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Exploring scenarios of light pollution from coastal development reaching sea turtle nesting beaches near Cabo Pulmo, Mexico

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ABSTRACT

New coastal development may offer economic benefits to resort builders and even local communities, but these projects can also impact local ecosystems, key wildlife, and the draw for tourists. We explore how light from Cabo Cortés, a proposed coastal development in Baja California Sur, Mexico, may alter natural light cues used by sea turtle hatchlings. We adapt a viewshed approach to model exterior light originating from the resort under plausible zoning scenarios. This spatially explicit information allows stakeholders to evaluate the likely impact of alternative development options. Our model suggests that direct light's ability to reach sea turtle nesting beaches varies greatly by source location and height—with some plausible development scenarios leading to significantly less light pollution than others. Our light pollution maps can enhance decision-making, offering clear guidance on where to avoid elevated lamps or when to recommend lighting restrictions. Communities can use this information to participate in development planning to mitigate ecological, aesthetic and economic impacts from artificial lighting. Though tested in Mexico, our approach and free, open-source software can be applied in other places around the world to better understand and manage the threats of light pollution to sea turtles.

1. Introduction

Declines in sea turtle populations around the world have been linked to various threats posed by humans including habitat degradation and loss, incidental capture, ingestion of plastics, poaching of eggs, and overhunting (Campbell, 2007; Epperly, 2003; Eckert, 1995). Egg-laying female sea turtles exhibit site fidelity, returning to their natal nesting beaches to reproduce (Nichols, 2003). Disturbances from development to critical nesting sites can modify a beach's physical features (e.g., slope, orientation, width) and certain nesting conditions preferred by mothers, including moisture content, temperature, and salinity (López-Castro et al., 2004; Mortimer, 1995; Salmon et al., 1995a). Recent increases in urban

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development near nesting beaches have introduced artificial illumination in places traditionally lacking a large human presence (Kyba et al., 2011; Troy et al., 2011). The ecological consequences of light pollution associated with new coastal development near sea turtle nesting beaches are twofold. First, anthropogenic light can deter nesting females from coming onshore, leading them to choose less ideal locations to lay eggs (Deem et al., 2007; Rich and Longcore, 2005) or to abandon their nesting efforts once started (Witherington and Martin, 2000). More frequently studied and better understood is the potential of artificial light originating from human settlements to disrupt the normal sea-finding behavior of sea turtle hatchlings (e.g., Berry et al., 2013, Karnad et al., 2009, Witherington, 1992).

1.1. *Sea turtle hatchlings*

Sea turtle hatchlings are extremely sensitive to light as they rely on visual cues during the sea-finding process (Kawamura et al., 2009; Salmon, 2003; Mrosovsky and Kingsmill, 1985). Introduction of artificial light presents a serious threat to hatchlings as they typically emerge from their nests and journey towards the ocean at night to avoid opportunistic predators (Salmon et al., 1995b; Witherington et al., 1990). Hatchlings' primary cues are light intensity and horizon elevation. In the absence of artificial light, the horizon over the ocean appears brighter than a landward dune or vegetation because water has a higher albedo than land (Nicholas, 2001). Hatchlings will therefore orient away from the shadows and high silhouettes created by beach vegetation or dunes (Salmon et al., 1992) and towards the lowest and brightest horizon (Limpus and Kamrowski, 2013; Bourgeois et al., 2009; Witherington and Martin, 2000). Newborn sea turtles are also sensitive to a particular range of colors in the visible light spectrum and will preferentially orient to short wavelength and higher intensity lighting from artificial sources (Karnad et al., 2009). Arena trials and field observations indicate that visible point sources and the sheer glow of artificial light can disorient hatchlings and hinder their ability to find the ocean (Limpus and Kamrowski, 2013; Berry et al., 2013; Karnad et al., 2009). When hatchlings that emerge from nests are exposed to artificial light, they experience difficulty aligning with the most direct path to the ocean. A circular pattern of movement with frequent changes in direction has been observed in newborn sea turtles when artificial light is present (Tuxbury and Salmon, 2005; Witherington and Martin, 1996). Even lighting from a distant human settlement can affect turtle orientation because it creates a haze of light (called sky glow) on the horizon that is perceived as similar to the light over the ocean horizon. This artificial illumination of the sky can result in greater mortality among newborns, mainly from exhaustion or dehydration (Deem et al., 2007; Rich and Longcore, 2005; Witherington and Martin, 2000). Studies in Cape Verde and US Gulf of Mexico show that more than half of hatched nests had disoriented newborns when artificial lights from nearby beachfront development spilled into nesting areas (Taylor and Cozens, 2010; Nicholas, 2001). Celestial and atmospheric conditions including the absence of a full moon, dense cloud cover, or higher than normal levels of particulate matter, can amplify artificial light pollution (Kyba et al., 2011; Troy et al., 2013). While different factors can either expand or reduce the reach of ecological light pollution, new urban development near sea turtle nesting areas poses a serious threat to the reproductive success of sea turtles.

