ATTACHMENT C: Public Comments and Responses

CITY OF SANTA CRUZ

SANTA CRUZ WHARF MASTER PLAN

Mitigated Negative Declaration / Initial Study

STATE CLEARINGHOUSE NUMBER 2016032038

Public Comments and Responses
Mitigation Monitoring and Reporting Program

August 4, 2016

CONTENTS:

I. INTRODUCTION

An Initial Study and Mitigated Negative Declaration (IS/MND) were prepared and circulated for a 30-day public review period from March 14 through April 12, 2016. The California State Clearinghouse (Governor's Office of Planning and Research) sent a letter to the City upon the close of the public review period to indicate that the City had complied with the State's environmental review process and that no state agencies submitted comments to the Clearinghouse. Comments were received by the City from the agencies and individuals listed below. The comment letters are included in ATTACHMENT A.

- California Coastal Commission
- California Department of Fish and Wildlife
- Monterey Bay Unified Air Pollution Control District (No Comments)
- Lu Erickson
- Gillian Greensite
- Mary McGranahan
- Reed Searle

Environmental issues raised in the submitted comments are summarized in Section III. The California State CEQA Guidelines (section 15074) do not require preparation of written responses to comments on a Mitigated Negative Declaration, but requires the decision-making body of the lead agency to consider the Mitigated Negative Declaration together with any comments received during the public review process. However, Section IV provides responses to comments regarding environmental analyses in the IS/MND. Minor revisions and/or corrections to the Initial Study as result of review of the IS/MND comments are provided in the following Section II.

II. INITIAL STUDY REVISIONS AND CORRECTIONS

Page 60 Biological Resources. Add the following before the Impact Analysis paragraph.

Fully Protected Species. The California Legislature has designated “fully protected” or “protected” species as those which, with limited exceptions, may not be taken or possessed under any circumstances. Species designated as fully protected or protected may or may not be listed as endangered or threatened. The classification of fully protected was the State of California’s initial effort in the 1960s to identify and provide additional protection to those animals that were rare or faced possible extinction. Lists for fish, amphibians and reptiles, birds, and mammals were created at this time. Most fully protected species were later listed as threatened or endangered species under more recent endangered species laws and regulations. Fully Protected species may not be taken or possessed at any time, and no licenses or permits may be issued for their take, except as a “covered species” pursuant to a Natural Community Conservation Plan (NCCP) developed under the Natural Community Conservation Planning Act.

The CDFW indicates that fully protected marine species in the Wharf area include: the Southern Sea Otter (*Enhydra lutris nereis*), Northern Elephant Seal (*Miroinga angustirostris*), Brown Pelican (*Pelecanus occidentalis californicus*), California Clapper Rail (*Rallus longirostris obsoletus*), and the California Least Tern (*Sterna antillarum browni*). The northern elephant seal moves throughout Monterey Bay during the migration to and from their breeding grounds.

Page 61 Add the following new (underlined) text to the second to the last paragraph:

The following discussion addresses: 1) impacts to benthic habitat with additional piles and during installation; 2) potential acoustical impacts to fish and marine mammals due to installation of piles; and 3) potential water quality impacts on fish due to potential leaching of treated wood piles. Future construction of projects recommended in the Wharf Master Plan, including installation of piles, would have no effect on habitat of fully protected species. Indirect impacts related to pile driving are addressed below, including marine mammals. The project would not result in take or possession of any fully protected species.

III. SUMMARY OF COMMENTS

California Coastal Commission (CCC): The letter indicates that as a whole, the Wharf Master Plan entails substantial public access improvements in accordance with Coastal Act policies and that CCC staff is supportive of the Plan. Support of the proposed stormwater improvements also is stated and that, overall, the Master Plan appears to be consistent with Coastal Act policies regarding water quality. Comments regarding environmental issues addressed in the Initial Study include potential impacts to the Westside Walkway due to sea level rise and coastal storms, visual impacts of the new entry gate and sign, and water quality issues related to use of treated piles. Responses are provided in Section IV below. The letter indicates that processing a Public Works Plan (PWP) as set forth in the Coastal Act and adopted by the Commission is an appropriate and efficient means of implementing coastal permitting requirements for the Wharf Master Plan. Due to location of the Wharf on public trust lands, any additional coverage of public trust land must be minimized and used for public access and recreational purposes and improvements only. The comments also address some of the project features and design, such as the relocated entry design, the western walkway, Wharf hours, use of oil/grease collection in the stormwater improvements, and location of commercial infill.

California Department of Fish and Wildlife (CDFW): Comments regarding environmental issues addressed in the Initial Study include adding a discussion of potential impacts to fully protected species, impacts to fish and marine mammals from pile installation, wood pile treatment and coating, and potential oil spills from equipment during pile driving. Responses are provided in Section IV below.

Monterey Bay Unified Air Pollution Control District (MBUAPCD): The MBUAPD letter did not address the IS/MND, but noted that project components such as shuttles may be eligible for grant funding, that the relocation of the pay station would minimize traffic congestion, and that removal of any old pipes that contain asbestos would be subject to compliance with Air District rules. There are no pipes with asbestos at the Wharf. Given the nearby proximity of pedestrians, the Air District recommends using cleaner construction equipment that conform to ARB's Tier 3 or Tier 4 emission standards, and whenever feasible, use alternative fuels such as compressed natural gas (CNG), propane, electricity or biodiesel for construction equipment.

Lu Erickson: The email comment letter did not address the IS/MND, but expressed concern on a new tall building at the end of the Wharf and that the Wharf should be left as it is.

Gillian Greensite: Comments regarding environmental issues addressed in the Initial Study include aesthetics (scenic views and lighting), impacts to biological resources (marine mammals and birds), cultural resources, and traffic; responses are provided in Section IV below. The comment suggests that expansion of kayaking and boat rentals will result in increased harassment of marine mammals. This is not an environmental issue that requires review under CEQA. However, the Wharf Master Plan does not propose expansion of kayak or boat rental facilities. The letter also suggests that provision of additional parking will result in narrow parking stalls. This is not necessarily the case as reorienting parking from 60% to 90% parking is more efficient and can achieve a ten percent increase in parking spaces. This kind of redesign can also provide improved circulation in a parking facility. The East Promenade site plans show the parking space width to be essentially the same with a very slight reduction in width.

Mary McGranahan: Comments were raised regarding the project, including additional visitors to the Wharf and building heights. Comments regarding environmental issues addressed in the Initial Study include aesthetics and traffic; responses are provided in Section IV below.

Reed Searle: Comments were raised regarding the project, including whether there should be changes to the Wharf, consideration of alternatives in the Master Plan, as well as social and economic concerns, i.e., displacement of tenants, that are not required to be analyzed under CEQA. Comments regarding environmental issues addressed in the Initial Study include aesthetics and traffic; responses are provided in Section IV below. The comment references considerations listed on page 3 of the Initial Study and states that the MND does not cover these. The referenced citation is to an existing City policy that calls for preparation of a comprehensive study of the Wharf, which the Wharf Master Plan provides.

IV. RESPONSES TO ENVIRONMENTAL COMMENTS

The following section provides responses to those comments regarding the environmental issues or analyses in the Mitigated Negative Declaration/Initial Study.

1. **Project Description.** Comments from CCC staff request clarification of whether the anticipated increase in commercial space entails any expansion of the existing commercial footprint. As discussed on page 17 of the IS/MND, the Master Plan identifies two areas of potential expansion of existing buildings that could result in a building increase of approximately 4,000 square; one of the locations is schematically shown on Figure 2-5C. As further described on page 17, the Master Plan encourages the development of second floors for uses such as rooftop dining within existing developed structures. The Plan provides a preliminary estimate that potential remodels and intensification within the existing commercial building footprint could result in a 20-30% increase in building space separate from the three new buildings. This would be approximately 12,000-18,000 square feet based on the existing approximate 60,000 square of buildings on the Wharf and would include the above specific infill locations. The Master Plan does not propose specific locations for potential intensification other than the two locations identified above, nor is it known when such expansion and intensification may occur.

2. **Aesthetics.**

   - Relocated Entry. The Coastal Commission letter states concern with the visual impacts of the relocated entry gate height and future sign to the adjacent areas including to and from Cowell and Main Beaches. CCC staff recommends reducing the bulk and scale of the proposed entryway and sign and suggest reducing the gate's width so that it does not completely close off pedestrian access to the Wharf. Concerns are further expressed regarding the character of a new entrance sign and that the sign should be designed to highlight the historical significance of the Wharf. As explained on pages 46-47 of the IS/MND, the entry gate height of 18 feet is less than the height of existing 22-foot tall light fixtures on the Wharf. The gate frame depth would be relatively narrow, and the structure would be transparent as shown on the elevation on Figure 3-1C. The general width and height are shown on Figure 4-2. The structure would not visually appear massive or bulky given the limited frame and roll-down gate features as seen from distant vantage points nor would the height be out of scale with overall existing heights of buildings and fixtures on the Wharf.

From either the Main Beach or Cowell Beach, the entry gate will have a slim appearance and will be transparent and would be at a height slightly below the existing light poles on the Wharf. A future sign on top of the entry gate would extend above the existing light poles depending on the ultimate design that is selected. With other development surrounding the beaches, including the Boardwalk and multiple hotels, an aesthetically designed sign would not result in degradation of the visual quality of the surrounding area given the extent and scale of surrounding development.

As indicated in the IS/MND, the entrance sign has not been designed and would be subject to additional review once designs are developed to ensure that the sign is compatible with the surrounding area. CCC staff suggests a natural design and rustic materials that blends with the overall aesthetic of the Wharf rather than a "modern, highly embellished sign" and the comment is noted. CCC staff's suggestion to reduce the gate width to allow pedestrian access is not related to an environmental issue, but the comment is noted.

It is also noted that the letter states that "the Coastal Act requires that all new development (in this case the sign, gate, and entryway) honors the unique character, history, and aesthetic of the Wharf." It appears that the reference is Coastal Act policy 30253(e) that requires new development to "where appropriate, protect special communities and neighborhoods that, because of their unique characteristics, are popular destination points for recreational uses." However, neither the entry gate nor the future sign would diminish the surrounding area that is characterized by significant recreational uses and commercial development including the Santa Cruz Beach Boardwalk.

- ❒ Impacts to Scenic Views and Surrounding Areas Due to Building Heights. One comment questions the impact on scenic vistas due to construction of three new buildings and states that the new buildings will significantly block scenic vistas. Locations of new buildings are noted on photos shown on Figure 4-1 that depict views from both East Cliff and West Cliff Drives. As discussed on pages 41-44, new and infill structures would not obscure or change the prominent views of the bay that are visible in the foreground and to the south of the Wharf from vantage points along West Cliff Drive . From this vantage point, the Wharf, Boardwalk and distant mountains are prominent features in views from West Cliff Drive. At some viewpoints along East Cliff Drive, new structural development would slightly obscure distant views of the Lighthouse at Lighthouse Field due to construction of the proposed Events Pavilion. However, the distant view of the Lighthouse would be potentially blocked from a very limited viewpoint, and distant views of the Lighthouse would remain available at other locations along East Cliff Drive and in the surrounding area. Therefore, this is not be considered a substantial change as the predominant ocean views in front of the Wharf are the dominant feature of the scenic views in this location, which would not be altered.

Two other comments question building heights. As discussed on pages 41-42, the three new buildings may be up to 45 feet in height and expansion of existing buildings could be constructed up to 35 feet in height according to the Design Standards included in the Wharf Master Plan. These heights are consistent with existing zoning regulations that allow a 40-foot height in the CB zone, and an additional 20% increase in height with approval of a Planned Development Permit. Future development supported by the Wharf Master Plan would slightly increase overall structural height and massing, but would be located in areas of existing structural development and heights would be consistent with existing zoning requirements. Furthermore, the three new buildings are relatively small for commercial buildings and the total square footage of all three buildings is only 15,000 square feet. Another comment indicated that the project shouldn't be compared to the Dream Inn. The visual analysis in IS/MND notes other prominent and larger development in the area including the Boardwalk, Coconut Grove and Dream Inn, but does not use any of them as a standard for comparison for new development. The IS/MND indicates that new and expanded structures would less massive and would not out of scale with other larger structures in the vicinity, including the Coconut Grove building at the Boardwalk and the Dream Inn. Furthermore, the positioning of the buildings will break up the mass of the structures by placing the new buildings at the beginning, center and end of the Wharf. The Events Pavilion is envisioned as having tall glass doors that could be opened for combined utilization of indoor and outdoor space, which would also reduce the appearance of structural mass for this building.

- ❒ Lighting. One comment questions the impact conclusion regarding introduction of new lighting on the Wharf, suggesting that the new LED lights on the Wharf are improperly shielded, have added significant glare to the Wharf, and that increased lighting, as well as lighting in new buildings, may significantly aggravate that problem. As discussed on pages 48-50 of the Initial Study, new lighting along the inner edge of the proposed East Promenade would be compatible with existing Wharf lighting and is located within an area that already has extensive nighttime lighting at the Boardwalk and other developments in the area. The introduction of approximately 30 new lights to the Wharf would not be substantial in comparison to the 112 light poles that currently exist. Therefore, implementation of the Wharf Master Plan would not result in creation a new source of substantial light or glare in the area. Furthermore, the lights would be shielded and directed downward and would not be directed into the marine environment.

3. **Biological Resources.**

- Fully Protected Species. The CDFW recommends including the fully protected species status in the biological discussion for species in the project area with a discussion of impacts fully protected species included in the Final IS/MND. This discussion has been added; see section II above.

- Impacts to Fish and Marine Mammals from Pile Driving. Comments from the CDFW indicate that the Department relies on guidance from the multiagency Fisheries Hydroacoustic Working Group for setting sound pressure level safety criteria for fish for pile driving projects and that the agreed upon criteria consists of sound pressure levels (SPL) of 206 decibels (dB) peak and 187 dB (or 183 dB for fish less than 2 grams body weight), which was used in the Initial Study analysis. The CDFW indicates that the agency prefers the use of the vibratory hammer for pile driving and recommends against using a dynamic or impact hammer. If an impact hammer is to be used, the Department recommends the use of a bubble curtain to decrease sound levels and deter sensitive marine species during construction in addition to SPL monitoring. The comments are noted. The CDFW also recommends monitoring for impacts to both marine mammals and fish during pile driving. However, as discussed on page 64, sound levels from pile driving are expected to be below the above criteria based on monitored sound levels for the size and type of piles to be used at the Wharf.

- Marine Mammal Monitoring Plan. Mitigation Measure 1 calls for preparation and implementation of a marine mammal monitoring plan and sets for the performance standards to be established in the plan. As indicated on page 65, the measure would be implemented as part of future approvals by NOAA of Incidental Harassment Authorizations (IHA) that would be required. The measure includes measures and monitoring that are typically included in an IHA. The details will be further refined once a construction plan and schedule is developed as an IHA is not typically issued earlier than a year before construction.

- Sea Lions at Wharf. Two comments ask why the there is no mention that the highly popular sea lion viewing holes will be removed or that the sea lions are expected to move to the new outrigger planks on the east side. This is not an environmental issue that requires review under CEQA.

- Impacts to Birds. One comment states that there is no mention of impact on birds from opening up access via the new proposed walkway on the west side of the Wharf and that bird's nest under the Wharf and perch on the railings outside the Wharf restaurants. CEQA-required reviews are focused on impacts to special status species and sensitive habitat and impacts that could result in a substantial reduction in habitat or cause as species to drop below self-sustaining levels. The project will not result in removal or alteration to habitats or result in impacts to special status species. It is expected that birds that perch at the Wharf would not be deterred or prevented from doing so in the future. There would be no significant loss or alteration of habitat that would cause a bird species to drop below self-sustaining levels.

4. **Cultural Resources.** One comment questions the conclusion that the impact to historic resources is less than significant based on the conclusion that the Wharf structure will not be demolished, destroyed or relocated. The Initial Study analysis follows the requirements established in the State CEQA Guidelines for evaluation of historic resources as explained on page 72. As indicated, a project that could "cause a substantial adverse change in the significance of an historical resource" may have a significant impact. CEQA Guidelines indicate that a "substantial adverse change in the significance of an historical resource" means "physical demolition, destruction, relocation, or alteration of the resource or its immediate surroundings such that the significance of an historical resource *would be materially impaired*." The significance of a historical resource is *materially impaired* when a project "demolishes or materially alters in an adverse manner those physical characteristics of a historical resource that convey its historical significance" that justify its inclusion in or eligibility for listing in the CRHR or its inclusion in a local register. While the Initial Study notes that the project will not demolish, destroy or relocate the Wharf, the detailed analysis on pages 71 to 76 evaluates whether any component of the Master Plan would materially impair the Wharf in a way that a significant impact would occur. The analysis, conducted by a professional historian, concluded that none of the proposed Master Plan elements or future projects would impair the significance of the historic character of the Wharf.

5. **Hydrology-Water Quality.** The CCC and CDFW letters express concern regarding use of treated piles. The CDFW prefers and recommends piles composed of benign materials such as plastics, metal or concrete, but indicates that if the project proceeds with the use of treated ACZA wood piles wrapped in plastic or coated with polyurea, the CDFW recommends annual monitoring of the plastic wrap around each pile. As explained on pages 66 and 91, timber piles would have a polyurea compound coating that is designed to encapsulate treated timber products to prevent toxins from leaching into the environment and this coating has been used for encapsulating AZCA-treated piles. Concern is expressed regarding the longevity of the polyurea compound, and if it can sustain repeated and frequent abrasion.

   Review by City staff and their consulting engineers indicate that polyurea coating was introduced about 15 years ago, and is currently the preferred method for encapsulating treated timber piles. Early formulations and applications of this compound in some harsh exposures did detach from the timber, including at the Wharf. Similarly, pile wraps have also have split and exposed the treated timber under similar harsh wave conditions. City Wharf maintenance staff have noted that the method of coating and the coating formulas have improved significantly since the earliest applications of coatings and that most of the separation issues occurred with use of creosote treated piles that off-gas in hot weather causing blisters in the coating that are more vulnerable to tears from waterborne storm debris.

   Polyurea treated piles in the past 5-7 years have stood up well (keep adhered to the pile) at the Wharf and similar locations. All replacement piles over the past 5 to 10 years have been coated piles. At a minimum, annual inspections have been and will continue to be performed by City staff and engineers. These inspections are performed several times a year and always after large wave events in the winter. The primary focus of these inspections is damage to the piles, and will include damage to the coatings particularly as the number of coated piles increases. Pile wraps are an alternative and final determination will be made during design.

The CDFW letter states that operation of support vessels during pile driving and construction activities can result in spillage leading to aquatic pollution, and spill contingency planning is important for protecting sensitive resources from damage and for improving cleanup strategies and methods. The City concurs that potential oil or fuel spills would be a concern, however, there are no proposed fuel stations or storage of fuel at the Wharf. There is a small building/shed that houses fuel (approximately 150 gallons±) for Santa Cruz Boat Rentals and Wharf Operations machinery. There is a contingency plan in place to handle spills. All construction in the City is subject to implementation of Best Management Practices (BMPs) in accordance with Chapter 4 of the Best Management Practices Manual for the City's Storm Water Management Program.

6. **Hydrology-Sea Level Rise and Coastal Storms.** As discussed on pages 90-92, sea level rise and effects of coastal storm wave runup were addressed based on current estimates of the National Research Council (2012) in conjunction with a committee with representatives from California, Oregon and Washington. City staff review of these sea level rise estimates indicates that proposed Wharf improvements, including the Western Walkway would be above projected sea level rise elevations.

7. **Transportation and Parking.** One comment states that the transportation section in the Initial Study is tiered from the General Plan, inadequately assesses the traffic and parking impacts of the expanded wharf, and does not identify traffic increases. The Initial Study does not tier off the City's General Plan for the traffic analysis. As indicated on page 28, The Initial Study tiers from the *General Plan 2030* EIR for the following topics: greenhouse gas emissions; public services and utilities, except for water supply; and cumulative impacts. The General Plan traffic analysis did not anticipate measurable growth on the wharf but it included a buildout scenario for the City overall. As discussed below, a traffic analysis with a trip generation estimate was provided for the Wharf Master Plan, which was added to the City buildout to provide a new cumulative traffic estimate. No significant project or cumulative traffic impacts were identified.

   Several comments questioned traffic from the project. As cited in the Initial Study, a traffic analysis was conducted by Ron Marquez, traffic engineer consultant to the City, based on review of existing traffic volumes to the Wharf throughout the year. The analysis provided on pages 100-103 incudes trip generation and consideration of traffic based on facilities envisioned in the Wharf Master Plan. Trip generation rates are inclusive of all trips, including employee trips. The traffic analysis prepared for the Wharf Master Plan used conservatively high projections of new traffic to provide a worst case scenario. Traffic volume with the proposed plan was estimated to be over 30% higher than existing volume during the weekday PM peak hour. With this additional volume no new circulation impacts were identified. The alternative transportation included in the Master Plan such as shuttle, improved bicycle facilities and pedestrian walkways can be expected to reduce the effects on circulation. However the circulation system does not rely on these mode choices to be effective.

V. MITIGATION MONITORING & REPORTING PROGRAM

The Mitigation Monitoring and Reporting Program (MMRP) has been prepared pursuant to the California Environmental Quality Act (CEQA – Public Resources Code, Section 21000 *et seq*.), the CEQA Guidelines (Cal. Code Regs., Title 14, Chapter 3, Sections 15074 and 15097). A master copy of this MMRP shall be kept in the Economic Development Office and shall be available for viewing upon request.

This MMRP includes mitigation measures in the Mitigation Monitoring and Reporting Matrix on the following pages that correspond to the final Mitigated Negative Declaration (MND) for the project. The matrix lists each mitigation measure or series of mitigation measures by environmental topic. For each mitigation measure, the frequency of monitoring and the responsible monitoring entity is identified. Mitigation measures may be shown in submittals and may be checked only once, or they may require monitoring periodically during and/or after construction. Once a mitigation measure is complete, the responsible monitoring entity shall date and initial the corresponding cell, and indicate how effective the mitigation measure was.

MITIGATION MONITORING PROGRAM – Santa Cruz Wharf Master Plan

Mitigation Measure	Implementation Actions	Monitoring / Reporting Responsibility	Timing Requirements	Reporting Requirements & Verification of Compliance
Biological Resources				
MITIGATION MEASURE 1: Prepare and implement a marine mammal monitoring plan that identifies the specific measures to avoid exposure of marine mammals to high sound levels that could result in Level B harassment including the following: • Pre-construction monitoring to update information on the animals' occurrence in and near the project area, their movement patterns, and their use of any haul-out sites. • Pre-construction training for construction crews prior to in-water construction regarding the status and sensitivity of the target species in the area and the actions to be taken to avoid or minimize impacts in the event of a target species entering the in-water work area. • In-water construction biological monitoring to search for target marine mammal species and halt project activities that could result in injury or mortality to these species. • Establishment of an underwater "exclusion zone"—defined as the distance where underwater sound levels exceed 180 dB if whales are present, and 190 dB if seals and sea lions are present—will be established. This will be refined based on hydroacoustic measurements in the field and in consultation with NOAA Fisheries. • Prohibit disturbance or noise to encourage the movement of the target species from the work area. The City will contact USFWS and NOAA Fisheries to determine the best approach for exclusion of the target species from the in-water work area. .	Actions are specified in the measure.	City staff is responsible for hiring qualified biologist to prepare plan in accordance with federal requirements and prepare Incidental Harassment Authorization application.	Prior to installation of piles for new facilities.	Monitoring protocols will be established in the Plan

ATTACHMENT A

Comment Letters

ATTACHMENT C

STATE OF CALIFORNIA

Governor's Office of Planning and Research

State Clearinghouse and Planning Unit

Edmund G. Brown Jr.
Governor

Ken Alex
Director

April 13, 2016

RECEIVED

APR 19 2016

Economic Development

Norm Daly
City of Santa Cruz
337 Locust St
Santa Cruz, CA 95060

Subject: Santa Cruz Wharf Master Plan
SCH#: 2016032038

Dear Norm Daly:

The State Clearinghouse submitted the above named Mitigated Negative Declaration to selected state agencies for review. The review period closed on April 12, 2016, and no state agencies submitted comments by that date. This letter acknowledges that you have complied with the State Clearinghouse review requirements for draft environmental documents, pursuant to the California Environmental Quality Act.

Please call the State Clearinghouse at (916) 445-0613 if you have any questions regarding the environmental review process. If you have a question about the above-named project, please refer to the ten-digit State Clearinghouse number when contacting this office.

Sincerely,

Scott Morgan
Director, State Clearinghouse

Document Details Report
State Clearinghouse Data Bas

ATTACHMENT C

SCH#	**2016032038**
Project Title	Santa Cruz Wharf Master Plan
Lead Agency	Santa Cruz, City of

Type **MND** Mitigated Negative Declaration

Description Project consists of adoption and implementation of the Wharf Master Plan and construction of two projects recommended in the Master Plan within the next two years. The two proposed near-term projects are relocation of the Wharf entry gate and construction of the East Promenade for pedestrian use. The Wharf Master Plan includes: policies; recommendations for expansion of the wharf for public access and construction of improvements and three new buildings; structural wharf improvements; circulation and parking improvements; and design standards for new buildings.

Lead Agency Contact

Name Norm Daly
Agency City of Santa Cruz
Phone 831-420-5109 ***Fax***
email
Address 337 Locust St
City Santa Cruz ***State*** CA ***Zip*** 95060

Project Location

County Santa Cruz
City
Region
Lat / Long
Cross Streets Beach Street/Front STreet
Parcel No.
Township ***Range*** ***Section*** ***Base***

Proximity to:

Highways 1
Airports
Railways
Waterways Monterey Bay
Schools Santa Cruz High
Land Use Santa Cruz Wharf (city owned) / CB- CZO - Beach Commercial - Coastal Zone Overlay / Regional Visitor Commercial

Project Issues Aesthetic/Visual; Air Quality; Archaeologic-Historic; Biological Resources; Coastal Zone; Flood Plain/Flooding; Geologic/Seismic; Traffic/Circulation; Water Quality; Water Supply; Wetland/Riparian; Landuse; Cumulative Effects

Reviewing Agencies Resources Agency; Department of Fish and Wildlife, Region 3; Department of Fish and Wildlife, Marine Region; California Coastal Commission; Department of Water Resources; Department of Parks and Recreation; California Highway Patrol; Caltrans, District 5; Air Resources Board; State Water Resources Control Board, Division of Water Quality; Regional Water Quality Control Board, Region 3; Native American Heritage Commission

Date Received 03/14/2016 ***Start of Review*** 03/14/2016 ***End of Review*** 04/12/2016

Note: Blanks in data fields result from insufficient information provided by lead agency.

ATTACHMENT C

STATE OF CALIFORNIA—NATURAL RESOURCES AGENCY EDMUND G. BROWN JR., *GOVERNOR*

CALIFORNIA COASTAL COMMISSION

CENTRAL COAST DISTRICT OFFICE
725 FRONT STREET, SUITE 300
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April 12, 2016

Norman Daly
Economic Development
City of Santa Cruz
337 Locust Street, Santa Cruz, CA 95060

Subject: Comments on the Santa Cruz Wharf Master Plan (Initial Study and Mitigated Negative Declaration)

Dear Norm:

Thank you for the opportunity to comment on the Initial Study/ Mitigated Negative Declaration (MND) for the Santa Cruz Wharf Master Plan (Wharf Master Plan), which proposes the following new facilities: a new public promenade on the east side of the Wharf; a new public walkway on the west side of the Wharf; three new public buildings; and two new ADA accessible boat landings. In addition, the Wharf Master Plan proposes structural and other improvements including installation of new and replacement piles, lateral bracing, and roadway and utility improvements, and improvements to the Wharf's trash collection system. As a whole, the Wharf Master Plan entails substantial public access improvements, in accordance with the Public Access and Recreation policies of the Coastal Act. Although Commission staff is supportive of the proposed Wharf Master Plan, we do have a handful of comments that, if incorporated, will ensure that the Wharf Master Plan is fully consistent with the Coastal Act's public access and recreation, visual resource protection and water quality protection policies, and will also ensure that the Wharf Master Plan aligns well with the Coastal Commission's Sea Level Rise Policy Guidance.

