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Artificial light may be changing marine ecosystems

Editor's note: Artificial light at night (ALAN)– whose undesirable effects are more colloquially referred to as light pollution – has long been known to affect sea turtles. Numerous studies document that adult sea turtles avoid nesting on artificially-lit beaches and artificial lights on land draw newly-hatched sea turtles away from the ocean, leading to increased mortality due to increased predation, dehydration and energy expenditure. But what about other marine organisms? In this article, we explore (Skimmer-style) recent research about how light pollution may be affecting many marine organisms and ultimately marine ecosystems.

Natural light cues structure a lot of behaviors and processes in marine ecosystems

- Most marine organisms in the surface ocean (from surface to 200 m depth) are adapted to natural light from the sun, moon, and stars. Cues from natural light – including its cycles, colors, intensities, and spatial orientation – help structure many organismal behaviors and ecological processes in marine ecosystems.
  - These behaviors and processes include migrations (e.g., lunar compasses for long distance migration, daily vertical migrations cued by moonlight), foraging, predation, rest, and reproduction (e.g., timing of broadcast spawning) for marine reptiles, amphibians, fish, birds, mammals, and invertebrates.
  - In addition to light being a source of information, light is also a resource for photosynthesis and primary production.
- Artificial light at night (ALAN) interferes with natural light patterns and the biological processes they help control and can dramatically affect the behavior of marine organisms, species interactions, distributions of marine organisms, and food webs and can potentially restructure coastal marine ecosystems.

Coastal light pollution is global and getting worse

- ALAN in marine environments comes from coastal development (e.g., buildings, streetlights, billboards, ports, piers, docks) as well as vessels (e.g., fishing and merchant marine vessels) and offshore infrastructure such as oil rigs. It has increased exponentially over the past 150 years and has become a significant issue for the marine environment in the last 60-90 years.
- Artificial skyglow is one of the most common forms of ALAN. It refers to the diffuse luminance of the night sky from artificial lighting – both upward-directed light as well as light reflected from the ground or water or other surfaces. Artificial skyglow often forms a dome of light over cities and towns and is visible from great distances.
  - Artificial skyglow can now be detected above 22 percent of the world's coasts nightly – with Europe, Asia and Africa having the highest percentages of their coastlines affected. Coastal populations are expected to double by 2060, with an attendant increase in coastal ALAN intensity and spread.
  - A recent global mapping effort (2020) found the coastal areas most threatened by ALAN to be in the Red Sea, the Persian Gulf, the eastern Caribbean, and the western Pacific regions. In the Gulf of Aqaba/Eilat, some areas are 60 times brighter than under a natural night sky, and even relatively unaffected areas of the gulfs are nearly 50 percent brighter.
- Another recent study (2020) examined the extent to which artificial light from coastal cities reaches the nearby seafloor. Researchers shined artificial lights that mimicked city skyglow and measured exposure at the surface of the water column, in the water column, and on the seafloor of a local estuary. They found that on cloudy nights (which have more light reflected back to the ground than clear nights) green and blue wavelengths of light-emitting diode (LED) light reach 70 percent or more of the three-dimensional space around seafloor habitats whereas less than 1 percent of the seafloor is exposed to "biologically important" levels of red wavelengths. In addition since estuaries generally have higher levels of sediment and less light penetration than many other coastal habitats, researchers estimate that ALAN could reach 100 percent of the seabed in clearer coral reef systems. These findings suggest that marine habitats near all coastal cities could be exposed to ALAN.
- Light pollution in marine environments in also becoming more severe due to the increasing prevalence of LED lights. LEDs now account for roughly half of global light sources, and that share is expected to grow to nearly 90 percent of global light sources by 2030. White LEDs produce broad spectrum light that is sensed by a wide range of organisms and have a peak at short wavelengths (blue and green light) to which many marine organisms are particularly sensitive. Moreover, these shorter wavelengths penetrate deeper into the water column, affecting organisms at greater depths.

