Artificial Light at Night: Public Perception, Sea Turtle Nesting, and Spatio-temporal Change in North Carolina's Outer Banks

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Abstract

The North Carolina Outer Banks is a chain of barrier islands that is experiencing population growth and increasing development. Artificial Light at Night (ALAN) is a pollutant associated with development that impacts natural ecosystems and humans. There has been research on artificial light at night in terrestrial systems but little is known about how it impacts coastal ecosystems. Our study sought to understand how ALAN t has changed over the last 9 years in the Outer Banks and if and how it has impacted sea turtle nesting habits. We also wanted to understand community perceptions of ALAN. To look at change over time we used satellite-based ALAN data and on-the-ground measurements collected with sky quality meters from the barrier islands just south of the Virginia border in Currituck county, south to Oregon Inlet. We compared ALAN measurements to turtle nesting data from 2014-2022. To understand community perceptions, we created a survey that was distributed to the community over the course of six weeks. We distributed this survey online, by intercepting community members, hanging up flyers, and via a newspaper article and town newsletters. Our results suggest that ALAN has increased significantly over the last 9 years and that our satellite data and on-ground measurements align, showing similar patterns in ALAN. We did not find a significant correlation between turtle nesting and light, but did find a correlation between false crawls and light when other confounding factors were controlled for. We found that our survey respondents had high levels of concern about ALAN. They perceived several negative effects of ALAN and expressed a willingness to implement reduction measures both on the individual, commercial, and municipal scales. We hope that our research will inform individuals and decision makers about ALAN on the Outer Banks of North Carolina to implement changes that ultimately lead to ALAN reduction.

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1. Introduction and Background

When people think about how humans have negatively impacted the environment, they might tend to think of things like factory pollution, greenhouse gas emissions, or plastic. It is more infrequent to think about artificial light as a form of pollution that is impacting natural processes, humans, and ecosystems. However, as more research is shared, the negative impacts of Artificial Light at Night (ALAN) have become more apparent. Artificial light at night is a type of light pollution. It is the alteration of the natural levels of darkness by an increased concentration of light in a night environment, resulting from human presence (Salvador & Fabio, 2023). ALAN comes from anthropogenic sources of light including, but not limited to; street lighting, car lighting, indoor lighting, and any light sources from man-made devices, including cell phones and computers. Artificial light at night is categorized into five main types: skyglow, glare, light trespass, energy waste, and clutter (Table 1).

Table 1 | The five types of artificial light at night listed and defined below. Definitions of each category of ALAN are listed to the right of the term. (Crawford, 1991)

Type of ALAN	Definition
Light Trespass	Light that extends into areas into areas where it is unneeded
Skyglow	Light irradiance that brightens the night sky
Light Clutter	The congregation of many lights bunched together
Glare	Lights that are especially bright and cause the eyes to adjust
Energy Waste	Unnecessary energy used on unneeded lighting

Although ALAN doesn't invoke the same connotations that plastic and carbon emissions do, ALAN is classified as a pollutant due to the potential negative effects it has on the environment. However, light at night has allowed for human activities such as driving, shopping, reading, cooking, and more to continue even after the sun goes down. The switch from a softer, but more energy-intensive, incandescent light to a brighter and more energy-efficient light-emitting diode (LED) light has helped with clean energy goals yet has exacerbated the effects of ALAN (Davies & Smyth, 2017). LED light is better for clean energy goals because it is more efficient, allowing for less total energy consumption overall (Gaston & Sánchez De Miguel, 2022). However, LED light has increased the issues caused by ALAN because it is a form of blue light, which is more disruptive to organisms than red light.

Artificial light at night is a fast-growing, widespread issue. An estimated 80% of the world's population is now living under skies affected by ALAN (Coetzee et al., 2023). ALAN is a big issue not only for inland cities, but also for coasts. In fact, the effects of ALAN in coastal areas can extend especially far because light paths are usually uninterrupted going out to sea (Gaston & Sánchez De Miguel, 2022). According to the Annual Review of Environment and Resources, 22% of the world's coastlines are exposed to ALAN (excluding Antarctica), and this number is only increasing as there is more development (Gaston & Sánchez De Miguel, 2022). This increase in the extent and rate of growth in ALAN is concerning given that it is known to negatively affect wildlife and human health (Wang et al., 2023).

To expand knowledge of the impacts and public perceptions of ALAN in coastal ecosystems, we studied the temporal and spatial changes in ALAN and its impacts on turtle nesting behavior, as well as local knowledge, attitudes, and behaviors surrounding ALAN. Our study took place in the Outer Banks of North Carolina.

1.2. History and Growth of Artificial Light at Night

Artificial light at night has increased significantly on a global scale throughout the 21st century. Since the Industrial Revolution, artificial man-made light has grown along the coast and inland areas because of the development of electrical lighting and rapid settlement by humans. (Bennie et al., 2014). According to a literature review that summarizes research on ALAN in Africa, done by Dr. Bernard Coetzee, the amount of global satellite-observed light emissions has increased at least 49% from 1992 to 2017 (Coetzee et al., 2023). The growth of ALAN has been the result of increasing point sources in municipal, industrial, commercial, and residential areas. Additional sources of ALAN such as streetlights, billboards, and car headlights are now contributing to light pollution in these developing areas. ALAN is becoming so indicative of development that it has previously been used as a measure of economic growth (Hochard et al., 2019).

The majority of studies on the topic have previously been based in Europe and North America, giving researchers limited understanding of how ALAN will impact humans and environmental health in the African and Asian continents. It is expected that major global contributions to future growth of ALAN will come from middle-income countries, particularly China, India, and those in South America and Africa (Coetzee et al., 2023).

Widespread lighting in coastal areas is associated with increased human population growth along the coast. Population densities along the coast are now three times greater than the global average (Smalls & Nicholls, 2003). Of the top 25 global megacities, classified as cities with populations larger than 10 million, 16 are coastal (United Nations, 2019). As populations along the coast increase, increased shoreline development creates more light pollution in nearby aquatic environments, and it is important to understand how this lighting may affect local marine populations and communities. Although development and ALAN can have destructive impacts on the natural environment, a topic which will be discussed in depth later, the economic value of coastal development has allowed their persistence in threatened ecosystems. However, one observational study claims that the financial gains of development on the coast can be outweighed by losses in ecosystem service value (Mendoza-González et al., 2012).

1.3. Effects of Artificial Light at Night

1.3.1. Ecological Consequences of ALAN

As researchers have become more aware of the potential impacts of artificial light at night, studies have shown that ALAN negatively affects five physiological categories in organisms. The five categories are suppression of the production of melatonin, disruption of reproductive cycles, interference with orientation, disruption of timing cues for seasonal events, and interference with interspecific relations (Gaston & Sánchez De Miguel, 2022). Several studies have been done that show examples of how light pollution can negatively alter these five areas in several groups of invertebrate and vertebrate marine life during different life cycle stages. A study done by Kramer et al. shows that when coral juveniles were exposed to artificial light, their skeletal morphology changed, impacting their ability to take in light (Kramer et al., 2023). ALAN has also been shown to decrease the effectiveness of camouflage in prey, thus making them more vulnerable (McMahon et al., 2022). A study by Hillyer et al., found that ALAN impacts the metabolic process in reef fish thus reducing their fitness levels (Hillyer et al., 2021). A recent comprehensive summary of the known impacts of ALAN by Marangoni et al. noted the impacts on sea turtle hatchling behavior. As development encroaches on their habitats, sea turtles can be disoriented by the light of cars, buildings, and streets causing hatchlings to crawl in the wrong direction while attempting to make their way to the ocean (Marangoni et al., 2022). A study done by Zhiyong et al. (2018) looking at the relationships between ALAN and turtle nesting in Florida using various models and satellite data, found that turtles tended to nest less in areas with more light. The same study also found that different sea turtle species are impacted at different levels. Green sea turtle nesting was most negatively correlated with light level while leatherback sea turtle nesting was the least (Zhiyong et al., 2018). As these studies that note the impacts of ALAN on wildlife appear, more and more questions as to what other impacts ALAN could be having on marine life and its behavior arise.

1.3.2. Human Health Consequences of ALAN

Artificial light at night affects humans as well as wildlife. One of the clearest impacts of ALAN on humans is on sleep cycles and circadian rhythms. Circadian rhythms in humans are set by blue light, controlled by the 24-hour cycle of the sun, but with increasing sources of blue light at all hours of the day, this clock has been altered (Wahl et al., 2019). Two bodily processes associated with people's circadian clocks are metabolism and homeostasis maintenance. The disruption of these processes is related to metabolic disorders and cancer morbidity. The reason ALAN contributes to cancer morbidity is because it suppresses the production of melatonin, which has an important role in keeping carcinogenesis at bay (Gaston & Sánchez De Miguel, 2022). There are many other health risks associated with alteration of circadian clocks such as high blood pressure and coronary artery disease (Zubidat et al, 2017).

Additionally, adults living in areas with more ALAN were found to get less sleep on average than adults in darker areas, and outdoor nighttime lights were correlated with later bedtimes for adolescents (Wang et al, 2023). Getting less sleep not only makes people tired, but has many other health effects like decreased immune system function and behavioral problems. Furthermore, the disruption of biological rhythms by nighttime light exposure makes it more difficult for the human body to regulate physiological processes such as sleep-wake behavior, hormone secretion, cellular function, gene expression, and the production of melatonin (Bedrosion, 2017). These effects happen in part because when people sleep, their bodies release important hormones, such as growth hormone and melatonin. When sleep schedules are disrupted, these hormones are not released correctly. These disturbances may not have immediate or obvious effects, but they could have long-term consequences.

1.3.3. Energy and Greenhouse Gas Consequences of ALAN

Artificial light at night also has an impact on our energy use. The more lights that are turned or left on at night, the greater our energy consumption. Not only does this have negative economic ramifications, but increased energy use also influences climate change, due to emission of greenhouse gasses like carbon dioxide by common fossil fuel-based sources of electricity.

To counteract this, LEDs have gained traction as a popular form of lighting because of being marketed as both a low-carbon technology and a more efficient one (Gaston & Sánchez De Miguel, 2022). However, according to the Annual Review of Environment and Resources, as LEDs have become more popular there has been an unexpected rebound effect (Gaston & Sánchez De Miguel, 2022). The increases in efficiency, as well as the lower costs for LEDs, have actually led to an increased demand for outdoor lighting. The increased demand for LEDs has led to the benefit of efficiency being offset, leading to the same amount of energy consumption (Gaston & Sánchez De Miguel, 2022). Therefore, artificial light at night is contributing to increased energy use, even with the switch to the more efficient form, LEDs.

1.3.4. The Night Sky Consequences of ALAN

The impacts of artificial light at night are not only on the ground. Artificial light at night, particularly in the form of skyglow, has a huge influence on our ability to see the night sky. It has become an intensely limiting factor in the ability of both amateur and professional astronomers to observe and measure the sky and celestial bodies (Gaston & Sánchez De Miguel, 2022). Not only is this a recreational loss, but a scientific one as well.

The night sky remains vastly unexplored and produces significant astronomical discoveries. There have not been many studies done on what effects artificial light at night has had on professional astronomical observations. The reason for this is mainly because the requirements for professional astronomical observations usually involve being far away from large sources of artificial light at night (so their observatories are in remote locations). However, as artificial light at night increases, there are fewer areas that are suitable for observatories. Still, even if we are not yet sure of the degree to which artificial light at night is impacting professional astronomical observations, it is still creating a major loss of opportunity for amateur astronomers.

1.4. Human Perception of ALAN and its Effects

1.4.1. Public Perception of ALAN

Public perception of ALAN can be influenced by a variety of factors. A 2013 study in Ireland suggested strong geographic relationships between public perceptions and ALAN, where Coogan and others found considerable differences in the perception of ALAN between rural and urban regions (Coogan et al., 2020). Specifically, rural respondents were more likely to report sleep disturbances than their urban counterparts. Rural respondents typically regarded domestic lighting as most bothersome while urban respondents reported public lighting as such. Researchers also found a potential relationship between age and perceptions of ALAN. Coogan et al.'s study suggests that perceptions of ALAN can be subjective and strongly tied to demographic and geographic factors. Another study conducted in Finland in 2013 identified public perspectives on a range of ALAN subtopics ranging from experiences with the night sky, perceived harm, and mitigation (Lyytimäki, 2013). In regards to perceived harm, the study found that residential areas, areas of car traffic, and commercial spaces were regarded as having the most light pollution. These results show what sources of ALAN people think have the biggest impact.

While the general public's perception is crucial to understanding attitudes toward ALAN, mitigation support requires consideration of specific stakeholder groups with expertise and influence regarding lighting decisions. Research conducted in 2019 studied the unique experiences of lighting professionals with light pollution (Schulte-Römer, 2019). This study emerged among prior consensus that lighting professionals were particularly critical of light pollution literature and policy. The 2019 study was unique in providing a perspective saying otherwise; lighting professionals showed general agreement with light pollution activists in defining light pollution as a problem. This research is significant in illustrating an under-researched and misunderstood stakeholder perspective in ALAN mitigation.

Going back to the 2013 Finland study, researchers also identified public perspectives on ALAN mitigation (Lyytimäki, 2013). Researchers found that the public had little knowledge of health and ecological effects but widespread support for ALAN mitigation policy. Another factor that could influence people's willingness to mitigate ALAN is safety. There are both real and perceived safety benefits of ALAN (Wang et al., 2019). For example, car headlights at night are a form of ALAN that has real safety benefits, and street lamps are a form of ALAN that people tend to perceive as having safety benefits. Some people may be opposed to decreasing ALAN because of both real and perceived safety benefits.

1.4.2. Subjective Effects of Human Perception of ALAN

A study by Cleary-Gaffney et al. (2022) reported that an individual's overall sleep quality is affected by artificial light sources and found a negative correlation between an increase in ALAN and human health. Although ALAN was found to have no impact on psychological well-being, frequent use of it was linked to poor mental health. Cleary-Gaffney et al. (2022) also found that individuals who were aware of ALAN in their environment were more prone to poor sleep quality, as well as higher levels of psychological distress . This suggests that those who are aware of ALAN may have a heightened attention bias toward it, which impacts the psychological health of those individuals. These findings may also support the notion that individuals with heightened attention to ALAN may experience poorer sleep quality and higher psychological distress.

An individual's view of ALAN can impact the way in which they view light pollution. Additionally, people who are aware of the effects that light pollution can have on human health are more likely to take action to reduce its impacts. Public attitudes toward artificial light at night are pivotal in community engagement and activism concerning light pollution, leading to advocacy for lighting regulations, responsible practices, and community initiatives (Zielińska-Dabkowska et al., 2020). The perception of artificial light influences policy and planning efforts at various governance levels, with communities valuing dark skies more likely to support and enact measures aimed at reducing light pollution (Zielińska-Dabkowska et al., 2020). Action to reduce the impacts of ALAN may include advocating for more responsible lighting practices, supporting dark-sky initiatives, and encouraging local governments to implement measures to mitigate light pollution.

1.5. How can ALAN be reduced?

1.5.1. Best Practices to Reduce ALAN

Managing ALAN will be partially dependent on public willingness to implement practices on an individual-level to limit light emission at night. To understand how willing citizens were to modify public lighting, researchers surveyed French citizens in a discrete choice experiment to understand their preferences on ALAN (Beaudet et al., 2022). Given scenarios defined by attributes of light intensity, light extinction, color of light, and change of tax to choose from, survey participants were not in favor of removing artificial light, but were in greater favor of decreased light intensity. The primary concern to limiting or eliminating artificial lights expressed by study participants was safety when traveling at night. Public opinion varied between socioeconomic class and gender, but will ultimately be used to inform future policies in France.

In an article for the *Journal of Environmental Management*, researchers offered suggestions to limit light pollution effects by evaluating the emissions of lamps based upon the spectral response functions of human eye photoreceptors (Falchi et al., 2011). The authors suggested simple light reduction methods, including full shielding of light fixtures (Figure 1), limiting the area of lighting, eliminating over-lighting, having a light curfew, and limiting the growth of new installed lighting. In another study looking at methods for limiting light pollution, the authors concluded that maintaining and increasing natural, unlit areas is the most effective change, but would conflict with social and economic needs (Gaston et al. 2012).

Figure 1 | Light shield applied to an outdoor lighting fixture. Light shields, such as the one pictured above, can be very effective in redirecting excess light that could contribute to skyglow. The light is directed downward onto the surfaces it is intended to illuminate.

In the *Handbook of Advanced Lighting Technology,* authors discuss lighting technologies that can be used in management plans to reduce ALAN for residences and commercial buildings

(Schroer & Hölker, 2014). The authors also state that LED and blue-rich light sources should be replaced with filters of warm-white light to decrease glare for drivers. Additionally, the authors stated that introducing curfew hours for light use was shown to decrease ALAN and reduce energy consumption and carbon dioxide emissions in France (Waks 2013). Authors of another study also recommended banning emission of light in wavelengths shorter than 550 nm to limit the negative impacts of ALAN on human alertness and melatonin secretion (Falchi et al., 2011).

Looking to the future, more management tools should be studied to interpret the social and economic needs for ALAN, so the needs can be met with minimal ecological cost (Gaston et al. 2012). Management plans specific to commercial or municipal structures should also be studied to make larger-scale, faster, and more impactful reductions in ALAN (Bará et al. 2021).

1.5.2. ALAN-related Policies and Ordinances

As communities across the globe begin to realize the ecological and social impacts of increased ALAN, governments are beginning to respond with regulations in an effort to reduce ALAN and mitigate its effects. In order to form such policies, governments must know why these regulations are needed in the first place. In an article written by Morgan-Taylor et al. (2020), the negative impacts of ALAN are divided into several categories as follows: "potential harm to human health and safety, ecological harm, the loss of the night time environment including the night sky, energy waste caused by the inappropriate use of lighting (with wasted greenhouse gas emissions), and general nuisance". In addition, some governments base their policies off of visual factors, such as aesthetics or the amount of light. Therefore, governments often react differently when deciding how to regulate light. Some countries like the U.K., choose to focus more heavily on aesthetics, while others, like South Korea, focus on the actual amount of night entering the environment. In the same article, Morgan-Taylor compares ALAN regulations in these countries. While the U.K. does not have any explicit ALAN regulations, choosing instead to embed these rules into city planning and nuisance laws, South Korea has ALAN specific laws, yet they are not well enforced. For example, the English consider light pollution during the planning stage of new buildings. However, often this consideration only spans the visual impact of the light fixtures during the day. Thus, the planning system is more interested in the appearance of lighting fixtures than their impact on controlling nighttime light pollution. Conversely, South Korea sets explicit metrics on how much light is allowed: "[a] level is either permitted or it isn't, so the rules are very clear and transparent" (Morgan-Taylor, et. al, 2020). In doing so, lighting designers, consumers, and those in commercial sectors know exactly how much light is permitted, and can adjust their decisions accordingly. The amount of light permitted is based on 4 specified zones in Korean Law, with Environmental Zone 1 (E1) being the darkest zone reserved for countryside areas and E4 is for the brightest commercial city areas. Looking towards the future, these laws may be a source of inspiration for stricter U.S. lighting pollution legislation.

1.6. Objectives

The objectives of this study were to explore ALAN on North Carolina's Outer Banks, including changes in its extent and levels, its relationships to sea turtle nesting, and resident and visitor perspectives of ALAN. Our study investigated natural and social science aspects surrounding this issue.

1.6.1. Natural Science Objectives and Research Questions

For the natural science aspects of the project, we evaluated the spatio-temporal patterns of ALAN from 2014-2022. We compared satellite imagery based measurements of ALAN to the levels of light reaching the beach face by taking measurements of night sky luminance during the fall of 2023. Satellite imagery gives the aerial, global-level view of ALAN over a longer period of time, while our on-ground measurements give the local-level view of ALAN from the vantage point of looking up at the night sky. According to an article by Huss and others, they found that satellite-measured levels of light at night did not correlate with manually measured levels of light in Dutch children's bedrooms, implying a discrepancy between light level measurements at a global and local scale (Huss, 2019). This implies that views of ALAN may vary based on the scale at and perspective from which it is studied, which is why we decided to use both the satellite data and sky quality meter data. To explore the influence of ALAN on sea turtle nesting, we compared sea turtle nesting data to satellite imagery from 2014-2022. Satellite imagery was used to identify the negative correlation between turtle nesting and light in the Zhiyong et al. study and a similar trend could be identified in the Outer Banks using this methodology (Zhiyong et al., 2023). With these objectives in mind, we developed the research questions below:

1. *How has ALAN changed, spatially and temporally, throughout the Outer Banks over the last 9 years?*

We explored how ALAN has changed spatially and temporally over the last nine years, from 2014-2022, using satellite measurements of nighttime radiance.

