terrestrial ERS model, the experts decided that an additional 3 km influence distance from the edge of the tourism zone should be used as a precautionary measure to capture any overflow of pressures on terrestrial biodiversity not occurring within the direct impact zones (Figure 6b, page 71). For the marine ERS model, experts decided not to use the 5 km direct impact buffer. Instead a 4 km influence distance from the coastline was used to reflect the direct close to shore impacts and subsequent gradual dispersion of related contamination into the marine coastal areas. Tourism intensity values were not incorporated into the freshwater surface because the extractive and pollution effects of tourism were represented under the water abstraction and sewage outfalls risk elements.

TEXT BOX 1 Calculations Used for Average Visitation Density per Km^2

1. Average daily number of overnight visitors in tourist zones:

(# of rooms in zone) x (average # of visitors per room) x (% occupation in zone for previous year)

2. Average # of visitors per day per room: ((# of overnight visitors) * (average stay)) /365) / (# of rooms)

3. Average daily # (per 24 hours) of non-overnight visitors (cruise ship visitors):

i) (# of visitors per year) x (average length of stay in hours) = # of visitor hours per year
ii) (# of visitor hours per year) / 24 = # of visitor days per year
iii) (# of visitor days per year) / 365 = average daily # (per 24 hrs) of non-overnight visitors

4. Final average tourism population density per km^2:

(Average daily # of overnight visitors) + (average daily # non-overnight visitors) / # of km^2 in tourist zone

TABLE 5 Tourism Zones and Intensity Values in Jamaica (based on 2003 visitation)

Tourist Zone	Average Daily Tourist Population 2003	Cruise Ship 24-hour Population Equivalent	Total Average Daily Tourist Population	km^2 in zone	Population Density Equivalent per km^2	Normalized Intensity Value (Terrestrial)	Normalized Intensity Value (Marine)
Negril	4389	0	4389	170.048	51.62	0.50	2
South Coast	253	0	253	450.936	1.12	0.05	1
Ocho Rios	4589	462	5051	232.788	43.40	0.25	1
Kingston Metro	1019	1	1020	321.964	6.34	0.11	1
Montego Bay	5896	182	6078	257.148	47.27	0.25	1
Port Antonio	43	1	44	132.873	0.66	0.05	1

Roads and Highways

Roads and highways have a profound and well-studied negative influence on biodiversity (Forman et al., 2002). Roads provide access to previously undisturbed areas which can lead to increases in human activities such as forest clearing, urban sprawl, and agriculture expansion. The biodiversity impacts of roads include traffic caused mortality (Fraser and Thomas, 1982) and increased landslide rates from road construction and related timber harvest (Sidle et al., 1985). Roads may influence sedimentation, invasive species introduction, and chemical contaminant rates in forest ecosystems, and this influence has been measured from a range of 25 meters to over 200 meters (Quarles et al., 1974; Dale and Freedman, 1982; Greenberg et al., 1997). Road avoidance for a variety of species including forest and wetland birds and various carnivores has been demonstrated especially related to high-volume highways. A number of studies have also described patterns of landscape fragmentation caused by roads and the direct and indirect impacts on biodiversity due to the presence of roads (Trombulak and Frissell, 2000).

In 2003, the Jamaican road system consisted of approximately 5,000 km of main roads and 11,000 km of parochial roads with around 70% being paved. The highway system has been evaluated as needing significant improvement and ongoing projects have been in place for the renewal and maintenance of the road system including the construction of the North Coast highway, which links the primary tourist sites of Montego Bay and Negril, and Highway 2000, a four lane highway that will cross the island linking Kingston and Montego Bay (CRII, 2003).

To incorporate roads and highways into the terrestrial and freshwater ERS models, all primary, secondary and tertiary classes of roads were obtained in GIS format. The average road dimensions for each class was obtained by consulting an engineer from a local roads construction firm and assigned in the GIS attribute table to reflect the direct impact of roads. The intensity values and influence distances for each road class are listed in Table 6. Intensity values for each were established by the core experts team based on logical rationale. Only a small influence distance was assigned (15m) based on the view that only the localized impact of roads could be modeled. Figure 6c, page 71, shows the final ERS model based on the distribution of roads. Roads were only included in the terrestrial human activities surfaces because the experts in freshwater and marine ecosystems did not consider roads to represent major risks relative to the other elements included in those surfaces.

TABLE 6 Standard Dimensions, Intensity and Influence Distance for Roads and Highways

Road Class	Dimension (carriageway/ lane) (ft)	Dimension (shoulder) (ft)	Width Buffer	Influence Distance	Intensity
A/primary	12 ft (x 2) – 24 ft	8 (paved)	10m	15m	0.5
B/secondary	10-11 (x 2) – 20 to 22ft	n/a - average of 3 to 4 ft	8m	15m	0.25
C/tertiary	20 to 22 (1 lane) or 16-18 (1 lane)	n/a	7m	15m	0.11
Other	Unpaved paths and roads	n/a	4m	15m	0.11

Source: J. Allgrove, civil engineer, Wallace Evans Jamaica Ltd., pers. comm. with Kimberly John, TNC

Mines and Quarries

Jamaica accounts for approximately 10% of the world's annual output of bauxite and is the world's third largest producer behind Australia and Guinea. Bauxite mining and alumina processing constitute Jamaica's second largest industry and is the country's leading economic sector in export earnings, accounting for approximately 75% of Jamaica's annual exports (Baumann, 2002; NEPA, undated). Estimates show that existing reserves will last more than 100 years at current production rates (Johansson, 2003).