1.2. *Sea turtles in Baja California peninsula, Mexico*

Seven species of sea turtles have a near global range throughout the tropics. Many have documented the local importance of these charismatic megafauna in terms of their existence value and as sentinel species (e.g., Finkbeiner, 2009, Aguirre and Lutz, 2004, Burkhalter, 1999). For five species of sea turtles, dating back millions of years, the Baja California peninsula in Mexico has served as an important foraging and development area along with being the northernmost breeding ground for two species (Nichols, 2003). Local threats to nesting sites include poaching of eggs, artificial light pollution, loss of suitable habitat due to coastal development, and longer-term impacts from climate change such as sea level rise and greater wave action (López-Castro et al., 2004). The olive ridley (*Lepidochelys olivacea*) and leatherback (*Dermochelys coriacea*) turtles are two species known to regularly nest on the beaches of the southern portion of the peninsula, Baja California Sur (Nichols, 2003). Both are listed as vulnerable by IUCN (2014) and endangered by the Mexican government's national red list (SEMARNAT, 2010). In just twenty years, from 1980 to 2000, leatherback numbers in the Pacific Ocean have declined by 95% or more (Bjorndal and Jackson, 2003; Spotila et al., 2000). There are more mixed findings from surveys to estimate olive ridley nests along the Baja California peninsula and Central America. At La Escobilla beach in Oaxaca, Mexico, olive ridley nesting has increased dramatically since 1990 when a ban on hunting was announced. Nearly three-quarters of a million nests were recorded during the 1994–1995 season alone (Márquez et al., 1996). This dramatic rebound is evidence of how sea turtle populations can respond to protection. In Baja California Sur, overlap of olive ridley and leatherback nesting occurs from the southern Pacific coast (near Todos Santos) around the East Cape region, which includes Cabo Pulmo Marine Park, and up to La Paz (Fig. 1). Green sea turtles (*Chelonia mydas*) have also been documented to nest along the Baja California peninsula but more sporadically (Nichols, 2003). The nesting season for the olive ridley in Baja California Sur is June to December with peak nesting from August through October (Olguin-Mena, 1990; Márquez et al., 1982). Leatherbacks nest from October through January (Fritts et al., 1982) but may not nest every year in the area (CONANP *per. communication*).

Sea turtles inhabiting the Baja California peninsula are of critical ecological and cultural importance. The recent surge in human activity near foraging and nesting beach areas threatens turtles and their ecological, cultural and economic role in these communities (Finkbeiner, 2009; Campbell, 2007; Nichols, 2006). Ecologically, sea turtles were once the most abundant

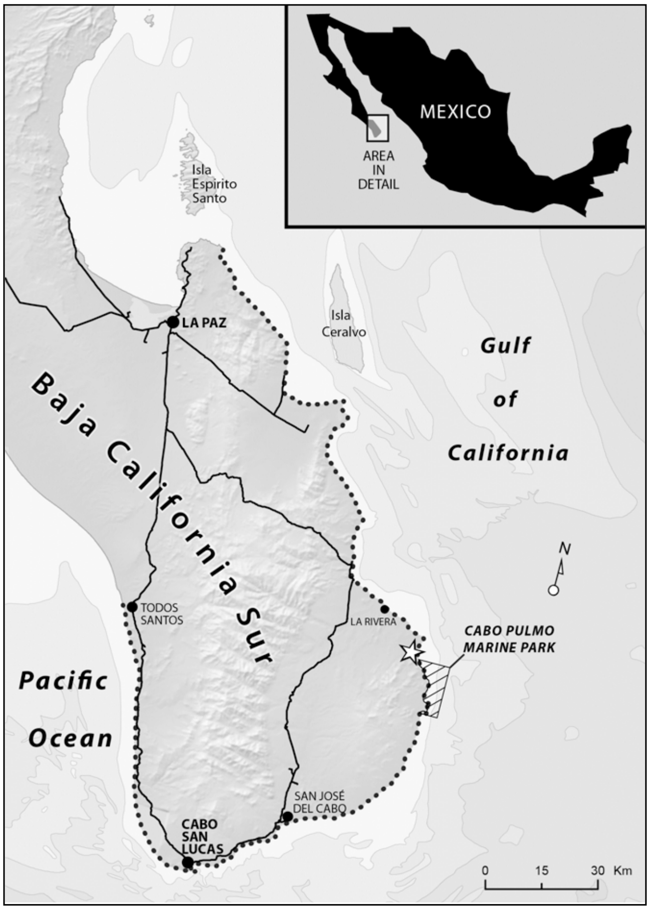

Fig. 1. Map overview of Baja California Sur, including the Cabo Pulmo study area. Overlap of the olive ridley and leatherback nesting range is indicated by the dotted coastline and the proposed mega resort location is denoted by a star.

air-breathing marine vertebrate in the Baja California region. Baja California fisheries relied heavily on sea turtles as a core source of protein for inhabitants and visitors to the peninsula (Nichols, 2003; Garcia-Martinez and Nichols, 2001). Sea turtles have played a crucial historic role in reef community structure (Aguirre and Lutz, 2004; Bjorndal and Jackson, 2003; Nichols, 2003). The region's sea turtles now offer the potential to support local economies through ecotourism and environmental education opportunities.