Artificial light at night (ALAN) interferes with marine ecosystem processes

A conceptual map of individual- to ecosystem-level responses to ALAN

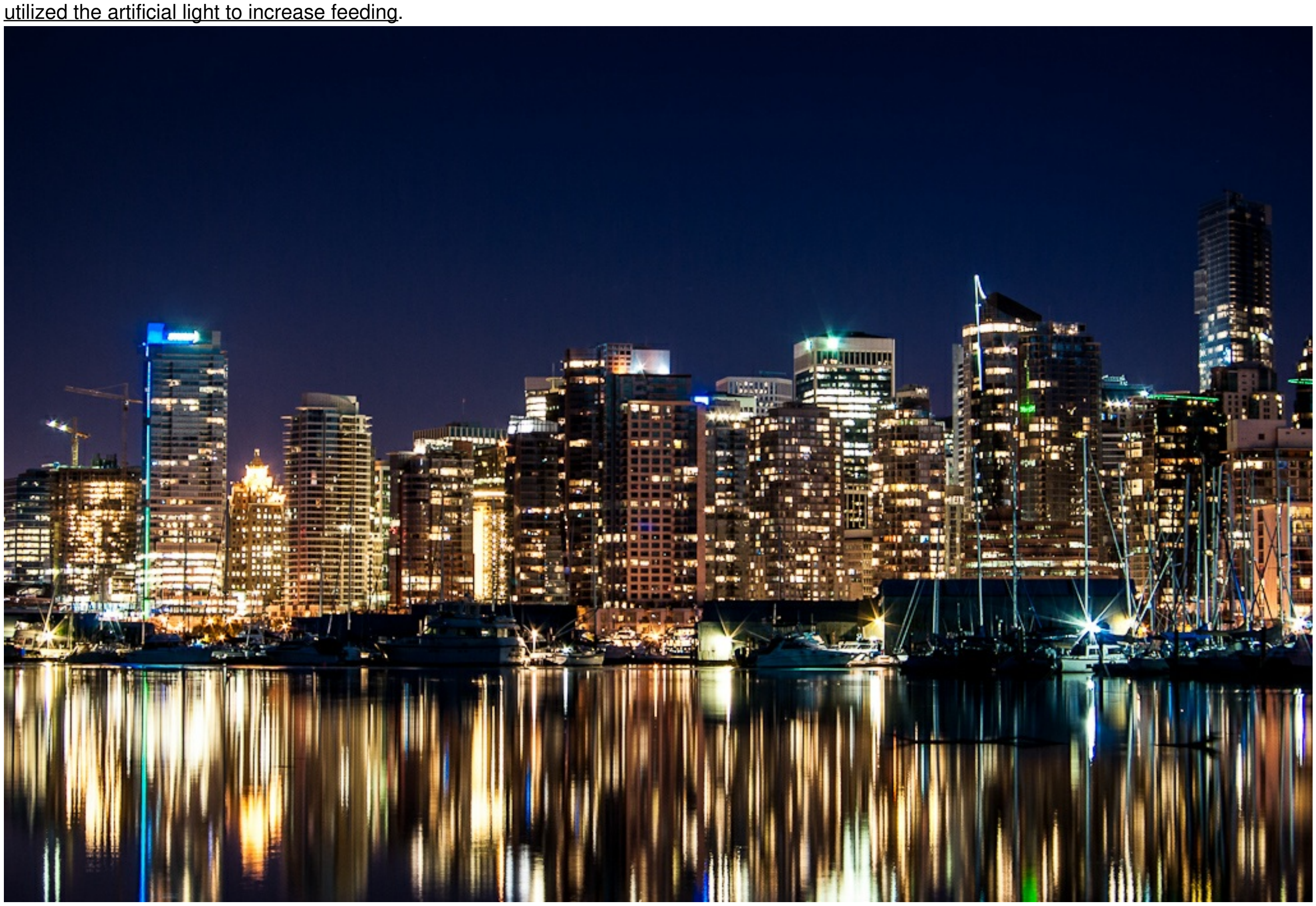
A conceptual map of individual- to ecosystem-level responses to ALAN in estuarine ecosystems by Zapata et al. (2019) classifies responses by level of organization.