Within the last few decades, large areas of forest have been cleared due to open pit mining for bauxite. The building of access roads to the bauxite mines causes a significant impact on forest habitat since loggers move in and illegally remove trees in and around the mining areas. Bauxite mining also reduces the water retention capacity of the soils, even in restored areas, and produces other impacts such as caustic soda contamination of water supplies (which elevates groundwater sodium and PH levels) and the spread of bauxite and alumina dust (Johansson, 2003, NEPA, undated).

In addition to bauxite, there are widespread sand, limestone and gravel quarries that operate on a smaller scale throughout Jamaica. The direct impact of these operations on terrestrial biodiversity is localized and related primarily to the clearing of vegetation and alteration of the natural landscape. On the other hand, the impact of quarries on freshwater ecosystems can be more widespread through the disruption of the substrate through runoff, sedimentation and increased turbidity. Table 7 displays the intensity values and influence distances used to incorporate mining into the terrestrial and freshwater ERS models. Freshwater influence distances for bauxite mining were based on evidence of downstream alkaline contamination in the Rio Cobre provided by a local expert. Other intensity values and influence distances were established by the core expert teams based on their knowledge of mining impacts in Jamaica. The final results of the ERS intensity model for mining and quarry activities in Jamaica is provided in Figure 6d, page 71.

TABLE 7 Intensities and Influence Distance for Mining and Quarrying

GIS Data Layer	Terrestrial Intensity	Terrestrial Influence Distance (meters)	Freshwater Intensity	Freshwater Influence Distance (meters)
Bauxite mines active	0.95	500	5	2000
Bauxite mines in restoration	0.85	500	5	2000
Sand, limestone and gravel quarries	0.95	500	6	5000
Bauxite processing plants	0.1	10000	10	8000

Fishing

Small-scale commercial and industrial fishing occurs all around the island of Jamaica and constitutes an important pressure on key marine biodiversity features. The commercial fisheries are primarily artesian coral reef fisheries that operate from over 200 fishing beaches around the island (CFRAMP, 2000). According to FAO (2007), in 2001-2002 the island included over 14,000 registered fishers and over 4,000 fishing vessels. The larger catch is made along the broad south coast shelf where approximately 60% of fishers are based (Woodley, 2000). However, the coral reef fish communities along the north coast, which includes a more accessible, much narrower shelf (most areas under <1 km), have been more severely degraded by fishing pressure (Zenny, 2006).

Industrial fishing operations primarily target Spiny Lobster and Queen Conch. Jamaica is the world's largest producer and exporter of Queen Conch. The larger-scale fishing primarily takes place on offshore banks, primarily the Pedro and Morant Cayes, as well as in Formigas, Henry Holmes and Grappler Banks (CFRAMP, 2000).

A fishing pressure model was developed to capture the distribution of fishing pressures in different coastal marine areas surrounding the island (Zenny, 2006). The model uses the most recent fisheries activity estimates available at a national scale, including major offshore banks (CFRAMP, 2001; Espeut, 2004). A GIS data layer of landing sites was developed that includes number and types of vessels and number of fishers per site.

Two sets of classifications and associated intensity scales were developed--one for number of fishers at each landing site and one for number of boats by type at the landing site--under the simple assumption that more fishermen and boats mean more fishing activity and pressure. The final intensity assigned to each fish landing site was calculated as the sum of fisher intensity and boat intensity (Table 8). Each landing site was stratified according to the types of boats present in the landing site to assign influence distances. The influence distances were based on the maximum estimated distances from the landing site that the different kinds of boats can travel from the landing site. Lower to higher influence distances were therefore attributed to scull, engine, and bighead vessels respectively (Table 9, page 77, and Figure 7, page 78).