2. *Do satellite measurements of ALAN align with on-the-ground measurements of ALAN?*

We measured the luminance of the night sky from the ground on the beach as a measure of ALAN. This is a different way of measuring ALAN than the satellite data, which measures from above. To determine if these two data sets align an analysis was conducted to better understand if our on-the-ground measurements were reliable compared to the satellite data.

3. *Is there a relationship between sea turtle nesting and ALAN across the Outer Banks over the last 9 years? If so, what is it?*

Spatio-temporal patterns in sea turtle nesting behaviors, including false crawls and nesting, and satellite-based measurements of ALAN were compared to explore potential relationships .

1.6.2. Social Science Objectives and Research Questions

For the social science aspects of our research, we gauged the perceptions of residents and visitors of the Outer Banks about ALAN. Due to the economic relevance of the tourism industry in the Outer Banks, it is important to understand opinions of seasonal and full-time residents, as well as those visiting the area. In this work, we sought a deeper understanding of the complex relationship between ALAN and the public in the Outer Banks, including documenting how they view light pollution and assessing the acceptability of light pollution reduction measures.

Public perceptions of ALAN have the power to affect the development of policies that regulate it. Thus, to fully understand the levels of ALAN in the Outer Banks, the perceptions the public has on ALAN should be collected. While, public lighting changes are relatively more feasible than changes to commercial or residential lighting due to less stakeholder involvement, some municipalities of the Outer Banks already have ALAN mitigative ordinances. These include shielded light fixtures and intensity restrictions on newly constructed lighting fixtures (Duck Outdoor Lighting Ordinance, 2021). Future management decisions could rely on support from stakeholders such as real estate, government, conservation groups, homeowners, and business owners.

We distributed a survey to residents and visitors of the Outer Banks to gauge attitudes and views of ALAN and support for the reduction of ALAN in the Outer Banks. To understand these perceptions, we developed the research questions below:

1. *What are the local (resident and visitor) attitudes and views of artificial light at night on the Outer Banks?*

We assessed local perspectives on ALAN through a series of questions about effects of ALAN, level of concern about ALAN and opinions about sources of necessary and disruptive light at night. We compared these responses to questions about knowledge about light pollution, night sky appreciation, and comfort being outside at night in the dark:

2. *Is there support for reducing artificial light at night among residents and visitors on the Outer Banks?*

We measured support, or lack thereof, among these stakeholders on the Outer Banks for reduction methods across residential, commercial, and municipal settings as well as support for reduction of ALAN in general on the Outer Banks.

2. Research Methods

2.1 Study Site

North Carolina's Outer Banks is a chain of barrier islands characterized by ocean-facing sandy beach and dune systems, soundside brackish marshes, and remnant maritime forest patches. Separated from the mainland by as much as 25 miles, these barrier islands are vulnerable to coastal and tropical storm systems and other disturbances. Despite the vulnerability, this region, like other coastal areas, has experienced broad population growth. According to U.S. Census data, the current population of year-round residents of nearly 40,000 is twice what it was in the mid-1980s. The region's population balloons to a daily population of over 250,000 (*Dare County, NC*). Our area of study focused on a portion of the Outer Banks, from Oregon Inlet to near the Virginia-North Carolina border. Within these barriers are very developed land areas and land-managed areas. Figure 2, shows the distribution of areas in conservation within our study area. Managed areas were plotted to illustrate areas with less development, which we anticipated would be some of the darkest areas. Managed land areas tend to fall within the southernmost and northernmost parts of our study site, while the middle of our study site contains the areas of higher development and dense populations.

Within our area of study, many plant and animal species are designated as endangered or threatened. Endangered and threatened species that utilize the barrier islands and coastal waters within the study area include the West Indian manatee, eastern black rail, piping plover, red knot, roseate tern, salt marsh sparrow, American alligator, green turtle, hawksbill turtle, Kemp's Ridley turtle, leatherback turtle, and loggerhead turtle (North Carolina National Heritage Program, 2023). Within this list of species, sea turtles are of particular interest to our research project as North Carolina is the northernmost point where sea turtles nest.

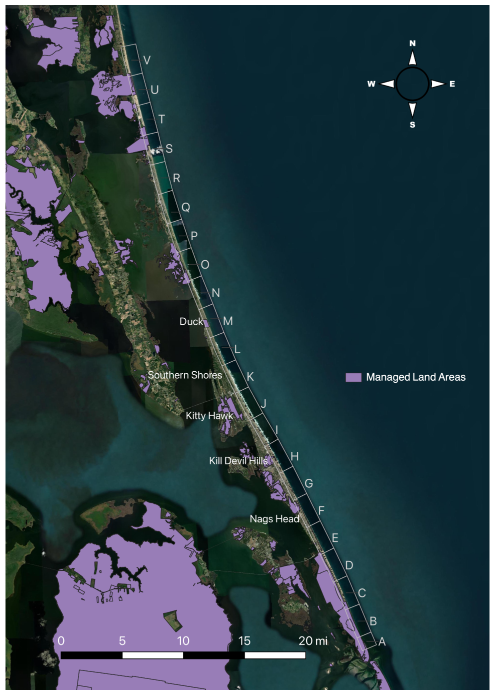

Figure 2 | Managed land areas, including conservation areas managed by state, federal, and nonprofit entities within Dare and Currituck counties, along the Outer Banks of North Carolina.

2.2 Natural Science Methods

2.2.1. Satellite-based ALAN measurements

Satellite-based measurements of ALAN are collected by the Visible Infrared Imaging Radiometer Suite (VIIRS) instrument, and processed, archived, and served by the Earth Observation Group (EOG; Elvidge et al., 2013 and Elvidge et al., 2021). The VIIRS instrument is on the Suomi National Polar-Orbiting Partnership spacecraft, and measures light levels from visible to infrared (Hillger et al. 2013). The VIIRS data that were retrieved from the EOG were the stray-light corrected ("vcmsl") day night band monthly cloud-free day night band (DNB) composites for 2014-2022.

Day night band monthly composites were extracted for our study site by Stu Hamilton, Professor and Chair of the Department of Coastal Studies, East Carolina University using ArcMap. Dr. Hamilton also fit the DNB data to a polygon grid extending roughly perpendicular to North Carolina State Route 12 (NC 12) from the southern end of the barrier island north of Oregon Inlet to the northernmost extent of NC 12 in Corolla. Each grid line running perpendicular to NC 12 was spaced 4 km apart aside from the southernmost grid, which was only 2 km wide, and extended 2 km seaward of NC 12 (Fig. 3). Average radiance was calculated based on the raster data for each month and in each grid location (Fig. 3). Subsequent geospatial analyses of VIIRS data were done using QGIS.

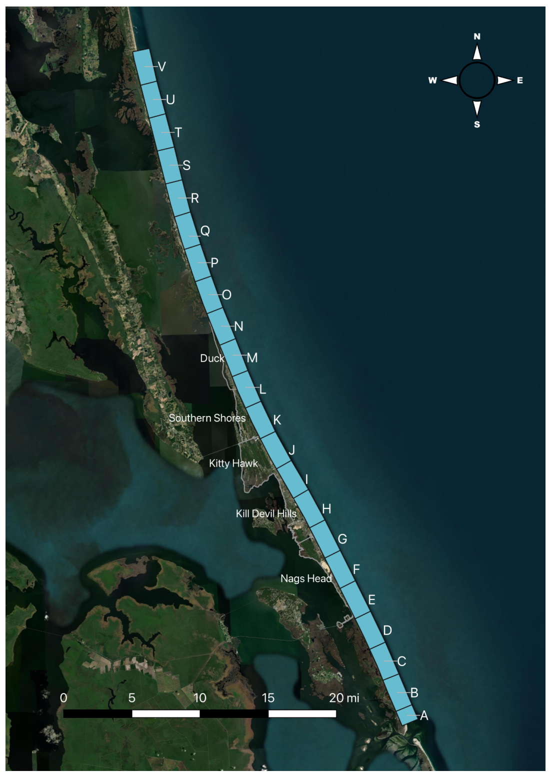

Figure 3 | The grids for binning of VIIRS satellite data of monthly average radiance from 2014-2022 are labeled A through V. A is the southernmost grid and V is the northernmost grid.

2.2.2. Beach-based ALAN Measurements

Sky Quality Meters (SQM) were used to measure luminance at fourteen sampling locations (Fig. 4) on the ocean beach along the Outer Banks of North Carolina, from Oregon Inlet to Corolla on three occasions. Sampling locations were selected between the southernmost National Park Service ramp on the Outer Banks barrier island north of Oregon Inlet to the northernmost ramp to the offroad area in Corolla, based upon the presence of public beach accesses that were spaced between 1600 and 2000 m apart. There are not any public beach accesses in the town of Duck, thus the gap in sampling locations between the Barrier Island and Corolla locations. Less developed areas in Corolla and within the Cape Hatteras National Seashore were intentionally included in the study.

We divided into groups to take measurements at all the sampling locations within the same 2-hour period during each of the new moons from September to November of 2023. Each group visited the same sampling locations on all sampling occasions. New moons and sampling occurred on 9/14/2023, 10/13/2023, and 11/13/2023. The measured SQM values are a measure of night sky brightness, and as such are inversely related to darkness. In other words, higher SQM values are measured in darker areas than in areas with ALAN. On each sampling occasion and at each sampling location, we recorded four SQM meter measurements of luminance, cloud cover percentage, and the constellations we could see and averaged them to get a measurement for each night and sampling location.

Figure 4 | Beach-based on-the-ground ALAN sampling locations along the ocean beach of the Outer Banks of North Carolina. Night sky luminance was measured on three new moon sampling occasions between September and November 2023.

2.2.3. Beach-based vs. Satellite Measurements

Satellite measurements of ALAN give a broad, global perspective by capturing data from above the Earth's surface, providing a comprehensive view of ALAN over large geographic regions. These measurements are well-suited for analyzing large-scale trends over time. On the other hand, beach-based, on-the-ground measurements offer more localized measurements of ALAN limited in space and time. The SQM meters used to make the on-the-ground measurements are inexpensive and easy-to-use making them ideal for non-experts and experts alike to make measurements in support of local assessment and mitigation of ALAN. Because of this, we used a combination of both satellite and on-the-ground measurements to see if it would provide a better understanding of ALAN and its impacts. Average SQM measurements for each sampling location and average VIIRS for 2022 for corresponding grid locations were transformed into z-scores to normalize the range of values. A Kruskal-Wallis test was applied to test for differences in the distribution of ALAN between the normalized data.

2.2.4. Sea Turtle Data

The Network for Endangered Sea Turtles (N.E.S.T) collects nesting data starting at the northern border of the Cape Hatteras National Seashore north to the Virginia state line. They collect data during the local sea turtle nesting and hatching season from May to October and patrol the beaches in the early morning for any new activity. The National Park Service (NPS) biological staff collect sea turtle nesting data along the Cape Hatteras National Seashore also during the nesting months of May to October. The NPS patrols the beaches in the morning and manages the turtle nests on their property. These entities shared their data with us, which allowed us to incorporate sea turtle nesting behavior as an ecological impact of ALAN into our research.Sea turtle datasets from both entities included instances of false crawls and nests laid and their location and date of observation. Many other variables were included in the datasets that we did not use in our analysis.

False crawls refer to instances when a female sea turtle comes ashore on a beach but instead of nesting, turns back around to re-enter the ocean. This can occur due to various reasons such as disturbances, unsuitable nesting conditions, or predation threats. Favored nesting locations for sea turtles are sandy beaches with fine, well-drained sand, which allows them to dig deep nest cavities. It is important that they nest close enough to the water's edge for a short path, but far enough to protect the nest from waves and changing tides. Nesting beaches should have minimal obstructions to ensure a smooth nesting process, and low light pollution to prevent disorientation caused by artificial lighting. Sea turtles often choose remote and undisturbed areas to reduce human disturbances, such as beachgoers and noise. Their nesting timing typically coincides with warmer months (May-October) when sand temperatures are suitable for egg incubation. We used QGIS to bin turtle activity count data into the same polygon grid used to average satellite data over the study area.

2.2.5. Data Analysis

Sea turtle nesting, false crawl, and total activity counts were calculated for each grid. We calculated monthly and yearly means and standard deviations for these sea turtle count data by grid location. We also calculated annual means and standard deviations for satellite-based ALAN data and means and standard deviations for the same period of our study, September through November, across all years (2014-2022) for comparison to our beach-based ALAN measurements. Simple and multiple linear regressions were also completed to explore possible explanations of the variation of turtle activity (false crawls, nests, and total) around the mean for each grid location by latitude, year, and satellite-based ALAN.

We analyzed patterns in satellite-based ALAN over time and space. One of the variables we analyzed was the percent change over time. We calculated the difference between the 2014 satellite data and the 2022 satellite data for each grid location. Then, for each grid location, we divided the 2014 satellite data by the difference to determine the percent increase. We completed linear regressions on the percent change over the years and for each grid. We performed significance tests to understand whether the change observed between 2014 and 2022 was statistically significant (alpha<0.05). We did this by calculating linear regressions for each grid location and performing paired T-tests to test for significant differences between the first and last year of the observation period. A Kruskal-Wallis test was done to look for a statistical relationship between our on ground measurements and satellite data (alpha=0.05).

2.3. Research Methods and Study Site for the Social Science

2.3.1. Survey Content

To gain an understanding of resident and visitor perceptions, knowledge, and experience surrounding ALAN, we developed a 28-question survey (Appendix A). Using a survey is a particularly effective means of gathering quantitative data quickly and effectively reaching a large sample population, thus demonstrating any statistically significant results and serving as a proxy for a verified experiment given limited resources (Jones et. al., 2013). As we aim to explore a large number of respondents' likely complex opinions and experiences with ALAN on the Outer Banks in a relatively short period of time, a survey stands as a fitting method of gathering such data.

Our survey was split into four main sections: knowledge, perception, experience, and willingness to change. Each of these sections included 5-7 questions. The knowledge section consisted of a self-assessment of informed level and a short "quiz" that tested knowledge of ALAN. The "quiz" questions and their multiple parts were assessed out of a total of nine points to create knowledge "scores". Respondents were provided the option to view an answer key to these questions at the end of the survey. The perception section asked about levels of concern about ALAN as well as respondents' perceptions of a suite of effects of ALAN, including ecological, human health, safety, energy, and night sky. Questions in the experience section were aimed at better understanding the personal relationships with ALAN, such as appreciation of the night sky, comfort with being outside at night without artificial light, and timing of turning out residential exterior lights. The willingness to change section was focused on perceptions of potential light reduction and management strategies in residential, commercial, and municipal settings as well as level of agreement with a general reduction in ALAN on the Outer Banks. The survey concluded with a few questions regarding demographics to better understand who was taking our survey and analyze results.

2.3.2. Survey Distribution

The survey was conducted online on the Qualtrics platform and using a paper version. We distributed the survey using the intercept method, flyers, electronic newsletters, and a newspaper ad from October 12, 2023 through November 26, 2023. Survey distribution and interception locations roughly aligned with the towns included in the SQM measurement sites, covering

Duck, Southern Shores, Kitty Hawk, Kill Devil Hills, and Nags Head. Due to its proximity, Manteo was added for survey distribution and interception even though it was not included in the ALAN measurement or sea turtle activity aspects of the study. Many businesses, ranging from coffee shops to farmer's markets, were selected as survey intercept distribution locations based on potential diversity of patrons and how busy they would be at different times. On each survey distribution instance, we approached individuals coming and going, introduced our study, and asked if they would be willing to take the survey. Potential respondents could scan a QR code and take the survey on their phone or take it on an iPad we provided. Interested respondents who could not complete the survey at the time of interception were offered a flyer (Appendix B) with a QR code and link to the survey to take it at a later time. Respondents who did not want to use a phone or iPad were supplied with a paper copy of the survey.

We also engaged in additional methods to distribute the survey. We reached a portion of respondents through a newspaper advertisement in the Outer Banks Voice, which ran on October 12, and through electronic town newsletters distributed to subscribers in the towns of Duck and Nags Head. We also posted flyers at the same locations where we conducted intercepts as well as additional stores and busy locations along the Outer Banks. Through this distribution, we gathered 466 usable surveys for analysis.

2.3.3. Data Analysis

To complete our analysis, we compiled all the usable surveys. After cleaning data, including removing incomplete submissions, we calculated summary statistics of all of the survey questions and variables, including means, standard deviations, and counts. We then performed statistical analyses on variables to address our research questions using the Chi-Square test of independence, Kruskal-Wallis test, and Goodman-Kruskal Gamma test (alpha=0.05).

3. Results & Discussion of Natural Science

3.1. Seasonal and monthly patterns in ALAN (satellite-based)

The monthly mean satellite-based ALAN measurements (radiance) varied from 0.284 to 7.214 nW/cm^2/sr across the fourteen study sites from 2014-2022. The mean ALAN across all study years (2014-2022) for individual months ranged from 0.229 nW/cm^2/sr (August; site B, Coquina) to 7.848 nW/cm^2/sr (December; site H, First Street). The monthly mean satellite-based ALAN across all years for several grid locations (Fig. 5; sites C, E, F, G, H, K, L, M, N, O, P, Q, R, S, V) peaks in summer months, such as in June (6) and July (7) (Fig. 8), which was expected given the population increase due to summer tourism. There is also a peak in the winter months, November (11), December (12) and January (1). After controlling for the number of hours of darkness due to longer nights throughout the winter (Figure 6), the peak in the winter months decreased, but the shape of the peak in the summer months was consistent with the peak in Figure 6. Therefore, according to our results, the average amount of ALAN across the Outer Banks is relatively consistent, but peaks in the summer months due to tourism.

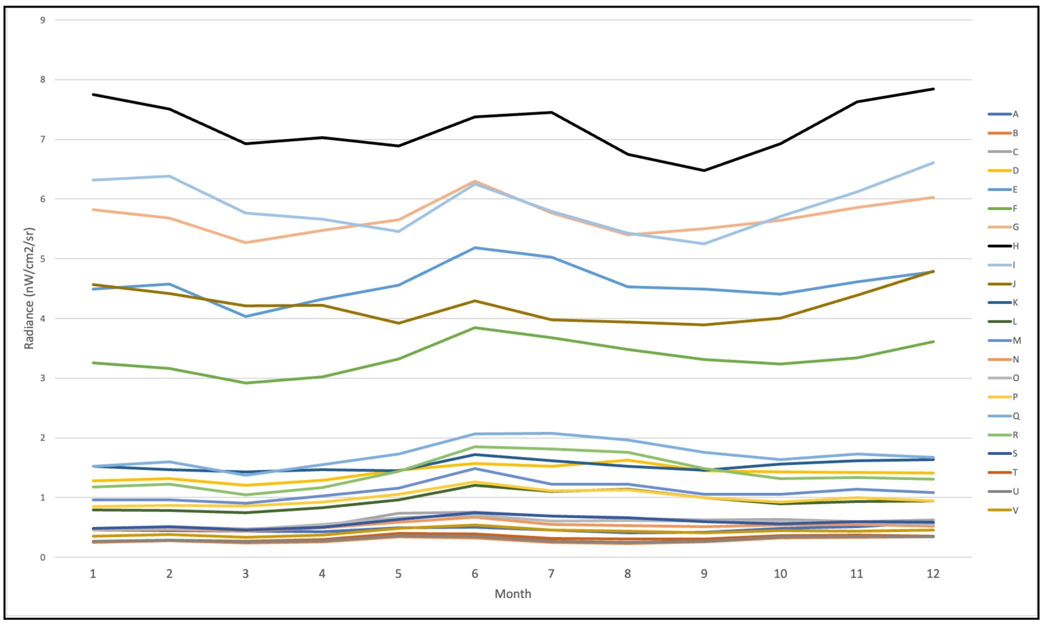

Figure 5 | Mean radiance (nW/cm^2/sr), a measure of ALAN, from 2014-2022, across the months of the year. Each line corresponds to one of our grid sites, A-V, along the Outer Banks of NC. The figure is organized left to right by months, with 1 being January, and 12 being December.