- At the **individual** level, ALAN can impact **physiology and behavior by increasing, decreasing, and/or altering diel and nocturnal activity**
    - Mechanisms for this occurring can include changes to visual sensitivity, circadian rhythms, predation risk, food availability, and stress and reproductive hormone levels.
- At the **population** level, ALAN can impact **performance by shifting diel or nocturnal activity which may enhance or reduce fitness**.
    - Mechanisms for this occurring can include lit areas serving as polarized or direct light traps or light expanding or constraining activity intervals.
- At the **species** level, ALAN can impact **interactions by altering predation and competition among diurnal and nocturnal taxa**
    - Mechanisms for this occurring include changes to the spatial, spectral, and temporal composition of light and the spatiotemporal distribution of food resources and habitat.
- At the **community** level, ALAN can impact **composition by changing relative abundance, species diversity, and distribution of taxa**
    - Mechanisms for this occurring include changes to the availability and partitioning of resources, risk regimes, and movement and dispersal patterns.
- At the **food web** level, ALAN can impact **structure by restructuring trophic network topology and functional attributes**.
    - Mechanisms for this occurring include altering interaction strengths via spatial and temporal shifts and changing aquatic primary productivity.
- At the **ecosystem** level, ALAN can impact **function by changing nutrient cycling, biodiversity, and ecosystem productivity**.
    - Mechanisms for this occurring include changes to cross-boundary nutrient flows.
- Changes at any of these levels of organization (e.g., individual, population, species, community, food web, and ecosystem) can in turn impact other levels of organization (e.g., individual responses can cause population and community level impacts).

Text from Zapata, M.J., Sullivan, S.M.P. and Gray, S.M. Artificial lighting at night in estuaries – Implications from individuals to ecosystems. Estuaries and Coasts 42, 309–330 (2019). https://doi.org/10.1007/s12237-018-0479-3

- There has been relatively little study of the impacts of ALAN on marine organisms and environments to date, but evidence of impacts is starting to emerge.
- There is now growing evidence that ALAN causes stress responses and changes activity levels, metabolic processes, and circadian rhythms in marine organisms.
    - A seminal work on light pollution in a freshwater lake (2000) found that urban light pollution reduced the amplitude of zooplankton diel vertical migration as well as the number of individuals migrating. Since nearly a third of global ocean primary production takes place in the coastal ocean and zooplankton diel vertical migration is a major pathway in the ocean carbon cycle, ALAN could be altering ocean carbon and nutrient cycling.
    - Another early study (2007) found that post-smolt Atlantic salmon exposed to high intensity blue LED lights showed an acute stress response (increase in cortisol levels) which subsided by 24 hours after the light exposure started. Elevated levels of cortisol over a long period can compromise immune response and affect metabolism.
    - In a study from 2015, Atlantic salmon fry exposed to broad spectrum light equivalent to that of street lighting dispersed later in development (mean delay of 1.4-2.3 days) and later in the day (mean delay of 1.5 hours later after dusk with a significant percentage not dispersing until daylight hours) than fry under normal light-dark cycling. The later dispersal (both in terms of days and time of day) may reduce fitness of the smolts due to decreased feeding opportunities and/or increased predation.
    - A study from 2019 found that, when exposed to ALAN, two coral species from the Gulf of Eilat/Aqaba in the Red Sea had higher rates of free radicals. Free radicals are chemically reactive forms of oxygen that can damage an organism's proteins and DNA. Researchers also found that the corals' symbiotic algae experienced population fluctuations and reduced photosynthesis under ALAN and that blue and white LED lights had a greater effect on the coral and algae than yellow LED light
    - Another study from 2019 found that when juvenile conch, a keystone species along southeastern Pacific coasts including the Chilean coast, were exposed to LED light, their metabolisms and the time they took to right themselves increased They also hunted more efficiently in darkened habitats than when exposed to artificial light.
    - And another study from 2019 found that rockfish, an abundant and ecologically important intertidal fish in the southeastern Pacific increased their activity and oxygen consumption and stopped displaying their natural circatidal and circadian activity cycles when exposed to artificial light of the same intensity to which local fish are exposed.
    - One of the few studies (2019) of the effects of ALAN on sandy beach ecosystems looked at common isopods on sandy beaches in north-central Chile. These isopods burrow in the sand during the day and migrate closer to the water at night. In the laboratory, isopods exposed to ALAN reduced their movements and lost their circadian rhythm relative to controls with a natural day/night cycle. In field experiments, isopod numbers were clearly lower under artificial light that mimicked public lighting relative to control transects.
    - And in the first study to look at the impacts of ALAN on marine fish larvae (2019), researchers found that coral reef fish larvae grew faster and heavier, exhibited different swimming behaviors, and experienced greater predation at night under ALAN. Mortality was higher for larvae exposed to ALAN than larvae under control conditions by the end of the 10-day experiment. Researchers also found that coral reef fish larvae avoided settling in artificially lit habitats.