TABLE 8 Fish Landing Site Calculations for Cost Surface

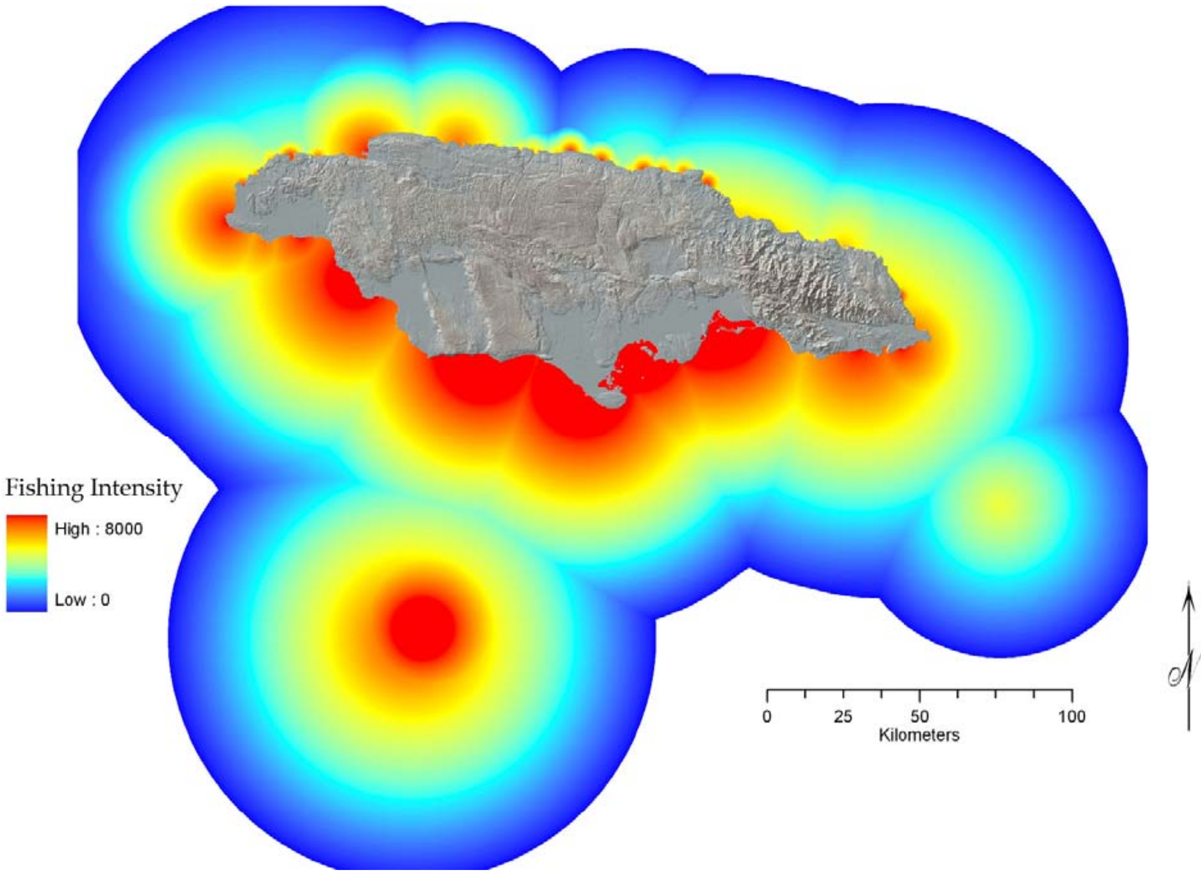
Number of boats	Frequency	Class	Intensity	Number of fishers	Frequency	Class	Intensity
1-10	106	v. small	2	1-19	102	v. small	2
11-30	61	small	3	20-80	69	small	3
31-80	26	medium	4	81-200	23	medium	4
81-240	7	large	5	201-679	8	large	5

Note: The number of landing sites = 231 (30 of which are no longer in use or fishing activity status is unknown)

TABLE 9 Influence Distance and Guiding Assumptions for Fishing Model

Type of Boat	Influence Distance	Assumption
Scull (non-motorized)	1.5km out to sea	Scull fishermen are limited by the absence of an engine. The north coast shelf is very narrow, maximum width less than 2km. Fishers tend to congregate around reef areas and at shelf drop-off. The south coast shelf is much wider but the lack of an engine limits range as on the north coast.
Motorized canoe (fiberglass or wood)	10km out to sea	North coast shelf is very narrow, maximum width less than 2km. Fishers tend to congregate around reef areas and at shelf drop-off as well as move parallel along the north coast.
Bighead/packerboat (large fiberglass canoes /decked vessels with icebox)	40km out to sea	Majority of bigheads and packerboats are found on the south coast. Those on the north do not tend to fish in as large an area as those on the south but are more likely to move parallel along the north coast.
Motorized canoe (fiberglass or wood)	50km out to sea	Depending on the landing site - ranges from approximately 20-80km with higher range linked to Pedro and Morant Banks fishing. Distance taken as average.
Bighead/packerboat (large fiberglass canoes /decked vessels with icebox)	80km out to sea	Majority of bighead and packerboats do business on the offshore banks. Due to small number of packerboats surveyed (22), these were lumped with bigheads and counted as active fishing boats instead of purely fish storage and transportation vessels.
Source: The fishing model and associated values and assumptions were developed by Nathalie Zenny, TNC Jamaica		

FIGURE 7 The ERS fishing pressure model to capture the distribution of fishing pressures in different coastal marine areas within Jamaican waters. This model used fish landing calculations (Table 8), expert-defined intensity and influence distances, and guiding assumptions based on the ratio of fisher and boat populations (Table 9).