Jurisdiction and Permitting

The MND notes that the Wharf is located in an area where the Coastal Commission has retained jurisdiction (MND p. 1-2), which means that new development on the Wharf must be consistent with the Chapter 3 policies Coastal Act, and will require review and approval by the Coastal Commission. We have discussed the potential for processing implementation of the Wharf Master Plan through a Public Works Plan (PWP) as set forth in the Coastal Act and its implementing regulations, and we understand that the City is in the process of preparing a draft PWP for review by Coastal Commission staff. We continue to believe that this would be an appropriate and efficient means of implementing coastal permitting requirements for the Wharf Master Plan and appreciate that this process has been outlined in the MND (p. 2).

Public Trust and Maximization of Public Access and Recreation

The Wharf and proposed improvements are located on public trust land. The Coastal Act requires that new development maximize public access and recreational opportunities (Sections 30210 through 30224), and limits the placement of structural pilings to public recreational piers that provide public access and recreational opportunities (Section 30233). For this project, maximization of public access and recreation means that any additional coverage of public trust land is minimized and used for public access and recreational purposes and improvements only.

The MND states that the new entry is designed to provide two inbound lanes and two outbound lanes with staffed kiosks at the entrance, and that the entrance will be framed with a roll down, transparent gate "so that the Wharf can be closed when not in operation" (MND p. 21-22). Staff believes that this element of the project raises significant issues with respect to public access. At a minimum, we believe the roll down gate should be limited to the vehicle entryway in order to maintain and maximize pedestrian access to the wharf. Furthermore, we note that Special Condition 1, Operational Plan of CDP 3-81-041-A5 (which provided for construction of the existing entry kiosk) states that the Wharf must continue to provide access "to vehicles, pedestrians, and bicyclists at all times except between 2:00am and 5:00am and during emergencies." Thus, per this condition, the roll down transparent gate should be limited to the hours of 2:00am to 5:00am only.

As outlined in the Wharf Master Plan, the proposed improvements would expand the Wharf by approximately 2.5 acres, which would increase the area of the Wharf dedicated to public access, recreation, and open space from 26% to 60%. These public access improvements include, but are not limited to three new buildings devoted to public access and recreation uses as well as a new promenade on the east side of the Wharf and a new walkway on the west side of the Wharf, which will provide a through walkway around the entire perimeter of the wharf. We recognize and appreciate that the footprint of existing commercial space and parking will not be increased. We further support the realignment of existing parking to create 10% to 15% more spaces without increasing the amount of space devoted to parking. On a similar note, we also support the potential infill of existing commercial space as long as the footprint of existing commercial space is not increased. However, it is unclear from the MND whether the proposed increase in commercial space (i.e.: the intended 4,000 square feet of new commercial space as well as the potential 20-30% increase through remodeling and second story expansions) entails any expansion of the footprint of existing commercial facilities. Please graphically depict and describe areas of proposed increased commercial space so that we can better understand the proposed expansion of commercial space.

Regarding the proposed walkway on the west side of the wharf, while we are highly supportive of fluid, unobstructed public access around the wharf, we have concerns with the proposed height of the west side walkway. The Wharf Master Plan says that the walkway will be located approximately eight feet below the existing Wharf. The Wharf Master Plan goes on to explain that this dropped-down height will allow for "undisturbed visual access from the restaurants and commercial spaces along that edge." However, because the westward walkway will be an expansion *westward*, there should be unencumbered visual access regardless of the height of the walkway. The Wharf Master Plan explains that the proposed height of the west walkway is above sea level rise projections, but does not detail the timeframe or what calculations were used to determine this, or how they were applied. Specifically, it is unclear if the sea level rise projection used in the Wharf Master Plan evaluated the cumulative impacts associated with climate change (i.e.: increased number and intensity of storms, thermal expansion, sea level rise, and ENSO events). As witnessed by the current El Niño storm season, waves frequently reach the height of the existing wharf. As such, any expansion of the wharf closer to the water raises potential concerns. The environmental review should consider the cumulative impacts of multiple climate change-related impacts in the sea level rise projection to ensure that the proposed westward expansion will be safe and durable long term.

The Wharf Master Plan recommends improvements to the existing trash collection system for the Wharf in order to eliminate the use of centralized garbage and reliance on large garbage trucks that impact public access and are currently the greatest source of damage to the Wharf and incur the greatest amount of Wharf maintenance costs to the City (MND p. 19-20). The Wharf Master Plan suggests that consideration be given to the use of an automated vacuum collection system that has been used extensively in Scandinavian countries and more recently has been adopted for use in some areas in the United States. Our understanding is that this trash collection system would be implemented during a later implementation phase of the Wharf Master Plan. Staff is highly supportive of this new technology and would recommend that activities proposed in the first phase of implementation be designed to incorporate and allow for implementation of an automated vacuum trash collection system in the future.

Visual Resources

Coastal Act Section 30251 requires the protection of the scenic and visual qualities of coastal areas. It also requires development to protect views to and along the ocean and scenic coastal areas, and to be visually compatible with the character of the surrounding areas. This Section further requires that development restore and enhance the visual quality in visually degraded areas. In terms of visual resource protection, the proposed development appears largely consistent with Section 30251. However, there are aspects of the proposed development that raise potential visual protection consistency issues, particularly the bulk, scale, and character of the proposed gate/entryway.

In terms of the entryway, we support its proposed relocation and widening. From a traffic and circulation standpoint, the relocation will facilitate smooth egress and ingress to and from the wharf. In addition, the relocated entryway coupled with the proposed East Promenade and the Western Walkway will further facilitate safe non-vehicular public access to and around the wharf.

While we recognize that the entryway has yet to be fully envisioned, and that it will undergo a lengthy public review process, we continue to have concerns regarding the proposed entryway's aesthetic and visual resource impacts based on the visual simulation provided in the MND. Specifically, we are concerned with the gate's 18-foot height and the fact that the gate appears to span the entire width of the Wharf. The sign as currently envisioned will be between six to eight tall and 70 feet long. The entryway's 18-foot height coupled with the rather large sign will have potential visual impacts. The Wharf Master Plan explains that "the narrow profile and height of the entrance gate would be difficult to distinguish from other surrounding development and the distant views of the Boardwalk rides." The report goes on to explain that from East Cliff Drive, another scenic road, the entrance sign would blend in with the Dream Inn and other adjacent development. However, we remain concerned with the visual impacts to the immediately adjacent areas including to and from Cowells and Main Beaches. Therefore, we strongly recommend reducing the bulk and scale of the proposed entryway and sign.

We also have concerns with regard to the proposed roll down transparent entry gate with regard to visual resource impacts. We would suggest that the roll down gate only extend the length of the *vehicular* entryway in order to better align with the Visual Resource and Public Access policies of the Coastal Act as discussed above. Specifically, reducing the gate/ entryway to the length of the vehicular entryway will help further reduce the bulk and scale of the entryway, which will help to minimize adverse visual impacts. In addition, as discussed above, reducing the entryway/ gate's width so that it does not completely close off pedestrian access to the wharf will better comply with Coastal Act policies in terms of maintaining and maximizing public access to the wharf.

In addition to concerns related to the bulk and scale of the proposed gate/ entryway, we also have concerns pertaining to the character of the sign, gate, and entryway. The Coastal Act requires that all new development (in this case the sign, gate, and entryway) honors the unique character, history, and aesthetic of the wharf. Though we understand the motivation to draw attention to the wharf, the Act requires the historical character and integrity of the wharf to be maintained and protected. Please consider a sign made of more natural and rustic materials that blends in with the overall aesthetic of the wharf as opposed to a modern, highly embellished sign. We believe the new entryway (including the sign) can be designed so that it will serve its function as a gate/ entryway, result in minimal adverse visual impacts, and highlight the historical significance of the Santa Cruz Wharf.

Water Quality

Coastal Act Sections 30230, 20231, 30232, and 30325 require marine resources, including water quality, to be maintained, enhanced, and restored. Section 30235 specifically requires that marine structures contributing to water stagnation, pollution, and fishkills shall be upgraded and phased out where feasible.

Overall, the Wharf Master Plan appears to be consistent with the above-cited Coastal Act sections. The Wharf Master Plan MND explains that "the Engineering Report recommends that roof downspouts direct roof runoff onto vegetated areas or into cisterns or rain barrels for reuse for all new buildings. We concur with this assessment, and highly recommend the inclusion of roof downspouts that connect to cisterns or rain barrels for reuse of stormwater for irrigation and/or other methods to limit runoff into the Monterey Bay. The Wharf Master Plan MND also identifies repaving as an opportunity to collect and treat stormwater prior to discharge into the Monterey Bay via directing runoff into designated collection areas for treatment prior to disposal. We are highly supportive of the proposed improvements to stormwater management, and look forward to additional refinements and implementation of these recommendations. The Wharf Master Plan MND also notes the potential implementation of oil and grease chambers, swirl chambers and media filters. We believe that implementation of these measures is necessary in order to comply with the Coastal Act's water quality requirements.

The only aspect of the Wharf Master Plan MND that raises concerns with respect to water quality is the treated piles. As currently proposed, approximately 800 treated piles will be incrementally added to the wharf or used to replace old, weathered piles. The MND states that the piles will be treated with ACZA (ammoniacal copper zinc arsenate) and coated with a polyurea compound (MND p. 61, 66, & 90). The Wharf Master plan explains that treated piles can be coated with the polyurea compound or wrapped to prevent toxins from leaching into the Monterey Bay. The MND should explain why treating the piles is preferred over wrapping the piles. We are especially concerned with the longevity of the polyurea compound, and if it can sustain repeated and frequent abrasion. However, we are open to the use of the polyurea compound if it is in fact the least environmentally damaging alternative.

Overall staff is very supportive of the Wharf Master Plan, especially the substantial proposed public access improvements. We look forward to continuing to work with you as future phases of the Wharf Master Plan unfold.

Sincerely,

Rainey Graeven

Rainey Graeven
Coastal Planner
Central Coast District Office

State of California – Natural Resources Agency
DEPARTMENT OF FISH AND WILDLIFE
Marine Region
1933 Cliff Drive, Suite 9
Santa Barbara, CA 93109
www.wildlife.ca.gov

EDMUND G. BROWN JR., Governor
CHARLTON H. BONHAM, Director

April 8, 2016

Norm Daly
City of Santa Cruz
Economic Development Department
337 Locust Street
Santa Cruz, CA, 95060
ndaly@cityofsantacruz.com

Subject: Initial Study/Mitigated Negative Declaration – Santa Cruz Wharf Master Plan

Dear Mr. Norm Daly:

The California Department of Fish and Wildlife (Department) has reviewed the Initial Study/Mitigated Negative Declaration (IS/MND) for the Santa Cruz Wharf Master Plan (Project). The Project consists of adoption and implementation of the Wharf Master Plan and construction of two near-term projects recommended in the Master Plan. The proposed near-term projects are the relocation of the wharf entry gate and construction of the East Promenade for pedestrian use. The Wharf Master Plan includes the following elements and recommendations: a new walkway on the west side of the wharf; three new buildings; and two new ADA accessible boat landings. The Master Plan also considers remodeling and intensified use of existing structures. Structural wharf improvements considered as part of the Project include installation of new and replacement piles for lateral bracing, and roadway and utility improvements including improvements to the wharf's trash collection system. The proposed new facilities would require installation of approximately 700 new timber piles in order to support new improvements and to increase the lateral stability of the wharf. Approximately 225 existing piles will require replacement over time. New and replacement piles are proposed to be 12-inch diameter timber (Douglas fir) treated with ACZA (ammoniacal copper zinc arsenate) and coated with a polyurea compound. A total of six piles are proposed to be 14-inch steel piles for the relocated wharf entrance. The piles are to be placed in water depths 0-35 feet and approximately 20 feet into the sand or until refusal is met. An 1800 pound drop (impact) hammer and a 400 pound follower block are proposed to be used for driving the piles into the sea floor.

As a trustee for the State's fish and wildlife resources, the Department has jurisdiction over the conservation, protection, and management of fish, wildlife, and habitat necessary for biologically sustainable populations of those species. In this capacity, the Department administers the California Endangered Species Act, the Native Plant

Protection Act, and other provisions of the California Fish and Game Code that afford protection to the State's fish and wildlife trust resources. The Department is the State's fish and wildlife "Trustee Agency" under the California Environmental Quality Act (CEQA guidelines §15386). The Department is also responsible for marine biodiversity protection under the Marine Life Protection Act (MLPA) in coastal marine waters of California. Pursuant to our jurisdiction, the Department has the following comments and recommendations regarding the Project.

Fully Protected Species:

The Department has jurisdiction over fully protected species pursuant to Fish and Game Code Sections 3511,505, 4700, and 5515. Fully Protected species may not be taken or possessed at any time and no licenses or permits may be issued for their take except for collecting these species for necessary scientific research and certain relocation situations. Therefore "take" of any fully protected animal species is prohibited and must be avoided by the Project. Fully protected marine species in the Project area include: the Southern Sea Otter (*Enhydra lutris nereis*), Northern Elephant Seal (*Miroinga angustirostris*), Brown Pelican (*Pelecanus occidentalis californicus*), California Clapper Rail (*Rallus longirostris obsoletus*), and the California Least Tern (*Sterna antillarum browni*). The Department recommends including the fully protected species status in the biological discussion for species in the Project area. Additionally, the Department recommends discussing the potential impacts fully protected species in the Final IS/MND. The Department maintains a list of fully protected species that can be found on the Department's web site:
http://www.dfg.ca.gov/wildlife/nongame/t_e_spp/fully_pro.html

Sound Level Impacts for Fish:

The Department has reviewed IS/MND section regarding potential impacts from pile driving activities. The Department relies on guidance from the multiagency Fisheries Hydroacoustic Working Group for setting sound pressure level safety criteria for fish resources, in particular for pile driving projects. The agreed upon criteria consists of sound pressure levels (SPL) of 206 decibels (dB) peak and 187 dB (or 183 dB for fish less than 2grams body weight) accumulated sound exposure level (SEL) for all listed fish within a project area. Impacts to marine organisms from underwater sound are influenced by the SELs, SPLs, sound frequency, and depth and distance from the sound output source. The Department prefers the use of the vibratory hammer for pile driving and recommends against using a dynamic or impact hammer. It is the Department's understanding from the IS/MND that an 1800 lb. drop (impact) hammer and a 400 lb. follower block are proposed for driving the piles into the sea floor. If an impact hammer is to be used, the Department recommends the use of a bubble curtain to decrease sound levels and deter sensitive marine species during construction in addition to SPL monitoring. In addition, the Department recommends monitoring for impacts to both marine mammals and fish during pile driving.

Wood Pile Treatment and Coating

The Project proposes the use of over 700 new Douglas fir timber piles treated with ACZA and coated with a liquid polyurea compound. California Fish and Game Code (FGC §5650) states that it is unlawful to deposit into, permit to pass into, or place where it can pass into waters of the state any of the following:

(1) any petroleum, acid, coal or oil tar, lampblack, aniline, asphalt, bitumen, or residuary product of petroleum, or carbonaceous materials or substance.
(2) any refuse, liquid or solid, from any refinery, gas house, tannery, distillery, chemical works, mill or factory of any kind.
(3) any sawdust, shavings, slabs, edgings.
(4) any factory refuse, lime, or slag.
(5) any cocculus indicus.
(6) any substance or material deleterious to fish, plant life, or bird life.

The Department prefers and recommends piles composed of benign materials such as plastics, metal or concrete. Pressure treated woods such as ACZA, CCA, ACQ are not recommended. There is potential for the materials to leach into the water and cause harm to fish, plants, and/or birds (FGC 5650, Item (6)). The Department recommends use of plastic wrapped treated wood products under the following specific conditions and situations:

1. For repair of existing projects constructed using wood products.
2. Where the use of plastic-wrapped treated pilings is restricted to marine waters.
3. Where measures are taken to prevent damage to plastic wrap from boat use. Measures may include installation of rub strips or bumpers.
4. Where the plastic wrapping is sealed at all joints to prevent leakage.
5. Where the plastic material is expected to maintain its integrity for at least ten years, and where plastic wrappings that develop holes or leaks are repaired or replaced in a timely manner.

In addition, should the Project proceed with the use of treated ACZA wood piles wrapped in plastic or coated with polyurea, the Department recommends annual monitoring of the plastic wrap around each pile. Annual monitoring and reporting will help insure that harmful materials do not leach into the water.

Hazards and Spills

The operation of support vessels during pile driving and construction activities can result in spillage leading to aquatic pollution. Spill contingency planning is important for protecting sensitive resources from damage and for improving cleanup strategies and methods. The Project should discuss and plan the prevention of spills that could impact important aquatic and wildlife resources. The Project should consult with the US Coast Guard and the Department’s Office of Spill Prevention and Response (OSPR) regarding federal and State protocols that exist for these types of projects. In addition, the Department recommends the use of Best Management Practices (BMPs) for all hazardous materials that may be used during the proposed Project and the creation of a Spill Response Plan prior to any construction activities. If any spills or leaks occur during the construction activities, the Department recommends immediately contacting the Governor's Office of Emergency Services, California State Warning Center, at 1-800-852-7550.

Conclusion

The Department appreciates the opportunity to provide comments on the Initial Study/Mitigated Negative Declaration for the Santa Cruz Wharf Master Plan. If you require additional information, please contact Mr. Eric Wilkins, Senior Environmental Scientist Specialist, at (831) 649-2813 or via e-mail at Eric.Wilkins@Wildlife.ca.gov.

Sincerely,

Craig Shuman, D Env.
Regional Manager
Marine Region

ec: Becky Ota, Program Manager
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cc: Brian M. Meux
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Monterey Bay Unified
Air Pollution Control District
Serving Monterey, San Benito, and Santa Cruz Counties

ATTACHMENT C

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April 11, 2016

Norm Daly
City of Santa Cruz
Economic Development Department
337 Locust St., Santa Cruz, CA 95060
Santa Cruz, CA 95060

NDaly@cityofsantacruz.com

Re: IS/MND for Santa Cruz Wharf Master Plan

Dear Mr. Daly:

Thank you for providing the Monterey Bay Unified Air Pollution Control District (Air District) with the opportunity to comment on the above-referenced document. The Air District has reviewed the document and has the following comments:

1. Construction, Page 53 - Given the nearby proximity of pedestrians, the Air District recommends using cleaner construction equipment that conform to ARB's Tier 3 or Tier 4 emission standards. We further recommend that, whenever feasible, construction equipment use alternative fuels such as compressed natural gas (CNG), propane, electricity or biodiesel.

2. Offsite Shuttles, Page 53 – Please note, project components such as shuttles which are designed to reduce the volume of cars driving directly to the wharf may be eligible for supplemental grant funding through the Air District's AB2766 Motor Vehicle Emission Reduction Grant Program. Please contact Alan Romero, Air Quality Planner III at 831-647-9411 x241 for details.

3. Hazardous Materials, Page 85 – Please note, if older asbestos containing pipes need to be removed during the renovation, the requirements of Air District Rule 424 National Emissions Standards for Hazardous Air Pollutants could be triggered. Rule 424 contains the investigation and reporting requirements for asbestos. If you have any questions about District Rule 424 and prior to any demolition activities, please contact Mike Sheehan, District Compliance Program Coordinator, at (831) 647-9411 x217.

4. Relocation of Pay Station, Figure 2-6 – The relocation of the pay station and inclusion of a pay on foot system should help alleviate back-up of vehicles into the roundabout, thus minimizing congestion and excess motor vehicle exhaust emissions.

Best Regards,

Robert Nunes

Robert Nunes
Air Quality Planner

cc: David Frisbey, Air Quality Planner
Alan Romero, Air Quality Planner
Mike Sheehan, Compliance Program Coordinator

From: luerickson@comcast.net
To: Norman Daly
Subject: Wharf revitalization
Date: Monday, April 11, 2016 6:15:48 PM

I read a letter in the Sunday Sentinel regarding the wharf proposed changes. The letter was from Mary McGranahan and I think she really hit the nail on the head. Every point she made was well taken. Why on earth would you build such a tall building at the end of the wharf? What is wrong with the Coastal Commission? I cannot believe they would even consider this proposed building. How are we going to pay for all the maintenance on these new promenades? Leave the wharf alone. It is fine as it is. Pretty soon it won't even be recognizable to us old-timers any more. Just like when everybody used to tear down all the lovely old victorian homes and replace them with modern eyesores which look terrible. Or the old McHugh-Bianchi building. That was a real gem only to be replaced with the unattractive building with no personality that is there now.

The wharf is fine. Please leave it alone. Many people agree with Ms. McGranahan.

Thanks.

Lu Erickson

To: Norm Daly
From: Gillian Greensite
Re: **Wharf Master Plan (WMP) Mitigated Negative Declaration (MND) Initial Study (IS)**
Date: April 11th, 2016

This project is arguably one of the largest ever planned makeovers of a Santa Cruz historical landmark. Where previous changes to the municipal wharf were deliberately kept modest in response to the community's preference to retain the character of the wharf, the current project if approved and developed will transform the wharf almost beyond recognition. At such a scale and impact, an EIR should have been prepared. Since the decision by the city was to prepare only a MND, such document should have thoroughly evaluated the impacts and their significance. If a MND is not capable of such detailed evaluation, an EIR should be prepared. The inadequacies in the MND are listed below.

1. There is no mention in the MND, the IS nor in the WMP, that the highly popular sea lion viewing holes will be covered over under this project. Nor any mention that they are expected to move to the 8 new outrigger planks proposed for the eastside. We read about this in the daily press. Why is the document silent on this issue? What if the sea lions refuse to move? This should have been evaluated under *Recreation.*

2. On the impact on *Biological Resources*, the MND asserts under BIO-1 that a marine mammal monitoring plan **will** be prepared to mitigate the potential Level B harassment during construction. Under Mitigation, the MND states that the city **will** contact USFWS and NOAA Fisheries to determine the best approach for exclusion of the target species from the in-water work area (emphasis added). Those agencies should have been contacted as part of the MND process and the detailed plan included in the document so the public has a chance to evaluate and comment. Such inclusion is missing.

3. There is no mention of impact on birds from opening up access to the piling area via the new proposed walkway on the westside of the wharf. Birds nest under the wharf. Families of snowy egrets perch on the railings outside the wharf restaurants. These areas are currently closed to the public. The new walkway opens this area up to the public. This impact should have been included and evaluated under *Biological Resources.*

4. The WMP proposes expansion of kayaking and boat rentals. I have documentation of kayakers and boats harassing otters and whales. There is no evaluation under *Biological Resources* of the significance level of increased recreational activity on these marine mammals in the IS.

5. Under *Cultural Resources,* the IS asserts less than significance to this makeover because the wharf will not be "demolished, destroyed or relocated." That is a very low bar for evaluating the proposed changes to this cultural icon.

6. Under *Aesthetics,* The IS states that there will be a less than significant impact on a scenic vista and less than significant impact in degrading the existing visual character of the site. With 3 new buildings of up to 45 in height plus architectural features, this conclusion is untenable. Each of these new buildings will significantly block a current vista. The IS states other vistas will be available. That fact does not negate the significant loss of view due to the cumulative effect of the 3 new large buildings plus infilling with the aim of doubling the number of commercial establishments, boat docks and second story additions which are all proposed. The view of the wharf from West Cliff Drive and the beaches will be significantly altered. The west side proposed walkway will significantly degrade the unique view of the wharf and pilings where the end of the wharf takes a bend in a southerly direction. Under the project, lines of people will replace the current uninterrupted vista. The impact of the lowered western walkway on views of the wharf from land should have been included and assessed.

7. The *Transportation and Traffic* category is tiered from the General Plan. This section inadequately assesses the traffic and parking impacts of the expanded wharf and asserts a less than significant impact. Entries in the WMP and MND on how much increased traffic is expected after completion of the project are filled with vague statements that profess no idea how much traffic will increase. This, despite the stated aim of the project to increase economic development via increased wharf usage. The project includes no expansion in total area devoted to parking, nor to wharf operations. Where will the wharf heavy equipment be housed under the new project? With respect to parking, the possible addition of 44 parking spaces to the current 440 can be implemented via new striping, according to the IS. This means narrower spaces. Narrowed parking spaces negatively impact accessibility for older wharf patrons. An environmental document should include a realistic traffic projection for this project, which has unique characteristics distinct from those examined under the General Plan EIR. It should not have been tiered from the GP. The inclusion of bicycle parking spaces and possibly a shuttle are inadequate to mitigate the impact of traffic and parking given that both are at capacity at peak periods now, prior to any development. The replacement of staff at the kiosks with twelve walk and pay parking stations will add to confusion, visual clutter and impact the elderly disproportionally. The wharf is not a typical parking lot. The WMP states that wharf employees will not be allowed to park on the wharf under the project but city staff will have reserved parking spots. This arrangement will negatively impact wharf businesses. The IS makes no mention of where wharf employees are expected to park. Many are unable to ride bicycles. Will this discriminate

against the older workers and female workers for whom walking to and from their wharf business at night may be unsafe?

8. Under *Lighting and Glare*, the IS claims no significant impact from the additional wharf lighting and lighting of wharf businesses. The IS states that the wharf is in an already developed and lighted area, citing the Boardwalk as the yardstick. The wharf projects half a mile into Monterey Bay. Current versus projected new lighting on the wharf, not lights on land, should be the yardstick by which to measure light and glare impacts. The IS should also assess how the new wharf will impact nighttime views of the wharf from the land. The new LED lights on the wharf, improperly shielded, already have added significant glare to the wharf. The project's increased lighting may significantly aggravate that problem. The new large multi-story buildings will mean not only more lights but lights at a higher elevation. The wharf development impacts the Monterey Bay National Marine Sanctuary. The IS has a responsibility to assess the ecological impact of this increased light pollution on marine mammals and birds.

From: Mary
To: Norman Daly
Cc: gumtree@pacbell.net
Subject: Wharf renovation concerns
Date: Thursday, April 07, 2016 10:04:31 AM

Mr. Daly,

I am just becoming aware of the details for the proposed wharf "renewal" project through the Sentinel News articles this past weekend. I have serious concerns about the proposal's intention of hosting several thousands more visitors on the wharf. The retail space will increase from the present 19 up to 35 businesses. Parking spaces will increase by 40 simply by making existing spaces smaller. Three additional buildings 45 ft in height will be added to existing structures.

1. Downtown Santa Cruz has a three - story height limit. Going even higher than that out in one of the most beautiful seascapes on the California coast is preposterous. Has the Coastal Commission weighed in on this? If retail space is in demand, please check out all the available space on the Pacific Garden Mall where you will find ample parking.
2. Traffic in and around Santa Cruz has become a nightmare. There are no provisions in your plan to mitigate the additional traffic that comes with the "thousands of additional visitors." And, they don't all drive compact cars, which are the only vehicles that till fit into your new, condensed parking spaces.
3. To use the Dream Inn for "comparable size" equation is ludicrous. Roma designers should look into the history of the construction of the Dream Inn in the 1960's. Construction was brought to a halt by objections to it's size/height, and the design was altered in height. Also, Santa Cruzans are very anti-BigBox stores, and you are proposing to put three of them out in our bay?
4. Our wharf has always been a part of our local family history, if you will. We are more closely aligned to the wharf in Monterey, not the mega-mercantilism of the Pier 39 variety, although I don't believe there are four-story buildings on the San Francisco piers either. I assume this "renovation" will increase the rents for the existing 19 businesses. Doubling the amount of retail space without provision for the additional traffic on and around the beach area is going to be a disaster to our local wharf businesses.
5. The last of our Redevelopment funds from the state was used to build the Exploratorium across from the entrance to the wharf. Though admission is free, I rarely see anyone there. Perhaps because of the lack of parking. The Surfing Museum is just up West Cliff Drive, and it was planned and built by local surfers. The IS calls for a duplication of these venues in one of the proposed 4-story buildings in our bay. Really?