1.3. Mega resort development near Cabo Pulmo

Cabo Pulmo is a marine park that contains the northernmost coral reef in the east Pacific—a reef approximately 20 000 years old (Natural Resources Defense Council, 2012). Described as one of the most robust marine preserves in the world, it is home to the only living coral reef in the Gulf of California, offering unique biodiversity and an abundant concentration of biomass (Aburto-Oropeza et al., 2011). The park contains over 25% of the area's species of fish, 154 species of marine invertebrates, and 25 species of corals. The reef is the backbone of the region's economy, providing habitat for marine mammals, reef fish, and sea turtles (Natural Resources Defense Council, 2012). The local community around Cabo Pulmo is mainly responsible for preserving this rich diversity of marine life. After decades of overfishing nearly decimated local fish populations, community members chose to halt fishing and protect the reef by requesting that the government declare Cabo Pulmo a 7 111 hectare protected area in 1995. Ten years after the establishment of the park, marine life has increased by about 463% (Aburto-Oropeza et al., 2011). The latest threat to this productive ecosystem is large-scale coastal development including multiple mega-resort proposals. Organizations in Cabo Pulmo are committed to protecting the area and maintaining recent gains in fish stocks and growing the stability of their ecotourism industry (Natural Resources Defense Council, 2010). They seek empirical evidence to better understand how anthropogenic change to the land and seascape will impact ecosystems and their livelihoods.

Hansa Urbana, a Spanish developer, had plans to build a huge resort complex called Cabo Cortés on the east cape of the Baja California peninsula, near the marine park (Fig. 2). While this proposal was rejected by Mexican President Calderón in June 2012, developers continue to pursue similar projects in the area. In the summer of 2012, a new project called Los

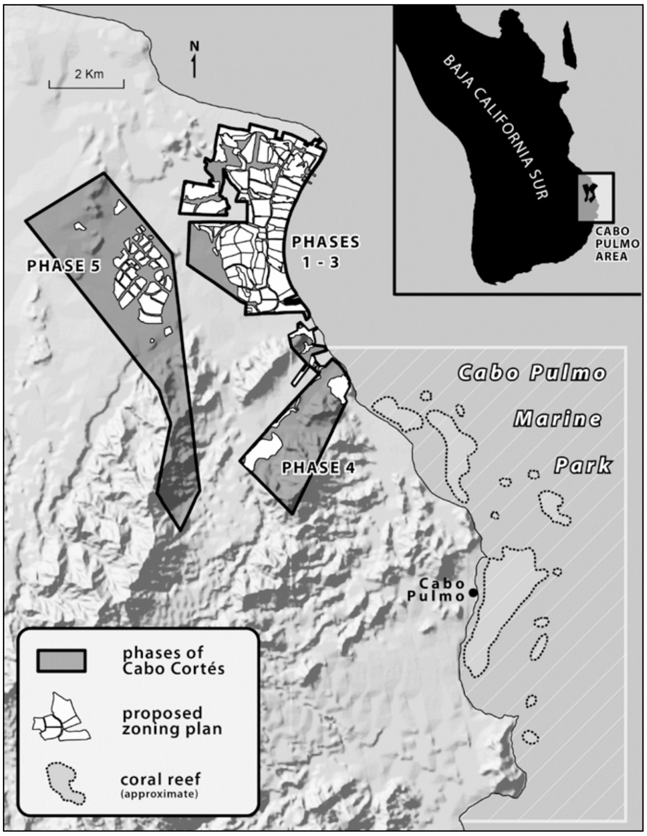

Fig. 2. Five phases and zoning plan for the proposed Cabo Cortés mega resort and its proximity to the Cabo Pulmo National Marine Park (hatched area).

Pericúes was proposed in the same location as Cabo Cortés with only slight modifications to the original Hansa Urbana plan (Herrera, 2012). The original project was proposed in five phases with construction estimated to occur over 40 years. The resort design includes five hotels with over 30 000 rooms, two 27-hole golf courses, a 490-slip marina and private airstrip (Cabo Cortés and Capso Corporativo, 2008). Large-scale development offers new jobs and investments in the Cabo Pulmo area but may also threaten local ecosystems and key wildlife that depend upon them, such as the vulnerable olive ridley and leatherback sea turtles that nest on the shores stretching from Cabo Pulmo to the Cabo Cortés property (Natural Resources Defense Council, 2012).

Here we explore how plausible development scenarios might impact sea turtle nesting. Previous studies have used GIS-based methods to model impacts from artificial lighting on migratory species (e.g., sea birds; Troy et al., 2013). Our analysis incorporates a viewshed tool to map the potential reach and relative intensity of direct light pollution originating from the proposed Cabo Cortés resort. We use the InVEST scenic quality model (Sharp et al., 2014) to assess the relative contribution of exterior lighting from five development phases in reaching nesting areas and highlight the spatial variation of potential light pollution under alternative zoning and height configurations. By documenting this approach in a real case study and providing recommendations for improvement through the incorporation of local knowledge, we offer the community of Cabo Pulmo and others like it with a science-based approach to make more informed coastal development and management decisions.