Flow Accumulation of Freshwater Intensity

Coastal marine habitats are highly impacted by run-off and land-based sources of pollution. A flow accumulation model can be used to measure the impact of defined risk elements on freshwater biodiversity by creating a raster model of accumulated risk intensities that flow into each watershed cell. This function requires the user to first specify a flow direction raster model (using a digital elevation model) which indicates the direction water flows on a cell-by-cell basis, starting at higher elevations and ridges moving downward. In order to define a drainage network, the steepest down-slope flow path between each cell is identified between its eight neighbor cells (Schill and Raber, 2008). For the Jamaica example, a 30 x 30 m cell size digital elevation model was used to create the flow direction model which was combined with the freshwater ERS model to create a network of accumulated intensity values assigned to each down slope watershed cell. A point feature was then created for each modeled river outlet and the corresponding total accumulated intensity value was added to each outlet, providing the accumulated upstream intensity value at each river outlet. For incorporation into the marine activities surface, the coastal outlets values were normalized to a 1-10 scale. Figure 8, page 80, shows the location of each coastal outlet and the corresponding accumulated intensity values. Finally, an influence distance of 3 kilometers was applied to each of the points, based on expert opinion, to reflect the approximate distance of the outflow from the coast.

Other Activities and Features

Other human activities and associated risk elements incorporated into the Jamaica ERS models include: dams; water extraction; airports; industrial zones; commercial/industrial ports; cruise ship ports; marinas; sewage outfalls; sewage seepage from latrines; natural areas and invasive species (John, 2006). Table 10, page 81, summarizes the intensities, influence distance and rationales associated with each of those risk elements.

CALCULATING THE COMPOSITE ERS MODELS

Having identified the spatial occurrence of all risk elements and assigned the appropriate intensity and influence distance for each of the three habitat realms, aggregate ERS models were created to summarize environmental risk to terrestrial, freshwater, and marine systems in Jamaica. The ERS tool processes and combines each risk element based on the spatial extent and the user-defined activity class, intensity level, and influence distance. These risk parameters are defined in the GIS feature attribute tables and included in the final calculation of the cumulative ERS model. The user defines the model output cell size and the maximum value and range of the output raster, specifying the function to be used for combining the individual raster layers (*e.g.* SUM, MEAN, MAX, MIN, or any other raster-based function). As another option, the ERS tool also permits the user to specify different weights that can be applied to each individual risk element.

In most cases, the ERS tool uses a standard Euclidian distance function to create a user specified cell size raster output in which each layer contains the value of the straight line distance away from the risk element being evaluated. Values are calculated up to the influence distance limit while cells beyond this distance are coded with NoData values. Next, if the user has specified a non-linear rate of distance decay, that function is applied as a local raster operation, with each cell being evaluated independently. The values in each raster layer are then inverted so that the highest values occur at the immediate border of the risk element and gradually diminish to zero within the limits of the influence distance. All NoData values are then converted to 0 so that the overlay functions will properly calculate these areas.

When the user has specified a constant value as the decay function or an influence distance of zero for a particular risk element, the ERS tool first buffers each vector risk element layer to the specified influence distance, then converts this buffer directly to a raster at the user specified cell size. Areas beyond the influence