Please extend the period for public input, as I believe this important factor has only been brought to light through the recent articles in the Sentinel News. We, the people who have lived, and paid property taxes here for generations, deserve a say in this horrific proposed desecration of our bay.

Thank you,

Mary McGranahan

From: Henry Searle
To: Norman Daly
Subject: revised comment on MND wharf plan
Date: Monday, April 11, 2016 6:12:34 PM

Norm, I hope this is an improvement, and sorry for the error yesterday:

The bottom line here is whether our City wants to change and enlarge our wharf substantially and irreversibly. The next to bottom line is whether the mitigated neg dec (MND) provides adequate information for the City Council to make an informed decision. We all agree that the Wharf is a very important part of the Santa Cruz image. It is also clear that this image would be permanently altered by the Wharf reconfiguration. This decision may and must not be taken lightly.

Changes in the Wharf are not required for safety or environmental concerns. They are proposed in order to increase use of the wharf, to make it into a larger (and different) element of our ocean front, to increase business. The wharf has been existence in substantially its present form for many years. To change it would surely be growth, but is this the kind of growth we want? And is this growth something the visitors to the Wharf will enjoy more than what is already there. For whose benefit are these changes intended, and why do people visit the Wharf??

The MND contains many estimates, approximations and suppositions about the effects of the project. Traffic may increase but not substantially (MND page 100, all references to numbers are to pages in the MND), bicycle use may reduce auto traffic and increased traffic will not reduce LOS (100), water use (109) will increase but not by a significant amount, global warming emissions will increase but this is with accepted parameters (82-83) etc. Views from the Wharf towards the ocean, from East and West Cliff will be impacted, but these may not be overly significant (40,41,42), the new buildings will not be out of scale with he rest of the Wharf, although substantially higher (45). In particular, the visual impacts of the Landmark building from the Wharf, East Cliff, West Cliff and the Boardwalk/beaches have not been thoroughly analyzed. I don't believe a story pole has been erected to show the height of this or other 3 story proposed buildings. Aesthetics are of course highly subjective but the assertions of minimal adverse effects is not justified. These are all estimates (or perhaps guesstimates) that should be subject to more rigid quantification.

With the information available, the MND could not be more specific. It is a valiant effort. But do we want to change the character of the Wharf based on probabilities and estimates or do we want to be sure we have all reasonably obtainable evidence before making this very substantial, expensive and permanent change.

Then too there are areas that are not covered at all, e.g. apparently the square "holes" at the end of the wharf that are very popular for looking at the sea lions will be closed. There is no discussion of whether the light that will be substantially reduced will make the area less attractive for the sea lions. or for the visiting public, for whom the views and sounds of thesea lions are major attractions. Nor is there any showing that the process and result of construction will not cause the sea lions permanently to leave the wharf (61). I could find no discussion of the effects of displacing long term tenants, either on economic or more personal considerations for the existing tenants. We don't know whether new or replacement businesses will be local or will have similar ambiance to those presently occupying the Wharf. And which do we want?

There is no consideration of possible alternatives to the draft master plan.

Some of these may not be appropriate to discuss in the CEQA process, but they are areas among many others that would be covered in an EIR. Surely we should have whatever information may be obtained about these and related issues. I understand that the cost of a full EIR could be very high and it is a cost we would like to avoid. But is it reasonably avoidable here and with a project of this magnitude ?

The MND cites a series of factors that should be considered. I quote them from page 3 of the MND:

- Physical inventory;
- Access, circulation and parking;
- Additional maritime potential;
- Marine sanctuary potential;
- Design and architectural character;
- Signature physical features or programs;
- Retail mix and performance; market niche; and
- A cost/benefit analysis of recommendations stemming from analysis.

I do not see that the draft neg dec covers these in adequate detail. In particular I do not see consideration of the last 3 crireria.

Reed Searle
114 Swift St
Santa Cruz, Ca. 95060
831-425-8721
hrsearle@sbcglobal.net

ATTACHMENT D: Public Comments Received After Public Review Period

-----Original Message-----
From: Gillian Greensite [mailto:gumtree@pacbell.net]
Sent: Monday, August 22, 2016 2:08 PM
To: City Council
Subject: MND for Wharf Master Plan

Dear Mayor and council members,

I have just become aware of the Wharf Master Plan's MND on tomorrow's agenda. I am out of state and unable to make the meeting. The full text of my comments on the WMP are not included in the agenda report and I am unable to access them from here to send to you. Ron Powers has a copy. I would appreciate your consideration of the concerns raised.

The staff response dismisses the concerns as not significant. To raise just one environmental issue: the staff response to comments states that birds that roost or rest on the wharf will not be impacted. Please note that Pigeon Guillemots (no relation to pigeons) are a protected species under the Migratory Bird Treaty Act. A small number of these birds nest under the wharf at the southern end. They migrate from Puget Sound to Santa Cruz and nest in the same spot each year. They are easily disturbed and will abandon their nests if disturbed. A pair that used to nest in the cliff next to the Sea and Sand at Cowell Beach abandoned its nest for the first time this year, possibly due to the disturbance from the construction of the two retaining walls on the cliff face. The MND makes no mention of this species, nor of Snowy Egrets, another protected species that inhabits the wharf on the western side where a walkway filled with people, bikes, segways etc. is proposed to be constructed. I am aware that your General Plan has not accurately mapped the Pigeon Guillemot species and incorrectly states that they are limited to the Lighthouse area. I brought that mistake to the attention of the Planning staff during the hearings for the retaining walls.

Please do not approve the MND without a more thorough bird survey conducted by an appropriate biologist to assess the impacts on these bird species from the proposed WMP.

Thank you,

Gillian

Gillian Greensite

From: Lisa Sheridan [mailto:trotrider@aol.com]
Sent: Monday, August 22, 2016 3:49 PM
To: City Council
Subject: Wharf Master Plan

Dear Santa Cruz City Council,

The Santa Cruz Bird Club has become aware of a proposal for the Santa Cruz Wharf, which is aimed at preventing birds from occupying portions of the wharf. There are a wide variety of birds which either nest, rest or shelter on the structure and may be significantly impacted by these changes. In particular the Pigeon Guillemont is regularly found nesting in this structure as well as other birds.

We urge you to prepare a through EIR review of any proposed construction or remodel on the wharf as required by CEQA when a significant adverse impact is likely to impact on the natural environment. If bird species can no longer nest or rest in this location, it seems appropriate to regard this proposal as having a "significant impact."

Best Regards,

Lisa Sheridan
Santa Cruz Bird Club President

Lisa Sheridan Photography...Mostly Birds
www.lisasheridanphotography.com

From: Barbara Riverwoman [mailto:river@cruzio.com]
Sent: Monday, August 22, 2016 3:30 PM
To: City Council
Subject: Wharf Master Plan

August 22, 2016

Dear Council Members,

The City Council must take seriously the requirements of our state regarding protection of wildlife, including migratory bird species such as the pigeon guillemot which nests under the wharf.

I just checked the Birds of North America website maintained by the Cornell Laboratory of Ornithology. According to this highly regarded site on the latest ornithological research, pigeon guillemots in California begin to build their nests up to 39 days before laying their eggs, as early as the last weeks of March. They generally lay their eggs between early May and mid-June. In case of the loss of eggs, a new clutch is initiated up to 18 days later. The average incubation period for pigeon guillemots in California is 29 days. There follows 38 days from hatching to departure from nest. Once the guillemot fledglings have left the nest, they are independent, not requiring further support from parents.

In other words, at a very minimum, no construction activity should take place after March 15 or before September 15, ie. 6 months.

This information refers only to pigeon guillemots and not to other nesting birds or sea mammals. I provide it only to give you some idea of the nesting requirements involved in the situation of pigeon guillemots. Only a qualified biologist should be relied on for a full study, conducted under the auspices of CEQA.

Sincerely,

Barbara Childs

From: Gary Patton [mailto:gapatton@icloud.com]
Sent: Monday, August 22, 2016 2:40 PM
To: City Council
Cc: William Parkin; Jonathan Wittwer; Celia Scott; Gillian Greensite
Subject: Wharf Master Plan

Dear Members of the City Council:

Below is a recent email to you from Gillian Greensite. I hope you will pay attention to her well-stated and very legitimate point.

I am not an expert on Pigeon Guillemots, but I do know quite a bit about the California Environmental Quality Act. CEQA requires you to prepare a full EIR if there "might" be a significant adverse impact on the natural environment, in connection with any project you propose to carry out. As you may remember, Ms. Greensite rather recently warned the City that it was proposing to modify its heritage tree ordinance without proper environmental review, and you ignored her warning; she sued you and won. Since I wasn't the attorney in that lawsuit, I don't know how much you paid in attorneys fees, for your own counsel and for Ms. Greensite's counsel, but I bet it was substantial. Do you want to do this all over again, this time on the Wharf Master Plan project?

As an environmental attorney, I suppose I could be happy that the City Council continues to take bad advice from its staff, and continues to try to dodge its legal responsibilities to the environment and the public. Money in the pockets of the environmental attorneys in town. I'll copy a few on this email.

As a local resident and voter, I would prefer the Council to require full environmental review of any project that might have a significant adverse environmental impact. Not only is that what state law requires, that is what is best for our community, if we want to help protect and preserve its special qualities.

The proposed Wharf Master Plan would make GIGANTIC changes to our delightful municipal wharf. There almost certainly will be some negative environmental impacts, and the public should get to weigh in on the process.

Please do a full Environmental Impact Report, to give both the public and the environment a chance.

Thank you for your attention to this request.

Yours truly,

Gary A. Patton, Attorney at Law
P.O. Box 1038
Santa Cruz, CA 95061
Telephone: 831-332-8546
Email: gapatton@gapattonlaw.com

Website: www.gapatton.net

Facebook: https://www.facebook.com/gapatton

PS: While I think the Brown Act would allow you to discuss this in a closed session, since a threat of litigation is involved, you don't have to do that. Why not hold your discussions about this issue in an open meeting, so the public can see what the various Council Members think about how to apply CEQA in this case?

From: Gillian Greensite <gumtree@pacbell.net>
Subject: MND for Wharf Master Plan
To: citycouncil@cityofsantacruz.com
Date: Monday, August 22, 2016, 5:07 PM
Dear Mayor and council members,

I have just become aware of the Wharf Master Plan's MND on tomorrow's agenda. I am out of state and unable to make the meeting. The full text of my comments on the WMP are not included in the agenda report and I am unable to access them from here to send to you. Ron Powers has a copy. I would appreciate your consideration of the concerns raised.

The staff response dismisses the concerns as not significant. To raise just one environmental issue: the staff response to comments states that birds that roost or rest on the wharf will not be impacted. Please note that Pigeon Guillemots (no relation to pigeons) are a protected species under the Migratory Bird Treaty Act. A small number of these birds nest under the wharf at the southern end. They migrate from Puget Sound to Santa Cruz and nest in the same spot each year. They are easily disturbed and will abandon their nests if disturbed. A pair that used to nest in the cliff next to the Sea and Sand at Cowell Beach abandoned its nest for the first time this year, possibly due to the disturbance from the construction of the two retaining walls on the cliff face. The MND makes no mention of this species, nor of Snowy Egrets, another protected species that inhabits the wharf on the western side where a walkway filled with people, bikes, segways etc. is proposed to be constructed. I am aware that your General Plan has not accurately mapped the Pigeon Guillemot species and incorrectly states that they are limited to the Lighthouse area. I brought that mistake to the attention of the

Planning staff during the hearings for the retaining walls.

Please do not approve the MND without a more thorough bird survey conducted by an appropriate biologist to assess the impacts on these bird species from the proposed WMP.

Thank you,

Gillian

Gillian Greensite

From: Celia Scott [mailto:twinks2@cruzio.com]
Sent: Monday, August 22, 2016 5:09 PM
To: City Council
Subject: Wharf Master Plan/Item 18, Aug. 23 agenda

Dear Council Members,

I am writing in support of the concerns of the Santa Cruz Bird Club, Gary Patton, Gillian Greensite and others who have identified inadequacies with the City's decision to adopt a CEQA Negative Declaration for the proposed Wharf Master Plan.

Among other issues, it is clear that the impacts on biological resources (birds and marine mammals) have not been adequately analyzed or mitigated under CEQA. Impacts on bird species are brushed off. The Mitigation Monitoring Plan for marine mammals will only be completed at some unspecified future date with no provision for public review prior to its adoption.

I urge the Council to do a full EIR on this project rather than a Negative Declaration. The biological resources impacted are too significant and already challenged by adverse changes in the quality of the ocean waters to do such a limited environment review.

Thank you for consideration of these comments.

Celia Scott

From: Jane Mio [mailto:jmio@earthlink.net]
Sent: Monday, August 22, 2016 5:57 PM
To: City Council
Subject: Wharf Master Plan/Item 18, Aug.23 rd agenda

Dear City Council Members,

From what I am able to tell from the records, there is no comprehensive bird study available for this area.
This lack of baseline data makes a well thought out approach for the Wharf Master Plan in regard to birds impossible.
It's highly advisable to gather this material before proceeding with action.
Thank you
jane mio

From: Rachel O'Malley [mailto:rachel.omalley@sjsu.edu]
Sent: Monday, August 22, 2016 6:01 PM
To: City Council
Subject: The Wharf Master Plan requires a full EIR

Dear Santa Cruz City Council,

Thank you for your thoughtful service on behalf of the people of Santa Cruz. We rely on you to make good decisions about the many proposals that come before you.

Today, it has come to my attention that you will be considering a substantial plan to change the face of the Santa Cruz Municipal Wharf during your meeting on August 23, 2016. I write now to strongly request that you **conduct a full EIR on this project** so that the effects of the substantial construction and greatly-increased level of human activity, sound, and lighting on marine mammals and other components of the ecosystem can be adequately assessed before you make a final decision.

I have carefully read the mitigated negative declaration and the responses to the substantive comments that are in your packet today. These documents do not adequately describe the significant impacts that this project will have on marine mammals including resident sea lions and migrating whales, migratory birds including pigeon guillemots and migratory and resident shorebirds, or other protected marine life in the Monterey Bay National Marine Sanctuary. The mitigations described do not reduce these impacts to less than significant, in large part because
- the details of the mitigation are inappropriately deferred to future study, permitting and undescribed actions, and
- the setting of this substantial development is a highly sensitive, globally unique, marine sanctuary.

In order to accurately assess the impacts on the ecosystem, full environmental review is needed. As described, substantial evidence suggests that significant unmitigated impacts will occur as a result of this project. It would be fiscally and environmentally dangerous to move forward with a decision on the basis of the flawed environmental documents before the council.

As you are aware, the Marine Mammal Act of 1972 prohibits "take" of marine mammals, including harassment due to activities such as lighting, sounds, human interactions, polluted runoff etc. The MND before you analyzes a very narrow range of such impacts on the marine mammals, rejecting the California Department of Fish and Wildlife requests for a higher level of study, and it relies on an as-yet-unwritten marine mammal monitoring plan to persuade the public that impacts will be reduced to less-than-significant. Finally, the document defers this inadequate mitigation until a further permitting step "future approvals by NOAA of Incidental Harassment Authorizations (IHA)," thus segmenting the environmental analysis.

I have attached three scientific articles to this letter.
1) Marine defaunation: Animal loss in the global ocean, documents the vulnerability of the marine

environment to adjacent human activities and development. These impacts are even more important adjacent to a national marine sanctuary that contains an unusual level of biodiversity and ecological sensitivity.
2) Effects of light pollution on the emergent fauna of shallow marine ecosystems, documents the effects of lighting on the prey of marine mammals, including baleen whales. Understanding the relationship between intensification of human use and lighting on the food resources of migratory whales in the bay is important to prevent strandings and other undesirable impacts.
3) Environmental pollution and biodiversity: Light pollution and sea turtles in the Caribbean, documents one example of how increased light can affects the marine environment in general.

These examples are not meant to be exhaustive, rather they reflect the kind of specific documentation I would expect to see for an environmental review of a project of the scope in this setting, and they provide some evidence of the kinds of significant impacts that could result from this project. Given the substantial scope of the wharf redevelopment proposed, and the sensitive location of project, a standard EIR is required before an informed decision can be made. The EIR process would allow the public and decisionmakers to learn more about the impacts and alternatives in the wharf redevelopment, and it would improve the project itself, as well as protect the environment and allow Santa Cruz residents to be heard in the process.

Thank you so much for your time and attention, and please forgive the rushed nature of this letter.

Sincerely,

Rachel O'Malley

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Rachel O'Malley, Professor
Department of Environmental Studies
San Jose State University
San Jose, CA 95192-0115
cell: 831-334-1066

NOTE: The attachments to Ms. O'Malley's email are included on CD and on the City's website at:

On the City's Planning and Community Development Department web page at http://www.cityofsantacruz.com/departments/planning-and-community-development/environmental-documents

AND

On the City's Economic Development Department webpage at http://www.cityofsantacruz.com/wharfmasterplan,

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journal homepage: www.elsevier.com/locate/marpolbul

Effects of light pollution on the emergent fauna of shallow marine ecosystems: Amphipods as a case study

Carlos Navarro-Barranco [a,*], Lauren Elizabeth Hughes [b]

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[b] Australian Museum, 6 College St., Sydney, New South Wales 2010, Australia

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Coastal management
Great Barrier Reef

ABSTRACT

Light pollution from coastal urban development is a widespread and increasing threat to biodiversity. Many amphipod species migrate between the benthos and the pelagic environment and light seems is a main ecological factor which regulates migration. We explore the effect of artificial lighting on amphipod assemblages using two kind of lights, LED and halogen, and control traps in shallow waters of the Great Barrier Reef. Both types of artificial light traps showed a significantly higher abundance of individuals for all species in comparison to control traps. LED lights showed a stronger effect over the amphipod assemblages, with these traps collecting a higher number of individuals and differing species composition, with some species showing a specific attraction to LED light. As emergent amphipods are a key ecological group in the shallow water environment, the impact of artificial light can affect the broader functioning of the ecosystem.

1. Introduction

Artificial light pollution is a threat to biodiversity, as it affects the natural behavior of communication, migration and reproduction within species, as well as disrupting community interactions such as competition or predation (Longcore and Rich, 2004; Hölker et al., 2010). Two thirds of the world population lives in coastal zones, where artificial light pollution is most prevalent (Elvidge et al., 1997; Cinzano et al., 2001). Predicted demographic spread indicates that longer stretches of the shoreline will become illuminated (Depledge et al. 2010).

The effect of artificial light on ecosystem functioning is largely unknown and research has mainly focused on terrestrial fauna and ecosystems (Rich and Longcore, 2006; Hölker et al., 2010; Lyytimäki, 2013). In the marine environment the impact of artificial light pollution has been documented for marine turtles and marine birds but few other fauna (Black, 2005; Montevecchi, 2006; Bourgeois et al., 2009; Mazor et al., 2013; Merkel and Johansen, 2011). The extent to which artificial light affects marine shallow water ecosystems is, as yet, unknown (Depledge at al. 2010). To establish conservation polices which maintain ecosystem services it is necessary to quantify the specific influence of artificial light pollution on the marine environment.

Light phase guides the activity of many marine organisms. In shallow waters, natural cycles of light and dark are an important factor which regulate the diurnal vertical migration of emergent small mobile invertebrates. Organisms with this behavior, frequently called emergent, demersal or benthopelagic zooplankton, burrow within the substrate during the day and migrate within the water column at night (Alldredge and King, 1977). Laboratory and field studies identify light as the main factor driving vertical migration, acting both as a 'releasing and directional stimulus', with organisms moving towards areas of greater luminosity as they begin to vertically migrate when a decrease in light intensity is detected (Jansson and Källander, 1968; Tranter et al. 1981; Saigusa and Oishi, 2000; Anokhina, 2006; Nakajima et al., 2009). Artificial light pollution can potentially modify the movement of emergent fauna. In fact, artificial light traps are an established sampling method in crustacean biodiversity studies, taking advantage of the attractiveness of light to small mobile invertebrates (Meekan et al., 2001).

In the marine environment artificial light pollution has two forms: firstly, the ambient glow emitted from terrestrial structures such as streetlights and housing, and secondly in situ marine light, placed either at the water's surface or slightly submerged, this includes lighting on marinas, wharfs, pontoons and on boats.

This study examines the effect of different types of urban light pollution on emergent amphipod assemblages. Control and light treatments will be assessed to understand specific impacts on these small mobile marine invertebrates.

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http://dx.doi.org/10.1016/j.marpolbul.2015.02.023
0025-326X/

2. Materials and methods

2.1. Study site

The experiments were carried out at Lizard Island (Northern Great Barrier Reef, Queensland, Australia) (Fig. 1). This remote location was chosen as it is not subject to urban light, previous studies have documented the amphipod fauna, and spatial variation of small mobile invertebrates for the region (Alldredge and King, 1977; Jones, 1984; Lowry and Myers, 2009). Experimental treatments were deployed 160 m from the shore at Casuarina Beach (14°40′46″S, 145°26′44″E) in 3.5 m depth of water. The reefal sediments beneath the treatments were composed of mainly soft sediment, with some coral-reef and seagrass patches. Alldredge and King (1977) identified this habitat as containing a high diversity and abundance of amphipods.

2.2. Light traps and sampling collection

We use a design similar to that used by Watson et al. (2002), with some modifications. Light traps were constructed from clear plastic storage boxes 40 cm long, 20 cm wide and 30 cm high. Ten entry points into the containers were made using a funnel devised from the neck of 2 l clear plastic soft drink bottles, held in position by clear silicone glue. Each funnel had a base of 15 cm diameter and a small aperture, 2 cm diameter, directed inward to the container. One additional funnel was set in reverse position at the bottom of the trap, with a drainage mesh at the end to collect the specimens when the trap was retrieved. Two lamps were installed inside each trap, fixed in position at the top of each box when submerged with lamps directing light towards the benthos (Fig. 2). Two different types of artificial light treatments were tested: 1. halogen and 2. Light Emitting Diodes (LED). Both lights are recommended for domestic use and street lighting with the aim of reducing energy consumption and light pollution (Directive 2009/125/EC of the European Parliament). Moreover, the use of high intensity LED is becoming more common to illuminate the water surrounding recreational boats. Light emission measurements of the traps were taken using a lux meter, approximately 30 cm away from the light source. Both halogen and LED showed a constant light intensity of 11 lux and 330 lux respectively during the entire duration of the experiment.

To compare the intensity of our traps with that present in an urban area, we also took light measures along Port Jackson, the body of water surrounded by the capital city of Sydney, Australia. Sixteen locations were measured at night using the lux meter. Locations were chosen based on an observed high level of artificial light pollution (tourist beaches, ferry wharfs). Six lux meter readings were made at each location from various water surface perspectives both horizontal and vertical. The mean value for

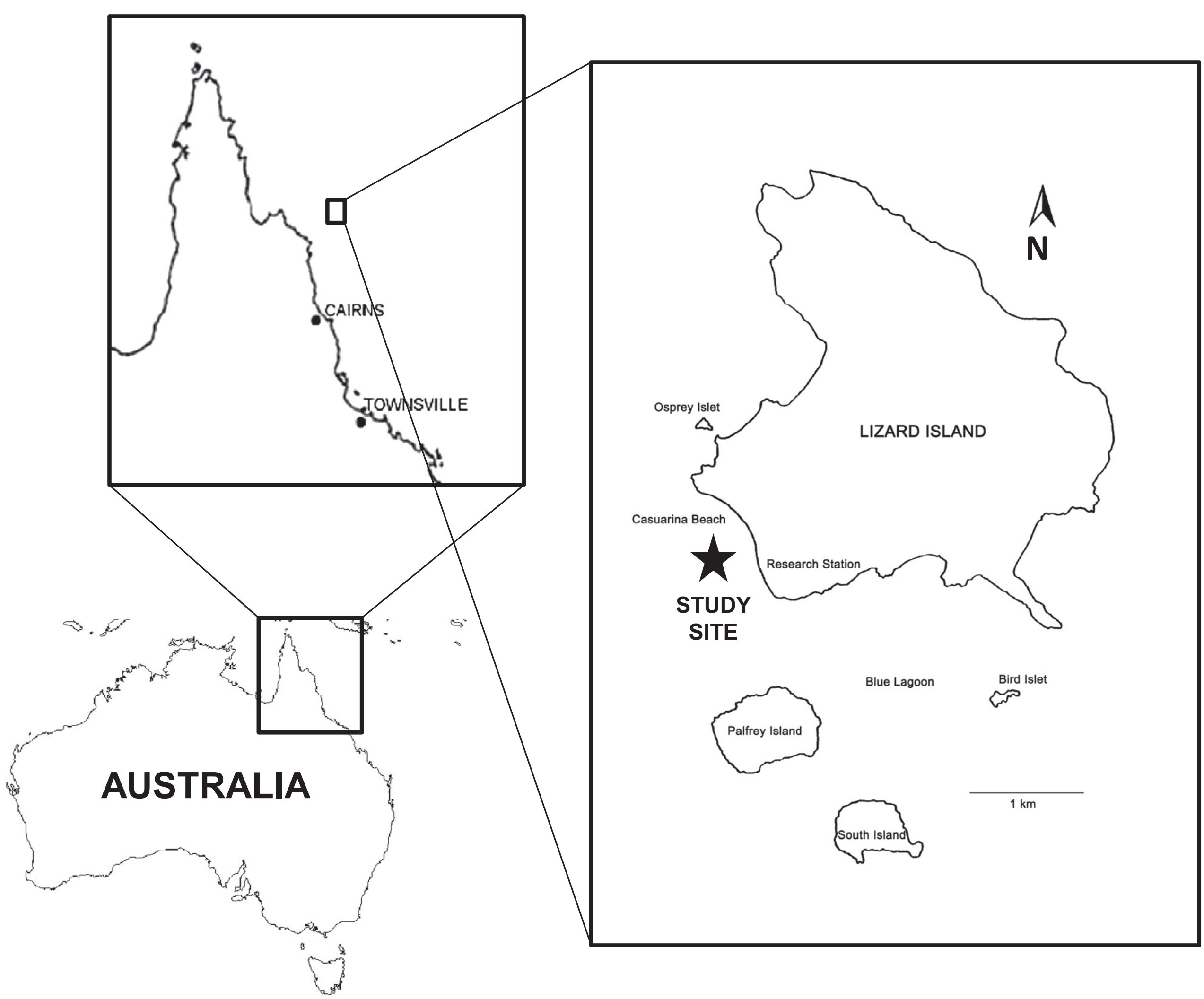

Fig. 1. Location of Lizard Island, the area of study.

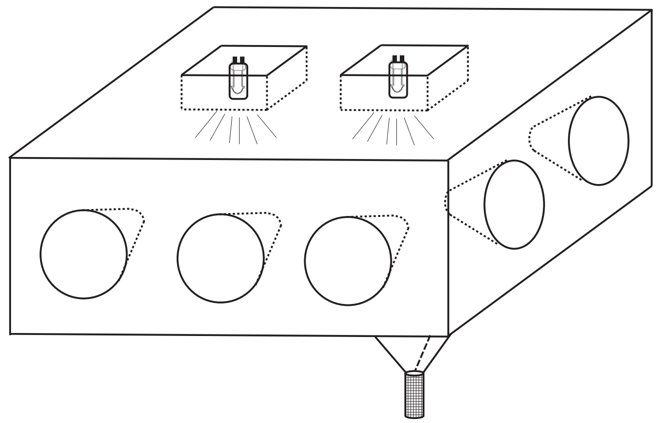

Fig. 2. Diagram of the light traps. See text for a detailed description of sizes and materials.

light measures in Port Jackson was 7 lux, varying between zero at Bondi Beach and under the well lit Sydney Harbor Bridge to 26 lux at Circular Quay Wharf. These reading varified that the halogen light traps used in our experiments were within the range of light pollution intensity observed in the waters surrounding the city of Sydney.

Six traps were deployed concurrently during twelve consecutive nights from the 1st to the 12th of November 2012. Three light treatment levels were tested: control treatment, consisting of a trap with no light, traps with LED lamps and traps with halogen lights. All traps were deployed at local sunset (approx. 7 p.m.) just below the sea surface, attached to a rope with a mooring in the bottom and a buoy in the surface, and were retrieved at local sunrise (approx. 6 a.m.). To maintain constant values of light intensity, the batteries of each trap were replaced every two days.