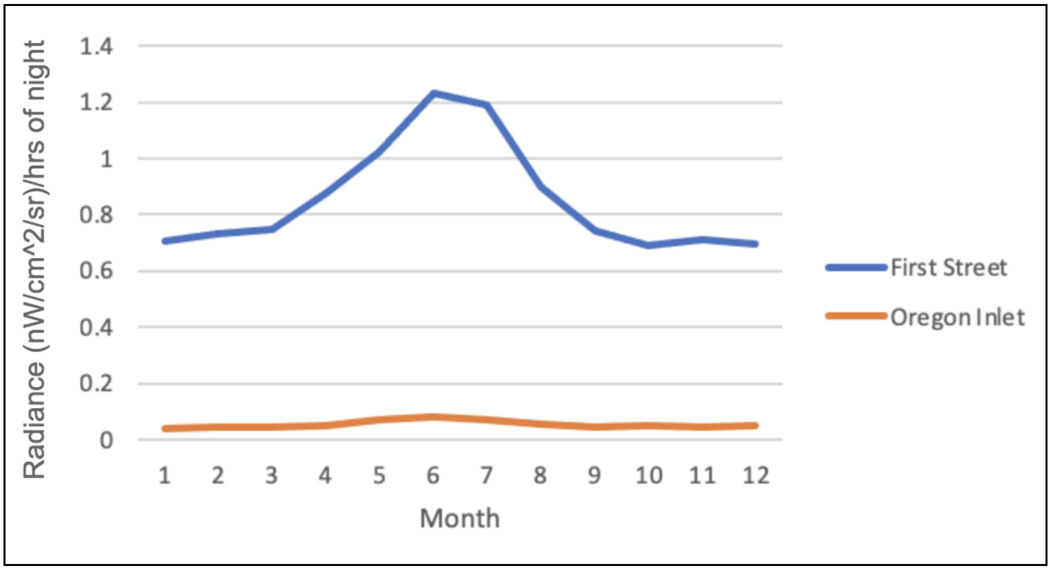

Figure 6 | Mean (2014-2022) radiance (nW/cm^2/sr; satellite-based ALAN) standardized by hours of darkness (per hours of darkness) across the months of the year. First St. had the highest luminance (highest mean ALAN), and Oregon Inlet had one of the lowest luminance (lowest mean ALAN). The data was controlled for hours of night, as winter months have more hours of darkness that results in more ALAN in locations with development.

3.2. Spatio-temporal patterns in ALAN (satellite-based measurement)

Mean annual ALAN (satellite-based radiance) for 2014-2022 ranged from 0.280 nW/cm^2/sr (site B, Coquina) to 7.177 nW/cm^2/sr (site H, First Street). The grid locations with the highest mean ALAN measures (2014-2022) were between grid locations E and J, as seen in Figure 7. Grid locations north and south of this area had a mean ALAN of 2 nW/cm^2/sr or less. This level of ALAN is low relative to our peak sites.

The grid locations E through J lie within the towns of Nags Head, Kill Devil Hills, and Kitty Hawk. These towns along the Outer Banks have greater populations and more development than the areas to their north and south. Likewise, many areas with lower radiance levels (ALAN) are found adjacent to or within conservation areas (Fig. 2), which limit development thus, radiance measurements at these sites are lower, indicating less ALAN.

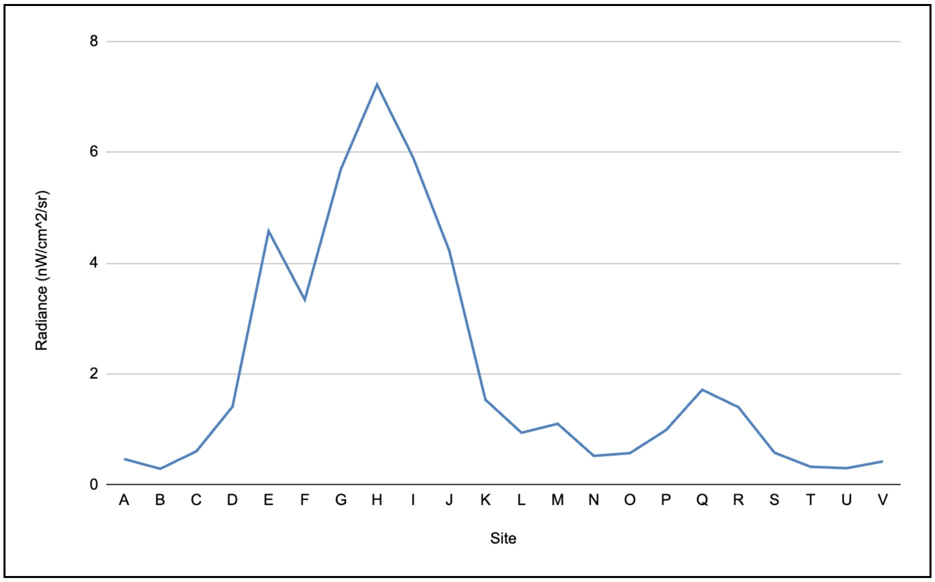

Figure 7 | Mean radiance (nW/cm^2/sr), a measure of ALAN, from 2014-2022 at each grid location along the Outer Banks of NC. The figure is organized left to right from our southernmost point (A) to our northernmost point (V). The graph shows greater radiance measurements at sites E-J, which are between the towns of Nags Head and Kitty Hawk, NC.

3.3. Change in ALAN from 2014-2022

Mean annual ALAN (satellite-based radiance) for 2014 ranged from 0.150 nW/cm^2/sr (site B, Coquina) to 7.609 nW/cm^2/sr (site H, First Street; Fig. 8). By comparison, the mean annual ALAN (satellite-based radiance) for 2022 ranged from 0.428 nW/cm^2/sr (site B; Coquina) to 8.003 nW/cm^2/sr (site B, First Street; Fig. 8).

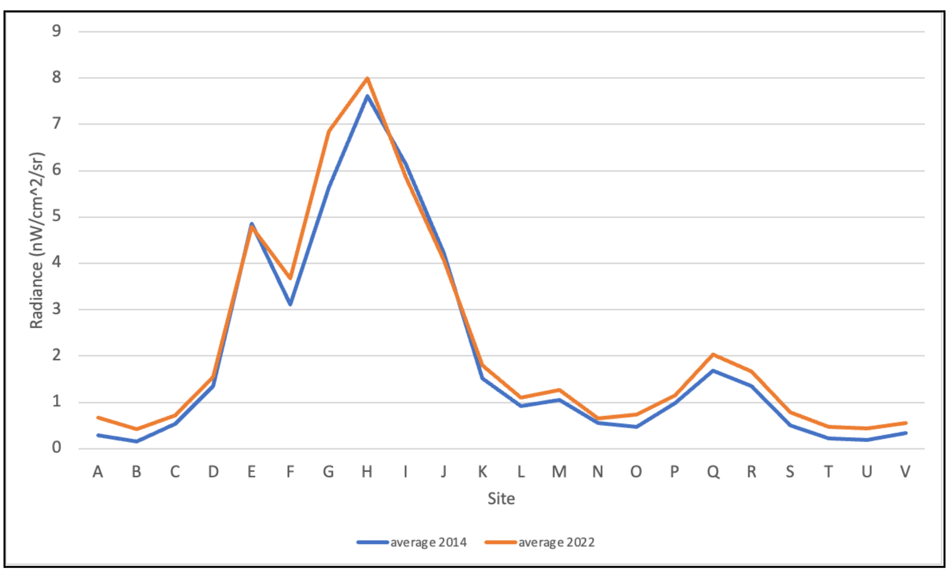

Figure 8 | Mean radiance (nW/cm^2/sr), a measure of ALAN, in 2014 and in 2022 at each grid location along the Outer Banks of NC. The figure is organized left to right from our southernmost grid (A) to our northernmost grid (V).

The percent change between 2014 and 2022 at each grid location varied from -1% to 181% (Fig. 9). Grid locations E, H, I, and J experienced the least amount of change over the nine-year period. In some cases (grid locations E, I, and J), the ALAN decreased from 2014 to 2022. On the other hand, some sites had greater than 100% change from 2014 to 2022 (sites A, B, T, and U). The greatest percentages of change were seen in the northernmost and southernmost areas of our study site.

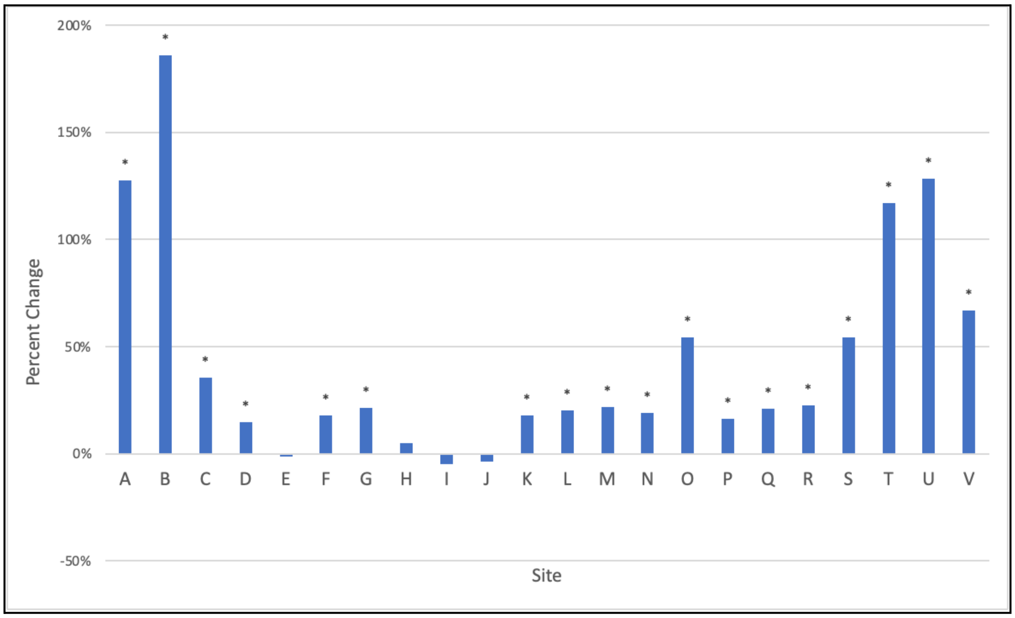

Figure 9 | Percent change in annual mean ALAN (satellite-based radiance; nW/cm^2/sr) between the first 12 months of the study period (January to December 2014) and the most recent 12 months of the study period (January to December 2022); asterisk signifies statistical significance (paired t-test; alpha=0.05).

As seen in Table 2, we performed linear regressions to understand whether the change observed between 2014 and 2022 was statistically significant (alpha=0.05). for each grid location. We also performed paired T-tests to measure significance between the first and last year of the observation period (alpha=0.05). The change in ALAN from 2014 to 2022 in all but four locations (E, H, I, and J) was significant (Table 2). Additionally, the slope of each linear regression of mean annual ALAN (satellite-based radiance) from 2014-2022 for each location was positive, indicating an increase in ALAN at each site over the nine-year period, even when the percent change from 2014 to 2022 was negative.

Table 2 | Annual mean ALAN (satellite-based radiance; nW/cm^2/sr) linear regressions from 2014 and 2022 and slopes, standard errors, and p-values for the linear regressions of annual means from 2014 to 2022 at grid locations along the North Carolina's Outer Banks.

Location	2014	2022	Slope	Standard Error	Significant Change (Difference between 2014 and 2022)	
A	0.29	0.66	0.00	0.10	**Yes**	**6.76E-08**
B	0.15	0.43	0.00	0.08	**Yes**	**2.64E-06**
C	0.53	0.72	0.00	0.14	**Yes**	**3.66E-04**
D	1.34	1.54	0.00	0.21	**Yes**	**1.05E-03**
E	4.85	4.79	0.00	0.67	No	3.86E-01
F	3.11	3.67	0.00	0.49	**Yes**	**3.87E-03**
G	5.64	6.84	0.00	0.87	**Yes**	**6.69E-04**
H	7.61	8.00	0.00	1.02	No	1.28E-01
I	6.14	5.85	0.00	0.79	No	2.00E-01
J	4.23	4.08	0.00	0.52	No	2.81E-01
K	1.52	1.79	0.00	0.19	**Yes**	**4.89E-03**
L	0.91	1.10	0.00	0.20	**Yes**	**4.95E-02**
M	1.05	1.27	0.00	0.24	**Yes**	**7.46E-03**
N	0.55	0.65	0.00	0.12	**Yes**	**2.59E-02**
O	0.47	0.73	0.00	0.12	**Yes**	**1.87E-04**
P	0.99	1.15	0.00	0.19	**Yes**	**3.53E-02**
Q	1.68	2.04	0.00	0.35	**Yes**	**4.49E-03**
R	1.35	1.66	0.00	0.34	**Yes**	**3.59E-02**
S	0.50	0.78	0.00	0.14	**Yes**	**4.10E-04**
T	0.22	0.48	0.00	0.09	**Yes**	**1.13E-05**
U	0.19	0.44	0.00	0.09	**Yes**	**1.67E-05**
V	0.33	0.56	0.00	0.10	**Yes**	**5.75E-05**

We compared the annual mean ALAN (satellite-based radiance; nW/cm^2/sr) for 2014 to 2022 and percent change over the nine year period to see if there was a relationship between the two (Fig. 10). A relationship would indicate that changes in ALAN over the last 9-years contributed to the patterns in mean ALAN between 2014 and 2022. We found that grid locations with the highest average ALAN were those that had the smallest percent change observed between 2014 and 2022. These were sites E, F, G, H, I, and J, which are all within the limits of the towns of Nags Head, Kill Devil Hills, and Kitty Hawk. One explanation for the observed pattern may be that the increases in ALAN occurred before 2014 and few changes have occurred since then, or that the changes in ALAN that occurred in those locations led to ALAN saturation (the satellite measurement detection limit).

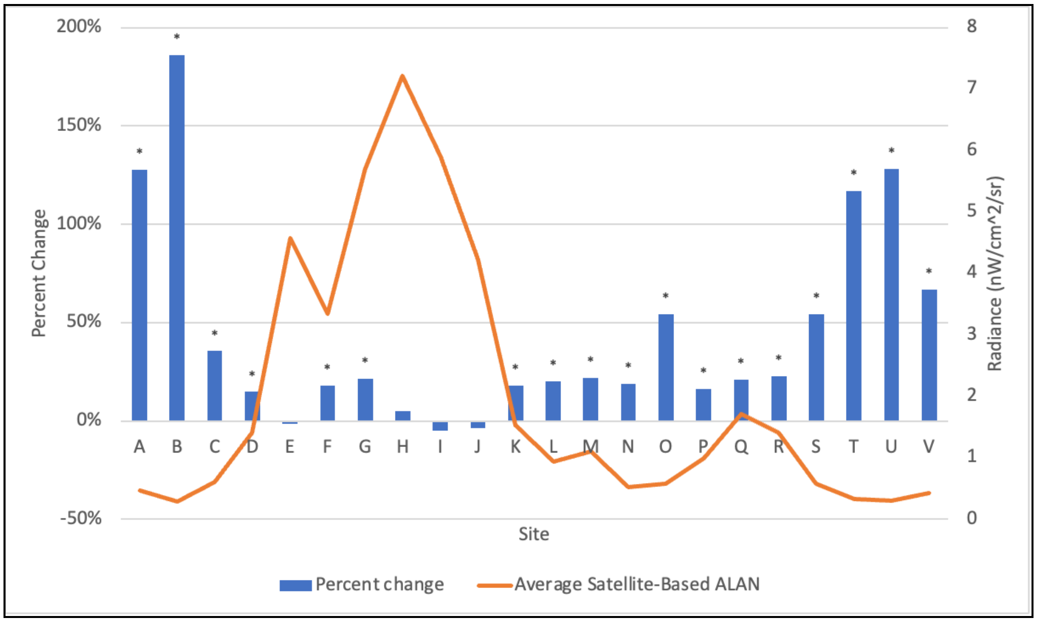

Figure 10 | Percentage of change between Jan-Dec 2014 and Jan-Dec 2022 overlaid with the mean radiance (nW/cm$^{2/}$sr), a measure of ALAN, from 2014-2022, across each site. The figure is organized from south to north, with A being the Oregon Inlet site and V being the site in Currituck County

Our findings suggest an increase in ALAN in most areas of the Outer Banks within our study site from 2014-2020. The areas that did not show a significant change were locations within the more developed towns, which may be because they reached the maximum possible levels of ALAN detectable by our satellite-based methods prior to the first year of our analysis (2014).

3.4. Beach-based ALAN

The ALAN (sky luminance, inverse to ALAN) measured from the beach on three occasions of new moons in the fall of 2023 varied from Oregon Inlet to Corolla across the fourteen study sites. The mean ALAN (sky luminance) across all sampling dates for each sampling location ranged from 20.73 mag/arcsec^2 (Corolla) to 19.27 mag/arcsec^2 (First Street; Fig. 11).

The northern and southernmost points where sky luminance was measured had the highest values (lowest ALAN), whereas our central sampling points had lower average luminance values (greater ALAN). Corolla, Oregon Inlet, and Coquina Beach are adjacent to or within large conservation areas (Fig. 2). In areas with less development and more conservation, there was a higher luminance from the stars and less artificial light impeding this view.

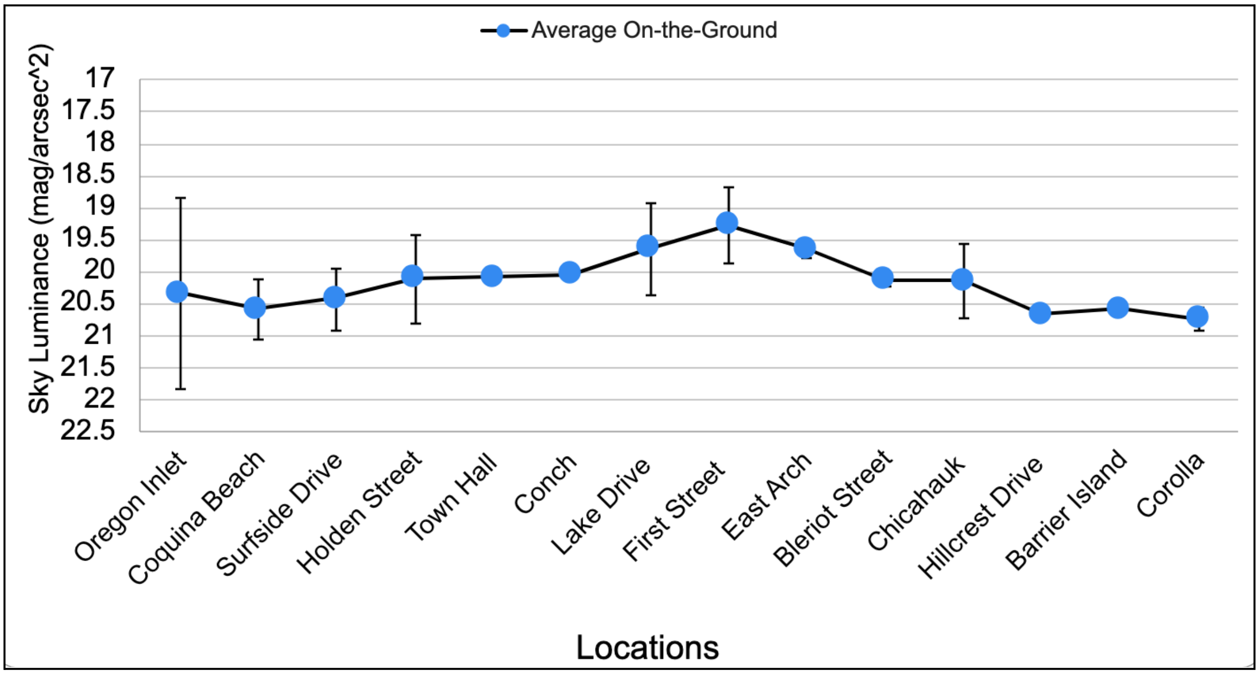

Figure 11 | The mean sky luminance measured with sky quality meters (SQM; mag/arcsec^2) at sampling locations across beaches on the Outer Banks of NC. This data was collected on three sampling occasions: the nights of 9/14/2023, 10/13/2023, and 11/13/2023. All three sampling occasions took place during a new moon. The sampling locations along the x-axis are oriented from South to North. Error bars represent one standard deviation from the mean.

A comparison of Figure 11, depicting the means of sky luminance across all three sampling occasions, and Figure 12, depicting the means of sky luminance across only the first two sampling occasions, reveals the sensitivity of our beach-based SQM meter measurements to ephemeral light sources, including those on the water. On the third night of measurements (11/13/2023), we observed a large fishing boat offshore of Oregon Inlet, and bright lights from a business were on when they had not been previously, contributing to the large standard deviation (1.49) around the mean, due to the much lower luminance SQM measurement (higher ALAN) on the third night than the first two nights of sampling at Oregon Inlet. Oregon Inlet had 0% cloud cover each collection night, and the stars were equally visible during each data collection.

As seen in Figure 11, there were very small variations across sampling occasions (time) amongst the other sites. Town Hall, Conch, East Arch, Bleriot Street, Hillcrest Drive, Barrier Island, and Corolla were the sites that had the least variation across the three data collection nights. These places each had 0% cloud cover, good star visibility, and similar light sources each night. Some variability at the Holden Street, Lake Drive, First Street, and Chicahauk locations is less significant than that at Oregon Inlet. Each had 0% cloud cover, equal star visibility amongst the three collection nights, and differing light sources. These different light sources did not cause as much change as was measured at Oregon Inlet. This reveals that the overall luminance remained relatively similar even with slight variations each night. This suggests that a small boat or a house light can influence ALAN, but less dramatically than a large fishing vessel.