2. Materials and methods

A combination of location (x, y) and height (z) of an artificial light source determines its reach. We first identify the phase(s) of the Cabo Cortés development plan most likely to reach frequent nesting beaches and then within three "high impact" phases (1, 2, and 3) assess change in the number of observed individual nesting events in 2012 that may be impacted by three offset lighting scenarios.

2.1. Viewshed analysis

Coastal development projects such as Cabo Cortés have the potential to introduce artificial light which can deter sea turtle mothers from choosing suitable nesting locations and disorient their hatchlings. A viewshed approach applied to modeling

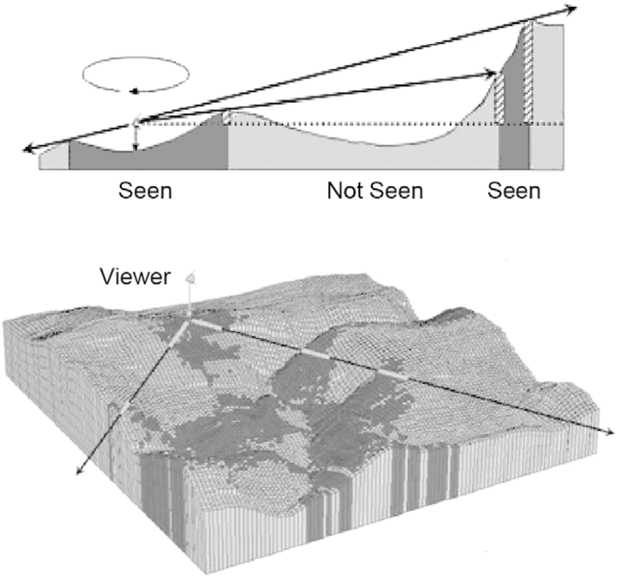

Fig. 3. Diagram of how a viewshed analysis maps visible areas (dark gray) and those not seen (light gray) by incorporating topographic information (*Graphic from Berry, Beyond Mapping Compilation Series*).

Table 1
Core inputs to the InVEST scenic quality model.

Model input	Description
Digital elevation model (DEM)	Three-dimensional representation of a terrain surface
Light sources (points)	Coordinate location of potential exterior lighting
Nesting areas	Areas where sea turtles are known to frequently nest

direct light pollution can help explore how artificial light reaching sensitive nesting beaches may change under different zoning schemes. A typical viewshed analysis implements line of sight calculations as shown in Fig. 3. When determining a viewshed for a given observer, if a straight-line vector can be computed from the viewer's location to a pixel on the landscape that cell is considered to be seen. For this study we used line of sight (viewshed) calculations to highlight areas within the resort that could potentially emit light that penetrates known sea turtle nesting areas. The original version of the InVEST scenic quality model employed a proprietary viewshed tool within the ArcGIS mapping software, developed by Environmental Systems Research Institute (ESRI). More specifics about the ESRI viewshed algorithm and how to use the tool can be found in their online documentation (ESRI, 2011) and the InVEST user's guide for the scenic quality model (Sharp et al., 2014). With the release of InVEST 3.0.1 in May 2014, the scenic quality model no longer requires an ArcGIS license, making this tool open source and free to use. Here we conduct a viewshed analysis to map the reach of direct light pollution originating from exterior lamps while considering topographical features of the landscape that can block the path of light.

Data requirements for the InVEST scenic quality model are basic and the user-friendly interface enables easier access to a non-technical audience (Table 1). First, a digital elevation model (DEM) depicting the landscape topography is required. A spatial resolution of 30-m or less is recommended for this input (USGS, 2006). We conducted a sensitivity analysis and it showed linear artifacts when a coarser resolution DEM was used. Free DEMs with worldwide coverage are available at 30-by-30 m cell size. Bathymetric information (ocean depths) are not necessary since the InVEST scenic quality model will adjust these depth values to zero and assume that light sources on the ocean will be at or above the water level. To produce line of sight calculations the model also requires locations of potential light sources (observer) and nests (observed). We created a uniform point grid of lights within the different phases and zones of development. The model then computes line of sight measurements to identify areas within the resort where direct light can reach turtle nesting beaches.

2.2. Data acquisition and preparation

We acquired two sea turtle nesting datasets near the proposed resort, (a) *frequent nesting areas*, two stretches of coastline, each about 2 km in length, where monitors consistently find high nesting density and adult females laying eggs year after year and (b) 67 GPS coordinates representing locations of individual nesting events from the year 2012 that together comprise six distinct *nest sites*. Campamento Tortuguero Parque Nacional Cabo Pulmo, BCS (CONANP) generously provided these data with the understanding that we would refrain from marking exact nest locations in this article. All frequent

Table 2
The three InVEST scenic quality model input parameters for a light source.