Samples were immediately preserved in ethanol (70%) and later examined in the laboratory using binocular microscopes. All amphipod specimens were counted and identified to genus level. Two species were found for the Synopiidae family; *Telsosynopia trifidilla* and *Synopia ultramarina*, whose exceptional morphological similarity has already been reported (Hughes, 2009). Given the difficulty in separating both genera (the only clear difference is the presence of an entire or cleft telson), we opted to reference these species together as Synopiidae. When the abundance of individuals was very high the Folsom plankton splitter (McEwen et al., 1954) was used to subsample material. Moreover, one hundred individuals of each genus were partitioned and gender determined. This was to identify any potential sex bias from genera which have a terminal male swimming phase. Terminal male morphology included a relative enlarging of the eyes, elongation of the second antennae and the uropod 3 developing marginal plumose setae. Morphological features which defined females were the presence of eggs in the brood pouch and/or well-developed oostegite plates.

2.3. Statistical analyses

Due to the demonstrated influence of the moon phase, this phenomenon was accounted for as another factor in our analyses. We separated three levels of moon phase, which each comprise four nights; full moon (nights when more than 70% of the moon was visible), quarter moon (between 30% and 70%) and new moon (nights with less than 30% of moon). Thus, the variations in the captures between treatments were examined by multivariate and univariate analyses, using a multifactorial design with the following factors; Light (Li), a fixed factor with three levels (LED, halogen and control), and Moon Phase (Mo), a fixed factor orthogonal with Li with three levels (new moon, quarter moon and full moon).

2.3.1. Multivariate analyses

A distance-based permutational multivariate analysis of variance (PERMANOVA) was carried out to test the differences in the amphipod community obtained by each treatment. Analysis was based on square root transformed data to reduce the importance of extreme values and the similarity matrix was calculated using the Bray–Curtis similarity index. Using the same similarity matrix, a cluster analysis with group-average linking was conducted to assess the affinities among treatments. An additional PERMANOVA was carried out following the same two factor design but based on standard transformed data per sample, in order to establish whether there are differences in the proportions of taxa between treatments. When analysis indicated a significant difference for a given factor, these were examined individually using appropriate pair wise comparisons in PERMANOVA. Analyses were performed using the PRIMER v.6+PERMANOVA package.

2.3.2. Univariate analyses

The variations in the abundance of each taxon between treatments were examined using a two-factor analysis of variance (ANOVA). Prior to ANOVA, the homogeneity of variances was tested using Cochran's test. When analysis indicated a significant difference for a given factor, they were examined individually using Student–Newman–Keuls (SNK) tests Univariate analyses were conducted with GMAV5.

3. Results

Eight different genera belonging to five families were identified in the traps. Only a few individuals were found for the genus *Perioculodes* and *Cymadusa* while the genus *Birubius, Dexaminoculus, Guernea, Paradexamine, Synopia* and *Telsosynopia* comprised more than 99.9% of the individuals. The genus *Guernea* was the most abundant group in all treatments, with an 89.5% of the individuals. For *Birubius, Dexaminoculus, Paradexamine, Synopia* and *Telsosynopia* genera both male and female individuals were recorded in samples, but males comprised more than 90% of individuals. No females of the genus *Guernea* were found.

According to the PERMANOVA analysis for square root transformed data, there were strong differences in the sample's composition among light treatments, while the moon phase had no significant effect (Table 1a). Pair wise comparisons showed that composition was different for all light treatments ($p < 0.001$). CLUSTER analysis also showed that the main factor responsible for separating the groups was the type of artificial light, with each light treatment forming a homogenous group. LED and halogen light treatments had a high degree of similarity with approximately 80%, while control samples only presented a similarity of 40% to both artificial light samples (Fig. 3). When data were standardized, PERMANOVA results differed. Light continued to be the only significant factor (Table 1b), but there were differences in the pair wise comparisons; LED samples differed significantly from halogen traps ($p = 0.002$) and control traps ($p = 0.011$) but no significant difference was found between these last two ($p = 0.273$). Fig. 4 also shows that only the captures of LED traps exhibited a different pattern, while similar percentages of each taxa were observed in halogen and control traps.

Comparing the light treatments for each species separately, LED traps consistantly had the highest abundance of organisms, with mean abundance varying from 3202 individuals per sample for *Guernea* to 15 individuals for genus *Dexaminoculus*. Traps with halogen lights came next and finally the control traps, with mean abundance less than 10 individuals per sample in all taxa (Fig. 5). The ANOVA results indicated that these differences among light treatments were significant for all taxa (Table 2), but the SNK

Table 1
Results of the multivariate analyse PERMANOVA for amphipod composition, based on Bray–Curtis dissimilarities of square root transformed data (A) and standardized data (B). *df* = degrees of freedom; MS = mean square; *P* = level of significance.

Source of variation	*df*	MS	*F*	*P*
(A)				
Light = Li	2	21987	27.989	0.001***
Moon = Mo	2	956.9	1.218	0.278 n.s
Li × Mo	4	568.6	0.724	0.779 n.s
Residual	63	785.5		
(B)				
Light = Li	2	5089.2	6.09	0.001***
Moon = Mo	2	2312.2	2.767	0.27 n.s
Li × Mo	4	1091.4	1.31	0.238 n.s
Residual	63	835.6		

*** $p < 0.05$

analyses reported these differences in abundance were only significant for LED traps ($p < 0.01$).

With regard to the moon phases, different patterns were observed in each taxon (Fig. 6), although ANOVA did not show any significant differences between moon phases for any taxa (Table 2). Only the captures of *Guernea* increased during the new moon. The genus *Birubius* showed the highest values on full moon nights and the lowest in new moon, and the family Synopiidae presents a strong increase in captures during quarter moon.

4. Discussion

4.1. Migration purpose

To understand how light pollution can modify amphipod behavior and their migrations it is important to know the objective of migration and the role of natural light cues. The nocturnal emergence of amphipods from the benthos to feed in the water column is an avoidance behavior against daytime visual predation (Sebens et al., 1998; De Robertis, 2002; Yahel et al., 2005). Alldredge and King (1980) suggest that dispersion to more favorable locations or mating could also be a factor that promotes the vertical migration of emergent species. Mills (1967) also suggests that the free swimming of *Ampelisca* allowed ovigerous females to disperse. However the results from this study show an almost exclusive presence of males in samples. Lastly it has been proposed that emergence may be related with ecdysis (Alldredge and King, 1980) but we did not find many individuals in that phase. Therefore, migration to the water column for feeding could be a best fit to our finding with the almost exclusive presence of males as the dispersing sex.

4.2. Moon phase effects

Our results showed no significant difference between moon phases for any taxa. Although many works reflect a higher

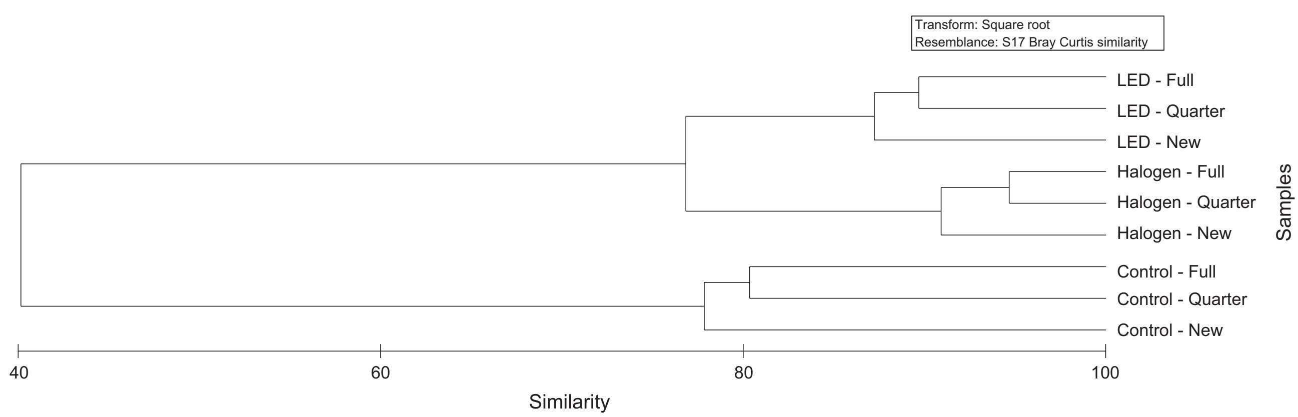

Fig. 3. Cluster analysis for species composition for each light treatment (LED, halogen and control) and moon phase (full, quarter and new moon). Data were square root transformed.

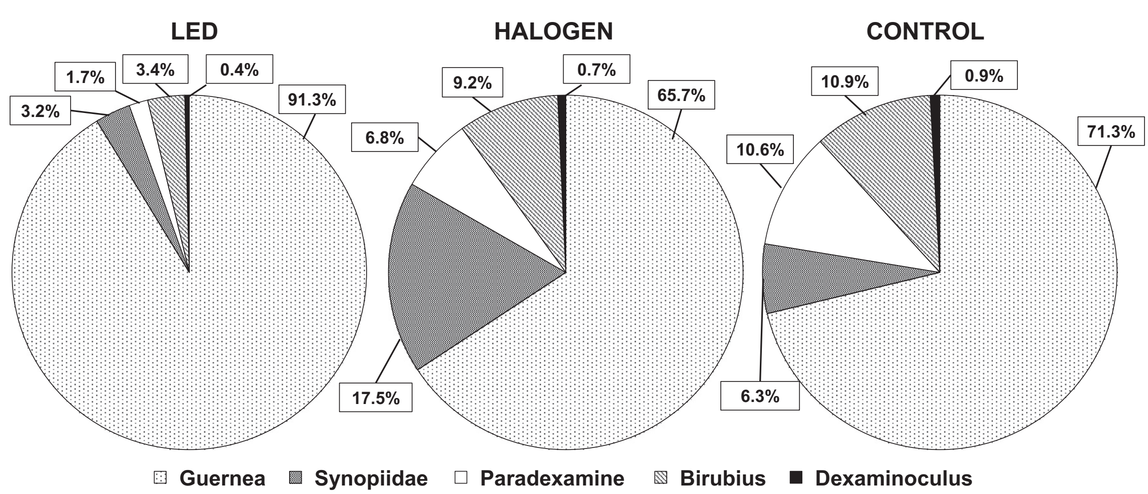

Fig. 4. Proportion of each amphipod taxa obtained by each light treatment.

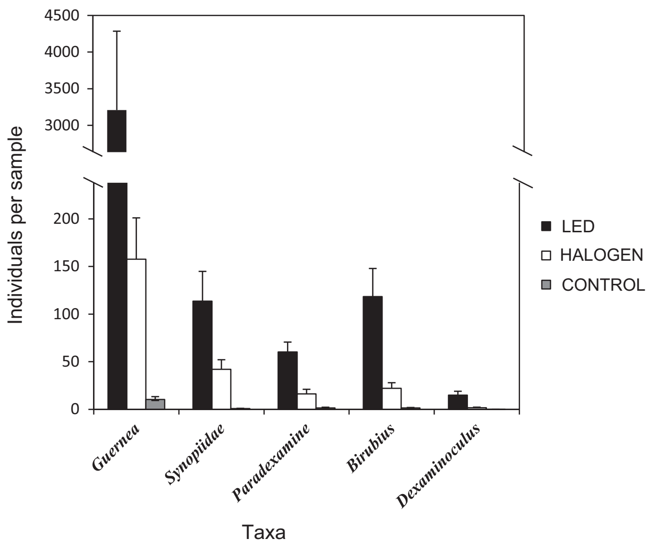

Fig. 5. Mean abundance (individuals/sample) of each amphipod taxa ± standard error of the mean obtained by each light treatment.

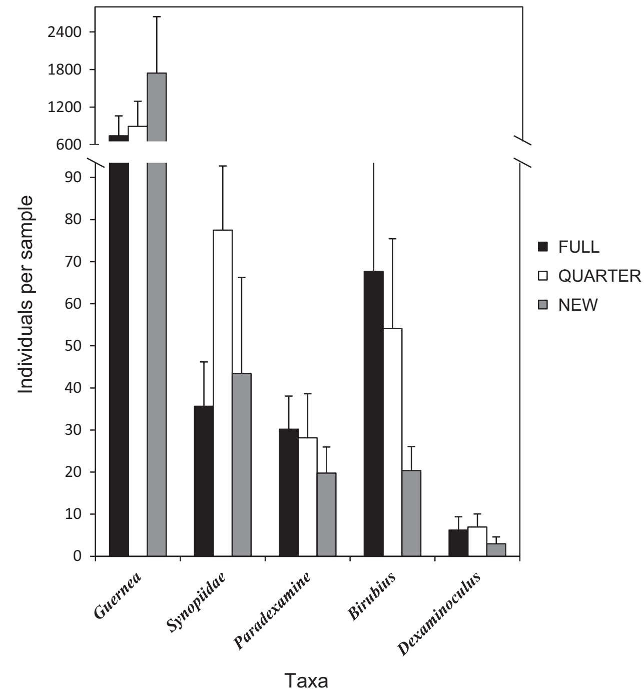

Fig. 6. Mean abundance (individuals/sample) of each amphipod taxa ± standard error of the mean obtained in each moon phase.

Table 2
Results of the two-way ANOVA for abundance of individuals of each taxa. *df* = degrees of freedom; MS = mean square; *P* = level of significance.

Source of variation	*Df*	MS	*F*	*P*
Birubius				
Li	2	93,543	13.67	0.000***
Mo	2	14,283	2.09	0.132^{ns}
Li × Mo	4	9417	1.38	0.252^{ns}
Residual	63			
Dexaminoculus				
Li	2	1433	10.49	0.000***
Mo	2	108	0.79	0.457^{ns}
Li × Mo	4	200	1.47	0.222^{ns}
Residual	63			
Guernea				
Li	2	85,714,867	8.97	0.000***
Mo	2	5,848,057	0.61	0.545^{ns}
Li × Mo	4	4,446,209	0.47	0.761^{ns}
Residual	63			
Paradexamine				
Li	2	22,396	20.38	0.000***
Mo	2	731	0.67	0.517^{ns}
Li × Mo	4	613	0.56	0.694^{ns}
Residual	63			
Synopiidae				
Li	2	78,002	8.93	0.000***
Mo	2	11,894	1.36	0.563^{ns}
Li × Mo	4	5717	0.65	0.626^{ns}
Residual	63			

*** $p < 0.001$

abundance of organisms on new moon nights (Tranter et al., 1981; Jacoby and Greendwood, 1988; Anokinha, 2006; Drazen et al., 2011), these results were obtained taking the whole zooplankton community into account. When these data were analyzed in more detail, it was found that different groups showed different patterns. Jacoby and Greendwood (1988) found that emergent amphipods did not exhibit significant peaks in emergence during any lunar period. Saigusa and Oishi (2000) did not observe any significant relation between the emergence rhythms of amphipod species and the lunar cycles. Thus, our results, with no significant difference between moon phases for any taxa, agree with these previous studies. Alldredge and King (1980) found that some amphipod species exhibited significant avoidance of moonlight, showing higher emergence during moonless periods than on nights of quarter moon, but not all the species followed that trend and there were not significant differences among moon phases in the total abundance of amphipods collected during the whole night. We also observed high variability in behavior among taxa and these notable differences were even present within the same family; genera *Dexaminoculus, Guernea* and *Paradexamine* (all belonging to family Dexaminidae) showed different trends. As pointed out by Jacoby and Greendwood (1988), these results show the need for caution when generalizing about emergent fauna.

This high variability in migration behavior among taxa also supports the previous hypothesis about feeding as the aim of the migration, as this interspecific difference in migration timing could have evolved as a mechanism to promote differentiation in resource use patterns to achieve competitive coexistence (Branch, 1984; Beerman and Franke, 2012).

4.3. Light impact

The consequences of increased vertical migrations in coastal communities can be especially relevant in coral reefs. Emergent fauna is especially conspicuous over coral reefs (Ohlhorst, 1982) and in these environments they could be less resilient to the introduction of artificial light pollution as tropical communities have year round consistant daily cycles, marking them as especially sensitive to alterations in natural daily patterns of light, (Gliwicz, 1999). Moreover, small-scale variations in the distribution of zooplankton has been suggested as an important ecological factor in coral reefs ecosystem structuring (Yahel et al., 2005).

Our results clearly support an increase in the concerntration of individuals in artificial light traps. Both light traps (LED and halogen) showed significantly higher number of individuals for all species, where light attraction seems to be a consistant behavior in all emergent amphipods. For example, the genus *Guernea*, the most abundant genus in our study, showed abundances more than eighty times higher in light traps than in control traps. Within the light traps, LED lights (with much higher light intensity) captured more individuals than halogen lights.

Finally, light pollution could effect a change in the amphipod composition of the pelagic assemblages at night. Halogen light traps attracted a higher abundance of amphipods, but the composition of this amphipod assemblage was similar to that which was present in non-illuminated control traps. However, LED lights have a stronger effect over emergent fauna, as they affect both abundance and composition. In our case, *Guernea* sp. seemed to have the highest attraction to LED lights.

The use of LED lights is restricted to marinas and recreational boats. In spite of this, we have to take into account that, only in Queensland, there were almost 230,000 registered recreational marine vessels in 2009, with an average annual growth rate of approximately 3.5% (Blackman and Jones, 2010). Ninety-five percent were vessels of less than eight meters, which operate and moor close to the shore, in sheltered environments such as bays, estuaries or back reefs. So, there are areas where the impact of these vessels and LED lights may be significant.

We can conclude that artificial lighting of shallow zones significantly modifies the behavior and distribution of amphipods and these modifications can have an impact on the whole ecosystem. Based on biomass, amphipods are the dominant taxa within emergent zooplankton (Anokhina, 2006), which is an important source of food for nocturnal planktivorous predators such as fishes, corals, and crinoids (Alldredge and King, 1985; Heidelberg et al., 2004; Holzman et al., 2005). Thus, alteration in the composition and abundance of amphipods in the environment caused by artificial light pollution will change prey availability for zooplanktivorous predators (Ioannou et at., 2012). The high attraction of emergent amphipods to light promotes a huge increase in abundance and thus biomass around artificially lit areas. Future specific studies should be carried out to evaluate the impact of such high amphipod attraction across the ecosystem and for other benthic environments.

Acknowledgments

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Environmental pollution and biodiversity: Light pollution and sea turtles in the Caribbean

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ABSTRACT

We examine the impact of pollution on biodiversity by studying the effect of coastal light pollution on the sea turtle population in the Caribbean. To this end we assemble a panel data set of sea turtle nesting activity and satellite-derived measures of nighttime light. Controlling for the surveyor effort, the local economic infrastructure, and spatial spillovers, we find that nighttime light significantly reduces the number of sea turtle nests. According to data on replacement costs for sea turtles raised in captivity, our result suggests that the increase in lighting over the last two decades has resulted in the loss of close to 1800 sea turtles in the Caribbean, worth up to $288 million. Incorporating our empirical estimates into a stage-structured population model, we discover that the dynamic effect of nighttime light on future generations of sea turtles is likely to be much larger, with a cost of approximately $2.8 billion for Guadeloupe alone. More generally, our study provides a new approach to valuing the cost of environmental pollution associated with species extinction.

Introduction

Over the last few decades, coastal areas have witnessed considerable growth in economic activity (UNEP, 2008). Inevitably, such growth has also been accompanied by significant increases in environmental pollution that potentially threatens the rich biodiversity that is characteristic of the world's coastlines (Jackson et al., 2001; Myers and Worm, 2003). One important aspect of the biodiversity debate is the protection of species from extinction, since any disappearance of species will reduce biodiversity (Polasky et al., 2005). More recently, the impact of increased lighting on biodiversity because of local economic development has been the focus of attention (Navara and Nelson, 2012; Gaston et al., 2013; Kyba and Holker, 2013). While a number of studies have already demonstrated that some marine species are particularly sensitive to light pollution (Bustard, 1967; Witherington and Martin, 1996; Bird et al., 2004), the impact of rising coastal illumination has gone largely unexplored (Hill, 2006; Rich and Longcore, 2006; USC, 2008). In this study, we investigate how light pollution in Caribbean coastal areas may have affected the critically endangered sea turtle

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population (IUCN, 2001).[1] As Nicholas (2001) points out, light pollution in the Caribbean is already thought to be an important threat to the three indigenous turtle species. Hence, in this paper we provide a quantitative estimate of the impact of light pollution on Caribbean sea turtle populations in both the short and long term.

In the natural sciences, considerable attention is given to the preservation of biodiversity and species extinction. Economists are also concerned with similar issues but have tended to concentrate on the design and implementation of conservation policies subject to resource constraints. Examples of different studies on this broader topic include harvesting (Clarks, 1973; Costello et al., 2008), habitat change (Polasky et al., 2004; Hanley et al., 2009), and the general problem of measuring biodiversity (Solow et al., 1993; Weitzman, 1992, 1998). Important related research includes studies on natural capital and sustainability (see Helm and Hepburn, 2014, for a recent survey).[2] In terms of pollution more generally, Polasky et al. (2005), Spangenberg (2007), and UNEP (2012) emphasise the detrimental role that pollution may play in loss of biodiversity or species extinction. Indeed, pollution is widely recognised as one of the key threats to biodiversity.[3] Moreover, biodiversity conservation is often the subject of public discourse in response to major pollution incidences such as the Deepwater Horizon oil spill.[4] Polasky et al. (2005) argue that an understanding of how human actions impact biodiversity and how this relationship changes over time is a major remaining challenge for the economics of biodiversity.

A number of papers in the natural science literature note that the presence of nighttime light is likely to interfere with sea turtle behaviour in several ways. Artificial nighttime light tends to deter sea turtle adults from nesting (Raymond, 1984; Hirth and Samson, 1987; Witherington, 1992; Johnson et al., 1996). It also reduces the ability of sea turtle hatchlings to find their way from the beach where they hatch to the sea, thus resulting in higher mortality rates due to exhaustion, dehydration, and predation (Bustard, 1967; Tuxbury and Salmon, 2005; Lorne and Salmon, 2007). However, the quantitative effect of nighttime light on sea turtle nesting and population levels has not yet been investigated statistically or has been limited to case studies of particular beaches (Kaska et al., 2003; Witherington and Frazer, 2003). The only exception is the study by Mazor et al. (2013), who investigated the effects of satellite-measured nighttime light on sea turtle nesting in coastal areas of Israel. However, although their descriptive statistics suggest a negative correlation between nighttime light and nesting activity, the authors find that the relationship between nighttime light and nesting is positive according to regression analysis.[5] Importantly, however, they did not control for either surveyor effort or potential spatial spillovers between beaches. Moreover, they did not, as we do here, interpret their quantitative estimates in terms of either the short- or long-term impact.

Our paper contributes to the existing literature in a number of ways. First, we provide a quantitative assessment of how a potentially important type of pollution affects an endangered species. More specifically, we estimate the impact of nighttime light pollution on sea turtle populations in Guadeloupe by combining data for satellite-derived nighttime light images, the location of nesting sites, nesting activity, local economic activity, and surveyor effort. From a methodological perspective, we explicitly take into account the spatial effects of nighttime light pollution on sea turtle nesting in the context of a count data model. We then apply our estimates to a population model that enables us to capture the dynamic implications of nighttime light on the sea turtle population. To this end, we incorporate our estimates into a simulation of sea turtle population dynamics for Guadeloupe using a stage-structured population model first described by Crouse et al. (1987) and Crowder et al. (1994). Our approach follows Crowder et al. (1994), who investigated how turtle excluder devices in trawl fisheries affect the sea turtle population in the Southeastern United States. However, in contrast to Crowder et al. (1994), we estimate rather than assume the impact of our factor of interest on the population dynamics.

To briefly summarise our main findings, we show that after controlling for local economic activity and the effort made in nest counting in the econometric analysis, there is a significant negative impact of coastal nighttime light on the nesting activity of sea turtles in Guadeloupe. Other things being equal, we provide evidence that an increase of 1 unit in nighttime illumination reduces the number of nests by approximately 4. Extending our estimate of the marginal effect of nighttime light to the whole Caribbean, we benchmark against the cost of rearing sea turtles in captivity and find that the replacement cost for the nearly 1800 sea turtles estimated as lost due to greater nighttime illumination since 1992 may be as high as $288 million. With respect to the impact of nighttime illumination on future generations of sea turtles, we conclude from our calibrated population model for Guadeloupe that the fertility drop caused by photopollution appears to substantially accelerate the extinction of sea turtles. For hawksbill and green turtles, coastal nighttime light decreases the time to extinction from 164 and 154 years to 130 and 139 years, respectively. This impact is even greater for leatherback turtles, which, under current light conditions, would disappear in 514 years, but without

[1] In this paper we consider three different species of turtle. Of those, both the green turtle (*Chelonia mydas*) and the leatherback turtle (*Dermochelys coriacea*) were classified as endangered in 1996, while the hawksbill turtle (*Eretmochelys imbricata*) was listed as endangered in 1986 before being changed to critically endangered in 1996.

[2] As observed above, species extinction is a key component of the biodiversity debate (Solow et al., 1993). Mace (2014) notes that conservation biologists, nature conservationists, and wildlife managers care explicitly about endangered species and extinction. Moreover, Polasky et al. (2005) distinguish between two categories of biodiversity measures: measures based on relative abundance and measures based on joint dissimilarity. It is the latter category that tends to be most frequently used in the economic literature when there is a focus on extinction (Weitzman, 1992).

[3] See the Convention on biological diversity at http://www.cbd.int for details.

[4] The report of the Center for Biodiversity (April 2011) showed that more than 82,000 birds, 6,000 sea turtles, 26,000 marine mammals, and an unknown large number of fish and invertebrates may have been harmed by the oil spill and its aftermath.

[5] See Figure 3 and Tables 2 and 3 of their paper. It is noteworthy that in an earlier study, Aubrecht et al. (2010) also found a positive relationship between nighttime light intensity and sea turtle nesting activity in Florida from a simple plot of their data. However, as the authors argue, this counterintuitive finding may have been a result of legislation in the mid-1980s that imposed regulations on beachfront lighting for protection of sea turtles on beaches that were more brightly lit.

nighttime light would not become extinct. Finally, our estimates suggest that offsetting the future impact of nighttime light pollution could cost up to $2.8 billion.

The remainder of the paper is organised as follows. Section "Sea turtle nesting and nighttime light" reviews the literature on the potential effects of light pollution on sea turtles. In Section "Data description", we describe our database. The econometric methodology is introduced in Section "Econometric model" and the econometric results are discussed in Section "Econometric results". In Section "Missing sea turtles in the Caribbean" we compute the replacement cost for lost turtles in the Caribbean, and in Section "Population dynamics" we investigate the population dynamics and value the implications under different scenarios. Section "Concluding remarks" concludes.

Sea turtle nesting and nighttime light

It is now widely accepted that coastal nighttime light may deter sea turtles from nesting (Raymond, 1984; Witherington and Martin, 1996; Witherington and Frazer, 2003; Jones et al., 2011). Although sea turtles spend very little of their life on beaches, where females nest and hatchlings emerge, almost exclusively at night, these nocturnal activities are critical to the creation of future generations of sea turtles and may be significantly disturbed by nighttime illumination. Raymond (1984) and Witherington (1992) have shown that artificial lighting drastically alters the way in which adults choose their nesting sites, as they generally prefer unlit beaches. Nighttime illumination also increases the possibility of direct human disturbance of nesting activity (Carr and Giovannoli, 1957; Carr and Ogren, 1958), frequently causing turtles to abandon their nesting attempts (Hirth and Samson, 1987; Johnson et al., 1996) and to expedite the process of covering the eggs and camouflaging the nest site (Johnson et al., 1996). Moreover, Witherington and Martin (1996) found that sea turtles discard their eggs in the ocean without nesting when there is a lack of appropriate dark beaches. Photopollution may also affect the return of adult sea turtles to the ocean after nesting. A number of experimental studies have shown that adult turtles rely on brightness to locate the sea (Caldwell and Caldwell, 1962; Ehrenfeld and Carr, 1967; Ehrenfeld, 1968; Mrosovsky and Shettleworth, 1975). However, this problem seems to be less severe for adults than for hatchlings (Witherington and Martin, 1996).