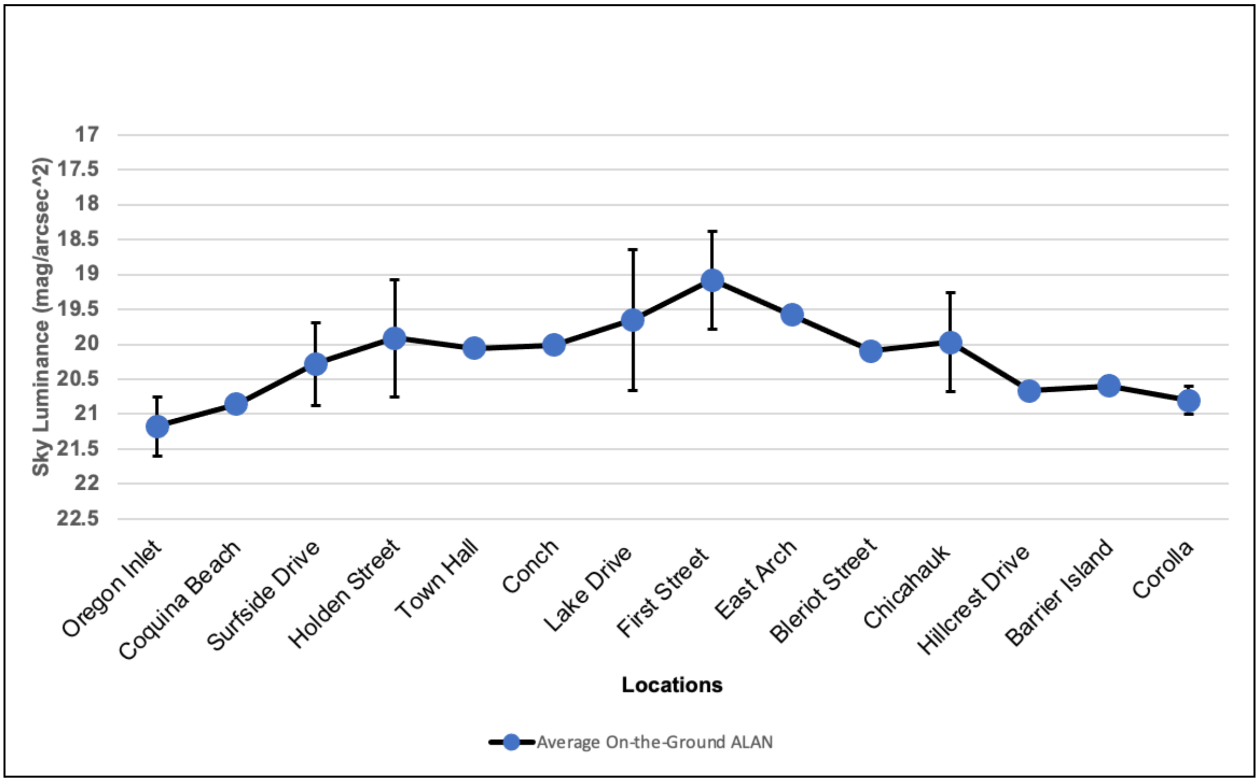

Figure 12 | The mean average sky luminance measured with sky quality meters (SQM) at sampling measurement locations across beaches on the Outer Banks of NC. These data were collected on two sampling occasions: 9/14/2023 & 10/13/2023. The two sampling occasions took place during a new moon. The locations along the x-axis are oriented from South to North. Error bars represent one standard deviation from the mean.

3.5 Beach-based and satellite measurement of ALAN method comparison

Our second research question addresses the relationship between the two methods we used to measure ALAN, beach-based measurements using SQM meters and satellite-based methods. The patterns in ALAN are similar when we compare mean satellite-based data from 2022 averaged across September through November to beach-based SQM measurements from the same locations in September through November 2023 (Figs. 13 and 14). The lowest light levels were observed using each method at our southern and northernmost beach-based sampling locations. Both methods also show a peak in ALAN in the middle of our study site. Again this pattern in ALAN was expected since there is more development and ALAN sources within towns and less in areas adjacent to and within conservation areas. We found no statistically significant difference between the distribution of mean SQM measurements for each sampling location and mean satellite data from 2022 for corresponding grid locations (adjusted H = 0.029, $p = 0.865$).

Our results suggest that when standardized, the two methods for measuring ALAN show similar patterns. This is important because it suggests that future research on ALAN can be conducted using SQM meters, which is an easier and less expensive option for decision-makers and others interested in light pollution without expertise in satellite imagery analysis.

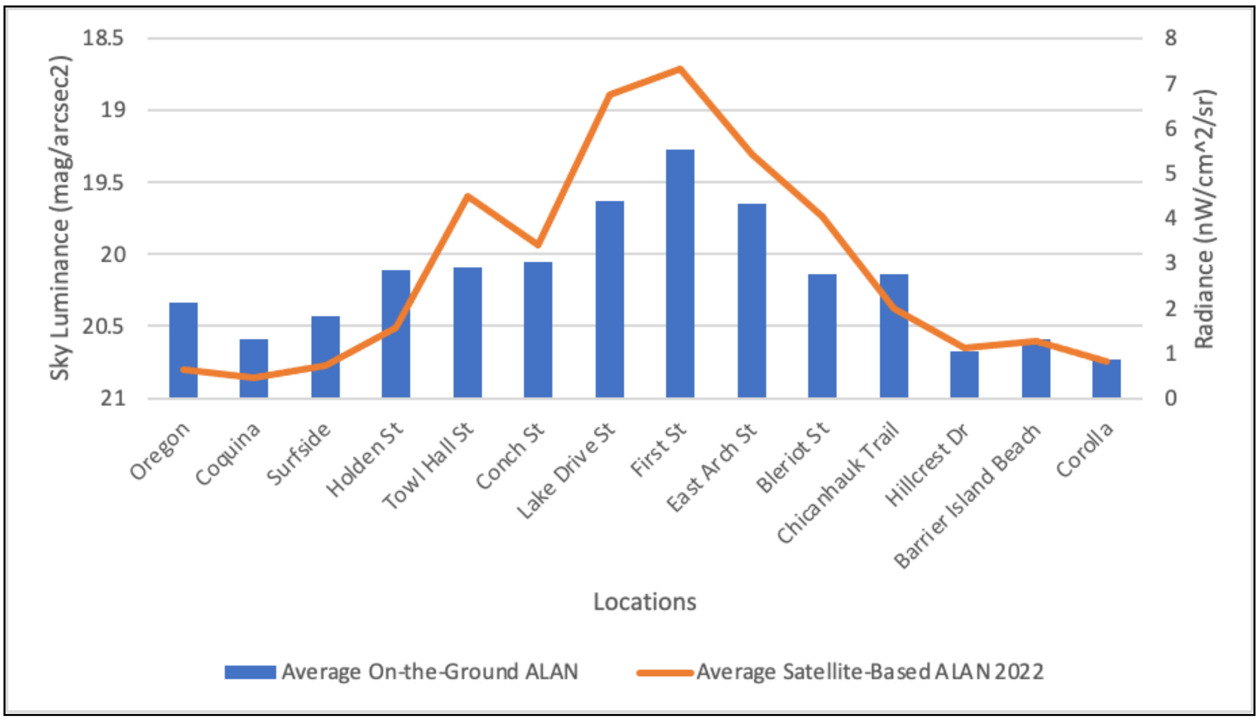

Figure 13 | Comparison of mean average (2022) radiance (nW/cm^2/sr; satellite-based ALAN) from September-November 2022 to mean average sky luminance measured from the beaches of the Outer Banks of NC with sky quality meters (SQM; mag/arcsec^2) during new moons in Sept., Oct., and Nov. of 2023.

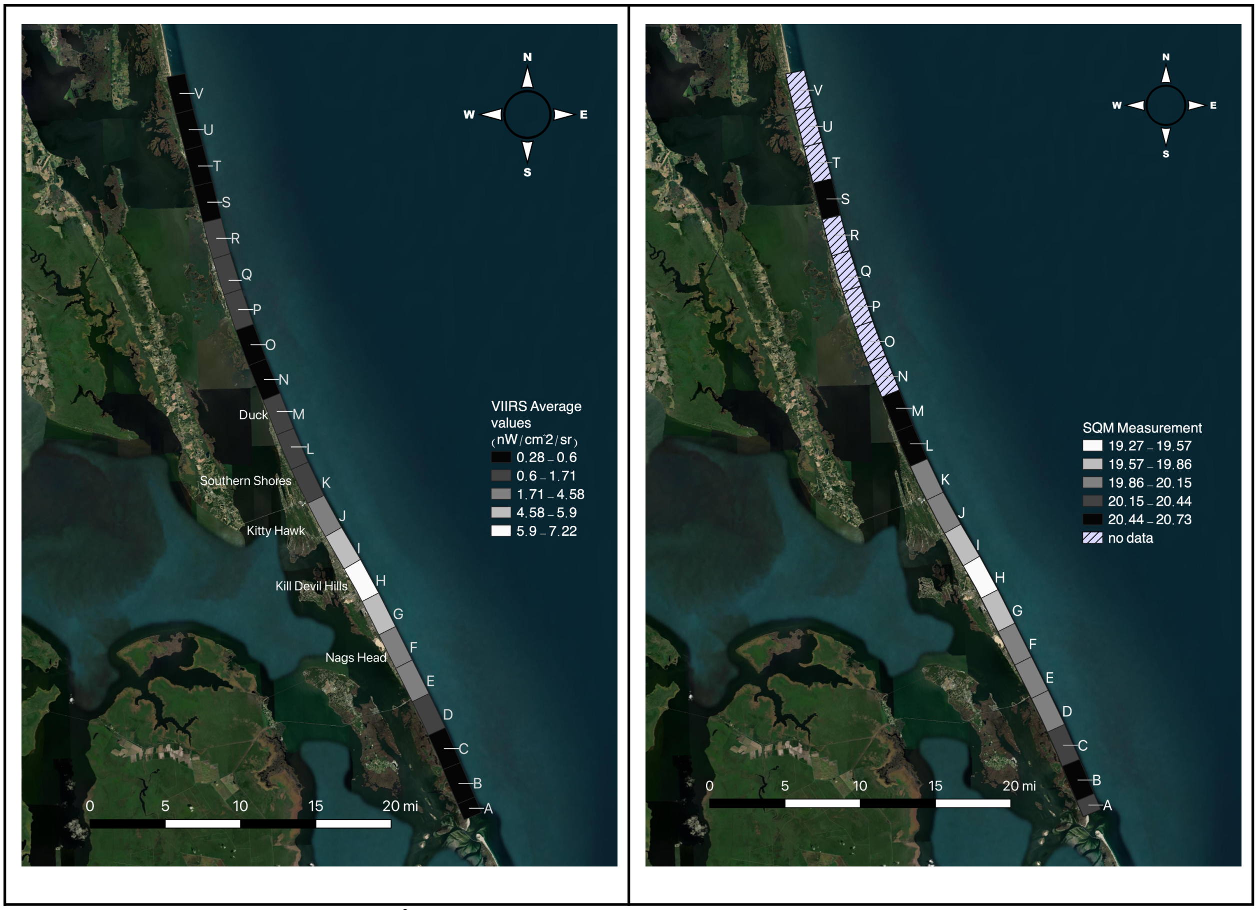

Figure 14 | (a) Average radiance (nW/cm^2/sr; satellite-based ALAN) values along the Outer Banks of NC. (b) Average sky luminance measured from the beaches of the Outer Banks of NC with sky quality meters (SQM; mag/arcsec^2) during new moons in Sept., Oct., and Nov. of 2023.

3.6. Patterns in turtle activity

Turtle activity, including false crawls, nests laid, and total turtle activity within our study site varied over time and space from 2014 to 2022. Turtle activity showed an overall increase over time (Fig. 15) and a simple linear regression revealed that year significantly predicted turtle activity (Table 3). The fitted regression model was: y = -482.87884 + 0.24047619x. False crawl and nest counts per year in our study site from 2014 to 2022 ranged from 5 and 41 and, respectively to 19 and 56 respectively (Fig. 16 and 17). The general increasing trend could be due to conservation efforts put in place like the Endangered Species Act and organizations such as N.E.S.T and the National Park Service managing these nests.

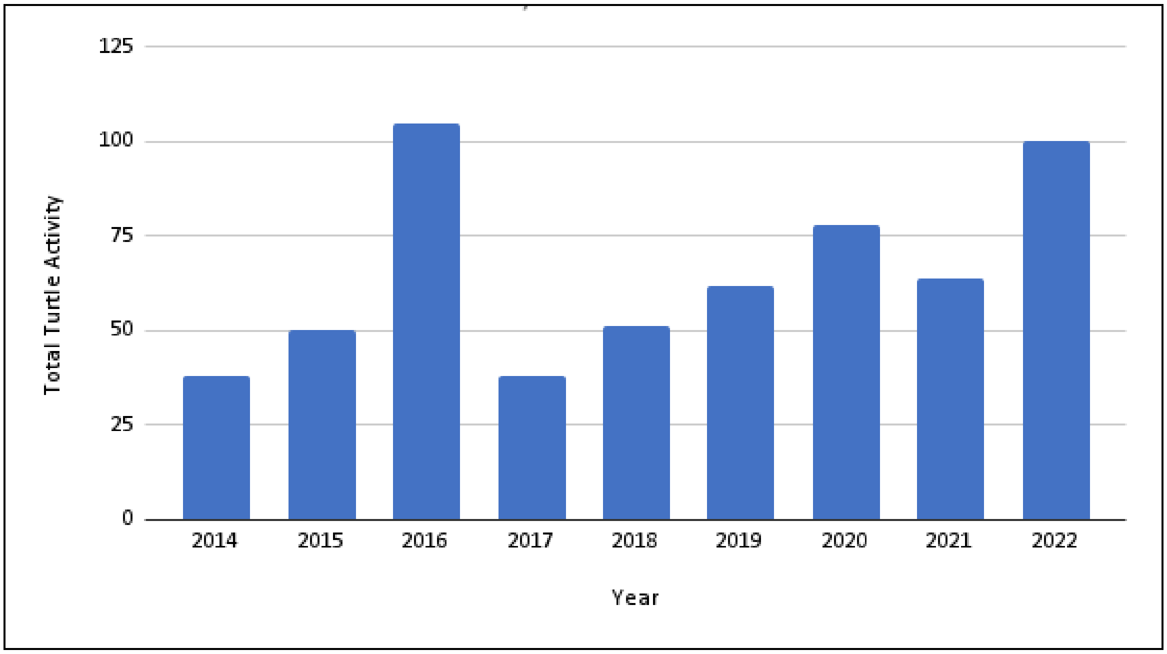

Figure 15 | Total count of sea turtle activities, including false crawls and nesting, for each year from 2014-2022 within the study site on the Outer Banks of NC.

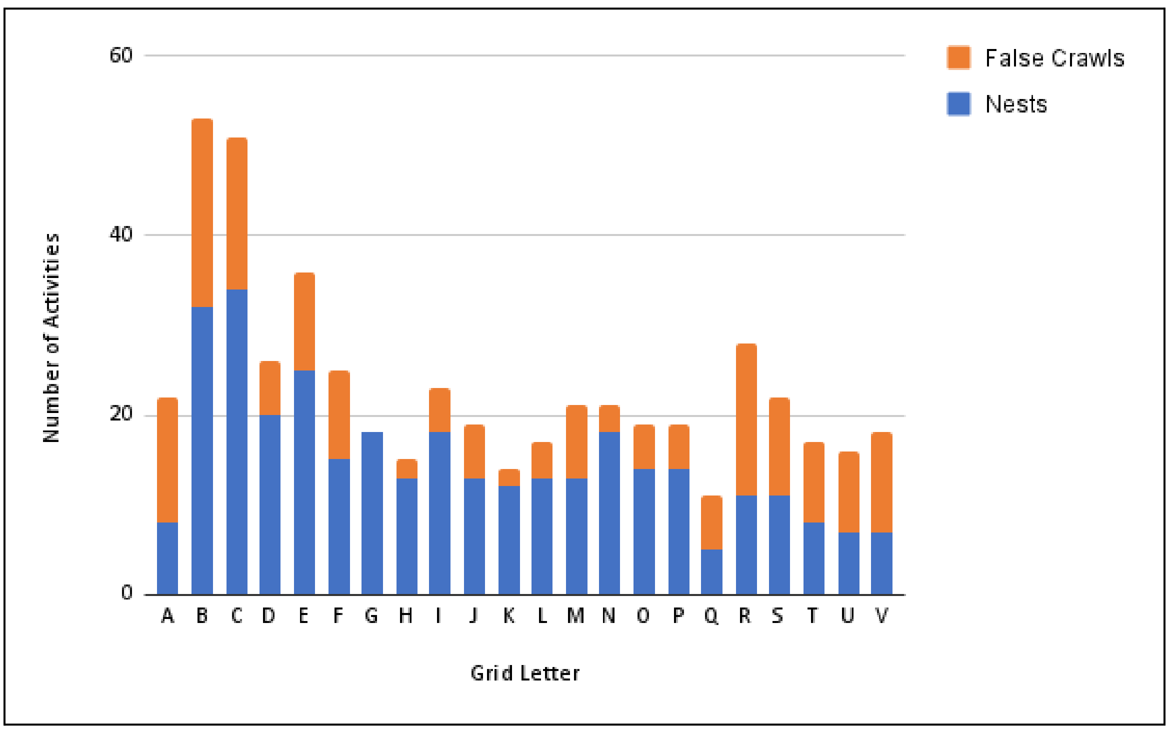

Figure 16 | Total count of turtle activities, including false crawls and nesting, from 2014-2022 within satellite-based ALAN grid locations on the Outer Banks of NC. Grid locations are listed from A-V, which is also from the southernmost to the northernmost grids.

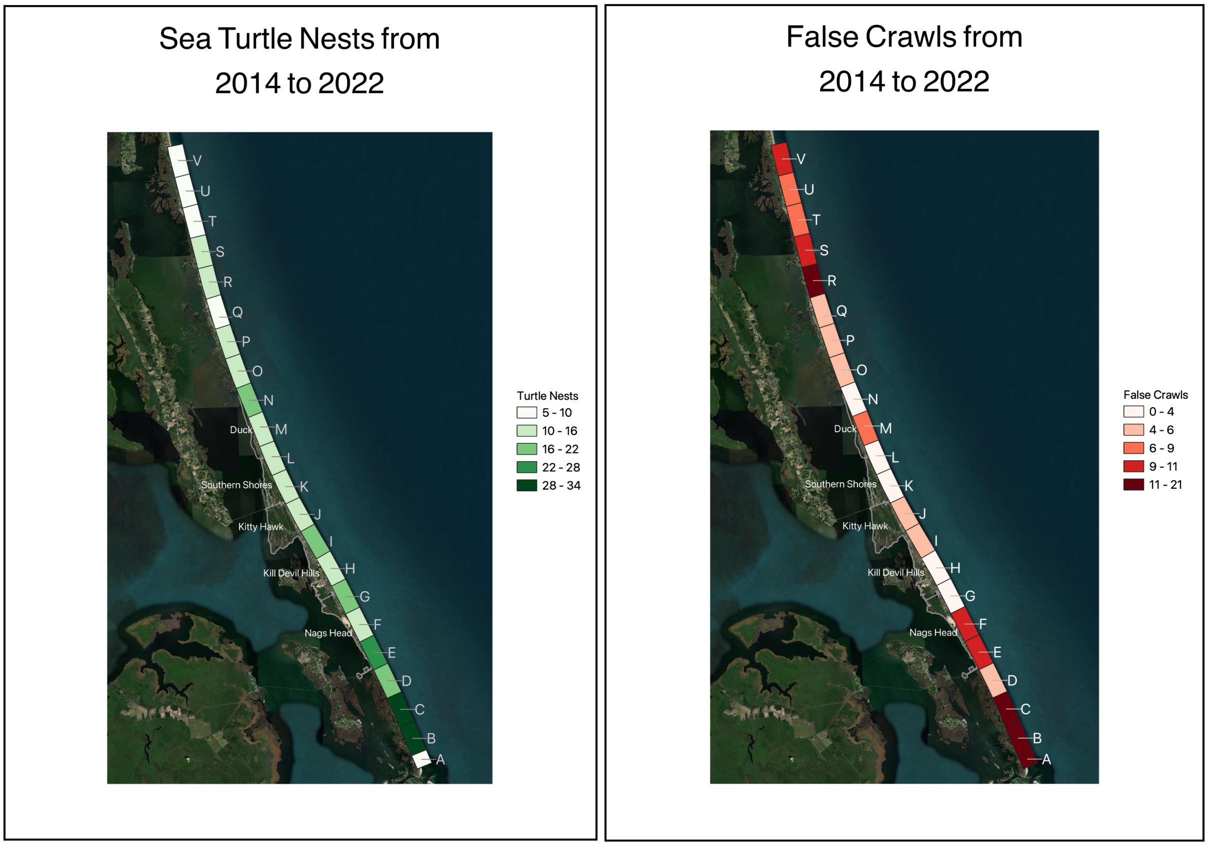

Figure 17 | Total counts of sea turtle (a) nests laid and (b) false crawls from 2014-2022 within the study site on the Outer Banks of NC. Sea turtle activity data were summed for each grid location used in analysis of satellite based ALAN. Sea turtle data were provided by NEST and the National Parks Service from 2014 to 2022.