Input parameters	Description
Configuration	Arrangement of light sources (phases 1 through 5)
Height	Offset of light source relative to ground
Outer radius	Farthest documented distance that artificial light illuminates the horizon

nesting areas and nest sites collected in 2012 are situated along the shoreline of Cabo Pulmo National Marine Park. Given that these high nesting density areas represent the northern and southernmost extents of these two datasets and overlap with three of the six nest sites, we are confident that the 2012 dataset is representative of typical nesting activities within the last few years.

In order to explore different exterior lighting scenarios, we georeferenced a map of the Cabo Cortés Master Plan and digitized using ESRI's ArcMap software. This map shows the locations of different phases of the resort as well as the proposed zoning configuration, including commercial, residential, recreation and undetermined. Table 2 summarizes the different input parameters of the model for each potential light source. We first used the viewshed tool to identify the percentage of area within the five proposed development phases that will reach frequent nesting areas if exterior lights are present. We then focused on impacts to individual 2012 nests based on alternative height scenarios for outdoor lighting.

Outputs from the model identify which areas within the proposed phases of development can reach nesting areas with outdoor lamps. The farthest straight-line distance between any phase of the Cabo Cortés resort and nesting location is 21.5 km. However, both frequent nesting areas and all six 2012 nest sites are no more than 10.5 km from the closest phase of the proposed resort. Safina (2006) observed that ambient light pollution originating from Boca Raton, Florida illuminates clouds near sea turtle nesting beaches as far as 32 km away from the city. We set this distance as the outer limit for which artificial light can negatively impact sea turtle hatchlings. Since all Cabo Pulmo nesting beaches are less than 11 km from the proposed resort, we highlighted proximal development areas since they are more likely to disorient hatchlings with higher-intensity light pollution.

We also explored three height scenarios for exterior lighting to determine if existing hills or dunes obstruct the direct path of potential light pollution. Scenario A (1 m) assumes a light source at 1-m height while B (10 m) and C (25 m) assume this offset height to be 10- and 25-m, respectively. This difference across scenarios can quantify any increase in the percentage of 2012 nest sites impacted by areas using elevated lighting such as residential high-rise or golf courses. A comparison of light penetration based on different offset heights can support recommendation on where to avoid elevated lamps (e.g., a fixture anchored to the balcony of a hotel at 25-m offset height). Finally, we summarized the potential reach of light pollution originating from different zoning categories to hone in on areas where shields and other lighting restrictions can mitigate impacts on nesting females and their hatchlings.

3. Results

Viewshed outputs show that exterior lights within the boundaries of phases 1, 2 and 3 have the greatest likelihood of emitting light that reaches frequent nesting areas and 2012 nest sites, regardless of source height. The percentage of a uniform 30-m grid of lights positioned within phases 1–3 capable of penetrating at least one of the two frequent nesting areas starts at 47% when lamps are 1 m high and expands to almost 75% for lights elevated 25 m off the ground. There is only a modest increase in areas within phase 4 that reach frequent nesting areas if lamps are elevated to 10- or 25-m offsets. Most exterior lamps sited within phases 4 and 5 are unlikely to reach nesting beaches regardless of height because phase 5 is farther inland and both are positioned behind elevated terrain. Table 3 summarizes our initial screening to determine the reach of exterior lighting sited evenly throughout the different phases. We used frequent nesting area data here as the analysis unit to give a sense for how general it might be as nesting changes from year to year. Given their overlap and qualitatively similar results to frequent nesting areas, we used the 67 individual nest locations collected in 2012 (herein referred to as "2012 nests") as our unit of analysis to explore impacts from the proposed zoning configuration for Cabo Cortés and across alternative lighting height scenarios.

Zone-specific impacts originating from within phases 1–3 indicate that undetermined areas, followed by recreational and residential, are least likely to reach 2012 nests regardless of offset height. Areas designated for residential and recreational activities can reach almost twice as many 2012 nests, however, when exterior lamps are elevated from 1 to 25 m. Lights positioned within the proposed commercial zone penetrate the most nest sites on average (Fig. 4(E)). If resort plans for commercial activities remain unchanged, the additional impact from elevated lighting on 2012 nests will be far less than the other three zoning types. Fig. 4(A)–(C) maps the percentage of 2012 nests reached by exterior lighting at 1-, 10- and 25-m offsets. Model results summarized by zoning categories represent another screening approach to hone in on individual zones that contribute most to light pollution when lamps are elevated. The potential of artificial light pollution to disorient hatchlings is partially a function of the distance between the light source and a nest. Therefore, we include a distance overlay in Fig. 4(D) to highlight areas where higher intensity light pollution is likely to originate. Within the southernmost portion of phases 1–3 and closest to frequent nesting areas in Cabo Pulmo National Park we find substantial variation in light pollution impacts across our three height scenarios.

Table 3
Percentage of total area within each phase of the proposed Cabo Cortés resort where exterior light at 1-, 10- and 25-m heights reaches at least one of the frequent nesting areas along the shores of Cabo Pulmo Marine Park.