Hatchlings emerge from eggs beneath the sand mainly at night, and then crawl to the sea via the most direct route possible to increase their survival chances (Hendrickson, 1958; Bustard, 1967; Neville et al., 1988; Witherington et al., 1990). However, by creating unnatural stimuli, nighttime light can disrupt their instinctive sea-finding mechanism, often resulting in disorientation and causing hatchling death due to exhaustion, dehydration, and predation (Bustard, 1967; Witherington and Martin, 1996). It has also been observed that indirect lighting can act as a perturbing factor by reflecting off buildings or trees that are visible from the beach (Witherington and Martin, 1996). The difficulty in finding the sea for hatchlings, together with the possibility of adult disorientation, has led in some cases to replacement of the common blue-light (shorter wavelength) beach illumination with red-light (longer wavelength) lamps, since it has been found that sea turtles are more sensitive to blue light.[6] Nevertheless, such measures are frequently criticised because any illumination tends to encourage human activity on beaches (Witherington and Martin, 1996).

It is important to note that sea turtles exhibit natal philopatry, so females are likely to return to their natal beach for nesting. However, they may nest on neighbouring beaches if the original site is no longer suitable (Worth and Smith, 1976; Witherington and Martin, 1996). Nighttime light may therefore have spatial spillover effects: a beach may receive additional turtles because neighbouring nesting sites are brighter. Not taking this into account could thus lead to a biased estimation of the effect of nighttime illumination.

Data description

Turtles nests

The sea turtle nesting data were provided by the *Guadeloupe Sea Turtles Recovery Action Plan*.[7] The survey identified a total of 156 beaches in Guadeloupe and their geolocation. Of these, 67 beaches are known nesting beaches and were regularly surveyed for nesting activity at night during the nesting season of 2008, 2010, and 2013. These 67 beaches thus constitute the basis of our analysis, including the identification of neighbouring nesting beaches. The data include the number of nests, the number of times the beach was surveyed, and the sea turtle species. The species indigenous to Guadeloupe are the green turtle (*Chelonia mydas*), the hawksbill turtle (*Eretmochelys imbricata*), and the leatherback turtle (*Dermochelys coriacea)*. Summary statistics and definitions of the nesting data, as well as all other variables used in our analysis, are provided in Table 1. On average, each beach was surveyed 52 times, with a mean discovery of 31 nests, although

[6] For instance, low-pressure sodium vapour lamps seem to affect nesting less than light from other sources (Witherington, 1992).

[7] Source: Réseau Tortues Marines Guadeloupe/ONCFS; funding: DEAL Guadeloupe/Conseil Régional de la Guadeloupe/FEDER. See http://www.tortuesmarinesguadeloupe.org and Santelli et al. (2010) for further details.

Table 1
Descriptive statistics.

Variable	Description	Obs. (n)	Mean	Std. dev.	Min.	Max.
All species	No. of nests	201	30.57	83.01	0	830
Hawksbill	No. of nests	201	20.19	74.38	0	830
Green	No. of nests	201	9.05	36.41	0	358
Leatherback	No. of nests	201	1.32	3.96	0	26
Nighttime light	Nighttime light intensity	201	14.50	10.83	0	53
Effort	No. of beach visits	201	52.44	50.86	0	237
Roads	Presence of roads	201	0.45	0.50	0	1
Marinas	No. of docks	201	25.72	51.78	0	224
Hotels	No. of beds	201	23.72	108.54	0	688
Ports	Distance (km)	201	25.12	14.38	2.22	57.58

Note: The total number of observations is 67 beaches × 3 years = 201, with variations over time for nesting activity, nighttime light, and effort. For roads, marinas, hotels, and ports we use data from the end of 2013.

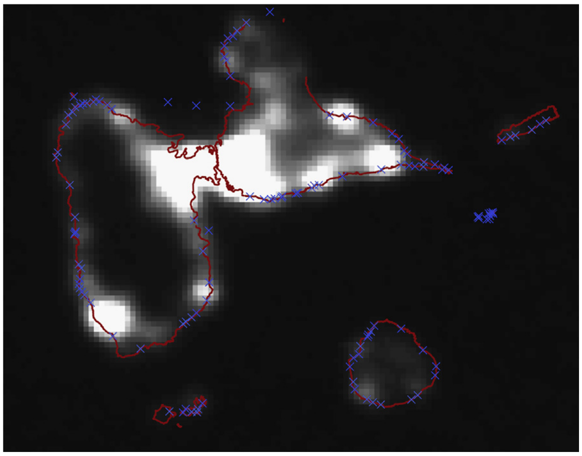


Fig. 1. Nighttime light and nesting sites in Guadeloupe.

there is considerable variation for both surveying effort and nest discovery across beaches. More than half of the nests found were for the hawksbill turtle.

Nighttime light

As a proxy for nighttime illumination at the local level, we use data derived from satellite images of nighttime light provided by the Defense Meteorological Satellite Program (DMSP). In terms of coverage, each DMSP satellite has a 101 min near-polar orbit at an altitude of approximately 800 km above the surface of the earth, providing global coverage twice per day at the same local time each day. In the late 1990s, the National Oceanic and Atmospheric Administration (NOAA) developed a methodology to generate “stable, cloud-free night light data sets by filtering out transient light such as produced by forest fires, and other random noise events occurring in the same place less than three times” from these data (see Elvidge et al., 1997 for a comprehensive description). The resulting images denote the percentage of nighttime light occurrences for each pixel per year normalised across satellites to a scale ranging from 0 (no light) to 65 (maximum light). The spatial resolution of the original pictures is approximately 0.008° on a cylindrical projection (*i.e.*, with constant areas across latitudes) and has been converted to a polyconic projection, leading to squares of approximately 1 km^2 near the equator. To obtain yearly values, simple averages across daily (filtered) values for grids were generated. Data are publicly available on an annual basis over the period 1992–2013.[8]

Fig. 1 shows a nighttime light image of Guadeloupe in 2013 and the location of nesting beaches. It is evident that there is an unequal distribution of nighttime light intensity across the islands. More importantly, a large part of the brightness is concentrated on or near the coast.

[8] Note that a number of studies have used nighttime light as a proxy for economic activity, such as Henderson et al. (2012). Here we use nighttime light as measure of local light intensity during the night, while controlling for economic activity in the area.

Other data

We gathered information on the location of hotels and their capacity from a number of sources, including www.guadeloupe-antilles.com, Google Maps, and the websites for the hotels. We identified 69 hotels near our nesting beaches as of 2013. The capacity of these ranges from 10 to 688 beds. We obtained information on ports and marinas from www.portbooker.com and general internet searches. Using this approach we identified the geolocation of the two main ports in Guadeloupe and calculated the distance to the nearest port for each beach. There were a total of 24 marinas, ranging in size from two to 224 docks. As a benchmark measure we summed the number of docks within 1 km of each beach. To generate a dummy variable indicating the presence of roads within 1 km of the beaches, we used the shape files available at www.diva-gis.org/gdata and the centroid for each beach.

Econometric model

Given that our dependent variable is a count of the number of nests, standard linear regression techniques would not be appropriate. In choosing the relevant model for count data it is important to first consider whether the data are characterised by overdispersion. The summary statistics in Table 1 reveal that this is clearly the case, as the variance is substantially greater than the mean. When overdispersion exists, it is generally preferable to use a negative binomial rather than the more common Poisson count model. However, overdispersion may also be caused by a large proportion of zeros in the data, rendering traditional distributions insufficient to describe the data at hand. In our data, 27% of nesting beaches had no nesting activity. We therefore follow Famoye and Singh (2006) and experiment with the zero-inflated Poisson (ZIP) and the zero-inflated generalised Poisson (ZIGP) models. The generalised Poisson regression (GPR) model is given by

$$f(\mu_i,\alpha,y_i)=\left(\frac{\mu_i}{1+\alpha\mu_i}\right)^{y_i}\frac{(1+\alpha y_i)^{y_i-1}}{y_i!}\exp\left[\frac{-\mu_i(1+\alpha y_i)}{1+\alpha\mu_i}\right], \tag{1}$$

where $y_i=0,1,2,\dots$ indicates the number of nests, $\mu_i=\mu_i(x_i)=\exp(\sum_{j=1}^{k}x_{ij}\beta_j)$ is the mean of y_i, $x_i=(x_{i1}=1,x_{i2},\dots,x_{ik})$ is the ith row of the covariate matrix X, and $\beta=(\beta_1,\beta_2,\dots,\beta_k)'$ is a k-dimensional column vector of parameters. Subscript i denotes beach $i=1,\dots,67$. The parameter α is a measure of dispersion, where there is overdispersion if $\alpha>0$, while the model reduces to a standard Poisson regression model if $\alpha=0$. As noted, any overdispersion due to an excess of zeros can be accounted for using the ZIGP model:

$$\begin{aligned}P(Y=y_i|x_i,z_i)&=\varphi_i+(1-\varphi_i)f(\mu_i,\alpha,0),\quad y_i=0\\&=(1-\varphi_i)f(\mu_i,\alpha,0),\quad y_i>0,\end{aligned} \tag{2}$$

where $0<\varphi_i<1$ and $\mu_i=\mu_i(z_i)$ and $\varphi_i=\varphi(z_i)$ satisfy $\text{logit}(\varphi_i)=\log(\varphi_i[1-\varphi_i])^{-1}=\sum_{j=1}^{m}z_{ij}\delta_j$. $z_i=(z_{i1}=1,z_{i2},\dots,z_{im})$ is the ith row of covariate matrix Z and $\delta=(\delta_1,\delta_2,\dots,\delta_m)$ is a m-dimensional column vector of known parameters. We assume that X and Z contain the same covariates. Note that the distribution of y_i is characterised by overdispersion when $\varphi_i>0$ and that this model reduces to the ZIP model when $\alpha=0$. The mean and variance of the count variable y_i are given by

$$E(y_i|x_i)=(1-\varphi_i)\mu_i(x_i) \tag{3}$$

and

$$\begin{aligned}V(y_i|x_i)&=(1-\varphi_i)[\mu_i^2+\mu_i(1+\alpha\mu_i)^2]-(1-\varphi_i)^2\mu_i^2\\&=E(y|x_i)[(1+\alpha\mu_i)^2+\varphi_i\mu_i].\end{aligned} \tag{4}$$

As argued earlier, there is reason to believe that nesting behaviour may be correlated across space. One possibility for modelling this correlation is the spatial correlation in the error term. To this end, we follow Czado et al. (2007) and use a Gaussian conditional autoregressive (CAR) formulation, which allows modelling of spatial dependence and dependence between multivariate random variables for irregularly spaced regions. More specifically, for our set of J beaches $\{1,2,\dots,J\}$ we let $\gamma=(\gamma_1,\gamma_2,\dots,\gamma_J)'$ be the vector of normally distributed spatial effects for each beach:

$$\gamma\sim N_J(0,\sigma^2Q^{-1}) \tag{5}$$

$$Q_{ij}=\begin{cases}1+|\Psi|\cdot N_i & i=j\\-\Psi & i\approx j\\0 & \text{otherwise},\end{cases} \tag{6}$$

where N_i is the number of beaches within area i and $\approx$ indicates that i and j are neighbouring beaches. The conditional distribution of the spatial effects γ_i is then

$$\gamma_i|\gamma_{-i}\sim N\left(\frac{\Psi}{1+|\Psi|\cdot N_i}\sum_{j\approx -i}\gamma_j,\sigma^2\frac{1}{1+|\Psi|\cdot N_i}\right), \tag{7}$$

where γ_{-i} are all the other values of γ and the sum above includes all the spatial effects of neighbouring beaches. Importantly, Ψ determines the degree of spatial dependence: when $\Psi=0$ there is no spatial dependence across the error term, but as spatial dependence increases the value of Ψ also increases. In other words, when $\Psi > 0$, then shocks to nesting activity on one beach will have an effect on neighbouring beaches.

Econometric results

The results for estimates of the determinants of nesting activity using the ZIGP model are given in Table 2. For all specifications we include year dummies. We used a Clarke (2003, 2007) test for all specifications to determine whether the model could be reduced to a ZIP model by setting the overdispersion parameter to $\alpha = 0$. The Clarke test statistic in Table 2 suggests that ZIGP is the preferred model for all specifications. In the baseline regression in column 1, we only include our time-varying nighttime light measure as an explanatory variable without any spatial effects. The results suggest that the nighttime light intensity has a significant negative effect on the number of sea turtle nests.

Since the ZIGP is a nonlinear model, the coefficients have no straightforward intuitive interpretation. Marginal effects on nesting activity for any explanatory variable x_k with estimated coefficient β_k are thus calculated as follows:

$$\frac{\partial y}{\partial x_k} = \beta_k \exp\left(\beta_1 + \sum \beta_j \cdot \overline{x_j}\right), \tag{8}$$

where β_1 is the constant in the regression, $\overline{x_j}$ denotes the average of covariate x_j, and the terms to which the summation operator $\sum$ apply are the explanatory variables found to be significant. The marginal effects of the significant coefficients for each specification in Table 2 are shown in Table 3. Accordingly, the estimated coefficient for the first specification suggests that a 1-unit increase in nighttime light reduces the number of nests by 0.59. As noted earlier, one concern is that sea turtle nesting behaviour may be spatially correlated. This would potentially induce correlation between the error term and the covariates, resulting in a biased estimate, particularly if there is omitted variable bias (Pace and LeSage, 2010). In the second specification we thus allow for spatial correlation of the error term as outlined above. As a benchmark, we considered beaches within 5 km of each other as neighbours. The significant positive estimate of the spatial parameter Ψ suggests that the data indeed exhibit spatial dependence across neighbouring beaches. The second specification reveals that the marginal effect is somewhat lower, at -0.48 nests, than without spatial correlation. We thus continue to allow for spatial effects in all remaining regressions.[9]

To confidently conclude that the estimated marginal effect in Table 3 is the causal effect of beach lighting intensity on sea turtle nesting activity, we need to assume that there is no omitted variable bias. It can be argued that this is unlikely to be the case. For instance, the number of nests discovered on a beach is likely to depend on the effort made by those counting. In addition, it is possible that greater effort might be undertaken on those beaches that are better lit, with a potential bias that could reduce the negative effect of nighttime light. To investigate this potential endogeneity bias, we included a proxy for surveying effort in the third specification. As expected, greater effort increases the number of nests discovered. Comparison of the marginal effects of lighting between specifications without and with the effort variable shows that there is a downward bias, with a reduction per unit of nighttime light of nearly 40% for the latter. This suggests that beaches with more illumination could be subject to greater monitoring.

Nighttime light intensity may also be correlated with a number of other features of local economic activity that may affect sea turtle decisions to nest on a particular beach. For example, beaches are usually more brightly lit the closer they are to hotels, and a nearby hotel is also likely to increase the probability of tourist disturbance of nesting activity. To ensure that the estimated effect of nighttime light intensity does not capture these other local features, *i.e.*, to further reduce any endogeneity bias, we included distance to the nearest port, the total number of hotel beds, the number of docks, and an indicator variable of the presence of roads within a 1 km radius of each beach. Column 4 in Table 2 shows that ports, roads, and marinas have no significant effect on nesting. By contrast, greater hotel capacity in the vicinity reduces the number of nests found on a beach. We find that the marginal effect increases multiple times: the estimated coefficients imply that 1 unit of nighttime light reduces the number of nests by 3.3.

In addition to the variables already controlled for, other location-specific variables could be correlated with nighttime light. For example, some parks, marine protection areas, and reserves on Guadeloupe are closed during the nesting season (Dow et al., 2007). If such closures result in reduced economic development in these areas but also increase the number of nests, then this would induce an upward bias in our coefficient for nighttime light. Fortunately the panel nature of our data set allows us to potentially control for all other such factors by assuming they are time-invariant and including a set of beach-specific dummy variables to capture the factors. Doing so, as shown in column 5 of Tables 2 and 3, produces a number of interesting findings. First, the marginal effect increases by approximately 17%, so that 1 unit of nighttime light intensity reduces the number of nests by 3.9. Thus, not controlling for beach-specific effects induces downward bias for our coefficient. Second, inclusion of beach dummies renders the effort proxy nonsignificant. Importantly, this suggests that even if we do not have information regarding the effort intensity for beach monitoring, we may be able to control for this by using beach dummies, at least in a short panel.

Our analysis can also be performed by sea turtle species. Our sample consists of 66% hawksbill, 30% green, and 4% leatherback nests. Given the small sample size for leatherback nests, estimation of the spatial model was not feasible, and we only re-estimate specification 5 for hawksbill and green turtle nests (columns 6 and 7, respectively). Reassuringly,

[9] According to the results in Table 2, the spatial effects are always statistically significant.

Table 2
Determinants of sea turtle nesting activity.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Nighttime light	−0.02247* (−0.04180, −0.01018)	−0.02729* (−0.04464, −0.00748)	−0.03149* (−0.05087, −0.01556)	−0.00256* (−0.00272, −0.00245)	−0.11807* (−0.16132, −0.05002)	−0.12641* (−0.21901, −0.01591)	−0.13019* (−0.16937, −0.01134)
Effort			0.00047* (0.00046, 0.00048)	0.00018* (0.00017, 0.00019)	0.00027 (0.00000, 0.00040)	0.00022 (0.00000, 0.00037)	0.00054 (0.00000, 0.00069)
Roads				0.00190 (−1.69819, 2.35419)			
Marinas				−0.01328 (−0.03047, 0.00037)			
Hotels				−0.00759* (−0.00901, −0.00464)			
Ports				−0.00296 (−0.00469, 0.00048)			
Spatial parameter		2.09022* (0.76854, 4.73306)	1.76970* (0.56410, 3.90416)	5.78680* (2.56654, 9.77264)	4.80544* (1.63450, 9.68552)	10.26844* (2.54525, 22.11406)	1.76499* (0.46203, 3.46992)
Constant	3.58882* (3.30556, 3.88891)	3.25698* (2.69388, 4.16273)	3.42896* (3.00681, 3.93080)	7.37333* (3.33115, 10.16583)	5.20018 (4.17769, 5.90093)	4.80563 (2.83331, 5.91242)	4.64058 (2.47524, 5.34186)
Observations	201	201	201	201	201	201	201
Beach dummies	No	No	No	No	Yes	Yes	Yes
Year dummies	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Clarketest:							
ZIP	0.00000	0.00000	0.00000	0.09735	0.01467	0.07154	0.00000
No decision	0.00000	0.14671	0.00017	0.35916	0.02688	0.07132	0.00486
ZIGP	1.00000	0.85329	0.99983	0.54349	0.95845	0.85714	0.99514

Notes: (a) Specifications (1)–(5) refer to all species, while specifications (6) and (7) are for the hawksbill and green turtle, respectively. (b) The 5% and 95% confidence bands are given in parentheses. (c) The Clarke test reports the proportion of decisions in favour of the ZIP, ZIGP, or neither of these models. (d) * Statistically significant at the 5% level.

Table 3
Marginal effects for significant coefficients.

Specification	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Nighttime light	−0.58709	−0.47709	−0.63048	−3.31499	−3.86179	−2.46902	−2.04096
Effort	–	–	0.00938	0.24539	–	–	–
Roads	–	–	–	–	–	–	–
Marinas	–	–	–	–	–	–	–
Hotels	–	–	–	−9.82565	–	–	–
Ports	–	–	–	–	–	–	–

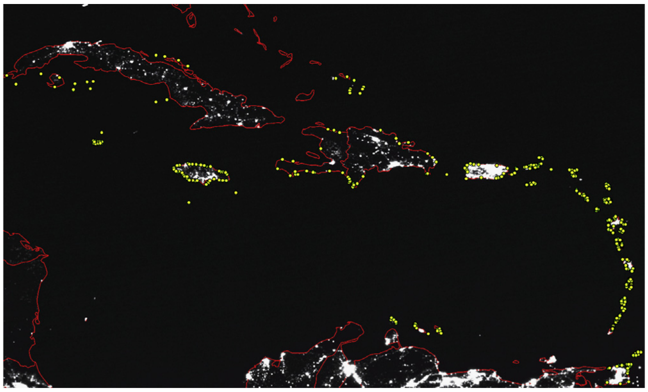


Fig. 2. Nesting sites in the Caribbean. *Note*: Dots indicate known nesting sites.

nighttime light significantly deters nesting for both species. The inferred marginal effects indicate that the impact of an additional unit of nighttime light intensity on nesting activity is greater for the hawksbill than for the green turtle.

Thus far we have controlled for spatial effects only via the error term. However, there may also be spatial effects in terms of the covariates. For instance, with regard to the main focus of this study, greater brightness on nearby beaches may have positive spillover effects on a local beach, as discouraged turtles may look for alternative nesting sites in the vicinity. To investigate this, we calculate the average nighttime light intensity for beaches within 5 km, excluding the value for the beach being considered. The results using beach dummies in Table A1 indicate that there are no direct spatial spillover effects of the nighttime light intensity for nearby beaches. Similar conclusions are reached when we extend the proximity threshold to 10 km.

Missing sea turtles in the Caribbean

In the previous section, we provided a quantitative estimate of the negative impact of light pollution on sea turtle nesting, taking account of other potentially confounding factors and spatial correlation. Apart from the arguable interest in the actual number, we can also use its value to derive a monetary interpretation for the wider Caribbean. To this end we would have ideally liked to expand our econometric analysis to the entire region. However, we were not able to obtain nesting activity data for other territories. Instead, we assume that Guadeloupe is representative of the Caribbean and use our econometric estimates to infer the total costs for the reduction in sea turtle nests due to nighttime light pollution.

As a proxy for the monetary value of "missing" sea turtles due to nighttime light pollution, we use the known costs for rearing sea turtles in captivity, an approach used by Freeman (2003) and Troeng and Drews (2004), for instance, in the absence of specific estimates for willingness to pay (WTP).[10] Moreover, in stated preference studies of animal populations, the evidence seems to indicate that people have difficulty in valuing individual animals, and instead value situations in which the size of a population remains above some critical size to avoid extinction (Bandara and Tisdell, 2003). To identify nesting beaches in the entire Caribbean, we used information from SWOT/OBIS-SEAMAP, which provides a list of known nesting sites and their location.[11] The 1086 known nesting beaches and the nighttime light intensity during 2010 are depicted in Fig. 2. It is evident that the location of nesting beaches and their

[10] Note that in our case we would need a WTP measure per individual turtle. To the best of our knowledge, the only WTP estimates for sea turtles are for particular conservation programmes; see, for example, Jin et al. (2010).

[11] SWOT – the State of the World's Sea Turtles – is a partnership led by the Sea Turtle Flagship Program at the Oceanic Society, Conservation International, IUCN Marine Turtle Specialist Group, and supported by the Marine Geospatial Ecology Lab at Duke University (SWOT, 2006, 2008, and 2009).

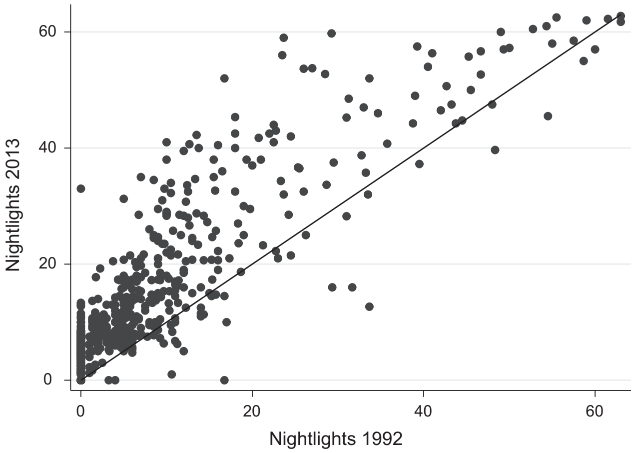


Fig. 3. Light pollution at nesting sites in the Caribbean, 1992 versus 2013.

Table 4
Replacement costs per species (in US dollars).

Farm	Species	Cost/15-year-old	Cost/adult in millions	Total cost
Ferme Corail	Green	1672	3455	6.2
Cayman Turtle Farm	Green	4185	8649	15.6
WMI Research facility	Hawksbill	18,045	26,466	47.8
TUMEC, Rantau Abang	Leatherback	112,128	159,504	287.9

nocturnal illumination vary widely across the Caribbean. Moreover, there has been an increase in nighttime light intensity on most nesting beaches over time, as can be seen from Fig. 3, which plots the nighttime light intensity for 1992 versus 2013 for each nesting site.

With the change in nighttime light intensity for each beach and our measurement of the marginal effect of nighttime light, we can estimate the number of missing turtles as follows:

$$\sum_{i=1}^{1086} \Delta \text{ Nighttime light}_i \times \frac{\partial \text{Nests}}{\partial \text{Nighttime light}} \times \frac{\text{Hatchlings}}{\text{Nest}} \times \text{survival rate to adulthood.} \tag{9}$$

The first term represents the overall change in nighttime light intensity for all nesting beaches over the period 1992–2013. For this we summed total net changes in illumination, which we found to be 3895 units of light (*i.e.*, a 42% increase over the 1992 intensity). For the marginal change in nests due to light pollution, we used the estimated marginal effect for all species as taken from specification 5 of Table 3, *i.e.*, -3.86. These data together suggest that the number of missing nests over our sample period is 15,041. Although the number of eggs per nest varies across species and location, the average is approximately 120 (Marquez, 1990). Finally, we assume that the hatchling survival rate is 1/1000 (Frazer, 1986; Triessnig et al., 2012). Eq. (9) then implies that there were 1805 missing sea turtles due to increasing nighttime light intensity over our sample period.

To calculate the monetary value of these missing turtles, we use the costs for rearing sea turtles in captivity estimated in case studies of sea turtle farms and marine conservation centres. We took information from three sources: Troeng and Drews (2004) for green and leatherback turtles, Webb et al. (2008) for hawksbill turtles, and a personal communication with the Cayman Turtle Farm in the Cayman Islands for green turtles. We summarise the replacement costs in Table 4 (Appendix B provides further details).[12]

The cost of raising a leatherback turtle in captivity to the age of 15 years or to adulthood is many times greater than for green and hawksbill turtles. This is not surprising since leatherback turtles are the largest of the three species, with a carapace length of 1.30–1.83 m and a weight of 300–500 kg. Green and hawksbill turtles are considerably smaller, with a carapace length of 83–114 and 71–89 cm and weight of 110–190 and 46–70 kg, respectively (Marquez, 1990).

Combining the cost per individual adult with our missing turtles estimate, we calculate the total replacement cost for missing sea turtles, which ranges from \$6.2 to 287.9 million, depending on the relative importance of each species nesting in the Caribbean (Table 4).[13] In other words, the cost of replacing the estimated number of missing sea turtles due to the increase in nighttime light

[12] We assume that green turtles reach adulthood at 31 years (Campbell, 2003), leatherback turtles at 21 years (Martinez et al., 2007; Saba et al., 2012), and hawksbill turtles at 22 years (Crouse, 1999).

[13] Unfortunately, there are no estimates of nesting activity by species available for the Caribbean.

with animals raised in captivity could be as much as $0.29 billion if these were all leatherback turtles. It is important to emphasise, as argued by Freeman (2003) and Troeng and Drews (2004), that the replacement cost as measured here should only be considered as a lower threshold of the true loss in ecosystem services, since it ignores the potential differences between sea turtles raised in captivity and those raised in their natural environment.

Population dynamics

In the previous section, we quantified and valued the number of missing turtles due to nighttime illumination in the Caribbean. However, these results only take into account a single generation, and neglect any population dynamics. In this section, we incorporate generational effects by integrating our estimates in a population dynamics model using the case study for Guadeloupe.