A study done by Patel et al. (2021) showed that loggerhead populations are expected to migrate to the NW Atlantic shelf as climate change increases. Turtle nests are mostly south of North Carolina, but with climate change, it is possible that as turtles start nesting more in the NW, NC will see and has seen more nesting. This also might explain the increase in turtle activity that we have seen along the coast.

We also saw a pattern in turtle activity across sampling locations. The most turtle activity, and especially nests laid, occurred in the most southern grid locations (Figs. 16 and 17). While we did not find that latitude significantly predicted false crawls (Table 3), it did significantly predict nesting (Table 3).

Turtles nest more the further south you go in North Carolina as the habitat is more compatible for them. However, we do not see the same pattern when looking at false crawls;

there seem to be more false crawls in the northernmost and southernmost areas compared with areas in between (Figs.17). These areas also happen to be the darkest areas in our study.

A simple linear regression was used to test if satellite-based ALAN (VIIRS radiance) significantly predicted turtle activity. Regressions were conducted with all turtle activity, only false crawls, and only nests. We did not observe any emergent patterns between ALAN (satellite-based measurements) and turtle activity using simple linear regression tests (Table 3) but did find that when using a multiple linear regression that among other variables ALAN did influence false crawls ($p=0.00886$).

We did not find a correlation between the satellite light data over the past nine years and nesting. This could mean that adult female turtles are not impacted by light as they nest. There is also a possibility that a certain threshold of light needs to be met to impact turtles. As darkness continues to disappear along the coast, there could be a level where turtles will be deterred from nesting in that location. Another possibility is that the influence of latitude along the Outer Banks is much greater than any other influence. Because North Carolina is one of the northernmost points for turtle nesting, the habitat becomes more and more suitable as you go south which explains the correlation between nesting and latitude. Perhaps that relationship overshadows any relationship with ALAN. A third possibility is that the sample size of our study range is too small to show this trend. Studies such as one done by Zhiyong et al. (2018) have shown a significant correlation between nesting and light, however, this study was done in Florida where the turtle activity is much greater than in NC.

Table 3 | Simple linear regression and multiple linear regressions done for dependent variables (all turtle activity, false crawls, nests) and independent variables (StoN, VIIRS, year). Table shows results of tests and if they are statistically significant.

Dependent Variable	Independent Variable(s)	R2 Value	P-value	T-stat	Statistically Significant?
All Turtle Activity	StoN	0.06872753	0.0002683	10.4652129	Yes
All Turtle Activity	VIIRS	0.000847591	0.690871594	10.58610184	No
All Turtle Activity	Year	0.07439389	0.001464	-3.8576329	Yes
All Turtle Activity	StoN, VIIRS	0.09672807	7.78E-05	9.3025335	Yes
All Turtle Activity	StoN, VIIRS, Year	0.17453634	9.19E-08	-4.2139031	Yes
False Crawls	StoN	0.0088193	0.90413196	3.93094877	No
False Crawls	VIIRS	0.01908267	0.058011487	7.364404221	No
False Crawls	Year	0.060617209	0.000374129	-3.612646329	Yes
False Crawls	StoN, VIIRS	0.022423149	0.121348534	4.290540161	No
False Crawls	StoN, VIIRS, Year	0.093489471	0.000398696	-3.791994863	Yes
Nest	StoN	0.144781868	6.63E-08	12.12902214	Yes
Nest	VIIRS	0.005216143	0.323346706	9.179088641	No
Nest	Year	0.033146301	0.012165224	-2.513998231	Yes
Nest	StoN, VIIRS	0.14690756	1.41E-07	9.885437982	Yes
Nest	StoN, VIIRS, Year	0.191873431	1.35E-08	-2.829455224	Yes

4. Results & Discussion of Social Science

4.1. Respondents & Demographic Descriptions

Our survey received a total of 512 responses, of which 467 were usable. Various reasons resulted in unusable responses, including the individual listing a home or visit location that was outside of our study site (from Corolla to Wanchese) or if the response was less than 50% complete. Of the total usable responses, 65% respondents identified as female and 29.2% identified as male (Table 4). The majority of respondents fell in the 40-79 age brackets (71.82%), with the largest group of respondents aged 60-69 (24.15%). According to U.S. Census data, the age distribution of our sample is largely representative of the regional population except for the 20s and 30s age brackets: our sample over-represented individuals in their 20s and underrepresented individuals in their 30s. However, our sample is not representative of the genders of the regional population, which is largely evenly split between male and female. Additionally, well over half of the survey respondents held a 4-year college, graduate, or professional degree (71.4% total).

Table 4 | Demographic data of survey respondents (age, gender, education level). Total number of respondents varied per question

Demographic Information	Responses	Percentage of Respondents (%)
Age n=439	18-20	1.40%
	21-29	14.58%
	30-39	10.02%
	40-49	13.96%
	50-59	18.45%
	60-69	24.15%
	70-79	15.26%
	80-89	2.28%
	90-100	0.23%
Gender n=466	Female	65.00%
	Male	29.20%
	Non-binary	0.90%
	Prefer Not to say	4.90%
Education Level n=452	Graduate or Professional Degree	34.50%
	4-Year College Degree	36.90%
	2-Year College Degree	10.80%
	Trade or Technical School	4.60%
	High School	13.10%

Of our respondents, 391 of them indicated that they live or stay in an Outer Banks town within our desired range (from Corolla south to Oregon Inlet). The largest number of respondents, 30.8%, stated Kill Devil Hills, with 20.9% of respondents indicating Nags Head, 16.5% Manteo, and 12.5% Duck. Our survey also received respondents from Southern Shores (5.3%), Wanchese (2.8%), and Corolla (2.5%) (Fig. 18). Additionally, our survey received 38 total responses from other locations in the Outer Banks that were outside of our study range. These locations included Avon (4), Buxton (8), Corova (2), Frisco (5), Hatteras Village (4), Manns Harbor (3), Ocracoke (2), Rodanthe (3), Salvo (4), and Waves (2). Fifteen respondents said they lived in or visited a town outside the Outer Banks entirely, which indicated they misunderstood the question.

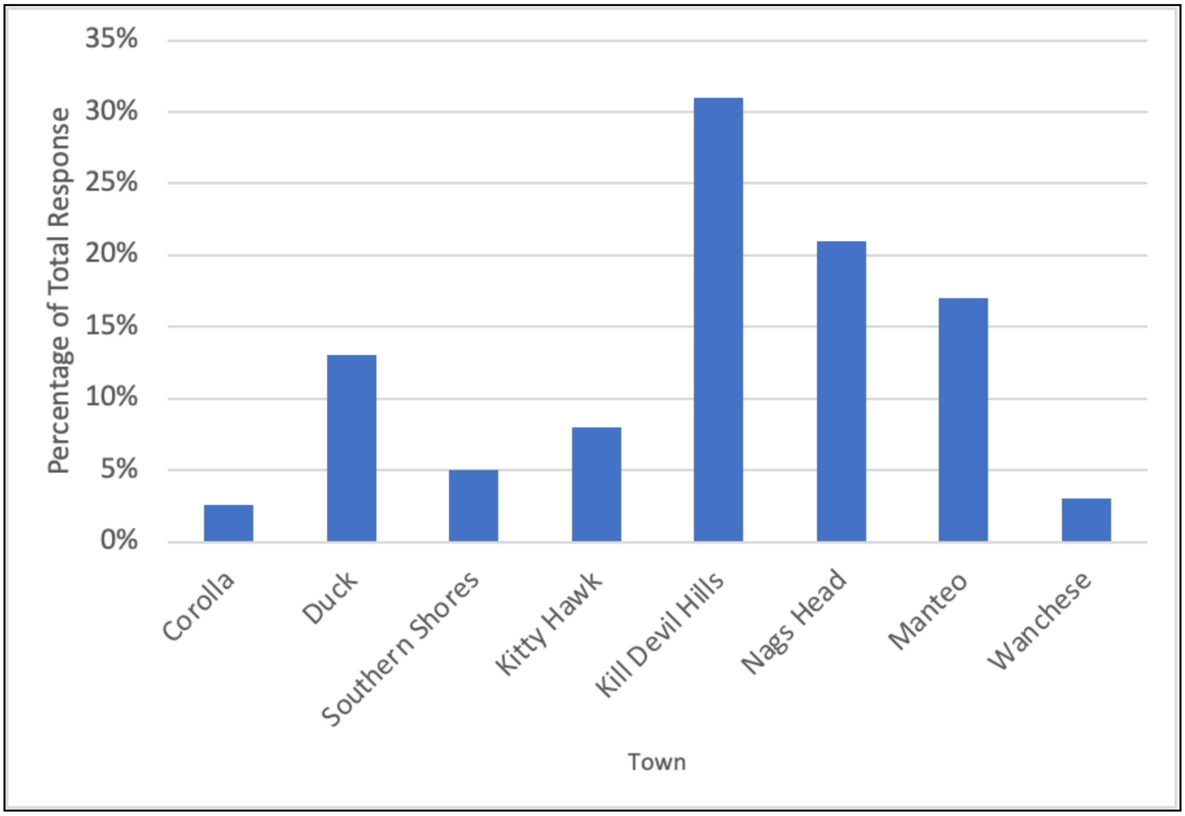

Figure 18 | Percentage of survey respondents by town in survey range (n=391). Towns are listed from the northernmost town (left) to the southernmost town (right).

We compared the proportionate size of our year-round resident respondent sample to the proportionate size of the year-round population for each town from Corolla to Nags Head, including Manteo and Wanchese, using 2020 census data. In doing so, we found that the proportionate populations of Corolla and Kill Devil Hills were similar to the proportion of respondents from those towns in our survey sample (Fig. 19). However, the towns of Duck, Manteo, and Nags Head made up a larger proportion of our survey sample than they do in the regional population, while the towns of Kitty Hawk, Southern Shores, and Wanchese were less so.

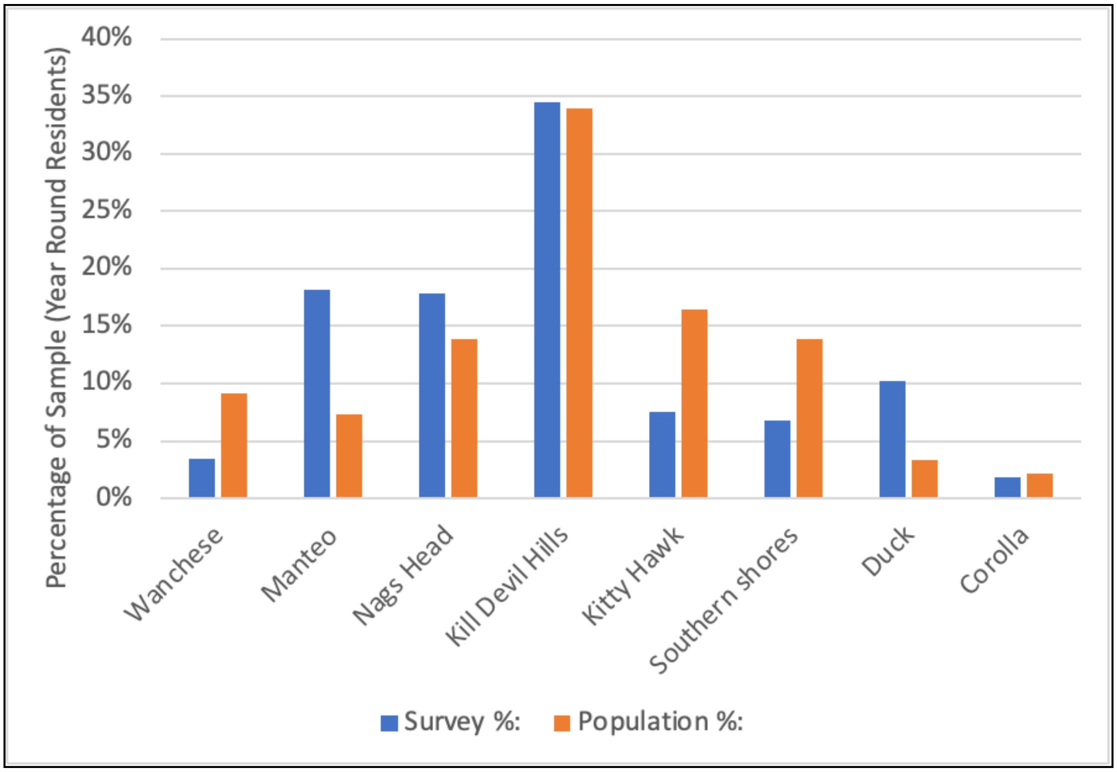

Figure 19 | Comparison of towns within the study site year-round population distribution and survey sample distribution. Total number of respondents from these towns was 391.

In an effort to explain differences between the regional population and our survey sample, we point to our survey distribution methods. For example, our close proximity to downtown and central Manteo and Nags Head allowed us to more thoroughly distribute our survey in those areas, via in-person intercept and electronic means. Despite its far distance, we believe the survey was completed by more respondents in Duck because this town agreed to include our survey in its weekly newsletter, as did Nags Head. This was not the case for Southern Shores, which, due to its farther location, saw less frequent in-person distribution and higher reliance on electronic survey dissemination.

Of the total number of respondents, 69.3% classified themselves as year-round residents, 19.3% were seasonal residents, and 11.3% were visitors. In the survey, we defined seasonal as those living in the Outer Banks 3-7 months out of the year. These segments of our sample did not differ in age or gender, with the average age being around 53 years for each group. However, after conducting a chi square statistical analysis, we found that resident status was significantly related to education level (p=0.0322). Visitors were more likely than year-round residents to have advanced degrees.

Further chi square analyses showed that resident status and town of residence had a statistically significant relationship (p=0.0035). In our sample, there were more seasonal residents from Duck than statistically expected while there were more year-round residents from Kill Devil Hills and visitors from Nags Head.

4.2. Knowledge and Awareness of ALAN

4.2.1. Self-Assessment

We hypothesized that greater knowledge and awareness about ALAN would lead to support for mitigating its effects so we included measures of knowledge and awareness in the survey. We asked survey participants to rate how informed they are about ALAN and its impacts on a scale ranging from "not at all" to "very well". The majority of respondents (32.19%) indicated they were "somewhat" informed, the answer choice in the middle of the range (Fig. 20). The responses showed a unimodal distribution around the middle of the response range.

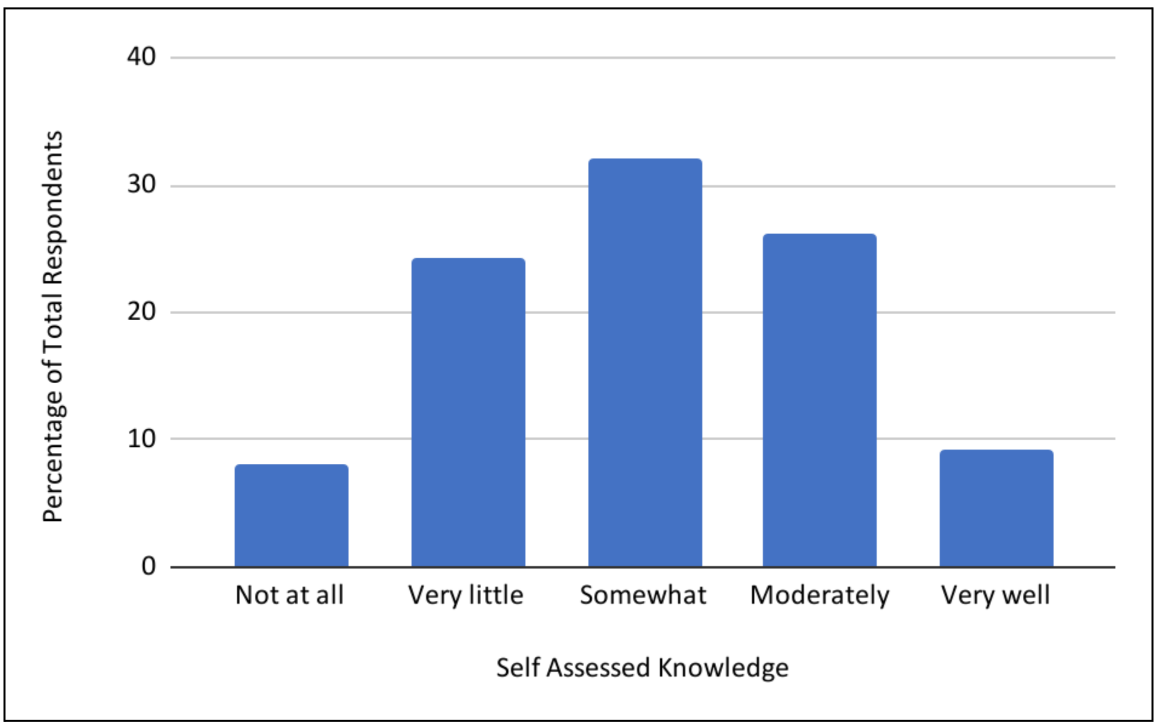

Figure 20 | ALAN knowledge by self-assessed informed level by survey respondents (n = 466)

4.2.2. ALAN Knowledge Score

To assess participants' knowledge of ALAN, we asked three questions covering the topics of ALAN identification, human health effects, ecological consequences, and night sky viewing. For each question part answered correctly, we awarded a point and summed points for a knowledge score. Because some questions consisted of multiple parts, the knowledge score was assessed out of a total of nine points. Participants' scores ranged from 1 to 9 (Fig. 21). The average knowledge score was 6.04 with a standard deviation of 1.34.

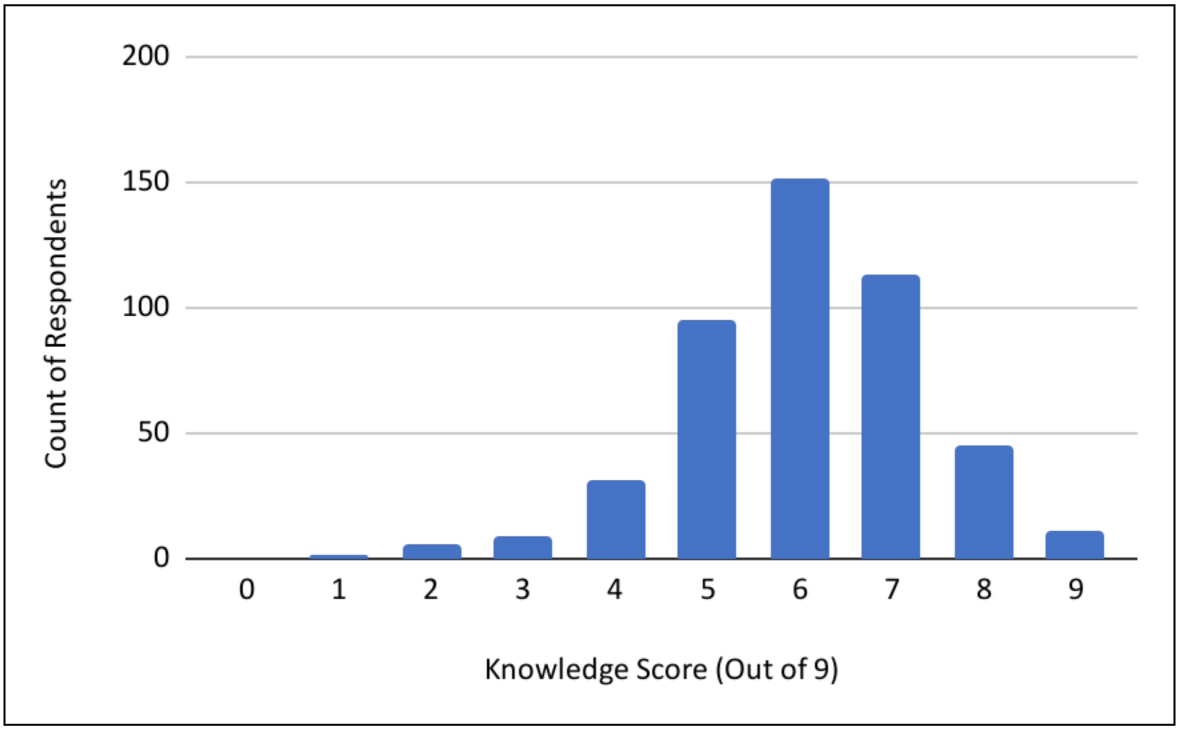

Figure 21 | ALAN knowledge scores of survey respondents (n = 466). Scores were calculated by summing points awarded for correct responses to a set of questions about ALAN.