- Other studies have also found evidence of changes to species distributions and interactions, particularly predator-prey interactions, due to ALAN. Among other influences, ALAN can function as a light trap concentrating prey species, make it easier for predators to see prey at night, and reduce natural camouflaging of prey species.
    - An early study published in 2000 found intense predation on juvenile Pacific salmon by seals under two brightly lit bridges in British Columbia. When the lights were turned off, the number of seals under the bridges initially decreased but eventually returned to prior levels as the seals seemed to learn to use the residual city lighting for their feeding.
    - A 2013 study of the impact of a 400-W sodium vapor floodlight on lit areas in a South African estuary found an increase in small shoaling fish in the lit areas (likely due to attraction to the light) as well an increase in large predatory fish (likely due to concentration of prey and enhanced visual predation capabilities). In turn, the lit area is a popular fishing spot for humans. These results suggest that artificial lighting has the potential to alter estuarine communities by creating optimal conditions for predators.
    - In a 2017 study, researchers placed LED spotlights under a wharf in an Australian harbor. Fewer fish utilized the areas at night relative to unlit control periods, but despite the decreased usage, predation on sessile invertebrate prey assemblages increased in the lit areas relative to unlit periods. These results suggest that some fish lost a nighttime refuge where they could rest and decrease their energy usage and some fish utilized the artificial light to increase feeding.



- There is also increasing evidence that ALAN impacts how sessile invertebrates select settlement sites and their subsequent survival rates. Many sessile invertebrates such as corals, bryozoa, polychaetes, tunicates, and barnacles are ecosystem engineers that create habitats for other organisms, and their settlement locations and survival and reproductive rates help determine community composition and function as well as ecosystem functioning (including controlling the depth at which photosynthesis can occur).
    - A 2015 study found that artificial light similar to that of streetlights (on the higher end of artificial light conditions in marine environments) led to changes in the composition of epifaunal marine invertebrate communities in the Menai Strait in the UK. Researchers observed changes in colonization rates for 39% of the taxa observed. Specifically, they found lower colonization rates on substrates by sea squirts and higher colonization rates by a range of species considered nuisance fouling species such as barnacles. Barnacle fouling is estimated to cost the global economy over US$300M annually, and this study raises the intriguing possibility that changes to ambient lighting around ships and ports could help address this issue.
    - In another 2015 study, traps set in shallow waters of the Great Barrier Reef under artificial light conditions caught more individuals for all species than traps in natural light conditions. For amphipods, the species assemblages caught under LED lights were different, suggesting that some amphipod species are specifically attracted to LED light.
- In addition to the findings that ALAN can cause stress responses in corals, increase larval mortality of coral reef fish, and discourage settlement of coral reef fish larvae, there is evidence that ALAN may impact coral reef ecosystems in other ways.
    - In a 2020 study, ALAN led to unsynchronized spawning in two coral species from the Indo-Pacific Ocean, and ALAN is currently hypothesized to be one of the main drivers for the lack of synchronization in spawning for three of five coral species in the Red Sea, one of the most light polluted coastal regions in the world. Synchronization of broadcast spawning events helps ensure successful fertilization, and interference with this timing may lead to declines in recruitment.

- In a year-long laboratory study (2020), settlement and photosynthetic efficiency of a Red Sea coral were lower under fluorescent and LED lights than under control conditions, but coral survivorship, growth, and calcification were higher under artificial light conditions.