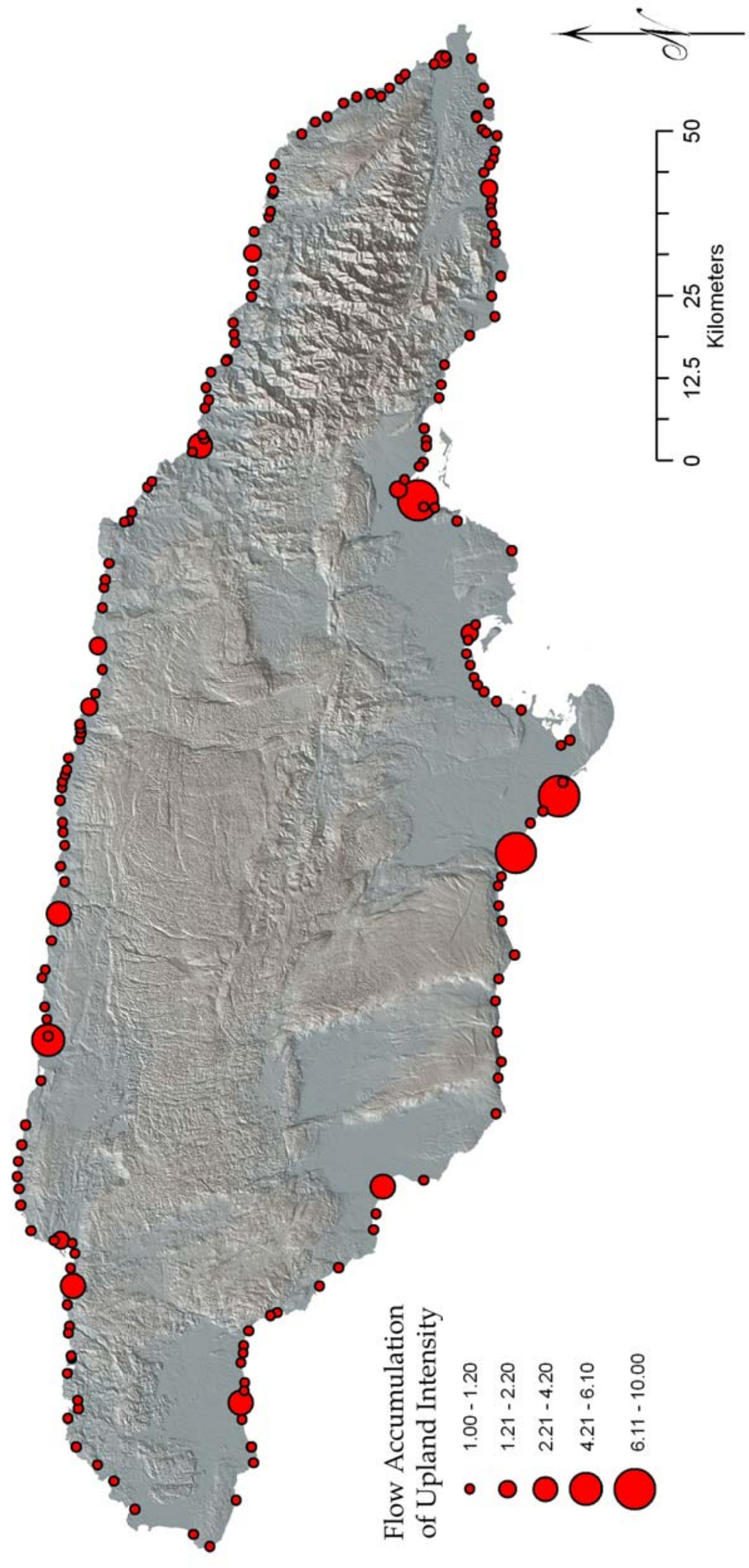


FIGURE 8 Coastal outlet points that represent the accumulated upland risk intensity values (based on flow accumulation models) and were used as input to the marine ERS model.

TABLE 10 Other Activities and Features Incorporated into the Surfaces

Activity/Feature and subclasses	Realm	Intensity	Influence Distance (m)	Rationale
Dams - HEP and other high dams - Irrigation	Freshwater	8 5	30000 30000	Dams alter the habitats, hydrology, longitudinal migration, and facilitates exotic species invasions.
Sewage outfalls (presence)	Freshwater	8	10000	Reduced DO, increased BOD and other toxins, reduced species diversity, and evenness
Sewage seepage - 0-25 pit latrines/km^2 - 25-50 pit latrines/km^2 - 50-500 pit latrines/km^2 - 500-5000 pit latrines/km^2 - >5000 pit latrines/km^2	Freshwater	1 2 4 6 8	500 2000 5000 10000 20000	Reduced DO, increased BOD and other toxins, reduced species diversity, and evenness
Excessive water abstraction - 25-50% of basin total extracted - 50-75% of basin total extracted - 75-100% of basin total extracted - >100% of basin total extracted	Freshwater	3 6 9 10	100 100 100 100	Can disrupt instream flow requirements and hydrology and upstream/ downstream linkages like dams
Cherax quadricarinatus (Australian redclaw)	Freshwater	5	100	Changes substrates, outcompetes native shrimp
Bambusa vulgaris (Bamboo)	Freshwater	5	1000	Changes allochthonous inputs into aquatic systems
Natural Areas	Freshwater	-1	1000	Mitigates deleterious effects
Marinas Number of boats < 40 (v small) >40 <80 (small) >80 (medium)	Marine	*Direct Impact* 5 for all classes *Indirect Impact* 2 for vs and s 3 for medium	*Direct Impact* - 500m for vs and small -700m for medium *Indirect Impact* - 4 km all classes	Direct intensity based on dredging, Docked and anchored boats Indirect intensity attributed to contamination
Coastal industry/ports Manufacturing_industrial Commercial_industrial Bauxite Powerplant Gypsum Cement Oil company Oil refinery Harbour/boat regulation, maintenance	Marine	Range from 2 to 5 depending on the specific port.	3000 or 4000 depending on specific port	Impact related to type of activity, size, volume of activity at port which determines volume of marine contamination
Ports 11 ports included with impact based on number of vessels and tonnage of cargo	Marine	7 (all)	Ranges from 700 to 1500 meters	Impact based on the physical size of the port and dredged area, and others related to impact of ships / e.g. anchorage outside of port
Cruise ship port of calls - Montego Bay/ Freeport - Ocho Rios - Pt. Antonio Ken Wright	Marine	4 4 3	4000 4000 3000	Intensity based on number of calls and number of passengers
Airports Major airports	Marine	5	1000	Effects are sewage pollution, run-off from fueling and maintenance activities; expansion; noise pollution (birds)
Perna viridis (SE Asian green mussel) invasive	Marine	2	(All of Kingston Harbor)	Outcompetes native mussel species and other magrove root prop species

distance are coded 0 and those within the distance are coded the maximum influence distance value.