In mathematical biology there are many different types of fairly sophisticated population models (Cushing, 2006; Wikan, 2012). However, calibration of these models is often constrained by data availability. Reproduction and survival rates, for instance, play a key role in these dynamic settings. For sea turtles it is well known that these data are age-dependent. It is thus argued that age-structured models, like the one introduced by Leslie (1945), would be an appropriate framework for studying the population dynamics of sea turtles. Unfortunately, there is little reliable age-specific information for long-lived iteroparous species such as sea turtles. However, the life cycle of sea turtles comprises a series of well-identified stages (Heppell et al., 2003) and information is available regarding the duration, survival, and reproduction rates for each stage. We thus follow the set-up introduced by Lefkovitch (1965), Crouse et al. (1987), and Crowder et al. (1994), in which individual animals are grouped by stage sharing the same reproduction and survival rates instead of age.

Stage-structured population model

As in Crowder et al. (1994), we consider five stages of development for sea turtles: (1) eggs/hatchlings, (2) small juveniles, (3) large juveniles, (4) subadults, and (5) adults. We thus define the stage distribution vector x_t at time t as

$$x_t = (x_{1_t}, x_{2_t}, x_{3_t}, x_{4_t}, x_{5_t}), \tag{10}$$

where x_{i_t} is the number of female sea turtles in stage i at time t for $i = 1, \dots, 5$. Let P_i denote the percentage of females in stage i that survive but remain in that stage, let G_i be the percentage of females in stage i that survive and progress to the next stage, and let F_i be the number of hatchlings per year produced by a sea turtle in stage i (annual fecundity). Therefore, the number of hatchlings produced by each stage class at time t is given by

$$x_{1_t} = F_1 x_{1_{t-1}} + F_2 x_{2_{t-1}} + F_3 x_{3_{t-1}} + F_4 x_{4_{t-1}} + F_5 x_{5_{t-1}}, \tag{11}$$

while the number of females present in the subsequent stage j, for $j = 2, \dots, 5$, is

$$x_{j_t} = G_{j-1} x_{j-1_{t-1}} + P_j x_{j_{t-1}}. \tag{12}$$

Taking (11) and (12), we can then rewrite the population model in matrix form:

$$x'_t = L x'_{t-1}, \tag{13}$$

where x' denotes the transpose of vector x, and L is the five-stage population matrix

$$L = \begin{bmatrix} F_1 & F_2 & F_3 & F_4 & F_5 \\ G_1 & P_2 & 0 & 0 & 0 \\ 0 & G_2 & P_3 & 0 & 0 \\ 0 & 0 & G_3 & P_4 & 0 \\ 0 & 0 & 0 & G_4 & P_5 \end{bmatrix}.$$

In general, the available stage-based life information comprises duration, and survival and reproduction rates. The fertility rates F_i are given by the fecundity data, while G_i and P_i need to be calculated. We follow the standard method of Crouse et al. (1987) and Crowder et al. (1994). If we denote the yearly survival rate and duration of stage i by σ_i and d_i, respectively, we can determine the percentage of sea turtles from stage i that grow into stage $i+1$ as

$$\gamma_i = \begin{cases} \dfrac{(1-\sigma_i)\sigma_i^{d_i - 1}}{1-\sigma_i^{d_i}} & \text{if } \sigma_i \neq 1 \\ \dfrac{1}{d_i} & \text{if } \sigma_i = 1. \end{cases} \tag{14}$$

Consequently, the percentage of turtles in stage i that remain in that stage is $1-\sigma_i$. We can finally determine G_i and P_i as

$$G_i = \gamma_i \sigma_i, \tag{15}$$

$$P_i = (1-\gamma_i)\sigma_i. \tag{16}$$

Population dynamics and nighttime light pollution

As pointed out above, the usual stage-based life table for a specific type of sea turtle consists of information about the stage duration and the survival and reproduction rates for each stage. Appendix C provides stage-based life tables for each type of sea turtle in Guadeloupe. Considering (14)–(16), we can use these to compute the population matrix L for each species. Taking (13) and an initial stage distribution vector x_0, we can then obtain the population dynamics for $t > 0$.

We now incorporate the effect of nighttime illumination into the population model. As we have shown earlier, nighttime light pollution significantly reduces the number of sea turtle nests, and consequently the annual fertility rate. Our objective is to adjust the parameter F_i to account for the marginal effect of nighttime light. Note that an additional negative consequence of nighttime light is the increasing difficulty in finding the sea after hatchlings emerge from their nest, resulting in a reduction in the annual survival rate σ_1 (Section "Sea turtle nesting and nighttime light"). Our analysis should thus be interpreted as a lower bound for the negative effect of nighttime light pollution, although we later investigate how incorporation of this aspect would affect our results.

As a starting point we assume nighttime light intensity and nesting activity to be the average observed on Guadeloupe nesting beaches, denoted by NL_{avg} and NT_{avg}, respectively. To modify the annual fertility, we need to estimate the reduction in hatchlings per year caused by nighttime light. Thus, the average percentage point reduction in nests τ due to nighttime illumination is

$$\tau(\beta_1) = \frac{|\beta_1| NL_{avg}}{NT_{avg} + |\beta_1| NL_{avg}} 100, \tag{17}$$

where β_1 denotes the estimated marginal effect of light pollution.

With no empirical evidence available, we assume that the percentage reduction in nests will result in the same percentage reduction in eggs per sea turtle. Since we are working at the individual sea turtle level, we adjust the marginal effect of nighttime light to take account of the remigration interval. Following Doi et al. (1992), we assume that this interval is 2.6 years, implying that $\tilde{\beta}_1 = \beta_1/2.6$.[14] The modified annual fertility rate can therefore be computed as $\tilde{F}_i = [1 - \tau(\tilde{\beta}_1)/100]F_i$. Recall from Table 3 that the marginal effect for hawksbill and green turtles is -2.47 and -2.04, respectively. For leatherback turtles, we assume that the marginal effect is equal to that for the total population, *i.e.*, -3.86. For example, for leatherback turtles the annual fertility rate would be reduced by 42%, changing the population matrix accordingly. Note that the analysis is based on the assumption of a constant level of nighttime light per beach, since our objective is to evaluate the generational consequences of the current level of light pollution. However, this set-up could easily be applied to evaluate different scenarios for nighttime light changes.

Dynamic population response

We can now evaluate the population dynamics under scenarios with and without nighttime light pollution. We can obtain the population dynamics for each turtle type, starting from a given initial stage distribution, by recursively applying Eq. (13) to the population matrix with and without nighttime light. Given that the number and stage distribution are highly uncertain because of difficulties in tracking sea turtles, we assume an initial number of turtles for each stage consistent with broad estimates for Guadeloupe (DREG, 2006; Delcroix et al., 2011). More precisely, we assume a population of 1000 females per stage for each turtle species, although we verified that the qualitative population response was robust to alternative demographic configurations.[15]

Population dynamics

In Figs. 4–6 we plot the evolution of the stage population for each sea turtle species with and without nighttime light. Even without light pollution, hawksbill and green sea turtles eventually become extinct, while the leatherback population continues to grow over time. This difference in the long-term population dynamics across species is in line with existing studies (Evans et al., 2001) and is driven by the underlying survival and fertility parameters for the population matrix. The presence of nighttime light considerably accelerates the extinction of hawksbill and green turtles. For leatherback turtles the negative impact of nighttime light reverses the population growth, so that this species also becomes extinct in the long run.

Note that the qualitative population dynamics do not depend on the initial stage distribution. Indeed, the eigenvalues of the population matrix allow us to identify the dynamic properties regardless of the initial conditions. An intrinsic characteristic of our population model is that a population either increases or decreases in the long run, since the model consists of a system of first-order linear difference equations. We can easily verify that the absolute value of all eigenvalues for the population matrices for hawksbill and green turtles is less than one (Appendix D). Consequently, their populations will be asymptotically extinct, regardless of the presence of light pollution. For leatherback turtles, however, there is an eigenvalue (λ_1) greater than one if there is no nighttime light pollution, so that the population increases in the long run. As for hawksbill and green turtles, nighttime light results in all eigenvalues being lower than one, leading to eventual depletion of this species too. As pointed out earlier, there are more sophisticated frameworks that consider non-linearities that induce steady populations. This is usually the case for models that incorporate the effect of agglomeration by allowing, for instance, food and/or space competition among individuals. Even if the data

[14] Other studies on remigration intervals include Carr and Carr (1970), Carr et al. (1978), Hays (2000), and Troeng and Chaloupka (2007).

[15] Details are available from the authors on request.

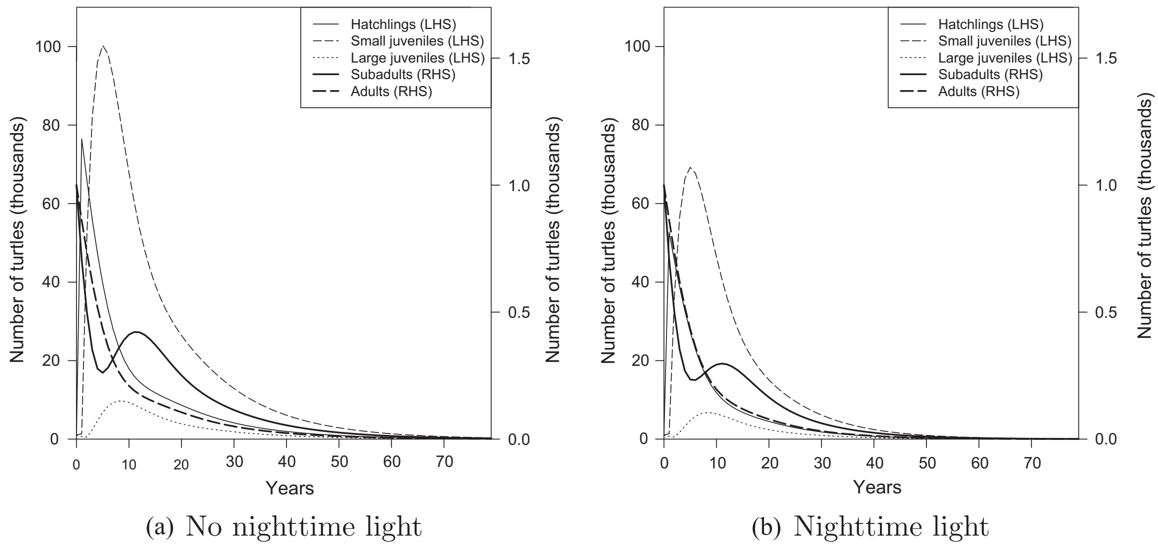


Fig. 4. Population per stage: hawksbill turtles.

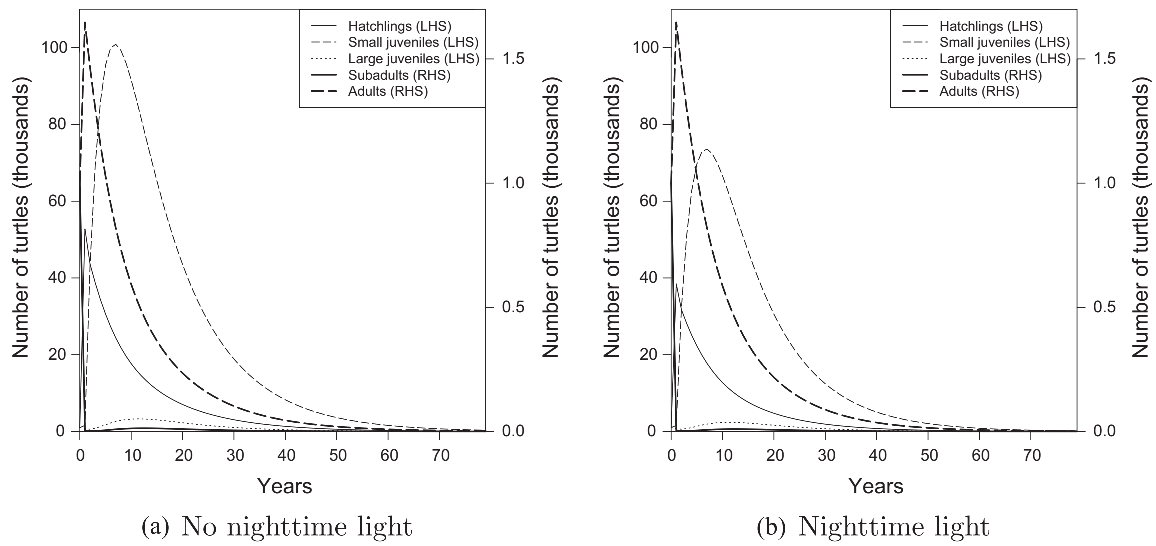


Fig. 5. Population per stage: green turtles.

required to estimate a model of this type were available, the existence of such agglomeration effects seems unlikely for endangered species such as sea turtles.

The eigenvalues also allow us to provide quantitative information regarding the long-run response of the population for each turtle type in terms of the growth rate and stage distribution. Since system (13) has constant coefficients and $|\lambda_1| > |\lambda_j|$ for $j = 2, \ldots, 5$ (Table D1), the unique solution in the long run takes the form:

$$x'_t \simeq c_1 v_{\lambda_1} \lambda_1^t, \tag{18}$$

where v_{λ_1} is the eigenvector corresponding to the eigenvalue λ_1, and c_1 is a constant.[16] Consequently, the long-run annual growth rate of the population (per stage and total) is equal to $\lambda_1 - 1$. Applying this result to our simulations, we observe that the population eventually decreases for both hawksbill and green turtles, while nighttime light increases the long-run annual depletion rate from 7.19% to 8.8% and from 7.9% to 8.56%, respectively. We also confirm that the leatherback

[16] The solution of system (13) for all t is $x'_t = \sum_{i=1}^{5} c_i v_{\lambda_i} \lambda_i^t$, where v_{λ_i} denotes the eigenvector corresponding to the eigenvalue λ_i of the population matrix, and c_i are constants determined by the initial population distribution.

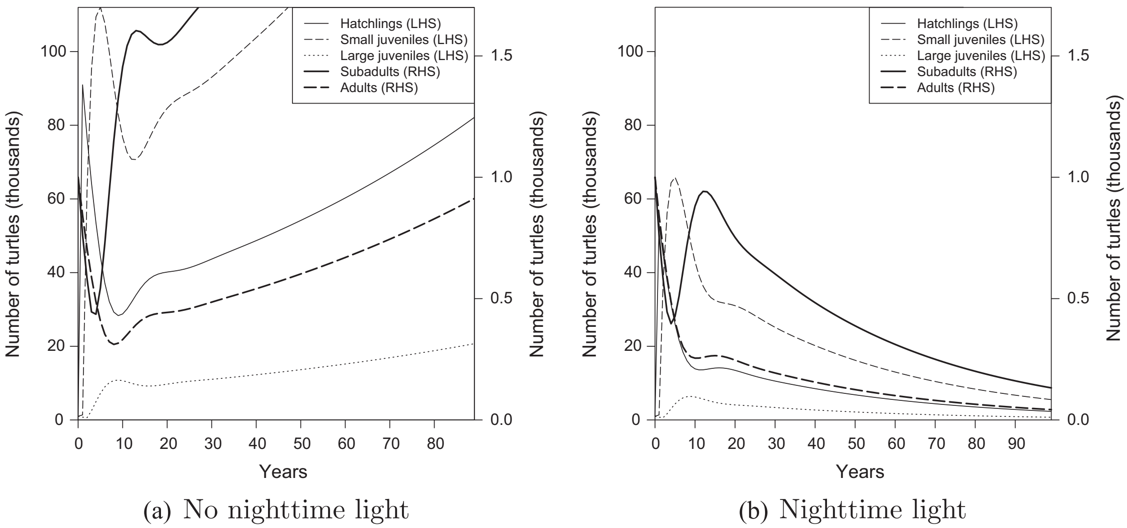


Fig. 6. Population per stage: leatherback turtles.

Table 5
Time to extinction (years).

	No light	*Light*	*Light* ($\tilde{\sigma}_1$)
Hawksbill	164	130	101
Green	154	139	122
Leatherback	∞	514	205

population increases if there is no light pollution, with a long-run annual growth rate of 1.07%. However, the presence of nighttime illumination reverses this trend, resulting in an eventual decreasing population rate of 2.18% per year.

With respect to the stage distribution of each type of turtle, using Eq. (18) the long-run proportion of the population in stage i is given by

$$\xi_i = \frac{v_{\lambda_1 i}}{\sum_{k=1}^{5} v_{\lambda_1 k}}, \tag{19}$$

where $v_{\lambda_1 k}$ is the kth coordinate of the eigenvector v_{λ_1}. Considering the eigenvalues and eigenvectors of Tables D1 and D2 in Appendix D, we obtain the stage distribution for each type of turtle with and without nighttime light. A well-known feature of these types of population model is that the population reaches a stable stage distribution in the long run (Table D3 and Fig. D2). It is evident from Table D3 that the proportion of hatchlings is most severely affected by nighttime light pollution. The reduction is particularly apparent for leatherback turtles, for which the proportion of hatchlings falls by more than 2.6 percentage points. This a major reason why the population reverses from its increasing long-run trend. These results are robust to the initial stage distribution and other population sizes because there are strong accumulative effects of the reduction in annual fertility.

The population model can also be applied to investigate how fast this extinction may occur. We define the time to extinction as the number of years it takes for less than one sea turtle to survive. Table 5 shows that for an assumed initial population of 1000 sea turtles per stage, nighttime illumination significantly accelerates the extinction of all three species. Without light pollution, hawksbill and green turtles will take 164 and 154 years, respectively, to become extinct, whereas there is no extinction for leatherback turtles and the population continues to increase. In the presence of nighttime light, all three species will eventually disappear. According to our simulations, the time to extinction would be 130 years for the hawksbill, 139 years for the green, and 514 years for the leatherback turtle. Thus, nighttime illumination of nesting sites has a clear accumulative effect in the long run by reducing fertility rates for adult females.[17]

Our estimates of the impact of nighttime light are likely to be only lower bounds as we do not allow for the fact that lighting will also reduce the number of hatchlings that make it from the nesting site to the sea because of disorientation.

[17] Note that the time to extinction depends on the distribution and size of the initial population; however, the qualitative results remain unchanged when we use alternative scenarios.

Unfortunately, we do not have any information on the impact of nighttime light on the survival rate of hatchlings during this period of their life cycle. However, Peters and Verhoeven (1994) studied the survival of loggerhead hatchlings during the voyage from their nests to the sea. They examined two nesting sites on the Turkish Mediterranean coast and found that only 21% of hatchlings reached the sea on the site that was well lit, compared to 48% for an adjacent unlit area. To obtain a rough idea of how far our estimates are from the upper bound, we modify the hatchling survival probability to $\tilde{\sigma_1} = 0.56\sigma_1$.[18] As expected, extinction accelerates. More precisely, the time to extinction is now 101, 122, and 205 years for hawksbill, green, and leatherback turtles, respectively (column 3 in Table 5).

Finally, Figs. 4–6 reveal that the short-run population dynamics are cyclical. This property is explained by the fact that sea turtles spend several years in each stage of development, resulting in accumulation or reduction of the number of individuals in a specific stage. This result is confirmed by examining the eigenvalues of the population matrix (Table D1).[19] Moreover, the negative effect of light pollution does not seem to be strong enough to eliminate these cycles in the short term.

Compensation costs

One conservation management tool used to address diminishing sea turtle populations is headstarting, which broadly entails captive hatching and rearing of sea turtles during the early part of their life cycle (Bell et al., 2005). For instance, the Cayman Turtle Farm released 16,422 neonates, 14,282 yearlings, and 65 older (19–77 months) green sea turtles during 1980–2001.[20] Using our results above, we can consider the costs of such a headstarting strategy to counteract the negative effect of nighttime light on sea turtles by calculating the number of headstarted turtles that would have to be released into the wild today to keep the extinction time the same as that without light pollution.[21] We can then infer an estimate for the potential cost of such a conservation strategy using our information on the costs incurred in raising turtles in captivity. Note that focusing on the costs of reducing the time to extinction is probably much more in line with how people value animal species, as stated earlier.

As mentioned before, headstarted turtles have been released at various life stages, normally well before they reach the age of 7 years. Moreover, since we do not have information on the replacement costs for hatchlings, we limit our analysis to the release of headstarted 1-year-old juveniles. For the green turtle we find that 3.5 million juveniles would be needed to keep the time to extinction at the no-illumination level of 154 years in the absence of light pollution, with an associated cost of between $0.4 and 0.9 billion, depending on the source used for the yearly replacement cost. In the case of the hawksbill turtle, 10 million yearlings would have to be released to keep the time to extinction at the no-illumination level of 164 years, with an associated cost of between $1.1 and 2.8 billion.

At first sight, the costs for headstarting as a conservation management tool may seem remarkably high. However, it should be remembered that this involves counteracting the negative effect of nighttime light for all the years until extinction. Moreover, in line with arguments made by Heppell et al. (1995) regarding the use of headstarting to compensate for reduced survival rates, these high costs are also related to the characteristics of sea turtles. First, for slow-maturing species such sea turtles, large increases in juveniles are needed to compensate for the reduction in nesting activity and hence hatchling production due to light pollution. Second, except for extremely small populations, it is not feasible to headstart enough juveniles to have an impact on the overall survival rate of a cohort.

There are other likely costs involved with headstarting, as reviewed by Bell et al. (2005). First, sea turtles raised in captivity may behave differently to their wild counterparts. For example, there is some evidence that headstarted sea turtles forage and nest outside of their natural range. Others have questioned the ability of headstarted sea turtles to survive as well as wild animals because of nutritional deficiencies and behavioural modifications resulting from insufficient exercise, a lack of or inappropriate stimuli, and the unavailability of natural food sources and feeding techniques during captivity. In addition, headstarted sea turtles may have negative spillover effects on wild sea turtles via transmission of diseases acquired during captivity and genetic pollution. Thus, the cost estimates provided here should only be viewed as a lower bound for the total costs of headstarting as a remedy for the detrimental effects of light pollution on sea turtle populations.

With the aforementioned replacement costs in mind, we can also consider the public WTP for such headstarting programs. To this end we need some measure of the WTP for sea turtles. Unfortunately, to the best of our knowledge there has been no study of WTP for sea turtles for Guadeloupe or even the rest of the Caribbean. However, a number of studies have been conducted for Asia and we use such results as a proxy for the WTP in Guadeloupe. Jin et al. (2010) calculated an average WTP of 0.19% of total household income for a 5-year sea turtle conservation programme for five major cities in four developing countries in Asia.[22] Using this average WTP and considering the total number of households in Guadeloupe (166,317) and the average annual income per household ($16,598) in 2011,[23] the present value of the total WTP for

[18] The value of 56% is the percentage reduction in survival rate observed by Peters and Verhoeven (1994).

[19] The existence of complex and/or negative eigenvalues implies short-run cycles in different equation systems.

[20] Other examples include the North Carolina Head Start Program (loggerhead turtles) and the National Marine Fisheries Service Program (Kemp's ridley turtles).

[21] Note that this exercise only considers a one-time release of sea turtles, but could of course be extended to yearly release programs.

[22] The estimates as a percentage of household total income were 0.24 for Beijing (China), 0.19 for Davao City (Philippines), 0.17 for Bangkok (Thailand), and 0.14 for Ho Chi Minh/Hanoi (Vietnam).

[23] Source: www.insee.fr/fr/bases-de-donnees, *Nombre de ménages*, and *revenu net déclaré moyen par foyer fiscal*, respectively.

Guadeloupe using a positive social discount rate of 10% would be approximately $21.5 million for a 5-year headstarting program. Using the replacement cost for 1-year-old juveniles (Appendix B), we calculate estimates for yearly release of the corresponding number of headstarted turtles over 5 years.[24] Our population model suggests that such a conservation programme would reduce the years to extinction by between 1 and 2 additional years. This limited population response emphasises the small scale of public WTP contributions regarding conservations programmes such as headstarting of sea turtles, although Jin et al. (2010) note that their WTP estimates are comparable to results from other studies for developed countries and endangered species such as the spotted owl (Loomis and Ekstrand, 1998) and grey and blue whales (Bulte and Van Kooten, 1999).[25] However, Tisdell and Wilson (2002) point out that the pro-conservation attitude of individuals significantly affects their WTP. In this respect, further investigation of the factors that may affect and foster the public WTP for the protection of endangered species is warranted.

Finally, it is important to discuss the limitations of using the results of Jin et al. (2010) in conjunction with data from Guadeloupe to infer the costs of a conservation program for the Caribbean, as we do here. First, in using average per household income we implicitly assume income elasticity of one with respect to WTP. However, this may not hold true for the valuation of biodiversity, as shown by Jacobson and Hanley (2009). Second, in using data from China for the Caribbean we are ignoring any cultural and institutional differences in the valuation of sea turtles. A meta-analysis by Lindhjem and Navrud (2008) showed that for valuation of non-timber benefits across three Scandinavian countries, WTP transfer errors due to differences in cultural and institutional environments across countries can be substantial.[26] This was confirmed by Lindhjem and Tuan (2012). Finally, scaling up of our results from Guadeloupe to the entire Caribbean may also be questionable. As noted by Brander et al. (2012), possible changes that occur across individual sites should ideally be taken into account when scaling up from one site to a greater region rather than using a simple aggregation or generalisation across sites, as we had to do here. Because of these weaknesses, our approach should be viewed only as a starting point for analysing the potential compensation costs of the negative effect of lighting intensity on sea turtle nesting. A substantial number of additional studies of the issue are needed before methods such as those proposed by Ready and Navrud (2006) and Brander et al. (2012) can be used to assess the welfare effects of conservation programmes in a more reliable manner.

Concluding remarks

We examined loss of biodiversity due to environmental pollution by studying the impact of coastal light pollution on the sea turtle population in the Caribbean. To this end, we assembled a data set for sea turtle nesting activity and satellite-derived measures of nighttime light for Guadeloupe. Using a spatial count data model, we showed that after controlling for the surveyor effort and local economic infrastructure, nighttime light reduces the number of nests on beaches. Considering the growth of nighttime light over the last 20 years across beaches used for nesting in the Caribbean, our quantitative estimate suggests that if we consider the value of a sea turtle to be its replacement cost in captivity, then the increase in coastal lighting in the region has resulted in losses of up to $288 million. We combined our statistical estimate with a stage-structured population model for Guadeloupe to study the generational implications of light pollution. The results suggest that light pollution will substantially accelerate the extinction of sea turtles. Moreover, we found that compensating for the negative effect of the current nighttime light intensity by rearing sea turtles in captivity and then releasing them into the wild, which is part of some current conservation strategies, may be an expensive remedy according to studies of public willingness to pay. This suggests that exploration of the economic costs of reducing coastal illumination near sea turtle nesting beaches as an alternative or supplementary conservation management tool is warranted. To the best of our knowledge, no such estimates are currently available.

More generally, our paper arguably provides a new approach to valuing losses due to species extinction caused by environmental pollution. In particular, given data for a species of interest and some type of relevant pollution, our paper shows that statistical estimates of the short-term impact within a population model can provide helpful insights into the range of the likely long-term impacts and their costs. The reliability of such predictions will obviously depend on the quantity and quality of data available. For example, for the case studied here, data spanning a longer time period and greater geographical area in the Caribbean would give greater confidence in the results.

Acknowledgments

We would like to thank the members of Office National de la Chasse et la Faune Sauvage (ONCFS) in Guadeloupe, particularly Antoine Chabrolle and Eric Delcroix, for sharing data on sea turtle nesting, and Walter Mustin, Chief Research Officer of the Cayman Turtle Farm (Cayman Islands). We are also grateful to Matthew Cole, Robert Elliott, and two anonymous referees for helpful comments. Agustin Perez-Barahona and Eric Strobl acknowledge financial support from the Chaire Developpement Durable (Ecole Polytechnique - EDF).

[24] Using these data, the conservation programme would imply yearly release of 18,471 (Cayman Turtle Farm) or 38,562 (Ferme Corail) 1-year-old green juveniles and 3573 hawksbill turtles (WMI research facility).

[25] According to IUCN (2001), the spotted owl is considered as "near threatened with a decreasing population trend", and the blue and grey whales are, respectively, "endangered" and "critically endangered" species.

[26] See Ready and Navrud (2006) for a general discussion of the issue of international benefit transfers.

Appendix A. Robustness checks

See Table A1.