Height scenario	Phases 1–3 (%)	Phase 4 (%)	Phase 5 (%)
A (1 m)	47.0	9.6	0.0
B (10 m)	70.0	14.1	0.0
C (25 m)	74.1	20.9	0.2

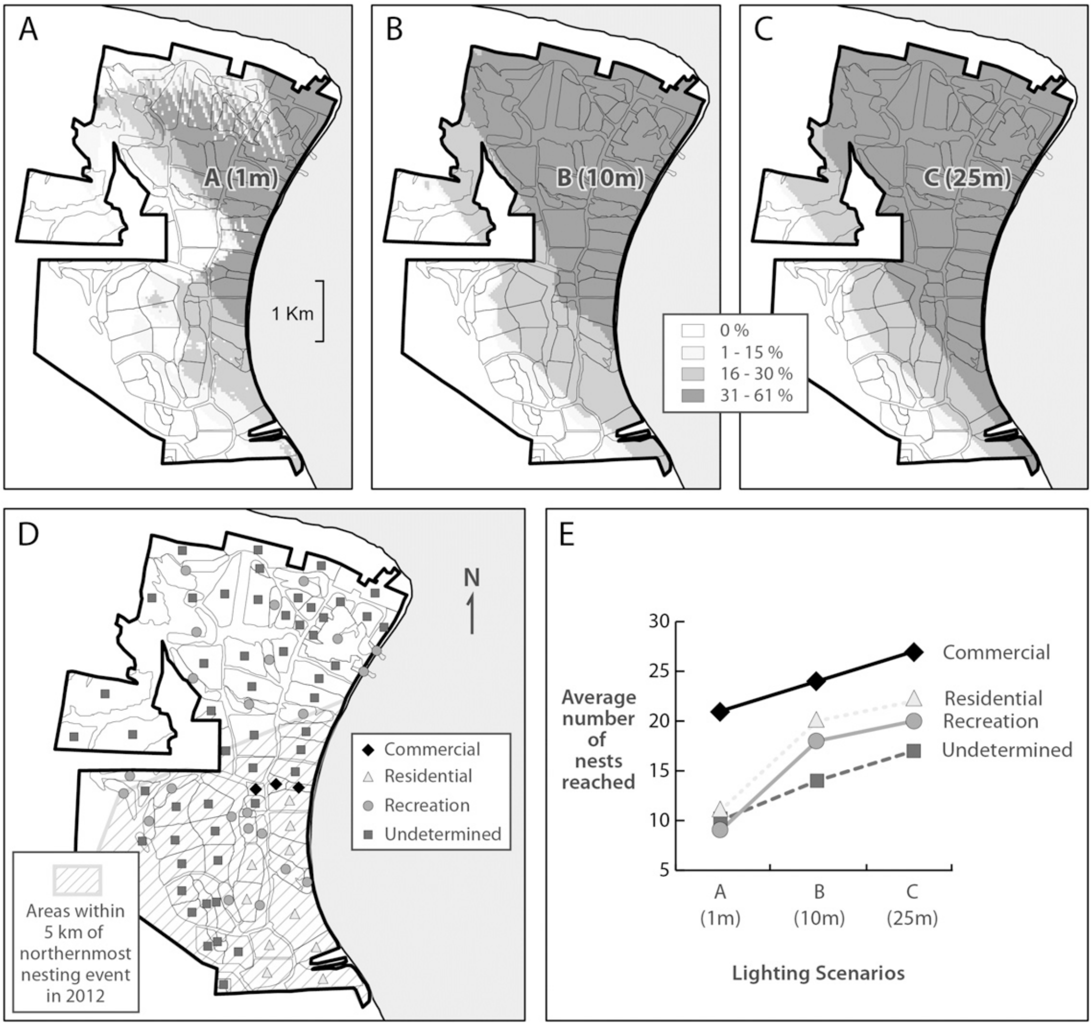

Fig. 4. (A)–(C) Percentage of observed nesting events in the year 2012 (67 nests total) that are determined by our model to be reached under the A (1 m), B (10 m), and C (25 m) offset height scenarios, (D) map of four zoning types and their proximity to 2012 nests, and (E) average number of 2012 nests reached by each zoning category. All results model lighting within proposed phases 1–3 of the Cabo Cortés Master Plan.

When mapping the percent increase in 2012 nests reached by the C (25 m) versus A (1 m) offset height scenarios, the highest impact areas are found within coastal residential, inland recreational and undetermined zones. In these distinct pockets of the southernmost section of phases 1–3, residential high-rises and hotels can reach 11 to 30 additional 2012 nests with elevated lighting. We also observe higher impact areas along inland recreational areas that could include tall lamps for illuminating a golf course. By quantifying this change in number of nests impacted, we identify hotspots where elevated lighting will have the greatest addition impact. It is important to interpret these results carefully as a percent increase map does not tell the entire story of the reach of light pollution. For example, areas where a light reaches half the 67 individual nesting events, regardless of source height, will show no change in Fig. 5. Instead, this change map serves to identify areas where if exterior lighting must be sited, then it will be least impactful to nesting sea turtle mothers and their hatchlings if positioned low to the ground.