At this point, each processed raster layer is converted from inverted distance values to scaled intensity values. This is done by multiplying the inverted distance rasters for each element by the intensity level, expressed as a proportion, which provides the final cell values for the output raster. For example, if the risk element has been assigned an intensity value of 85 and an influence distance of 1000 m, the inverted distance raster would contain values ranging from 0–1000. These values would be rescaled to 0–85 in the final raster layer for that risk element. The individual risk element raster layers are then combined according to the user specified overlay function (*e.g.* SUM, MIN, MAX, etc). In the case of all ERS models described in this article, the sum was used to reflect the cumulative intensity of each risk element on the landscape for each respective habitat realm. The final terrestrial, freshwater, and marine ERS models (Figure 9, page 83) were reviewed with experts to ensure that there were not any major anomalies or questions based on a visual inspection of the distribution of human pressures or other risk elements.

RESULTS AND DISCUSSION

Normalized intensity values in the cumulative ERS model can be viewed as the relative conservation cost of conserving biodiversity within each cell, based on the spatial distribution of intensity scores. This interpretation is based on the simple assumption that biodiversity is more likely to persist in the long term in areas with low levels of human pressure and alteration than in areas that demonstrate a high degree of human activity; therefore, conservation efforts in time, labor, and investment will be less (for other recent studies on threat and cost incorporation see Newburn et. al., 2005; Naidoo et. al., 2006; Wilson et. al., 2006; McBride et. al, 2007; Wilson et. al., 2007; Underwood et. al., 2008). Close examination of ERS models can be beneficial when setting up conservation strategies, as overlapping risk elements can be more closely examined and cumulative impacts on biodiversity features observed. GIS-based zonal statistics can be used to summarize the ERS model statistics by conservation planning unit (*e.g.* hexagon, watershed) or habitat polygon. In doing so, planning units can be assigned a mean cost or habitat polygons/lines/points can be ranked by the underlying ERS area-weighted statistics (Schill and Raber, 2008). For example, results of the Jamaica terrestrial ERS model indicated the habitat with the highest mean risk value was dry forest on extrusive bedrock (24.55) and the lowest mean value was premontane forest on intrusive bedrock (3.06). If values are summarized by planning unit, the mean risk value can be used as a cut off point in determining an impact threshold for habitats based on the intensity and influence distances of the aggregated underlying risk elements.

The mean values of the ERS intensity scores can also be used as a cost factor into conservation portfolio design considerations using conservation goal optimization software such as Marxan (Ball and Possingham, 2000; Possingham et al., 2000). Marxan is a portfolio design program that applies an algorithm called “simulated annealing with iterative improvement” to efficiently select sets of areas to meet biodiversity conservation goals. The algorithm attempts to minimize total portfolio cost by selecting the fewest planning units and smallest overall area needed to meet as many goals as possible at the lowest cost. Parameters in Marxan can be adjusted to meet individual country conservation values, allowing for multiple portfolio production and analysis to achieve acceptable conservation results with explicitly defined trade-offs. For the Jamaica Marxan analysis, the combined average intensity value was extracted into hexagonal shaped planning units of 2.5 km^2. Figure 10, page 84, shows the summarized mean intensity (cost) values by hexagon planning unit and the stratification of the island based on the mean intensity value. This provides a good indication of areas that fall above and below the mean risk threshold that could be considered intact or disturbed areas, based on model results. In addition to ranking habitats to their relative risk, protected areas can also be categorized based on the underlying

FIGURE 9 Final ERS models for the terrestrial, freshwater, and marine realms representing the cumulative intensity values for all corresponding risk elements.