Table A1
Direct spatial spillovers.

	5 km	Marginal effect	10 km	Marginal effect
Nighttime light	−0.03000*	−3.14012	−0.04203*	−3.08470
	(−0.05185, −0.01431)		(−0.06617, −0.01303)	
Effort	0.00055		0.00020	
	(0.00000, 0.00076)		(0.00000, 0.00036)	
Neighbouring nighttime light	0.00020		0.00370	
	(0.00000, 0.00028)		(0.00000, 0.00650)	
Spatial parameter	10.13342*		8.03332*	
	(0.52779, 22.96918)		(0.71158, 18.66336)	
Constant	5.08590*		4.90550*	
	(3.28418, 6.48527)		(3.12482, 6.09731)	
Observations	201		201	
Beach dummies	Yes		Yes	
Year dummies	Yes		Yes	
Clarke test:				
ZIP	0.00000		0.00000	
No decision	0.00000		0.00625	
ZIGP	1.00000		0.99375	

Notes: (a) Nighttime light refers to nighttime light intensity within 1 km. Neighbouring nighttime light refers to nighttime light intensity for beaches within 1–5 km and 1–10 km in the first and second specifications, respectively. (b) The 5% and 95% confidence limits are given in parentheses. (c) The Clarke test reports the percentage of decisions in favour of the ZIP or ZIGP or neither of these models. (d) * Statistically significant at the 5% level.

Appendix B. Replacement costs

We present here the information used in Section ""Missing" sea turtles in the Caribbean" to construct Table 4 (See Table B1).

1. *Ferme Corail* (*Reunion*): Assuming an age at maturity of 15 years, the estimated cost of raising one green turtle is US$1672, corresponding to an annual cost of US$111.45 (Troeng and Drews, 2004).
2. *TUMEC*, *Rantau Abang* (*Malaysia*): This marine conservation centre mainly focuses on leatherback turtles. They estimate a monthly cost of US$132 per turtle during the first year, and US$658 per month for each subsequent year (Troeng and Drews, 2004).
3. *WMI research facility*: This facility ran a prototype pen for captive breeding of farm-raised turtles for 18 hawksbill adults over 18 months and found that the total running cost was US$34,285, corresponding to US$1203 per turtle per year (Webb et al., 2008).
4. *Cayman turtle farm*: This farm specialises in green sea turtles. In a personal communication, Walter Mustin, Chief Research Officer of Cayman Turtle Farm, provided the following production cost estimates per turtle and year.

Table B1
Annual production cost per turtle.

Item	Cost/turtle/year (US$)
Energy	106
Salaries and wages	56
Feed	53
Repairs and maintenance	25
Security	13
Depreciation	13
Chemicals	6
Waste removal	4
Other	3
Total	279

Appendix C. Stage-based life tables

Crouse (1999) provides the following table for the hawksbill sea turtle.

For the green sea turtle, we take the five-stage life table from Campbell (2003).

For the leatherback turtle, we refer to Saba et al. (2012) and Martinez et al. (2007) for annual fecundity data (See Tables C1–C3).

Table C1
Hawksbill sea turtle.

Stage	Description	Stage duration (d_i)	Annual survival (σ_i)	Annual fecundity (F_i)
1	Eggs/hatchlings	1	0.6747	0
2	Small juveniles	7	0.75	0
3	Large juveniles	8	0.6758	0
4	Subadults	6	0.7425	0
5	Adults	> 32	0.8091	76.5

Table C2
Green sea turtle.

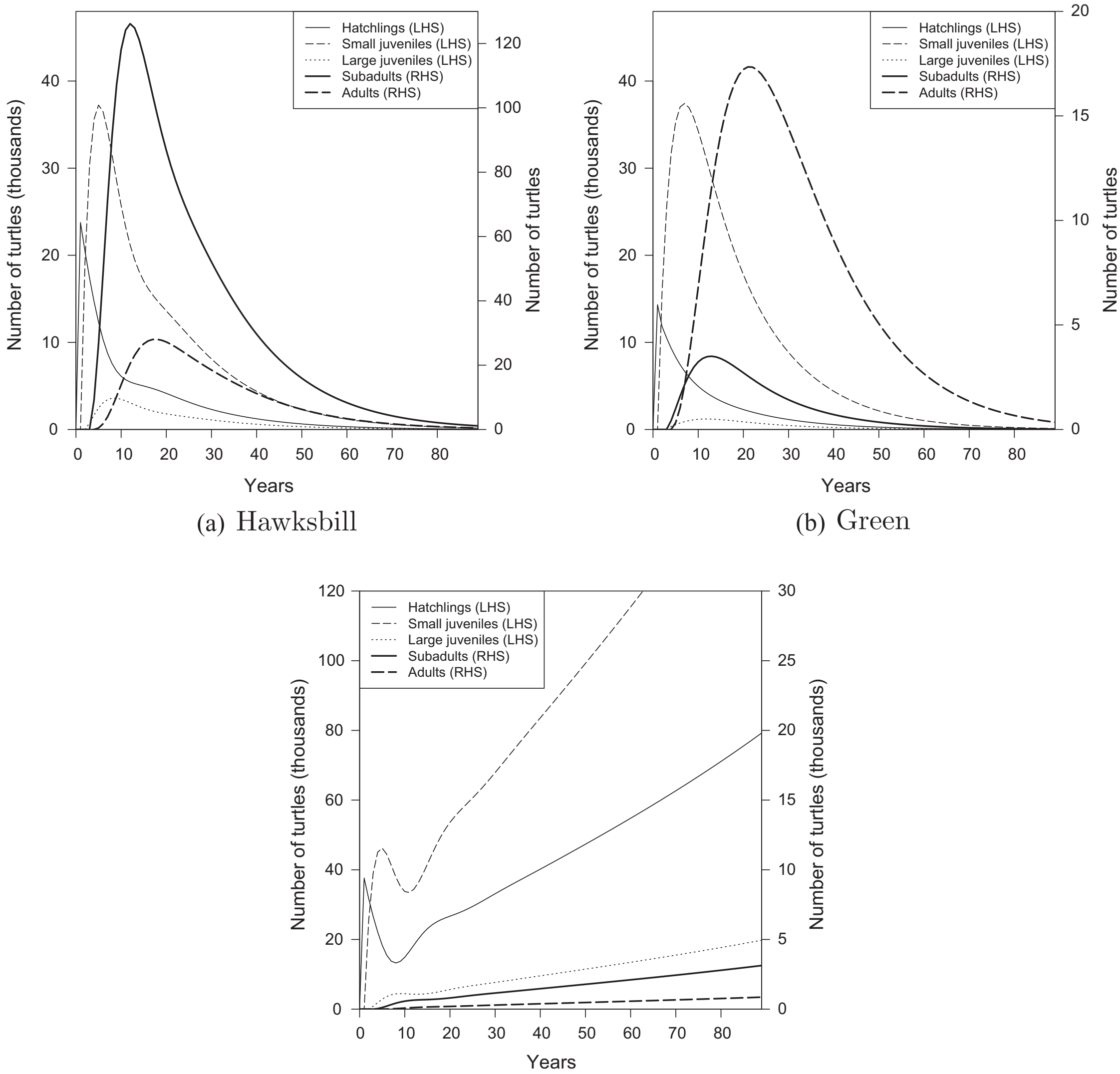
Stage	Description	Stage duration (d_i)	Annual survival (σ_i)	Annual fecundity (F_i)
1	Eggs/hatchlings	1	0.8	0
2	Small juveniles	14	0.8	0
3	Large juveniles	15	0.76	0
4	Subadults	1	0.76	26.4
5	Adults	> 32	0.89	26.4

Table C3
Leatherback sea turtle.

Stage	Description	Stage duration (d_i)	Annual survival (σ_i)	Annual fecundity (F_i)
1	Eggs/hatchlings	1	0.6747	0
2	Small juveniles	7	0.727	0
3	Large juveniles	7	0.78	0
4	Subadults	6	0.78	0
5	Adults	> 32	0.78	91

Appendix D. Dynamic results

See Figs. D1 and D2 and Tables D1–D3.

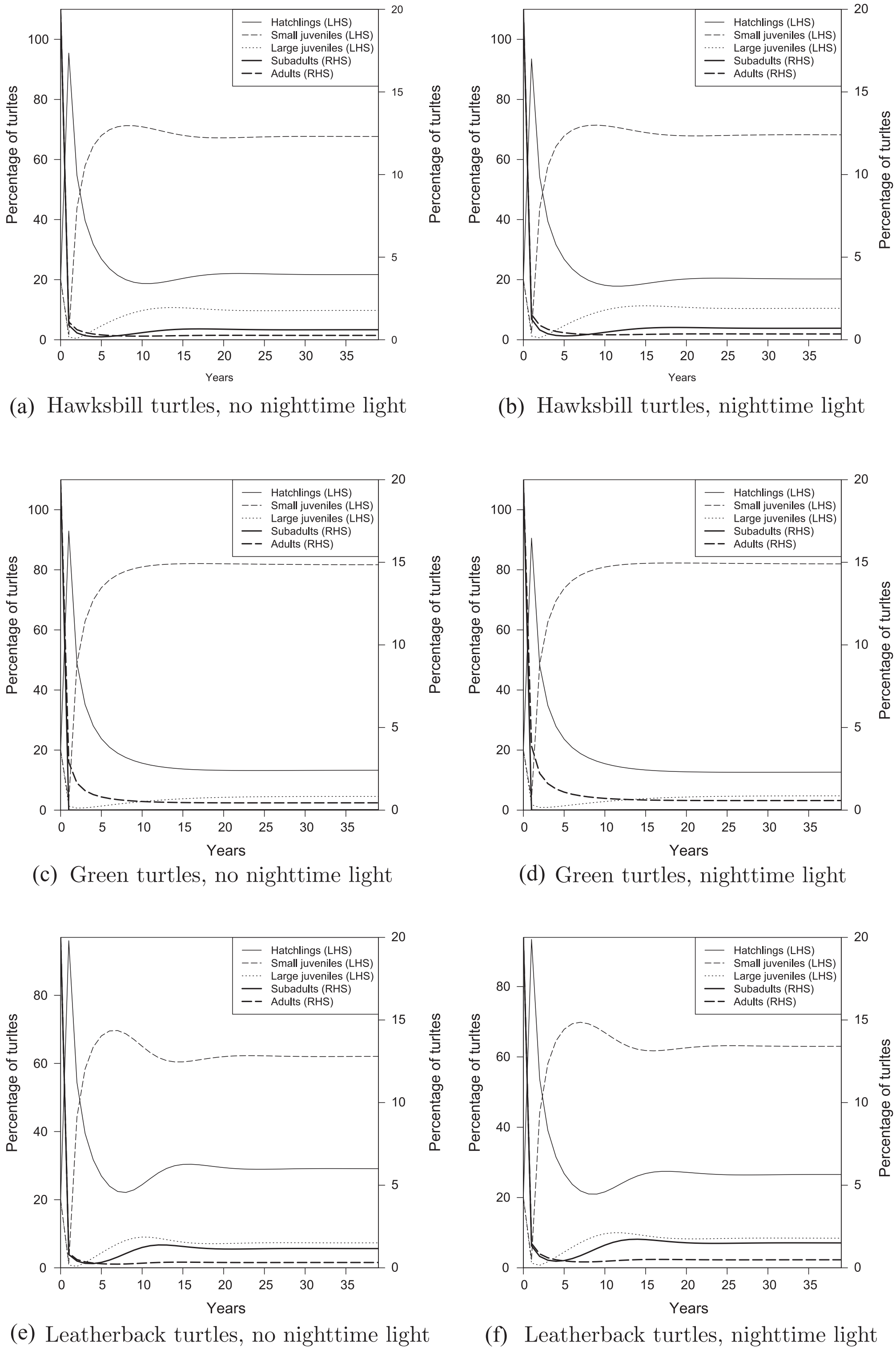


(a) Hawksbill

(b) Green

(c) Leatherback

Fig. D1. Population difference per stage.



(a) Hawksbill turtles, no nighttime light
(b) Hawksbill turtles, nighttime light
(c) Green turtles, no nighttime light
(d) Green turtles, nighttime light
(e) Leatherback turtles, no nighttime light
(f) Leatherback turtles, nighttime light

Fig. D2. Stage distribution.

Table D1
Eigenvalues.

		λ_1	λ_2	λ_3	λ_4	λ_5
Hawksbill	*no light*	0.9281	$0.7318+0.2037i$	$0.7318-0.2037i$	0.4744	0.0060
	light	0.9120	$0.7292+0.1849i$	$0.7292-0.1849i$	0.4975	0.0041
Green	*no light*	0.9210	$0.7569+0.0717i$	$0.7569-0.0717i$	−0.0140	0.0132
	light	0.9144	$0.7601+0.0624i$	$0.7601-0.0624i$	−0.0119	0.0113
Leatherback	*no light*	1.0107	$0.7578+0.2908i$	$0.7578-0.2908i$	0.3726	0.0243
	light	0.9782	$0.7520+0.2557i$	$0.7520-0.2557i$	0.4275	0.0134

Table D2
Coordinates of the eigenvector v_{λ_1} corresponding to λ_1.

		$v_{\lambda_1 1}$	$v_{\lambda_1 2}$	$v_{\lambda_1 3}$	$v_{\lambda_1 4}$	$v_{\lambda_1 5}$
Hawksbill	*no light*	0.3028	0.9432	0.1360	0.0084	0.0037
	light	0.2818	0.9483	0.1455	0.0097	0.0049
Green	*no light*	0.1604	0.9855	0.0550	0.0002	0.0054
	light	0.1524	0.9866	0.0573	0.0002	0.0070
Leatherback	*no light*	0.4223	0.9000	0.1064	0.0169	0.0047
	light	0.3851	0.9144	0.1224	0.0219	0.0071

Table D3
Long-run stage distribution (%).

Stage	Description		Hawksbill	Green	Leatherback
1	Eggs/hatchlings	*no light*	21.72	13.29	29.12
		light	20.27	12.66	26.54
2	Small juveniles	*no light*	67.65	81.69	62.06
		light	68.21	81.97	63.03
3	Large juveniles	*no light*	9.76	4.56	7.34
		light	10.47	4.76	8.44
4	Subadults	*no light*	0.61	0.019	1.17
		light	0.69	0.02	1.51
5	Adults	*no light*	0.26	0.44	0.32
		light	0.35	0.58	0.49

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REVIEW SUMMARY

MARINE CONSERVATION

Marine defaunation: Animal loss in the global ocean

Douglas J. McCauley,* Malin L. Pinsky, Stephen R. Palumbi, James A. Estes, Francis H. Joyce, Robert R. Warner

BACKGROUND: Comparing patterns of terrestrial and marine defaunation helps to place human impacts on marine fauna in context and to navigate toward recovery. Defaunation began in earnest tens of thousands of years later in the oceans than it did on land. Although defaunation has been less severe in the oceans than on land, our effects on marine animals are increasing in pace and impact. Humans have caused few complete extinctions in the sea, but we are responsible for many ecological, commercial, and local extinctions. Despite our late start, humans have already powerfully changed virtually all major marine ecosystems.

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ADVANCES: Humans have profoundly decreased the abundance of both large (e.g., whales) and small (e.g., anchovies) marine fauna. Such declines can generate waves of ecological change that travel both up and down marine food webs and can alter ocean ecosystem functioning. Human harvesters have also been a major force of evolutionary change in the oceans and have reshaped the genetic structure of marine animal populations. Climate change threatens to accelerate marine defaunation over the next century. The high mobility of many marine animals offers some increased, though limited, capacity for marine species to respond to climate stress, but it also exposes many species to increased risk from other stressors. Because humans are intensely reliant on ocean ecosystems for food and other ecosystem services, we are deeply affected by all of these forecasted changes.

Three lessons emerge when comparing the marine and terrestrial defaunation experiences: (i) today's low rates of marine extinction may be the prelude to a major extinction pulse, similar to that observed on land during the industrial revolution, as the footprint of human ocean use widens; (ii) effectively slowing ocean defaunation requires both protected areas and careful management of the intervening ocean matrix; and (iii) the terrestrial experience and current trends in ocean use suggest that habitat destruction is likely to become an increasingly dominant threat to ocean wildlife over the next 150 years.

OUTLOOK: Wildlife populations in the oceans have been badly damaged by human activity. Nevertheless, marine fauna generally are in better condition than terrestrial fauna: Fewer marine animal extinctions have occurred; many geographic ranges have shrunk less; and numerous ocean ecosystems remain more wild than terrestrial ecosystems. Consequently, meaningful rehabilitation of affected marine animal populations remains within the reach of managers. Human dependency on marine wildlife and the linked fate of marine and terrestrial fauna necessitate that we act quickly to slow the advance of marine defaunation. ■

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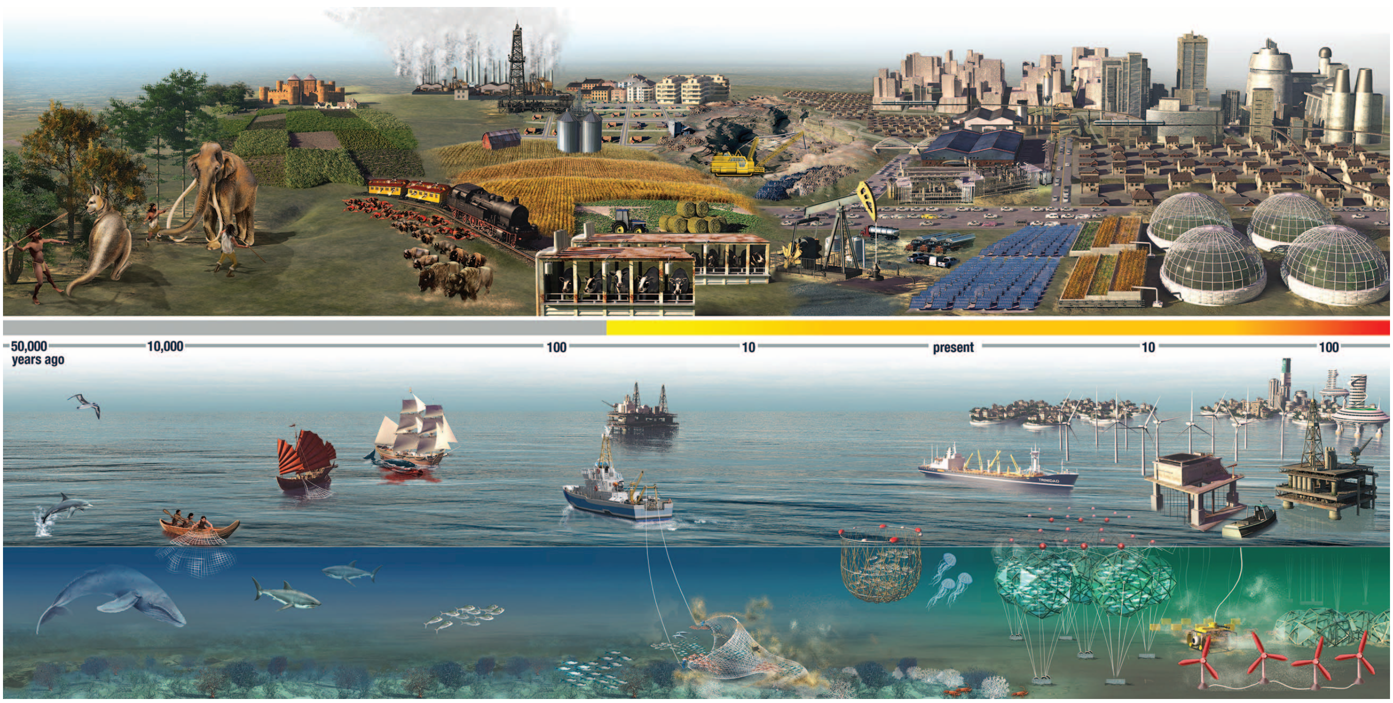

Timeline (log scale) of marine and terrestrial defaunation. The marine defaunation experience is much less advanced, even though humans have been harvesting ocean wildlife for thousands of years. The recent industrialization of this harvest, however, initiated an era of intense marine wildlife declines. If left unmanaged, we predict that marine habitat alteration, along with climate change (colored bar: IPCC warming), will exacerbate marine defaunation.

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REVIEW

MARINE CONSERVATION

Marine defaunation: Animal loss in the global ocean

Douglas J. McCauley,[1*] Malin L. Pinsky,[2] Stephen R. Palumbi,[3] James A. Estes,[4] Francis H. Joyce,[1] Robert R. Warner[1]

Marine defaunation, or human-caused animal loss in the oceans, emerged forcefully only hundreds of years ago, whereas terrestrial defaunation has been occurring far longer. Though humans have caused few global marine extinctions, we have profoundly affected marine wildlife, altering the functioning and provisioning of services in every ocean. Current ocean trends, coupled with terrestrial defaunation lessons, suggest that marine defaunation rates will rapidly intensify as human use of the oceans industrializes. Though protected areas are a powerful tool to harness ocean productivity, especially when designed with future climate in mind, additional management strategies will be required. Overall, habitat degradation is likely to intensify as a major driver of marine wildlife loss. Proactive intervention can avert a marine defaunation disaster of the magnitude observed on land.

Several decades of research on defaunation in terrestrial habitats have revealed a serial loss of mammals, birds, reptiles, and invertebrates that previously played important ecological roles (1). Here, we review the major advancements that have been made in understanding the historical and contemporary processes of similar defaunation in marine environments. We highlight patterns of similarity and difference between marine and terrestrial defaunation profiles to identify better ways to understand, manage, and anticipate the effects of future defaunation in our Anthropocene oceans.

Patterns of marine defaunation

Delayed defaunation in the oceans

Defaunation on land began 10,000 to 100,000 years ago as humans were expanding their range and coming into first contact with novel faunal assemblages (2–4). By contrast, the physical properties of the marine environment limited our capacity early on to access and eliminate marine animal species. This difficulty notwithstanding, humans began harvesting marine animals at least 40,000 years ago, a development that some have suggested was a defining feature in becoming "fully modern humans" (5). Even this early harvest affected local marine fauna (6). However, global rates of marine defaunation only intensified in the last century with the advent of industrial fishing and the rapid expansion of coastal populations (7). As a result, extant global marine faunal assemblages remain today more Pleistocene-like, at least with respect to species composition, than terrestrial fauna. The delayed onset of intensive global marine defaunation is most visible in a comparative chronology of faunal extinctions in which humans are likely to have directly or indirectly played a role (8) (Fig. 1).

Comparing rates of animal extinction

Despite the recent acceleration of marine defaunation, rates of outright marine extinction have been relatively low. The International Union for Conservation of Nature (IUCN) records only 15 global extinctions of marine animal species in the past 514 years (i.e., limit of IUCN temporal coverage) and none in the past five decades (8, 9). By contrast, the IUCN recognizes 514 extinctions of terrestrial animals during the same period (Fig. 1). While approximately six times more animal species have been cataloged on land than in the oceans (10), this imbalance does not explain the 36-fold difference between terrestrial and marine animal extinctions.

It is important to note that the status of only a small fraction of described marine animal species have been evaluated by the IUCN, and many assessed species were determined to be data deficient (11) (Fig. 2). This lack of information necessitates that officially reported numbers of extinct and endangered marine fauna be considered as minimum estimates (11). There remain, however, a number of data-independent explanations for the lower extinction rates of marine fauna. Marine species, for instance, tend to be more widespread, exhibit less endemism, and have higher dispersal (12, 13).

Complacency about the magnitude of contemporary marine extinctions is, however, ill-advised. If we disregard the >50,000-year head start of intense terrestrial defaunation (Fig. 1) and compare only contemporary rates of extinction on land and in the sea, a cautionary lesson emerges. Marine extinction rates today look similar to the moderate levels of terrestrial extinction observed before the industrial revolution (fig. S1). Rates of extinction on land increased dramatically after this period, and we may now be sitting at the precipice of a similar extinction transition in the oceans.

Three other kinds of extinction

The small number of species known to be permanently lost from the world's oceans inadequately

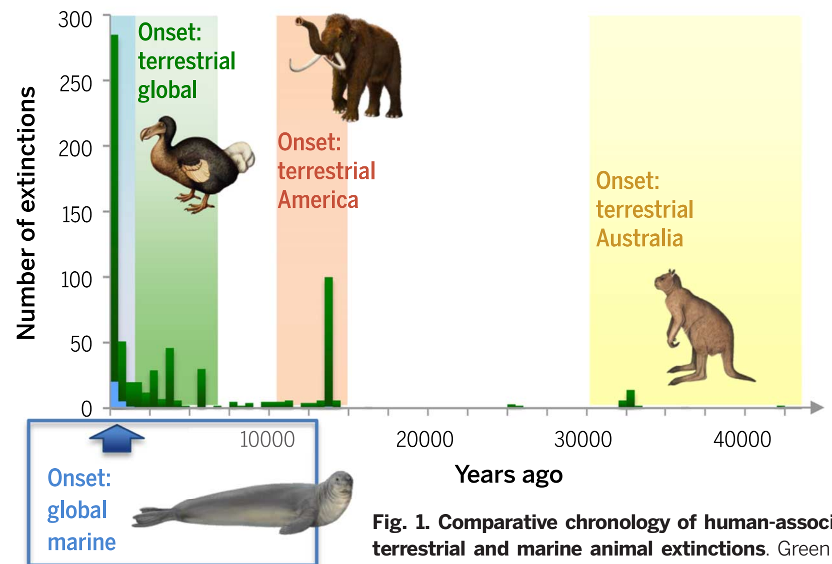

Fig. 1. Comparative chronology of human-associated terrestrial and marine animal extinctions. Green bars indicate animal extinctions that occurred on land, and blue bars indicate marine animal extinctions. Timeline measures years before 2014 CE. Only extinctions occurring less than 55,000 years ago are depicted. Defaunation has ancient origins on land but has intensified only within the last several hundred years in the oceans. See details in (8).

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reflects the full impacts of marine defaunation. We recognize three additional types of defaunation-induced extinction.

Local extinction

Defaunation has caused numerous geographic range constrictions in marine animal species, driving them locally extinct in many habitats. These effects have been particularly severe among large pelagic fishes, where ~90% of studied species have exhibited range contractions (*8*, *14*) (Fig. 3). Local extinctions, however, are not unique to large pelagic predators. Close to a third of the marine fishes and invertebrates off the North American coasts that can be reliably sampled in scientific trawl surveys (often small to medium-bodied species) have also exhibited range contractions (Fig. 3). Such contractions can result from the direct elimination of vulnerable subpopulations or from region-wide declines in abundance (*14*). Available data suggest that the magnitude of the range contractions for this diverse set of trawl-surveyed marine species is, on average, less than the contractions observed for terrestrial animals such as mammals, birds, and butterflies. Though data deficiencies are abundant, most marine animal species also do not yet seem to exhibit some of the most extreme range contractions recorded for terrestrial animals. Asian tigers, for example, have lost ~93% of their historical range (*15*), whereas tiger sharks still range across the world's oceans (*16*).

Ecological extinction

Reductions in the abundance of marine animals have been well documented in the oceans (*17*). Aggregated population trend data suggest that in the last four decades, marine vertebrates (fish, seabirds, sea turtles, and marine mammals) have declined in abundance by on average 22% (*18*). Marine fishes have declined in aggregate by 38% (*17*), and certain baleen whales by 80 to 90% (*19*). Many of these declines have been termed ecological extinctions—although the species in question are still extant, they are no longer sufficiently abundant to perform their functional roles. Ecological extinctions are well known in terrestrial environments and have been demonstrated to be just as disruptive as species extinctions (*20*). On land, we know of the phenomenon of "empty forests" where ecological extinctions of forest fauna alter tree recruitment, reshape plant dispersal, and cause population explosions of small mammals (*1*, *20*, *21*). We are now observing the proliferation of "empty reefs," "empty estuaries," and "empty bays" (*7*, *14*, *22*).