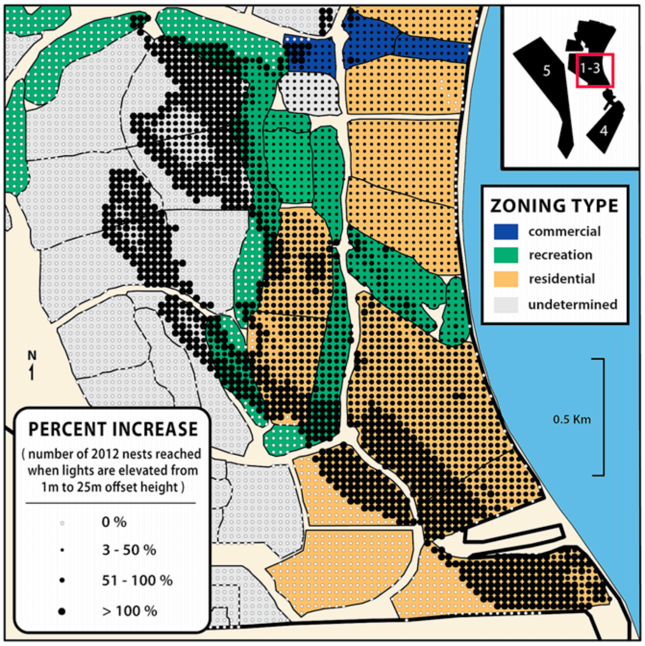

Fig. 5. Percent increase in the number of 2012 nests reached under the 1- and 25-m offset height scenarios; percent increase is symbolized using graduated dot symbols and background colors indicate the proposed zoning configuration for Cabo Cortés. Lights positioned within this southern section of phases 1–3 range in distance from 3 to 10 km away from the northernmost frequent nesting area in Cabo Pulmo National Park.

4. Discussion

We conducted a GIS-based viewshed analysis to map line of sight light pollution and demonstrate how resort managers, planners and local communities can use a simple framework to mitigate light pollution impacts on sea turtles. The data input requirements for our model are basic and methods can easily be replicated worldwide. By combining details from a proposed resort development (e.g., zoning plan) with globally-available elevation data and the location of nesting beaches, planners can coordinate with resort managers, community members and other stakeholders to produce new knowledge and enhance communication. Spatially explicit information produced by our tool offers the Cabo Pulmo community – and others wrestling with light pollution – new scientific evidence to help inform decisions. Given that the relative reach of lamps positioned within phases 1–3 is the greatest, considerations for lighting restrictions should focus on these phases. Our results in the southernmost section of phases 1–3 identify areas of the undetermined and recreation zoning where restrictions on elevated lighting can reduce impacts on 2012 nest sites (largest dot symbol in Fig. 5). More informed decisions on where to build high-rise residential for visitors seeking dramatic ocean views are possible if light pollution maps are in the hands of planners, developers and resort managers. By incorporating these and other relevant findings into development plans, it is possible to better manage outdoor lighting and mitigate this particular threat to sea turtle reproductive success.

4.1. Improving elevation input data

While this article describes the application of a simple tool to map direct light pollution, there are some limitations to our use of the model in this context. These challenges are mainly due to the paucity of high resolution elevation data available for this study area and our intent to use a free, globally-available elevation survey to demonstrate an approach that can be used worldwide. They do not, however, eliminate or discredit our findings. Our input DEM does not account for trees, buildings, or structures that can block or modify the path of light, thus overestimating the reach of anthropogenic light. When quantifying change in individual 2012 nests impacted by different height scenarios we assume that no other buildings exist between the elevated light source and nesting beaches. Thus, our analysis provides a "worst case" scenario for direct light pollution from each of the development phases explored. We believe it appropriate to use the "worst case" scenario for this analysis because it serves as a starting place from which to explore potential mitigation options including the addition of structures or vegetation. Site visits may reveal the presence of previously undetected objects like trees that can obstruct the path of artificial light. Inputs to a viewshed analysis can be iteratively improved through stakeholder consultations allowing users to adjust the DEM based on local knowledge. Higher-resolution elevation surveys such as aerial radar sensors or LiDAR can improve globally-available DEMs, which typically only include surface heights (e.g., top of a tree canopy or building). Detailed elevation surveys that map canopy structure or building geometry by collecting multiple laser returns are expensive to acquire. While the cost of commissioning a LiDAR flight can be millions of US dollars, new technological advances in unmanned aerial vehicles (UAV) show promise in significantly lowering this cost. Future analyses using our model could supplement global DEMs with surveys indicating the locations of buildings, vegetation, and dunes to more accurately model how these features obstruct the path of anthropogenic light. Other mitigating factors such as the length of nesting and hatching seasons, timing of hatchling emergence (e.g. during full moon they are less effected by artificial light, Berry et al., 2013) as well as longer-term climate impacts from changes in temperature, humidity, and beach slope (López-Castro et al., 2004) were not considered in this study.