The knowledge questions are shown in Table 4. Almost all respondents correctly identified "streetlight shining in a bedroom window" as light pollution. While more than 90% of respondents knew that ALAN does not increase the visibility of the night sky and does affect sea turtle hatchlings, only 48% correctly identified blue light as a disruption to organisms. This suggests that individuals can correctly identify ALAN but are less familiar with its impacts. Individuals may struggle identifying effects of personal technology, in particular, due to its prevalence in society.

Table 5 | Knowledge Assessment Questions, Answer Choices, and Accuracy Rate (n = 466). Correct responses are shown in bold.

Question	Answer Choices	Percentage of respondents with correct responses
Which of the following can be considered a form of light pollution?	a. Moonlight reflecting off the ocean b. Fireflies flashing **c. Streetlight shining in a bedroom window.** d.I Don't Know	96.35%
Studies have shown that arificial light at night is associated with which of the following health concerns in humans? (selec all that apply)	**a. Disrupted circadian rhythms** b. Scoliosis **c. Cancer** **d. Obesity** **e. Mood disorders** f.I don't know	55.11%
True or False: Blue light is more disruptive to organisms a night than other colors of light	**a. True** b. False	48.07%
True or False: Artificial light at night increases visibility of the night sky	a. True **b. False**	92.49%
Artifical light at night affects sea turtles' ability to find the ocean after hatching	**a. True** b. False	91.63%

When asked about health concerns associated with ALAN, most respondents correctly identified circadian rhythms and mood disorders but failed to identify other health concerns that have been associated with ALAN. Obesity was only correctly identified as a related health concern by 19% of respondents and cancer was correctly identified by only 6% of respondents (Fig. 22). This suggests that respondents tend to associate ALAN with direct outcomes affecting mental and hormonal processes rather than indirect physical outcomes.

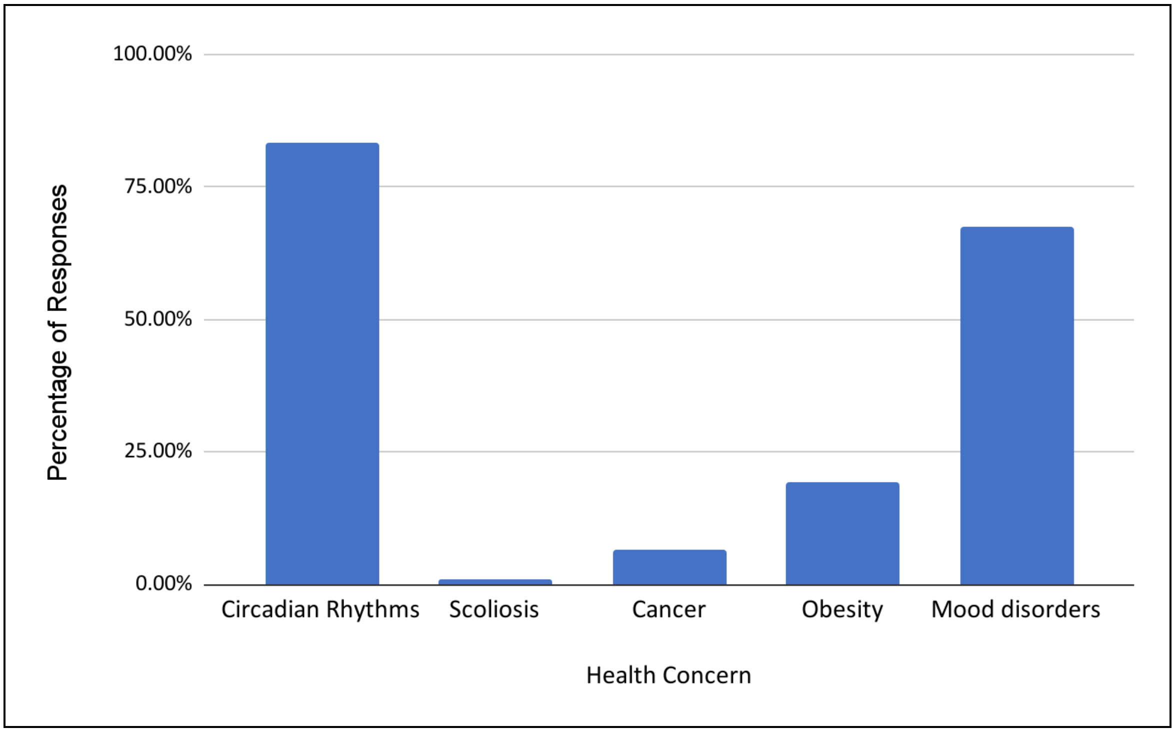

Figure 22 | Respondents' knowledge of ALAN human health impacts (n = 453). Responses show the percentage of respondents that indicated each health concern as being associated with ALAN. Scoliosis was the only health concern that we did not determine to be associated with ALAN.

4.2.3. Self-Assessment and Knowledge Scores

To determine the accuracy of respondents' self-assessed knowledge level, we compared self-assessed informed levels and knowledge scores. Responses were split into levels of self-assessed knowledge and then average knowledge scores calculated for each group of respondents. While average knowledge scores increased with increasing self-assessed level of awareness, the closeness of average knowledge scores in Figure 23 suggests that respondents have similar levels of knowledge but widely varying perceptions of their own knowledge. The difference between the average knowledge score of the highest and lowest self-assessment level was only 1.33 points.

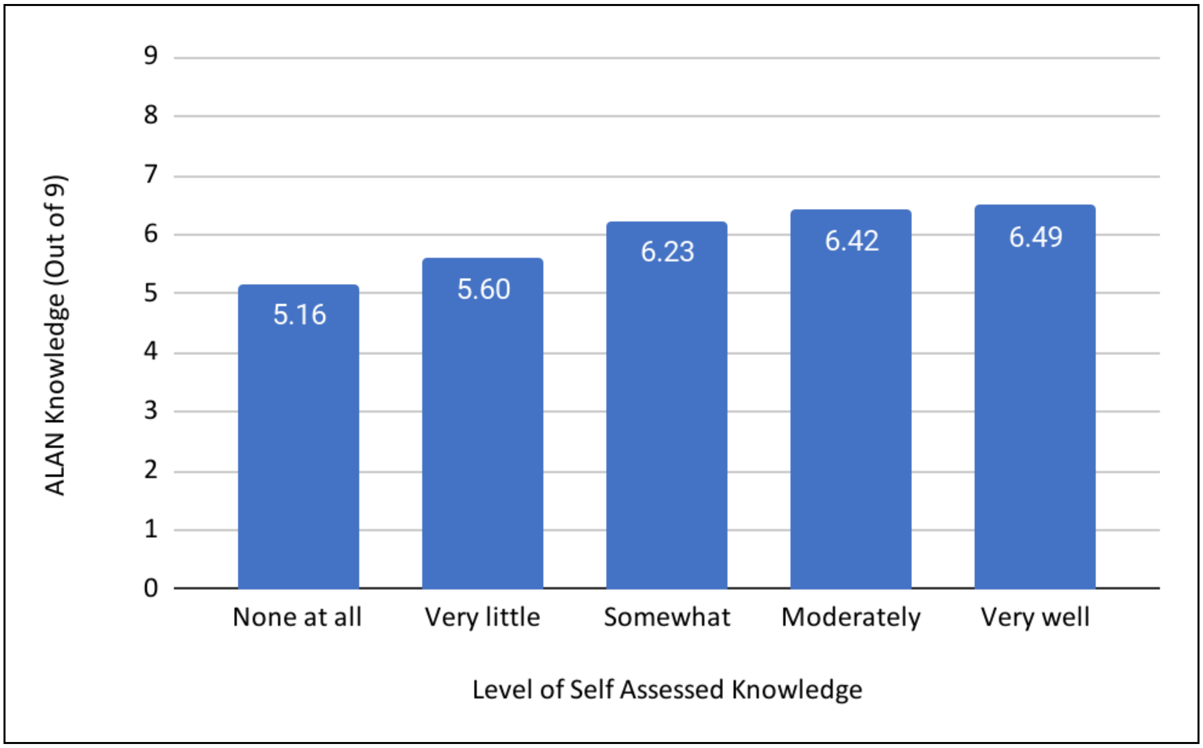

Figure 23 | Average ALAN knowledge score by self-assessed knowledge level (n = 466)

4.2.4. Knowledge by Residency

To understand potential variation in knowledge across residents and visitors, we examined both knowledge variables with residency status. We found that the majority of year-round residents rated themselves as "somewhat" or "moderately" informed while the majority of seasonal residents rated themselves as "very little" or "somewhat" informed - a slightly lower rating (Fig. 24). Visitors overwhelmingly indicated that they felt "somewhat" informed. The variation in self assessed knowledge may suggest that year-round residents feel more confident in their level of ALAN knowledge due to their closer proximity to the issue relative to seasonal residents and visitors.

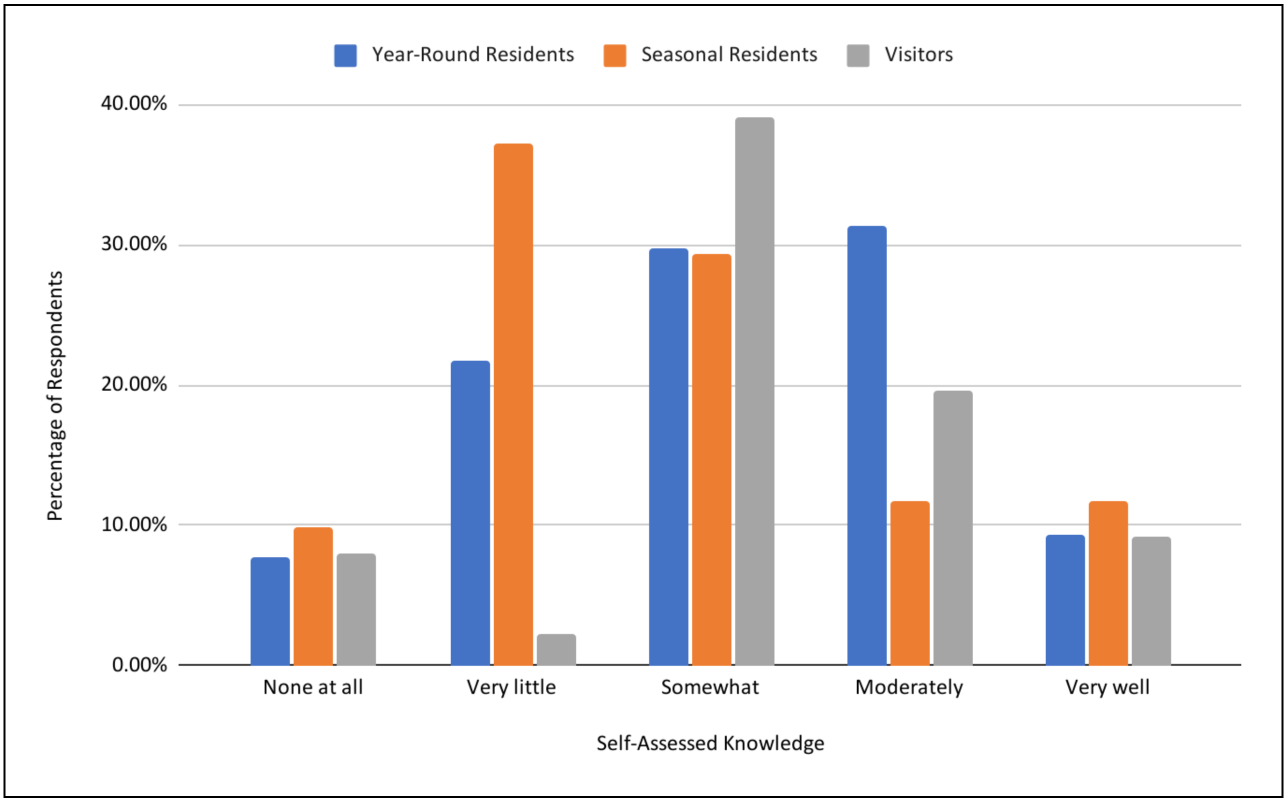

Figure 24 | Self-assessed ALAN knowledge score by residency status (n = 450)

To attempt to understand variation in assessed knowledge, we examined knowledge scores by residency status. We found that the most common score, regardless of residency, was six out of nine points (Fig. 25). When averaged, year-round residents earned 6.08 points, seasonal residents earned 5.98 points, and visitors earned 6.15 points. It should first be acknowledged that these are very similar average scores, suggesting that residency status is not driving variation in knowledge. However, where there is variation in these averages, we can point to several potential reasons. Similar to the suggestion posed by self-assessed knowledge and residency, perhaps year-round residents are slightly more knowledgeable due to more time spent in the area. Residents may also hold stronger attachments to their environments when it is their only place of residence throughout the year. The higher average score earned by visitors could suggest that many visitors live in urban areas with high amounts of ALAN relative to those of the Outer Banks.

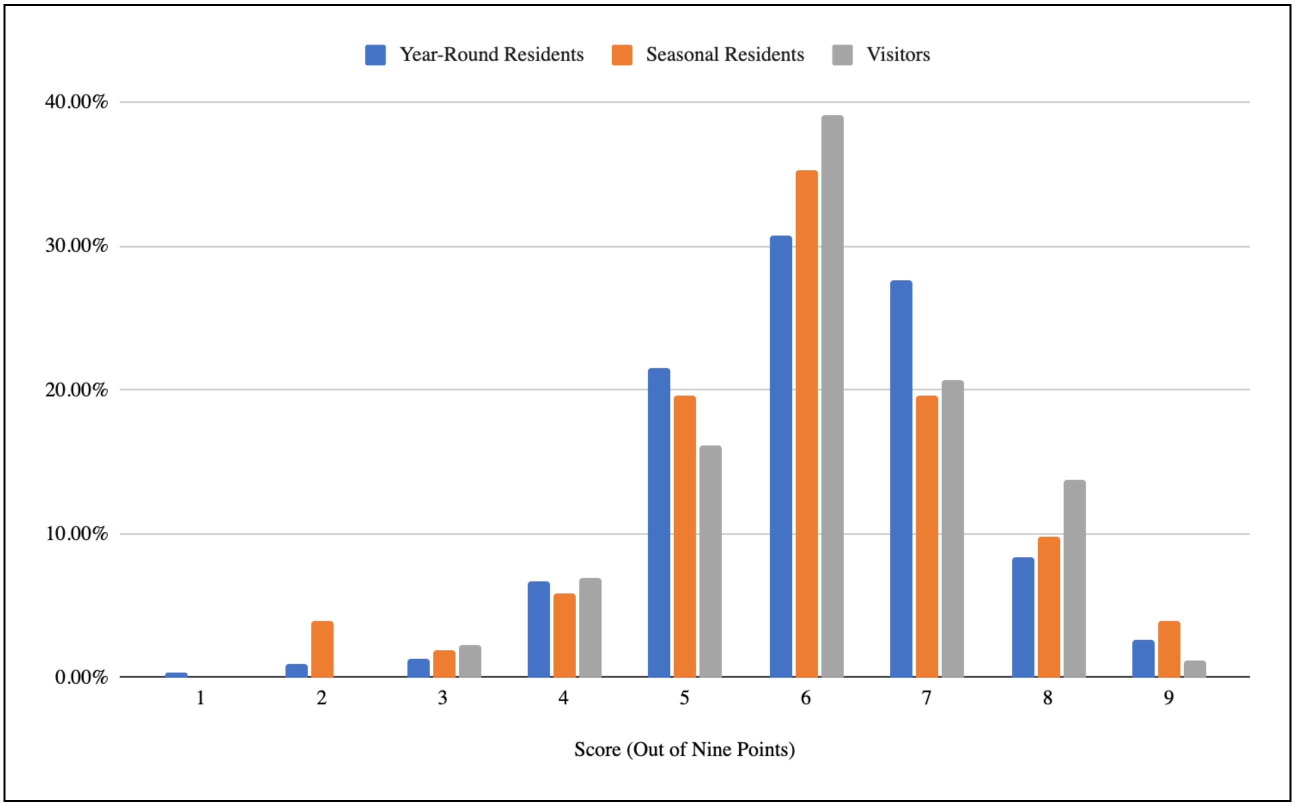

Figure 25 | Assessed knowledge score by residency status (n = 450)

4.3. Attitudes and Views about ALAN of Residents & Visitors

Most respondents indicated that they were very concerned about artificial light at night (Figure 26). A Kruskal-Wallis test showed that there was a statistically significant difference in level of concern across residency status (adjusted H=12.239, p=0.0022, n=450), towns (adjusted H=55.717, p=0.00000000107, n=394), and gender (adjusted H=24.031, p=0.00000605, n=452). Full time residents chose higher levels of concern than visitors and seasonal residents. Respondents from Duck and Southern Shores more commonly responded with the answer choices of "I'm very concerned about it" and "I'm concerned about it". Women had a higher level of concern than men. A Kruskal-Wallis test showed no statistically significant difference across age (adjusted H=8.003, p=0.332, n=441). A Goodman-Kruskal gamma showed that there was a relatively strong association between being informed (self-assessed knowledge) and level of concern (γ =0.4355, $p < .001$), a moderate association between frequency of appreciating the night sky and level of concern (γ =0.383, $p < .001$), and a moderate association between comfort with the dark and level of concern (γ =0.2673, $p < .001$).

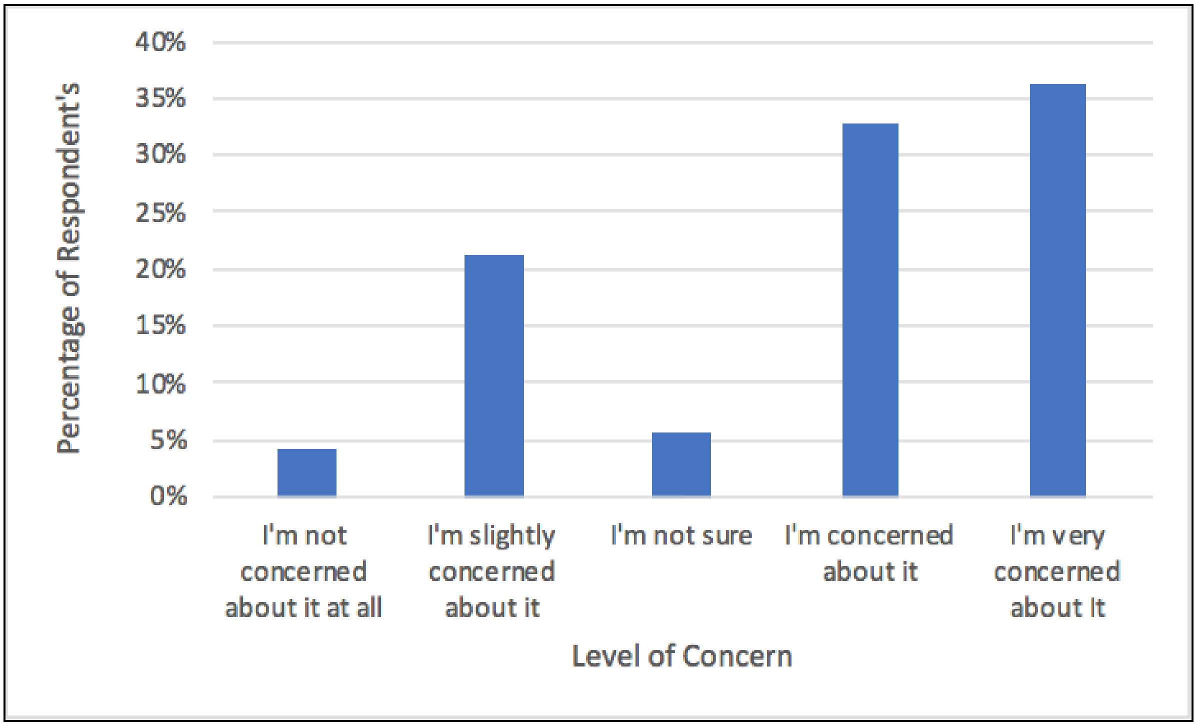

Figure 26 | Level of concern about artificial light at night among survey respondents in the OBX 2023, n=466

The pattern of responses about perceived effects of ALAN varied widely across the factors surveyed. (Figure 27). The response choices ranged from highly negative to highly positive effect. The responses for effect on stargazing and sea turtles had little variety, with the majority of respondents choosing a highly negative effect. The responses for effect on personal safety and greenhouse gas (GHG) emissions were more varied, with no clear majority in any answer choice. For the remaining effects of energy consumption, human health, and shorebirds, respondents mainly chose either the answer choice of highly negative or negative.