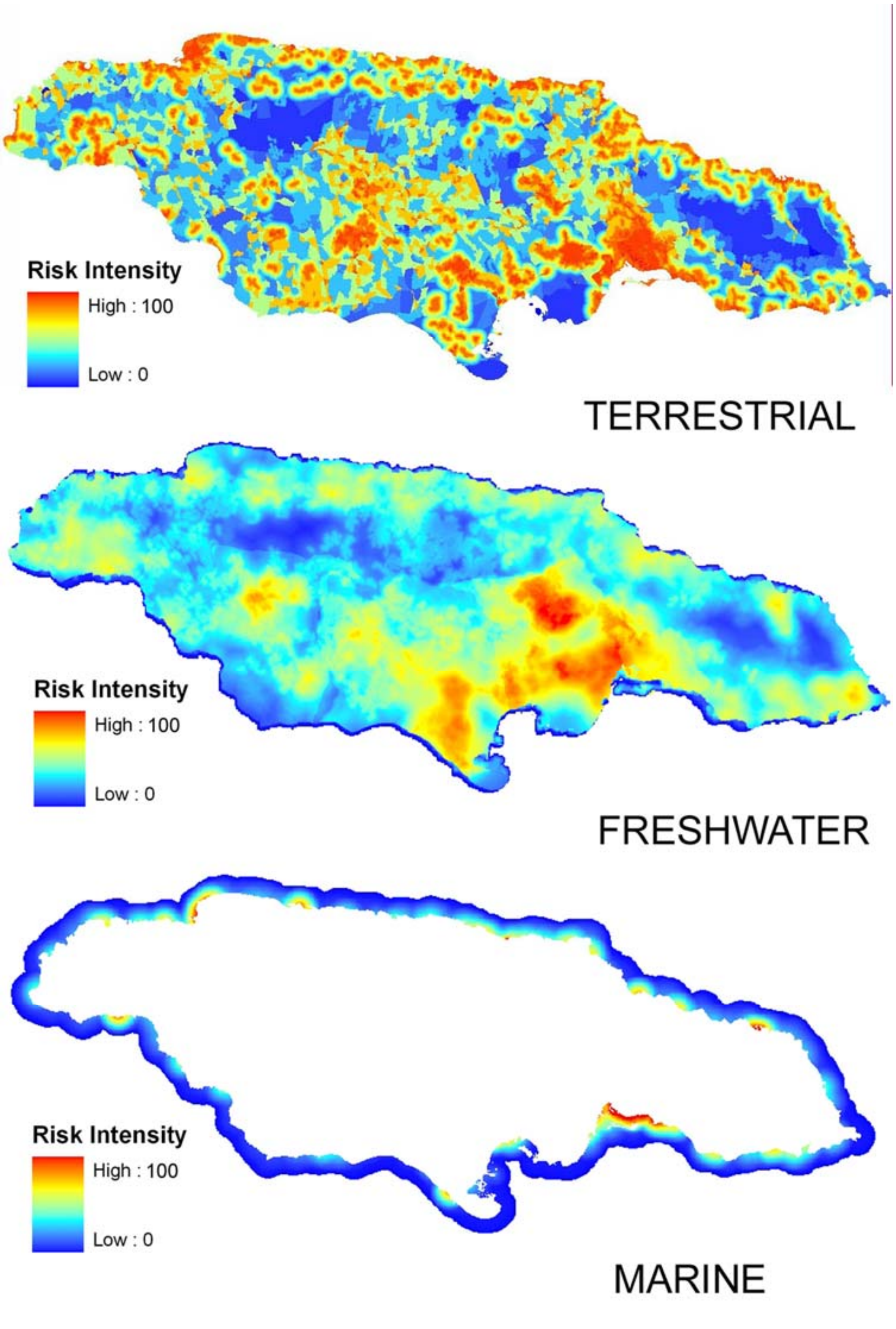
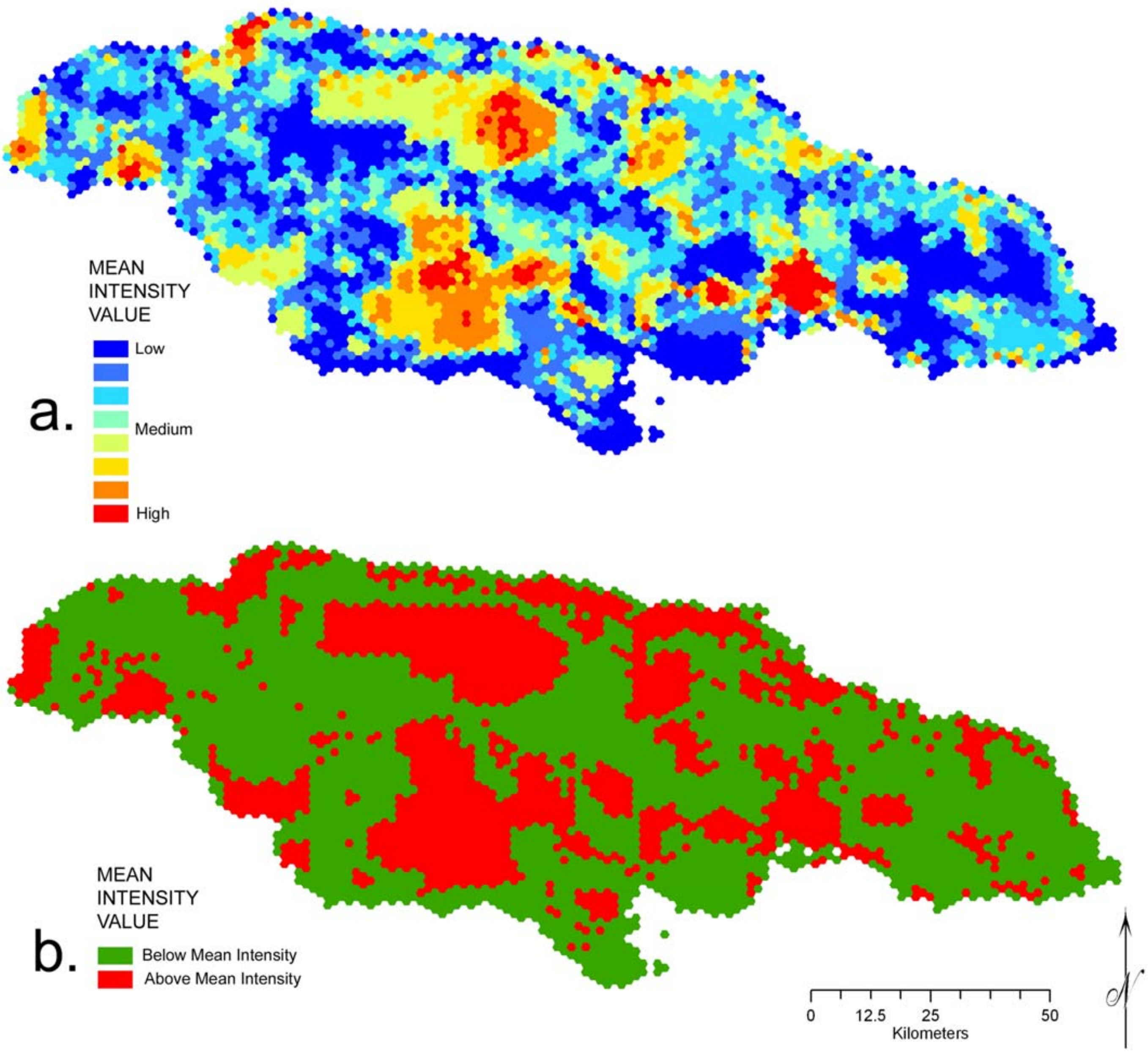