4.2. Management of light pollution

Light pollution can be managed through smart design and development techniques. Because of natural and man-made features dotting the landscape, where you position outdoor lamps makes a huge difference as to the reach of light pollution. Outdoor lighting techniques used by cities and resorts often produce ambient light pollution (sky glow), where less than half the light released strikes the intended illumination surface (Illinois Coalition for Responsible Outdoor Lighting, 2008; Rich and Longcore, 2005). There are, however, various light management options for resort operators including designated lighting requirements, installation of fixtures with shields, timers and motion-detectors, and adjusting lamp heights or angles. By exploring the relative reach of exterior lighting at different heights, stakeholders can also identify alternative zoning configurations to reduce direct light pollution. Resort planners and managers can use this viewshed approach to make more informed decisions on where to focus enforcement of shielding requirements, operational restrictions (e.g., seasonal shutdowns), or install longer wavelength and low wattage light fixtures. Light pollution maps combined with information on the timing of local sea turtle nesting seasons can serve to hone in on the highest impact development areas and guide developers as to where construction should not be permitted. Finally, architects and engineers can use our tool to make the case for introducing or restoring beach vegetation, an effective barrier to artificial light when at least 50 m away from the high tide line (Karnad et al., 2009), or proposing modifications to a beach profile so the lowest angle of elevation is in the direction of the ocean.

By classifying phases 1–3 into two distance ranges we begin to explore potential variation in light pollution intensity based on distance decay. This offers stakeholders an indication of areas where exterior lamps are most likely to disorient hatchlings. It is possible that our model also underestimates the reach of ambient light pollution that originates from the resort, becomes trapped in the atmosphere, and as a result illuminates the distant sky. Although not incorporated in this analysis, accounting for local atmospheric conditions such as dense cloud cover or sudden increases in particulate matter that trap ambient light is possible with our tool. Here we set 32 km as the maximum threshold distance (outer radius) from nesting beaches to an exterior light source considered to negatively impact hatchlings. Local observations of sky glow produced by a distant light source using a similar fixture type as the resort could be used to justify an increase or decrease in this outer radius. While line of sight calculations can accurately estimate the direct pathways of light, further research is needed to better understand ambient light pollution especially under varying atmospheric conditions like fog, mist, or moisture. Together these limitations underscore the importance of consultations with engineers, surveyors, and other experts to better characterize the different sources of light, landscape, and atmospheric conditions of the study area.

The primary concern among local conservation groups opposed to Cabo Cortés is its proximity to Cabo Pulmo National Park and the lack of consensus among stakeholders regarding the resort's potential environmental impact (Natural Resources Defense Council, 2012). Poorly designed and managed development can threaten Cabo Pulmo's significant environmental assets through the discharge of pollutants, nutrient release, sedimentation from construction and dredging, and desalination plant brine (Natural Resources Defense Council, 2012). A 2012 study found seasonal variability in the direction of currents within the Gulf of California and that winds from the northwest, especially in the winter and spring, could push pollutants originating from the resort to the Cabo Pulmo reef in as quickly as one hour (Castro et al., 2012). This counters a claim that runoff and other pollution from the proposed resort do not present a risk to the reef directly to the south because the prevailing currents flow northward (Cabo Cortés and Capso Corporativo, 2008; Natural Resources Defense Council, 2012). Light pollution from coastal development can be mitigated using smart spatial analysis and stakeholder involvement. Artificial light pollution, however, is just one of many social and environmental threats a new urban center could bring to an area with historically low population density. Nichols' "conservation mosaic" (2006, 2003) emphasizes the importance of integrating science with community-based initiatives to bring together a diverse range of stakeholders and opinions. Community efforts to establish this network in the Baja California peninsula have led to reductions in poaching and turtle bycatch along with greater local enforcement and government support (Nichols, 2006). New analyses in Cabo Pulmo studying a range of different impacts to this local ecosystem, and how they may or may not be mitigated, need to be put together in order to make a decision on whether a resort should be built.

5. Conclusion

The potential economic benefits from tourism and other activities supported by new resorts are substantial. However, coastal development that is not well planned can result in many negative externalities. Smart management can promote long-term sustainability and the balancing of multiple objectives. Here we focus on one factor known to influence sea turtle nesting site selection and hatchling survival. We offer a simple tool that can mitigate the unintended consequences of artificial light pollution created by coastal resorts. In this context, our method can provide a useful tool to developers in Cabo Pulmo for planning and management of resorts and other development near sea turtle nesting beaches.

Many local people seek better approaches to identifying and managing threats to critical ecosystems and species. The adoption of our tool has significant implications for conservation in Cabo Pulmo and throughout the world. The empowerment of communities with science-based tools offers the opportunity to enhance decision-making. Scientific evidence produced by local communities has the power to change decisions on how we balance development goals while preserving natural capital. It begins with engagement and then knowledge generation among a diverse set of stakeholders including developers, engineers, resort managers, and local citizens. Spatial information produced by our model can facilitate compromise and cooperation even among actors with opposing interests and viewpoints. This shared knowledge and understanding can serve to protect sea turtles while maintaining tourism and recreation benefits for businesses and local communities.

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