We found that demographic variables impacted participant's responses for the effects on sleep, sea turtles, shorebirds, GHG emissions, and stargazing.A Kruskal-Wallis test showed a statistically significant difference in perceived effect of ALAN on sleep between genders (adjusted H=9.038, p=0.011, n=448) and across age (adjusted H=14.999, p=0.036, n=429). Women appeared to have higher levels of concern, as did middle aged people (40s and 50s) with more choosing the "highly negatively" option. For the effect of artificial light at night on sea turtles, a Kruskal-Wallis test showed a statistically significant difference in perceived effect across residency (adjusted H= 12.91, p=0.001573, n=367), between town (adjusted H=18.659, p=0.009324, n=367), between gender (adjusted H=9.038, p=0.011, n=421) and across age (adjusted H=14.999, p=0.036, n=415). The groups with higher levels of concern about the effect of artificial light at night on sea turtles were residents, the towns of Corolla and Duck, women, and participants in their 20s and 30s. For the effect of artificial light at night on shorebirds, a Kruskal-Wallis test showed a statistically significant difference in perceived effect between gender (adjusted H=8.058, p=0.018, n=457). Women appeared to be more concerned about the effects of artificial light at night on shorebirds than men and those who chose the "prefer not to say" option. For the effect of artificial light at night on GHG emissions, a Kruskal-Wallis test showed a statistically significant difference in perceived effect between gender (adjusted H=9.038, p=0.011, n=270) and across age (adjusted H=14.999, p=0.036, n=259). Men were more likely to say that artificial light at night has no effect on GHG emissions than women and people who chose "prefer not to say". Respondents in their 80s also tended to say that artificial light at night has no effect on GHG emissions. For the effect of artificial light at night on stargazing, a Kruskal-Wallis test showed a statistically significant difference in perceived effect between gender (adjusted H=3.911, p=0.048, n=427). Men chose the "highly negatively" option more than women.

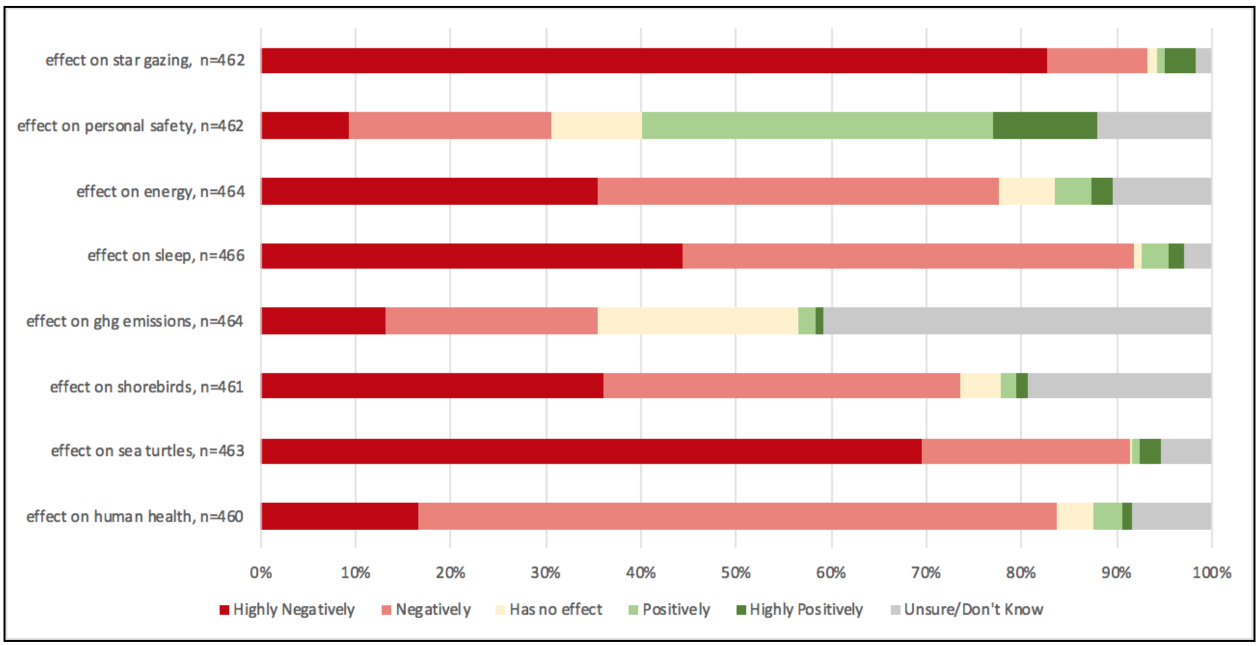

Figure 27 | Perceived effects of artificial light at night by survey respondents in the Outer Banks, n=460

Table 6 | Perceived effects of artificial light at night in the Outer Banks statistical results for a survey conducted in fall 2023. Bold indicates statistically significant.

	Residency	Town	Gender	Age (binned)
Effect on Personal Safety	Adjusted H= 0.479 D.f.= 2 P value= 0.787 n= 390	Adjusted H= 10.46 D.f.= 7 P value= 0.164 n= 337	Adjusted H= 1.473 D.f.= 2 P value= 0.479 n= 388	Adjusted H= 6.908 D.f.= 7 P value= 0.439 n= 383
Effect on Energy	Adjusted H= 0.287 D.f.= 2 P value= 0.866 n= 402	Adjusted H= 6.843 D.f.= 7 P value= 0.445 n= 349	Adjusted H= 4.953 D.f.= 2 P value= 0.084 n= 404	Adjusted H= 9.704 D.f.= 7 P value= 0.206 n= 392
Effect on Sleep	Adjusted H= 0.428 D.f.= 2 P value= 0.807 n= 439	Adjusted H= 5.511 D.f.= 7 P value= 0.598 n= 385	**Adjusted H= 9.038** **D.f.= 2** **P value= 0.011** **n= 448**	**Adjusted H= 14.999** **D.f.= 7** **P value= 0.036** **n= 428**
Effect on Sea Turtles	**Adjusted H= 12.91** **D.f.= 2** **P value= 0.001573** **n= 422**	**Adjusted H=18.659** **D.f.= 7** **P value= 0.009324** **n= 367**	**Adjusted H= 12.022** **D.f.= 1** **P value= 0.000526** **n= 421**	**Adjusted H= 15.296** **D.f.= 7** **P value= 0.032** **n= 415**
Effect on Human Health	Adjusted H= 0.598 D.f.= 2 P value= 0.741 n= 410	Adjusted H= 2.076 D.f.= 7 P value= 0.956 n= 362	Adjusted H= 2.872 D.f.= 2 P value= 0.238 n= 417	Adjusted H= 11.172 D.f.= 7 P value= 0.131 n= 400
Effect on Shorebirds	Adjusted H= 1.498 D.f.= 2 P value= 0.473 n= 361	Adjusted H= 9.953 D.f.= 7 P value= 0.191 n= 317	**Adjusted H= 8.058** **D.f.= 2** **P value= 0.018** **n= 368**	Adjusted H= 10.516 D.f.= 7 P value= 0.161 n= 357
Effect on GHG Emissions	Adjusted H= 0.248 D.f.= 2 P value= 0.883 n= 263	Adjusted H= 4.52 D.f.= 7 P value= 0.718 n= 235	**Adjusted H= 19.481** **D.f.= 2** **P value= 0.000059** **n= 271**	**Adjusted H= 15.166** **D.f.= 7** **P value= 0.034** **n= 258**
Effect on Stargazing	Adjusted H= 0.178 D.f.= 2 P value= 0.915 n= 437	Adjusted H= 5.188 D.f.= 7 P value= 0.637 n= 375	**Adjusted H= 3.911** **D.f.= 1** **P value= 0.048** **n= 427**	Adjusted H= 13.807 D.f.= 7 P value= 0.055 n= 428

We then explored respondents' personal opinions on ALAN in their everyday lives based on their perceptions of the disruptiveness and necessity of ALAN sources where the respondents live or stay. Based on survey results, we selected four of the ALAN sources originally presented in the survey to expand upon based on the respondent's observed lack of consensus on how disruptive and necessary they were. The sources selected were ALAN emitted from public buildings, streets, parking lots, and exteriors of residential properties (Fig. 28). The general trend we observed was an inverse relationship between the perceived disruptiveness of a light source and level of necessity: when a light source was perceived to be necessary, it was less commonly perceived as being excessively or moderately disruptive. (Fig. 29). Lights on public buildings were considered the least necessary across the board (Fig. 28), and among those who did indicate that those lights were necessary, fewer said they were excessively disruptive than those who said they were not necessary (Fig. 29).

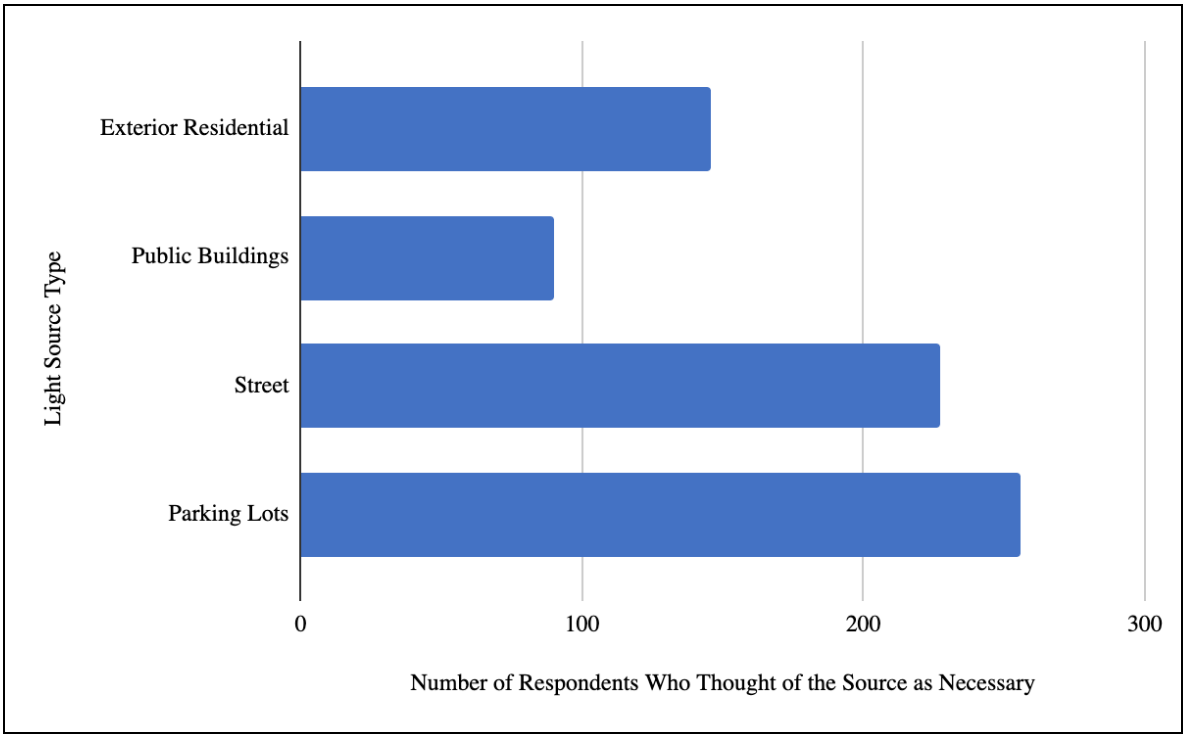

Figure 28 | Perceived necessity of light sources on North Carolina's Outer Banks gathered using a survey instrument in fall 2023.

Table 7 | Level of Disturbance of Exterior Residential-Sourced ALAN on NC's Outer Banks Based on Necessity

	Level of Disturbance:				
Necessary Source?	**Excessively**	**Moderately**	**Not at all**	**Slightly**	**Grand Total**
No	104	103	19	91	317
Yes	14	29	38	65	146
Grand Total	118	132	58	156	464

The most commonly selected disturbance level among respondents' attitudes about exterior residential lighting was "Slightly", a considerable difference from the rest of the provided sources of ALAN in the survey (Table 7). This might suggest that residents and visitors in North Carolina's Outer Banks view exterior lighting for personal residences as the least disruptive, and it would be worthwhile for further research to explore the motives behind this consensus, especially as rapid, dense development in coastal areas has led to greater levels of light pollution in residential areas.

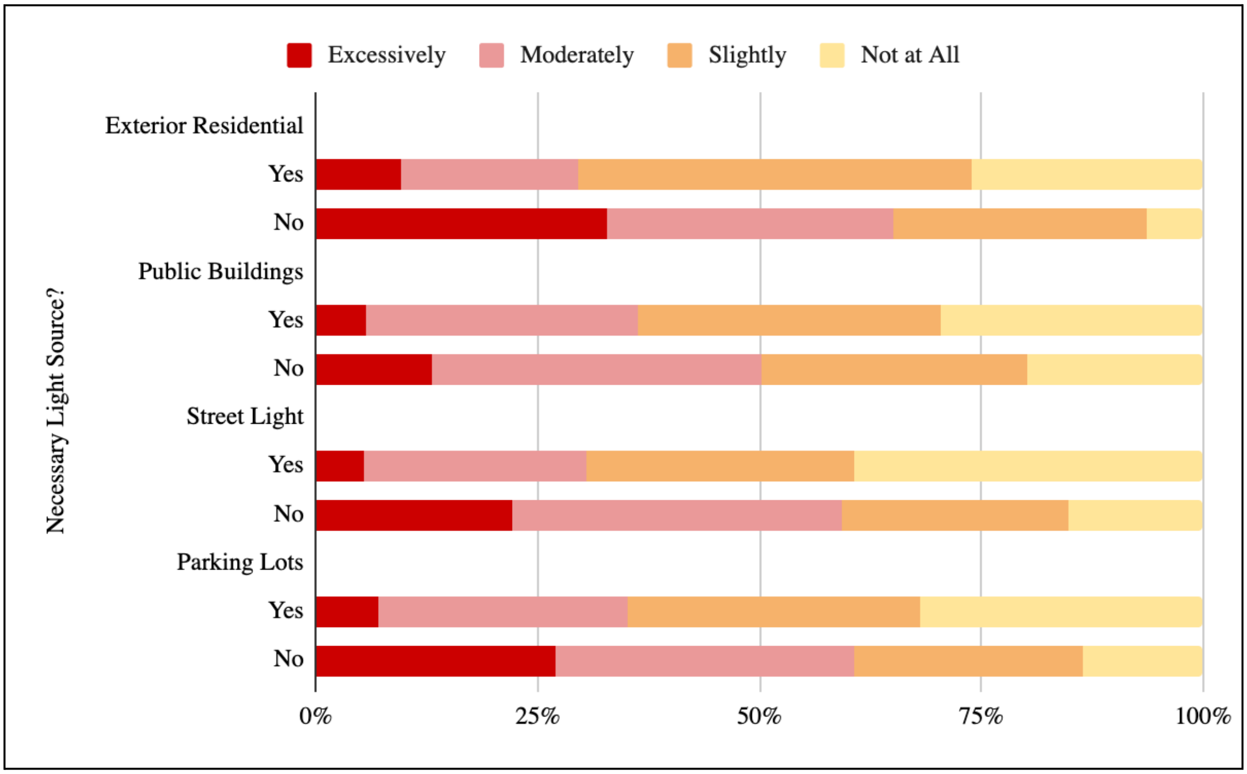

Figure 29 | Perceived Necessity of Light Emitted from Various Sources vs. Level of Disruption

In summary, these data suggest that lights that are considered more disruptive are considered less necessary, pointing to a potential for high levels of ALAN reduction across the Outer Banks and similar coastal municipalities. If light sources viewed as necessary are less disruptive, future research requires a look into what this may mean for light pollution-related policy.

In the survey, we also included an open response question that asked what time the respondent turned off their exterior lights in their residency. We converted the answers into 24 hour clock times. In Figure 30, the responses are displayed starting from the earliest time respondents turned off their lights and ending with the latest time. For each time, the total number of respondents whose lights are turned off during the time are represented. By 10:00 PM, the majority of respondents had their exterior lights turned off at their residencies. 9% of respondents indicated that their exterior residential lights are never turned off.

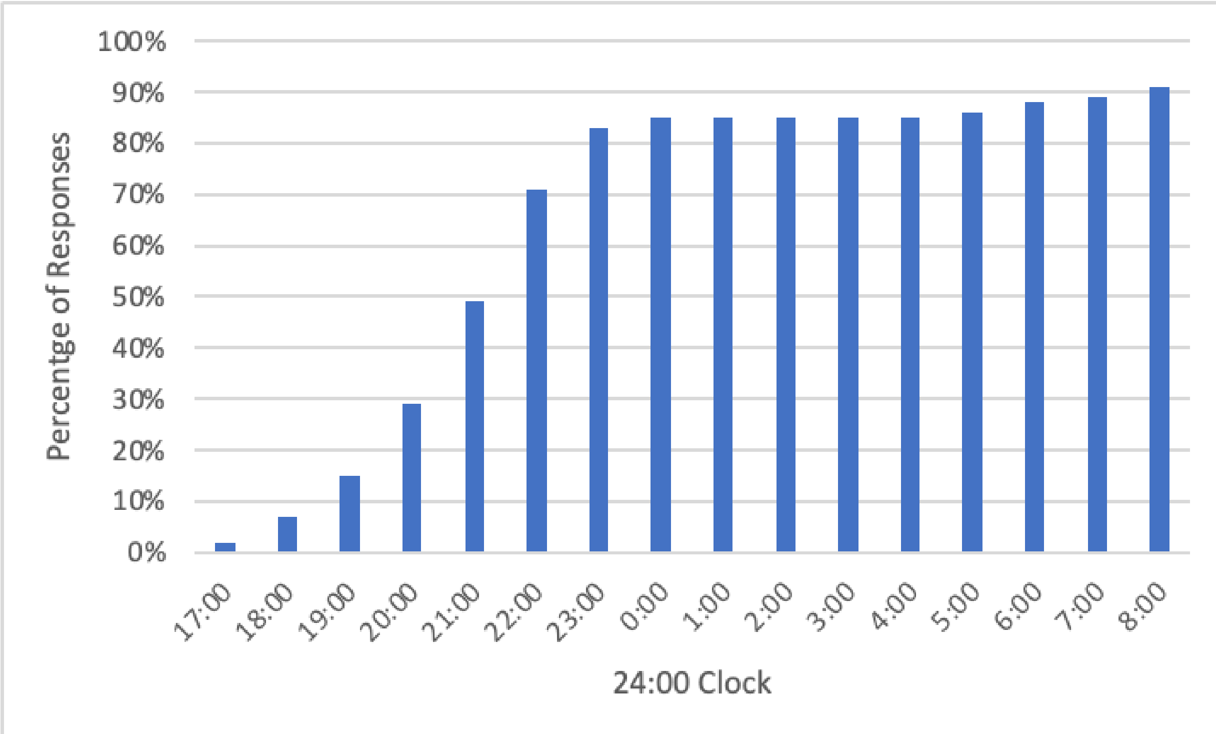

Figure 30 | Cumulative percentage of respondents with the exterior residential lights on the house they live or stay at in the Outer Banks turned off by a given time. n=338

4.4. Willingness to Reduce ALAN in the Outer Banks

Agreement that ALAN in the Outer Banks should be reduced varied somewhat across our survey respondents (Fig. 31). Most respondents either agreed or strongly agreed that it should be reduced. A Kruskal Wallis test showed that there was a statistically significant difference in agreement to reduce ALAN in the Outer Banks across different residency types (adjusted H = 10.042, p =0.007) (Table 8). The majority of responses from year round residents (66%), seasonal residents (61%), and visitors (47%) strongly agreed that ALAN should be reduced in the Outer Banks (Fig. 32).

A Kruskal-Wallis test showed that there was no statistically significant difference in the agreement to reduce ALAN in the Outer Banks between different town locations, gender, and age (Table 8), adjusted H = 13.316, H = 1.414, H = 8.884, p = 0.065, p = 0.493, p = 0.261, respectively.

A Goodman-Kruskal gamma showed that there was a strong association between agreement ALAN in the Outer Banks should be reduced and level of concern about ALAN in the Outer Banks, $\gamma = 0.6932$, $p < .001$, and a moderate association between agreement ALAN in the Outer Banks should be reduced and comfort in the dark, frequency of appreciating the night sky, and being informed about the impacts of ALAN, $\gamma = 0.2956$, $\gamma = 0.31$, $\gamma = 0.3735$, $p < .001$, respectively (Table 9).