Furthering ALAN research in marine ecosystems

- Minimizing ALAN and its attendant impacts on marine ecosystems will require a great deal more research, management, and policy making. Some suggestions from the literature for furthering ALAN research include:
    - Considering light intensity, exposure cycles, spectra, and directionality as well as differential effects on individuals (e.g., different life stages) and species when studying the effects of ALAN on marine organisms and ecosystems.
    - Increasing the temporal and spatial resolution of ALAN monitoring, including more widespread sensing at the ocean surface and in the water column.
        - Satellites detect light emitted upward under clear sky conditions but don't provide a thorough understanding of conditions below the sea surface. In the water column, organisms are exposed to direct or scattered light and light reflected back from atmosphere, and different wavelengths attenuate at different depths.
        - In addition, the lack of spatial resolution of satellite measurements of ALAN makes it difficult to detect impacts on marine populations. Strategic "ground-based sensing" at the ocean surface and in the water column could fill this gap.
        - Some opportunistic ways to add resolution to ALAN monitoring include mounting sensors on coastal and offshore infrastructure such as oil platforms, ships of opportunity, and Global Ocean Observing System buoys. Predictive models can also help flesh out ALAN dynamics in time and space.
    - Targeting research to species and ecosystems which provide obvious and documented ecosystem services so that the economic impacts of changes in ecosystem structure and function can be considered in policymaking.
- In addition, existing ALAN research suggests that oceanographic research in general needs to assess and potentially adjust lighting on biological sampling platforms like research vessels to avoid corrupting the biological data collected. This is especially critical for research conducted in low-light conditions such as the Arctic polar winter and the deep ocean where organisms are adapted to extremely low light levels.
    - For instance, in the deep ocean, the natural light available is very dim, monochromatic, and downward directed or comes from the bioluminescence of marine organisms. Consequently, most deep sea organisms have highly specialized visual systems sensitive to extremely low light levels that may be damaged by the bright lights of submersible vehicles used for exploration and research.
    - And during the polar winter in the Arctic, all natural light comes from the moon, stars, and aurora borealis. In a study published in 2018, researchers studied the behavior of fish and zooplankton in an un-light-polluted environment in the high Arctic during the polar winter and compared it to behaviors close to their research vessel to see what impact the ships' lights might have. They found that when the ship's light turned on, fish and zooplankton changed their vertical positions and swimming behavior quickly (within five seconds) and that the ship's light affected the behavior of organisms as deep as 200 m and in an area 125 m^2 around the ship. These results suggest that ships' light may influence the results of ship-based biological research and assessments of both commercial and non-commercial marine stocks.
- New initiatives are now forming to improve and standardize ALAN research. In January 2020, a new international network GLOW (Global artificial Light Ocean netWork) formed to study the potential effects of ALAN on "coastal assemblages colonizing artificial structures". GLOW will survey the intensity and quality of ALAN and its effect on intertidal algae and invertebrates.

Furthering ALAN policy for marine ecosystems

- The only marine areas currently managed for ALAN are some sea turtle nesting beaches where broad-spectrum lights have been replaced with longer wavelength lights to reduce hatchling mortality. In the future, consideration of ALAN – particularly its intensity and spectra – needs to be embedded in all coastal and marine development and use decisions. To reduce ALAN that is harmful to marine (and freshwater and terrestrial) environments, individuals and groups developing and using coastal and marine areas can reduce excess lighting by:
    - Reducing the number of lights, light intensity, and the time that lights are on. Reducing artificial light at dawn and dusk may be especially beneficial to marine environments because of the numerous biological processes that are focused on these time periods.
    - Installing limited-angle lights or shielding lights to prevent light spilling into unwanted areas.
    - Installing motion-sensitive lights in areas where lighting may be needed for safety.
    - Using LED bulbs that emit less blue and green (shorter wavelength) light. Red (longer wavelength) light attenuates faster in water and is not detected as easily by marine organisms.
- There is currently a dearth of legal and regulatory tools for minimizing the impact of ALAN on marine environments and ecosystems. As these tools are developed (e.g., it has been suggested that MARPOL recognize artificial light as a pollutant), ALAN researchers suggest incentivizing authorities to reduce ALAN by creating a "Marine Dark Sky Park" designation for MPAs. In 2012, 35 percent of the world's MPAs were subject to ALAN, with 57 percent of those exposed to light across their entire domain and 72 percent exposed to light across more than half of their domain.

Photo credit: Lights of Vancouver, British Columbia, Canada, as seen from Stanley Park by Seán Ó Domhnaill