FIGURE 10 Mean intensity (cost) value summarized by hexagon planning unit (a) and the stratification of the island based on the mean intensity value (b). High environmental risk areas are shown in red and low risk in green.



risk model. Table 11 shows a ranking of terrestrial protected areas (not including forest reserves) based on the summarized terrestrial ERS model. The intensity values have been area weighted based on the area size of each protected area. This technique provides conservation planners useful information to further investigate threats to habitats and prioritize strategies to abate these threats within protected areas.

CONCLUSION

ERS models are powerful tools for conservation decision-makers who need to understand spatial interactions of human activities and other factors that influence the health and viability of critical habitats and key species. This approach provides an efficient method to characterize habitat intactness and allow users to identify high-risk areas that can help establish priority conservation areas and inform habitat-specific conservation strategies. Moreover, the ERS model approach can be used to evaluate activities or events that may be threatening habitat health, predict maximum return on conservation investment by spatially documenting risk trends, and incorporating risk information in conservation goal optimization models for building representative networks of conservation areas.

Measuring threats and selecting intensity and influence distance thresholds is not an exact science and is in the early stages of development. For many practitioners, it is a constant struggle to select and justify intensity and distance scores when ranking or aggregating threat data. Careful consideration must be taken when assigning these values, relying heavily on local knowledge of impacts followed by critical expert review. It is useful to convene a workshop of experts who understand the nature of each identified risk element, and who can rank and assign corresponding intensity and influence distance values. Although ranking threats is an emerging field, the analytic hierarchy process (AHP) is a structured technique for dealing with complex decisions and could be used as a defendable way to develop quantitative ranks for risk elements (Wu, 1998). Carr and Zwick (2007) have developed a technique called Land-Use Conflict Identification Strategy (LUCIS) where 'what if'

TABLE 11 Ranking of Terrestrial Protected Areas Based on Summarized Mean Risk Terrestrial Values

Protected Area	Category	Hectares	Mean Intensity	Area-Weighted Score
Coral Spring	Conservation Area	162.956	605.9072	3718
Mason River Savanna	Conservation Area	88.286	62.0826	703
The Great Morass Game Reserve	Game Reserve	1304.525	649.1658	498
Upper Morass Black River	Game Reserve	3150.139	179.2933	57
Palisadoes	Conservation Area	6803.304	293.1705	43
Negril	Environmental Protection	22130.349	685.5235	31
Blue&John Crow Mts.	National Park	49519.328	160.6954	3
Portland Bight	Conservation Area	197306.781	197.5069	1

scenarios are simplified to the point where they can be more easily understood. When conservation planning is concerned, it is important that the cumulative effect of land-use policies be translated into comprehensible assessments of existing ecological integrity, threats and visualizations of the future.

The method presented here is aimed at supporting the conservation process, but the user must always remember that the model output is only as good as the quality of the input data. The rule of “garbage in, garbage out” cannot be emphasized enough. The ERS method can be replicated at any scale and used for a variety of suitability modeling needs; however the user should match the appropriate scale data to the project area and research question. In addition, understanding the potential effects of risk elements on the actual viability of species or ecosystem function is often limited and future research should be directed at investigating these relationships. This understanding will help guide the development of quantitative intensity and influence distance values and help to distinguish between perceived threats and actual negative effects on biodiversity. Sensitivity analysis could also be applied to test the effect of weightings on final outputs. As the ERS tool continues to be refined, it is hoped this new method will make it easier for conservation planners to identify, design, protect, and manage functional landscapes that support all elements of biodiversity and provide insight into minimizing environmental risk to critical habitats and key species.

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