Commercial extinction

Species that drop below an abundance level at which they can be economically harvested are extinct from a commercial standpoint. On land, commercial extinctions affected species ranging from chinchilla to bison (*23*). Cases of commercial extinction are also common in the oceans. Gray whales were commercially hunted starting in the 1840s. By 1900, their numbers were so depleted that targeted harvest of this species was no longer regionally tenable (*24*). Likewise, the great whales in Antarctica were serially hunted to commercial extinction (*25*).

Not all species, however, are so "lucky" as to have human harvesters desist when they become extremely rare. Demand and prices for certain highly prized marine wildlife can continue to increase as these animals become less abundant—a phenomenon termed the anthropogenic Allee effect (*26*). Individual bluefin tuna can sell for >US$100,000, rare sea cucumbers >US$400/kg, and high-quality shark fins for >US$100/kg. Such species are the rhinos of the ocean—they may never be too rare to be hunted.

Differential vulnerability to defaunation

Are certain marine animals more at risk than others to defaunation? There has been considerable attention given to harvester effects on large marine animals (*27*). Selective declines of large-bodied animals appear to be evident in certain contexts (*28*, *29*). As a result of such pressures, turtles, whales, sharks, and many large fishes are now ecologically extinct in many ecosystems, and the size spectra (abundance–body mass relationships) of many communities have changed considerably (*7*, *30*, *31*). Marine defaunation, however, has not caused many global extinctions of large-bodied species. Most large-bodied marine animal species still exist somewhere in the ocean. By contrast, on land, we have observed the extinction of numerous large terrestrial species and a profound restructuring of the size distribution of land-animal species assemblages. The mean body mass for the list of surviving terrestrial mammal species, for example, is significantly smaller than the body mass of terrestrial mammal species that lived during the Pleistocene (*1*, *32*). Such effects, however, are not evident for marine mammals (*8*) (fig. S2). Recent reviews have drawn attention to the fact that humans can also intensely and effectively deplete populations of smaller marine animals (*29*, *33*). These observations have inspired a belated surge in interest in protecting small forage fishes in the oceans.

A review of modern marine extinctions and listings of species on the brink of extinction reveals further insight into aggregate patterns of differential defaunation risk in the oceans (Fig. 2). Sea turtles have the highest proportion of endangered species among commonly recognized groupings of marine fauna. No modern sea turtle species, however, have yet gone extinct. Pinnipeds and marine mustelids, followed very closely by seabirds and shorebirds, have experienced the highest proportion of species extinctions. Many of the most threatened groups of marine animals are those that directly interact with land (and land-based humans) during some portion of their life history (Fig. 2). Terrestrial contact may also explain why diadromous/brackish water fishes are more threatened than exclusively marine fishes (Fig. 2).

Although many marine animal species are clearly affected negatively by marine defaunation, there also appears to be a suite of defaunation "winners," or species that are profiting in Anthropocene oceans. Many of these winners are smaller and "weedier" (e.g., better colonizing and faster reproducing) species. Marine invertebrates, in particular, have often been cited as examples of

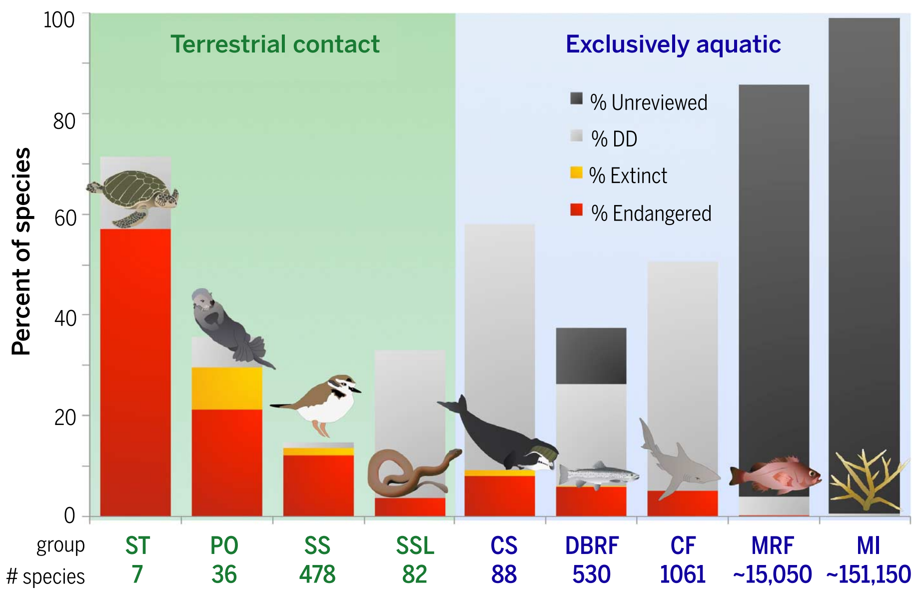

Fig. 2. Marine defaunation threat. Threat from defaunation is portrayed for different groups of marine fauna as chronicled by the IUCN Red List (*113*). Threat categories include "extinct" (orange), "endangered" (red; IUCN categories "critically endangered" + "endangered"), "data deficient" (light gray), and "unreviewed" (dark gray). Groups that contact land during some portion of their life history (green) are distinguished from species that do not (light blue). The total number of species estimated in each group is listed below the graph. Species groupings are coded as follows: ST, sea turtles; PO, pinnipeds and marine mustelids; SS, seabirds and shorebirds; SSL, sea snakes and marine lizard; CS, cetaceans and sirenians; DBRF, diadromous/brackish ray-finned fishes; CF, cartilaginous fishes; MRF, exclusively marine ray-finned fishes; MI, marine invertebrates. See further details in (*8*).

species that are succeeding in the face of intense marine defaunation: lobster proliferated as predatory groundfish declined (*34*), prawns increased and replaced the dominance of finfish in landings (*35*), and urchin populations exploded in the absence of their predators and competitors (*36*). Numerous mid-level predators also appear to benefit from the loss of top predators [e.g., small sharks and rays; (*37*)]—a phenomenon analogous to mesopredator release observed in terrestrial spheres (*38*). The status held by some of these defaunation winners in the oceans may, however, be ephemeral. Many of the marine species that have initially flourished as a result of defaunation have themselves become targets for harvest by prey-switching humans as is evidenced by the recent global expansion of marine invertebrate fisheries (*39*).

Spatial patterns of vulnerability

Patterns of marine defaunation risk track differences in the physical environment. Global assessments of human impact on marine ecosystems suggest that coastal wildlife habitats have been more influenced than deep-water or pelagic ecosystems (*40*). The vulnerability of coastal areas presumably results from ease of access to coastal zones. This relationship between access and defaunation risk manifests itself also at smaller spatial scales, with populations of marine wildlife closest to trade networks and human settlements appearing often to be more heavily defaunated (*41*, *42*). The relative insulation that animal populations in regions like the deep oceans presently experience, however, may be short-lived because depletions of shallow-water marine resources and the development of new technologies have created both the capacity and incentive to fish, mine, and drill oil in some of the deepest parts of the sea (*28*, *43*).

Coral reefs, in particular, have consistently been highlighted as marine ecosystems of special concern to defaunation. Coral reefs have been exposed to a wide range of impacts and disturbances, including sedimentation and pollution, thermal stress, disease, destructive fishing, and coastal development (*44*, *45*). Such stressors negatively influence both corals and the millions of species that live within and depend upon reefs (*46*). Risk, however, is not uniform, even across a reefscape. Shallow backreef pools, for example, routinely overheat, and consequently, corals in these parts of the reef are more resistant to ocean warming (*47*). Environmentally heterogeneous areas may in fact act as important natural factories of adaptation that will buffer against some types of marine defaunation.

Effects of marine defaunation

Extended consequences of marine defaunation

Marine defaunation has had far-reaching effects on ocean ecosystems. Depletions of a wide range of ecologically important marine fauna such as cod, sea otters, great whales, and sharks have triggered cascading effects that propagate across marine systems (*37*, *48*–*51*). Operating in the opposite direction from trophic cascades are changes that travel from the bottom to the top of food chains as a result of the declining abundance of lower–trophic level organisms (*52*). Depletions of fauna such as anchovies, sardines, and krill cause reductions in food for higher-trophic level animals such as seabirds and marine mammals, potentially resulting in losses in reproduction or reductions in their population size (*33*, *53*).

The extended effects of defaunation on marine ecosystems also occur beyond the bounds of these top-down or bottom-up effects. Defaunation can reduce cross-system connectivity (*54*, *55*), decrease ecosystem stability (*56*), and alter patterns of biogeochemical cycling (*57*). The ill effects of food web disarticulation can be further amplified when they occur in association with other marine disturbances. For example, mass releases of discarded plant fertilizers into marine ecosystems from which defaunation has eliminated important consumers can create "productivity explosions" by fueling overgrowth of microbes and algae that fail to be routed into food webs (*58*, *59*).

The selective force of human predation has also been sufficiently strong and protracted so as to have altered the evolutionary trajectory of numerous species of harvested marine fauna (*60*). Harvest has driven many marine animal species to become smaller and thinner, to grow more slowly, to be less fecund, and to reproduce at smaller sizes (*61*). There is also evidence that harvest can reduce the genetic diversity of many marine animal populations (*62*). The genetic effects of defaunation represent a loss of adaptive potential that may impair the resilient capacity of ocean wildlife (*63*).

Importance of marine defaunation to humans

Marine defaunation is already affecting human well-being in numerous ways by imperiling food sustainability, increasing social conflict, impairing storm protection, and reducing flows of other ecosystem services (*64*, *65*). The most conspicuous service that marine fauna make to society is the contribution of their own bodies to global diets. Marine animals, primarily fishes, make up a large proportion of global protein intake, and this contribution is especially strong for impoverished coastal nations (*66*). According to the U.N. Food and Agriculture Organization (FAO), 40 times more wild animal biomass is harvested from the oceans than from land (*67*). Declines in this source of free-range marine food represent a major source of concern (*65*).

A diverse array of nonconsumptive services are also conferred to humanity from ocean animals, ranging from carbon storage that is facilitated by whales and sea otters to regional cloud formation that appears to be stimulated by coral emissions of dimethylsulphoniopropionate (DMSP) (*57*, *68*, *69*). Another key service, given forecasts of increasingly intense weather events and sea-level rise, is coastal protection. Coral, oyster, and other living reefs can dissipate up to 97% of the wave energy reaching them, thus protecting built structures and human lives (*70*). In some cases, corals are more than just perimeter buffers; they also serve as the living platform upon which entire countries (e.g., the Maldives, Kiribati, the Marshall Islands) and entire cultures have been founded. Atoll-living human populations in these areas depend on the long-term health of these animate pedestals to literally hold their lives together.

Outlook and ways forward

Will climate change exacerbate marine defaunation?

The implications of climate change upon marine defaunation are shaped by ocean physics. Marine species live in a vast, globally connected fluid

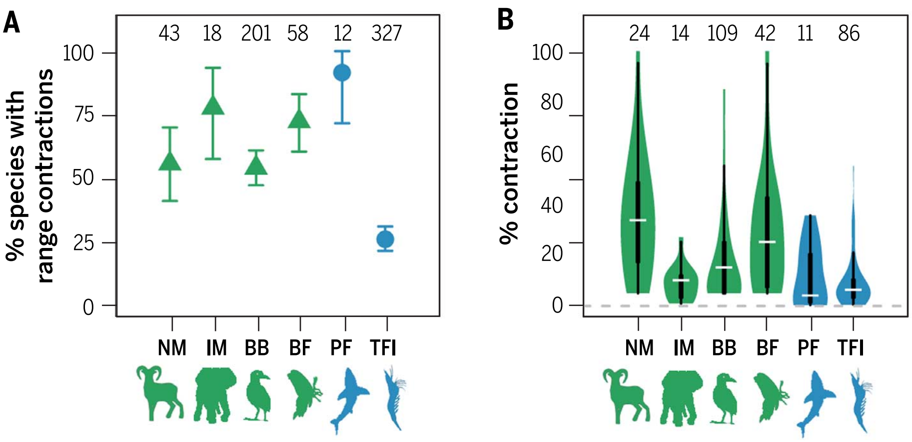

Fig. 3. Comparisons of range contractions for select marine and terrestrial fauna. Terrestrial (green) and marine cases (blue) include evaluations of geographical range change for: 43 North American mammals over the last ~200 years (NM) (*114*), 18 Indian mammals over the last 30 years (IM) (*115*), 201 British birds from ~1970 to 1997 (BB) and 58 British butterflies from ~1976 to 1997 (BF) (*116*), 12 global large pelagic fishes from the 1960s to 2000s (PF) (*14*), and 327 trawl-surveyed North American marine fish and invertebrates from the 1970s to 2000s (TFI). (**A**) Percent of species whose ranges have contracted with binomial confidence intervals and (**B**) distribution of percent contraction for those species that have contracted (violin plot). Sample sizes are shown above each data point, white horizontal lines (B) show the medians, and thick vertical black lines display the interquartile range. See details in (*8*).

medium that has immense heat-storage capacity and has exhibited a historically robust capability to buffer temperature change over daily, annual, and even decadal time scales (71). While this buffering capacity at first seems to confer an advantage to marine fauna, the thermal stability of the oceans may have left many subtidal marine animals poorly prepared, relative to terrestrial counterparts, for the temperature increases associated with global warming. The same logic supports related predictions that terrestrial fauna living in more thermally stable environments will be more vulnerable to warming than those found in areas of greater temperature variability (72).

Ocean warming presents obvious challenges to polar marine fauna trapped in thermal dead ends (73). Tropical marine species are, however, also highly sensitive to small increases in temperature. For example, coastal crabs on tropical shores live closer to their upper thermal maxima than do similar temperate species (74). Likewise, the symbiosis of corals and dinoflagellates is famously sensitive to rapid increases of only 1° to 2°C (75). Even though corals exhibit the capacity for adaptation (47), coral bleaching events are expected to be more common and consequently more stressful by the end of the century (76). The effects of rising ocean temperature extend well beyond coral reefs and are predicted to affect both the adult and juvenile stages of a diverse set of marine species (77), to reshuffle marine community composition (78), and to potentially alter the overall structure and dynamics of entire marine faunal communities (79).

The wide range of other climate change–associated alterations in seawater chemistry and physics—including ocean acidification, anoxia, ocean circulation shifts, changes in stratification, and changes in primary productivity—will fundamentally influence marine fauna. Ocean acidification, for example, makes marine animal shell building more physiologically costly, can diminish animal sensory abilities, and can alter growth trajectories (80, 81). Climate change impacts on phytoplankton can further accentuate defaunation risk (82). At the same time that humans are reducing the abundance of marine forage fish through direct harvest, we also may be indirectly reducing the planktonic food for forage fish and related consumers in many regions.

Mobility and managing defaunation

Many marine animals, on average, have significantly larger home ranges as adults [Fig. 4 and figs. S3 and S4; (8)] and disperse greater distances as juveniles than their terrestrial counterparts (13). This wide-ranging behavior of many marine species complicates the management of ocean wildlife as species often traverse multiple management jurisdictions (83–85). On the other hand, the greater mobility of many marine animal species may help them to better follow the velocity of climate change and to colonize and recolonize habitats, so long as source population refuges are kept available (71, 73, 78, 86, 87).

Marine protected areas can offer this sort of refuge for animal populations (88). The establishment of protected areas in the oceans lags far behind advancements made on land, with an upper-bound estimate of only about 3.6% of the world's oceans now protected (8) (fig. S5). One source of optimism for slowing marine defaunation, particularly for mobile species, is that the mean size of marine protected areas has increased greatly in recent years (fig. S5). However, most marine protected areas remain smaller (median 4.5 km^2) than the home range size of many marine animals (Fig. 4). Though much is lost in this type of crude comparison, this observation highlights what may be an important disconnect between the scales at which wildlife use the oceans and the scale at which we typically manage the oceans.

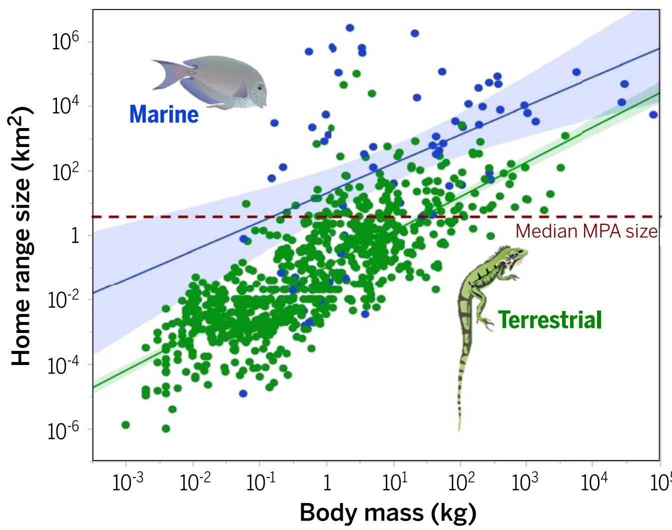

Fig. 4. Mobility of terrestrial and marine fauna. Because mobility shapes defaunation risk, we compare the size-standardized home range size of a representative selection of marine (blue) and terrestrial (green) vertebrates. Data are presented for adults over a full range of animal body sizes, plotted on a logarithmic scale. Species include seabirds, marine reptiles, marine fishes, marine mammals, terrestrial birds, terrestrial reptiles, and terrestrial mammals (see details in (8); table S2 and fig. S3). Regression lines enclosed by shaded confidence intervals are plotted for all marine and all terrestrial species. The dotted red line demarcates the current median size of all marine protected areas (MPAs).

This spatial mismatch is just one of many reasons why protected areas cannot be the full solution for managing defaunation (83). We learned this lesson arguably too late on land. Protected areas can legitimately be viewed as some of our proudest conservation achievements on land (e.g., Yosemite, Serengeti, Chitwan National Parks), and yet with four times more terrestrial area protected than marine protected area, we have still failed to satisfactorily rein in terrestrial defaunation (1) (fig. S5). The realization that more was needed to curb terrestrial defaunation inspired a wave of effort to do conservation out of the bounds of terrestrial protected areas (e.g., conservation easements and corridor projects). The delayed implementation of these strategies has, however, often relegated terrestrial conservation to operating more as a retroactive enterprise aimed at restoring damaged habitats and triaging wildlife losses already underway. In the oceans, we are uniquely positioned to preemptively manage defaunation. We can learn from the terrestrial defaunation experience that protected areas are valuable tools, but that we must proactively introduce measures to manage our impacts on marine fauna in the vast majority of the global oceans that is unprotected.

Strategies to meet these goals include incentive-based fisheries management policies (89), spatially ambitious ecosystem-based management plans (83), and emerging efforts to preemptively zone human activities that affect marine wildlife (90, 91). There have been mixed responses among marine managers as to whether and how to embrace these tools, but more complete implementation of these strategies will help chart a sustainable future for marine wildlife (43, 90, 91). A second, complementary set of goals is to incorporate climate change into marine protected area schemes to build networks that will provide protection for ocean wildlife into the next century (92). Such built-in climate plans were unavailable, and even unthinkable, when many major terrestrial parks were laid out, but data, tools, and opportunity exist to do this thoughtfully now in the oceans.

Habitat degradation: The coming threat to marine fauna

Many early extinctions of terrestrial fauna are believed to have been heavily influenced by human hunting (2, 93), whereas habitat loss appears to be the primary driver of contemporary defaunation on land (1, 11, 86, 94). By contrast, marine defaunation today remains mainly driven by human harvest (95, 96). If the trajectory of terrestrial defaunation is any indicator, we should anticipate that habitat alteration will ascend in importance as a future driver of marine defaunation.

Signs that the pace of marine habitat modification is accelerating and may be posing a growing threat to marine fauna are already apparent (Fig. 5). Great whale species, no longer extensively hunted, are now threatened by noise disruption, oil exploration, vessel traffic, and entanglement with moored marine gear (fig. S6) (97). Habitat-modifying fishing practices (e.g., bottom trawling) have affected ~50 million km^2 of seafloor (40). Trawling may represent just the beginning of our capacity to alter marine habitats. Development of coastal cities, where ~40% of the human population lives (98), has an insatiable demand for coastal land. Countries like the United Arab Emirates and China have elected to meet this demand by "seasteading"—constructing ambitious new artificial lands in the ocean (99). Technological advancement in seafloor mining, dredging, oil and gas extraction, tidal/wave energy generation, and marine transport is fueling rapid expansion of these marine industries (43, 100). Even farming is increasing in the sea. Projections now suggest that in less than 20 years, aquaculture will provide more fish for human consumption than wild capture fisheries (101). Fish farming, like crop farming, can consume or drastically alter natural habitats when carried out carelessly (102). Many of these emerging marine development activities are reminiscent of the types of rapid environmental change observed on land during the industrial revolution that were associated with pronounced increases in rates of terrestrial defaunation. Marine habitats may eventually join the ranks of terrestrial frontier areas, such as the American West, the Brazilian Amazon, and Alaska, which were once believed to be impervious to development, pollution, and degradation.

Land to sea defaunation connections

The ecologies of marine and terrestrial systems are dynamically linked. Impacts on terrestrial fauna can perturb the ecology of marine fauna (54) and vice versa (103). Furthermore, the health of marine animal populations is interactively connected to the health of terrestrial wildlife populations—and to the health of society. People in West Africa, for example, exploit wild terrestrial fauna more heavily in years when marine fauna are in short supply (104). It is not yet clear how these linkages between marine and terrestrial defaunation will play out at the global level. Will decreasing yields from marine fisheries, for example, require that more terrestrial wildlands be brought into human service as fields and pastures to meet shortfalls of ocean-derived foods? Marine ecosystem managers would do well to better incorporate considerations of land-to-sea defaunation connections in decision making.

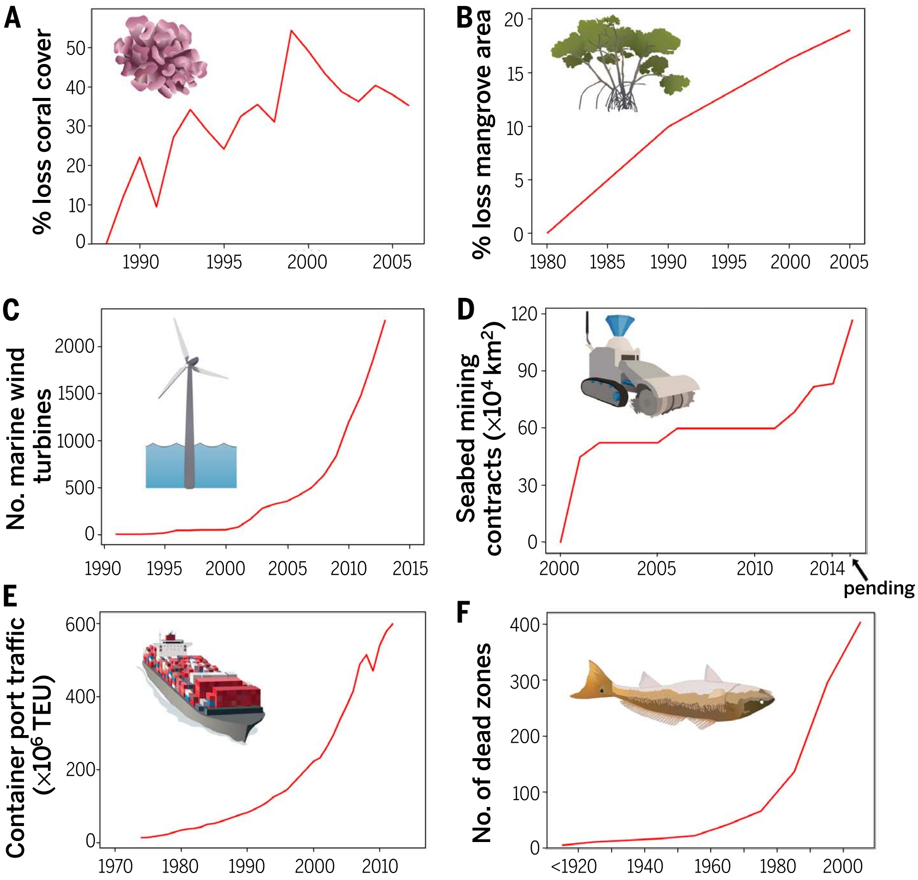

Fig. 5. Habitat change in the global oceans. Trends in six indicators of marine habitat modification suggest that habitat change may become an increasingly important threat to marine wildlife: (**A**) change in global percent cover of coral reef outside of marine protected areas [percent change at each time point measured relative to percent coral cover in 1988 (44)]; (**B**) global change in mangrove area (percent change each year measured relative to mangrove area in 1980) (117); (**C**) change in the cumulative number of marine wind turbines installed worldwide (118); (**D**) change in the cumulative area of seabed under contract for mineral extraction in international waters (119); (**E**) trends in the volume of global container port traffic (120); and (**F**) change in the cumulative number of oxygen depleted marine "dead zones." See details and data sources in (8).

Not all bad news

It is easy to focus on the negative course that defaunation has taken in the oceans. Humans have, however, demonstrated a powerful capacity to reverse some of the most severe impacts that we have had on ocean fauna, and many marine wildlife populations demonstrate immense potential for resilience (47, 105–107). The sea otter, the ecological czar of many coastal ecosystems, was thought to be extinct in the early 1900s but was rediscovered in 1938, protected, and has resumed its key ecological role in large parts of the coastal North Pacific and Bering Sea (108). The reef ecosystems of Enewetak and Bikini Atolls present another potent example. The United States detonated 66 nuclear explosions above and below the water of these coral reefs in the 1940s and 1950s. Less than 50 years later, the coral and reef fish fauna on these reefs recovered to the point where they were being described as remarkably healthy (109).

There is great reason to worry, however, that we are beginning to erode some of the systemic resilience of marine animal communities (110). Atomic attacks on local marine fauna are one thing, but an unimpeded transition toward an era of global chemical warfare on marine ecosystems (e.g., ocean acidification, anoxia) may retard or arrest the intrinsic capacity of marine fauna to bounce back from defaunation (75, 111).

Conclusions

On many levels, defaunation in the oceans has, to date, been less severe than defaunation on land. Developing this contrast is useful because our more advanced terrestrial defaunation experience can serve as a harbinger for the possible future of marine defaunation (3). Humans have had profoundly deleterious impacts on marine animal populations, but there is still time and there exist mechanisms to avert the kinds of defaunation disasters observed on land. Few marine extinctions have occurred; many subtidal marine habitats are today less developed, less polluted, and more wild than their terrestrial counterparts; global body size distributions of extant marine animal species have been mostly unchanged in the oceans; and many marine fauna have not yet experienced range contractions as severe as those observed on land.

We are not necessarily doomed to helplessly recapitulate the defaunation processes observed on land in the oceans: intensifying marine hunting until it becomes untenable and then embarking on an era of large-scale marine habitat modification. However, if these actions move forward in tandem, we may finally trigger a wave of marine extinctions of the same intensity as that observed on land. Efforts to slow climate change, rebuild affected animal populations, and intelligently engage the coming wave of new marine development activities will all help to change the present course of marine defaunation. We must play catch-up in the realm of marine protected area establishment, tailoring them to be operational in our changing oceans. We must also carefully construct marine spatial management plans for the vast regions in between these areas to help ensure that marine mining, energy development, and intensive aquaculture take important marine wildlife habitats into consideration, not vice versa. All of this is a tall order, but the oceans remain relatively full of the raw faunal ingredients and still contain a sufficient degree of resilient capacity so that the goal of reversing the current crisis of marine defaunation remains within reach. The next several decades will be those in which we choose the fate of the future of marine wildlife.

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SUPPLEMENTARY MATERIALS

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Marine defaunation: Animal loss in the global ocean
Douglas J. McCauley, Malin L. Pinsky, Stephen R. Palumbi, James A. Estes, Francis H. Joyce and Robert R. Warner (January 15, 2015)

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Editor's Summary

Marine animals are disappearing, too

The loss of animal species in terrestrial environments has been well documented and is continuing. Loss of species in marine environments has been slower than in terrestrial systems, but appears to be increasing rapidly. McCauley *et al.* review the recent patterns of species decline and loss in marine environments. Though they note many worrying declines, they also highlight approaches that might allow us to prevent the type of massive defaunation that has occurred on land.
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