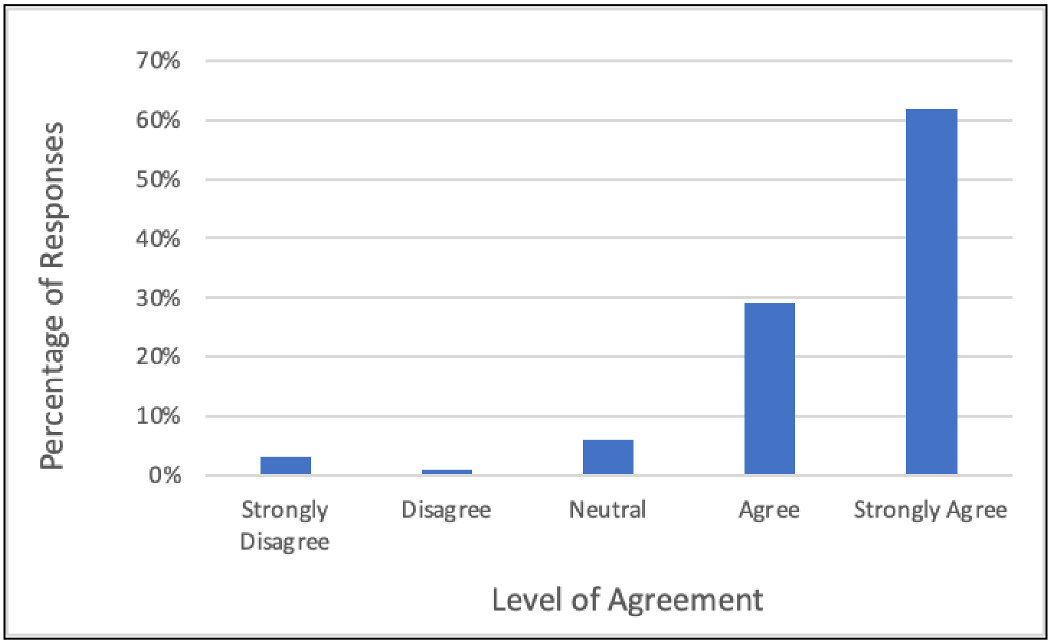

Figure 31 | Survey respondents' level of agreement with the following statement: "Artificial light at night in the Outer Banks should be reduced." (n=499)

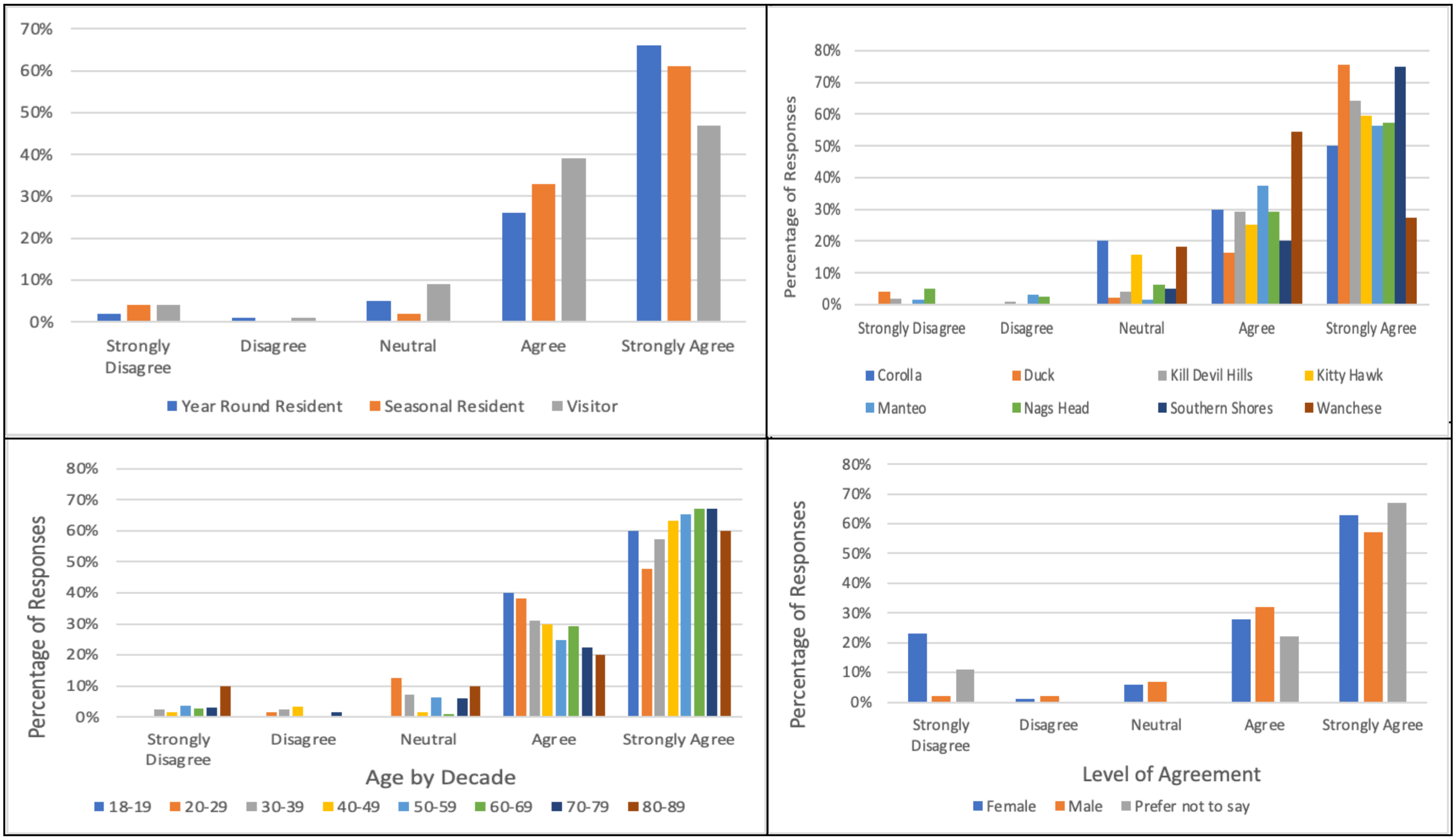

Figure 32 | Percentage of responses collected for level of agreement for the following statement: “Artificial light at night in the Outer Banks should be reduced.” Going clockwise, each figure was compared with demographic explanatory variable responses starting with residency status n=447, town location n=388, gender n=449 and age n=436.

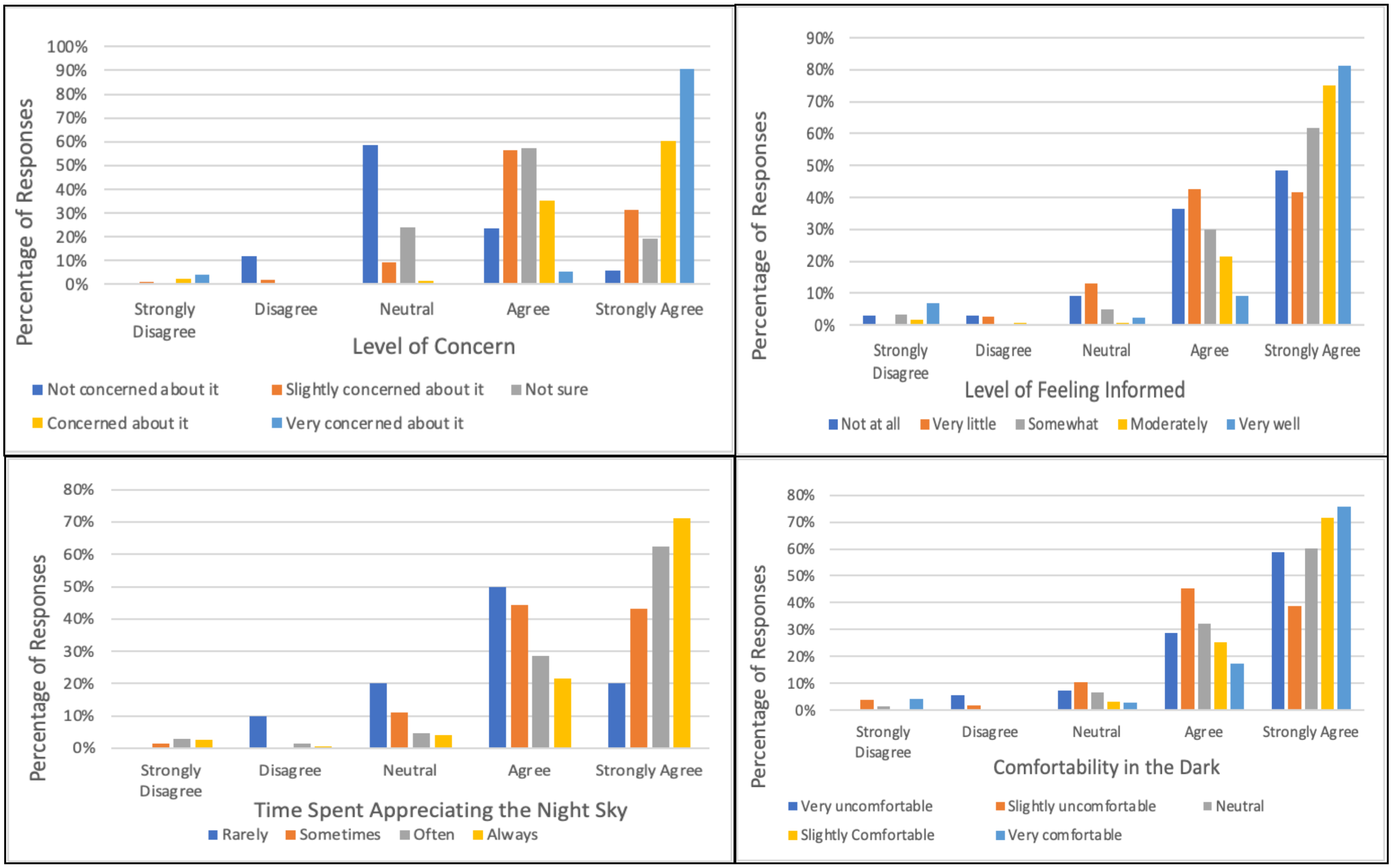

Figure 33 | Percentage of responses collected for level of agreement for the following statement: "Artificial light at night in the Outer Banks should be reduced." Going clockwise, each figure was compared with responses to questions from the survey with explanatory variables starting with response to level of concern about ALAN in the Outer Banks (n=449), self-reported level of feeling informed about ALAN (n=449), time spent appreciating the night sky (n=449), and comfortability in the dark (n=499).

Table 8: Kruskal-Wallis Test Results for comparing responses to the Level of Agreement to Reduce ALAN in the OBX with demographic responses. Table includes the values for p, h, and degrees of freedom for the test of each comparison.

	Age	Gender	Residency	Town
P-Value	0.261	0.493	0.007	0.065
H-Value	8.884	1.414	10.042	13.316
DF (Degrees of Freedom) Value	7	2	2	7

Table 9: Gamma Test Results from comparing the Level of Agreement to Reduce ALAN in the OBX with responses of other questions asked in the survey. Table includes the gamma value for the test of each comparison.

	Level of Concern about ALAN in the OBX	Being Informed about the Impacts of ALAN	Appreciation for the Night Sky	Comfortability with the Dark
Gamma Value	0.693	0.374	0.31	0.296

Respondents that agreed ALAN should be reduced in the Outer Banks tended to be more concerned about ALAN in the Outer Banks. This result could be expected as those who think ALAN should be reduced in the Outer Banks are most likely concerned that ALAN levels in the Outer Banks are too high.

Few previous studies have directly explored the relationship between perceptions of reducing ALAN and concern about ALAN levels. We found that the majority of respondents for our survey are very concerned about ALAN levels (36.27%), much like how the study conducted by Lyytimäki and Rinne in 2013 found the majority of their respondents agreed that light pollution from ALAN had spread to too wide of an area (Lyytimäki, 2013). However, they did not specifically ask in their survey if respondents thought ALAN should be reduced. In 2021, a student report explored the perceptions the public has about light pollution in Princeton, Massachusetts (Kelleher et al., 2021). They found that the majority of their respondents (60.9%) agreed or strongly agreed that they were concerned about how light pollution would negatively impact the night sky in the future. This result shows that respondents were generally concerned about light pollution and the negative effects it has, similar to how our study shows that respondents are concerned about ALAN levels. Our findings for the strong association between agreement to reduce ALAN in the Outer Banks and level of concern about ALAN in the Outer Banks provides a new insight into what drives desires to reduce ALAN.

As seen in Figure 31, nearly 90% of respondents stated that they agree or strongly agree that ALAN should be reduced in the Outer Banks, including both types of residents and visitors. Figure 32 also shows that respondents who said they were concerned or very concerned about ALAN in the Outer Banks agree or strongly agree with the statement. Our results suggest that residents and visitors would like to see ALAN reduced in the Outer Banks. While this can partially be accomplished through individual actions, policy measures can even more effectively and broadly reduce ALAN.

We continued to investigate support for reducing ALAN by asking survey participants if they would be willing to make various adjustments to their place of residence that would reduce their contribution to ALAN. The reduction methods that were proposed to the participants included using blinds and curtains at night, changing electronic devices to emit warmer toned light instead of blue light, changing outdoor lights to warmer tones, installing lighting shields on outdoor lights to redirect ALAN downwards, using light dimmers on outdoor lights, installing motion sensors to activate lighting, and turning off outdoor lights at night. The most popular options selected were turning off outdoor lights at night, selected by over 93% of the sample, and closing blinds and curtains at night, chosen by over 89% of participants. The least favored reduction method was the use of light dimmers with 63% support (Figure 33).

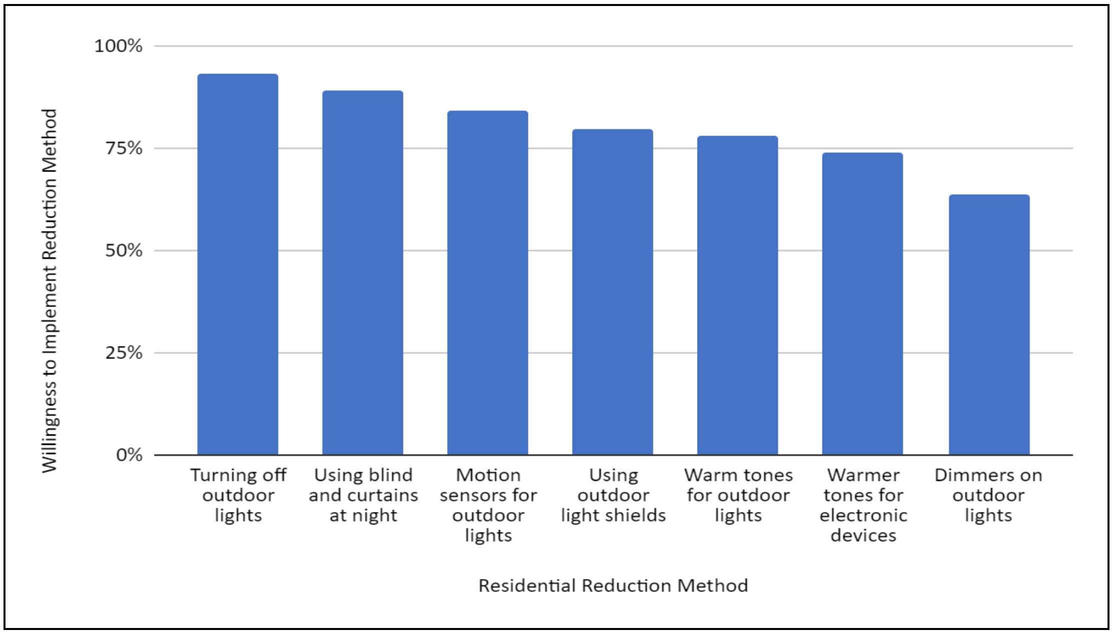

Figure 34 | Willingness to apply a variety of ALAN reduction methods at respondents' places of residence. Willingness is measured by the percentage of respondents who answered "Yes" when asked if they would support each ALAN reduction method out of the total number of respondents who gave an answer for willingness to employ each reduction method. (n=453)

The more popular adjustment options require relatively little additional effort and resources to implement compared to the less popular reduction methods such as outdoor light dimmers. While some reduction measures were more popular than others, there was substantial support observed for all of the reduction methods. A very similar degree of public interest to engage in ALAN reduction was reported in an ALAN reduction engagement study conducted in 2012. That study found over 75% of respondents desired to participate in reducing ALAN, specifically in the form of skyglow (Kamrowski et al., 2014).

A Chi-Square test showed that there was a significant relationship between level of ALAN concern and willingness to begin using outdoor dimmers, warmer toned light for electronics, and warm toned outdoor lights ($p=0.00091$, $p=2.58E{-}6$, and $p=8.5E{-}8$ respectively, $n=453$) (Figure 35). Those respondents who were willing to implement the reduction methods were more likely to say that they were "concerned" or "very concerned" about ALAN. This result is logical since we would assume that higher levels of concern would warrant more urgent ALAN reduction measures and support from the survey participants. Interestingly, this relationship was not observed between ALAN concern levels and the other reduction methods suggested.

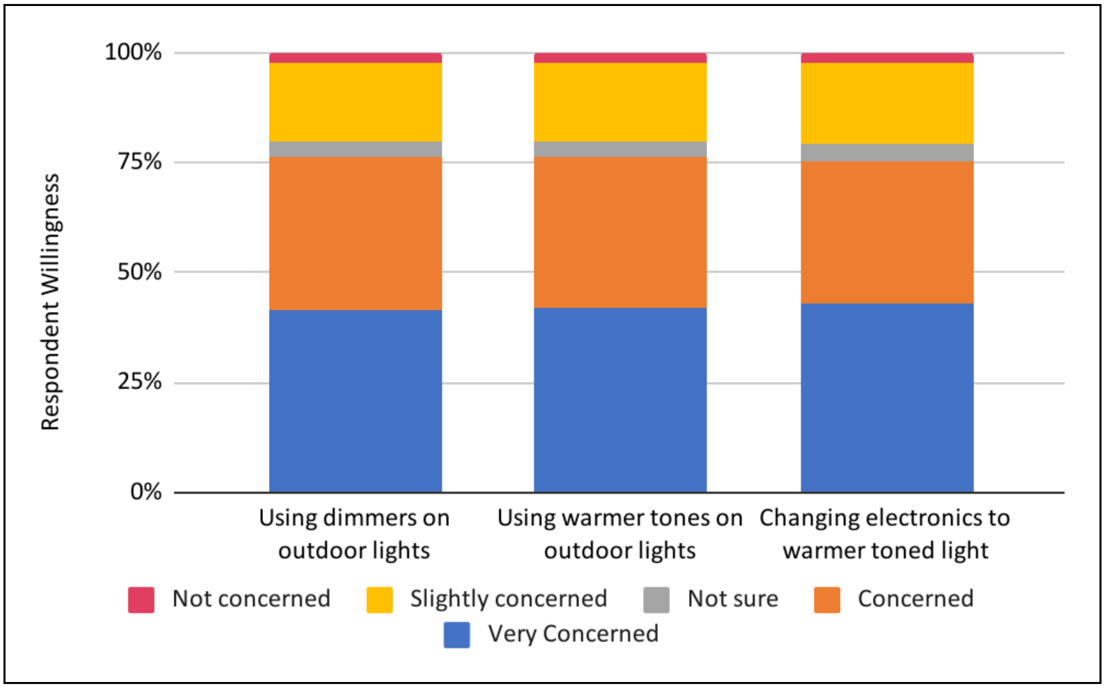

Figure 35 | Number of respondents who agreed to employ ALAN reduction methods and their ALAN concern levels. Higher concern pointed to more agreement to take action towards reducing ALAN. (n=453)

We also studied how willingness to take action against ALAN at one's personal residence was affected by comfort outside at night without artificial light. A Chi-Square test showed that there was a statistically significant relationship between comfort levels and willingness to incorporate outdoor light shields (p=0.01795, n=453). We observed that as comfort levels increase, willingness to use outdoor light shields to mitigate ALAN also increased (Figure 36). This was the only statistically significant relationship that was identified between comfort levels outside at night time without ALAN and willingness to incorporate one of the suggested reduction methods. We expected to see more significant relationships between the residential reduction methods and comfort levels without ALAN since those who require less light at night to feel safe would logically be more willing to reduce their ALAN contributions. Another study found that safety was perceived as more positively affected by ALAN than other components affected by ALAN such as wildlife, astronomy, and energy consumption (MacMillan, 2015). Because safety is perceived to have positive effects on safety, we also expected to see a statistically significant relationship between unwillingness to implement reduction measures and low levels of comfort outside without ALAN.

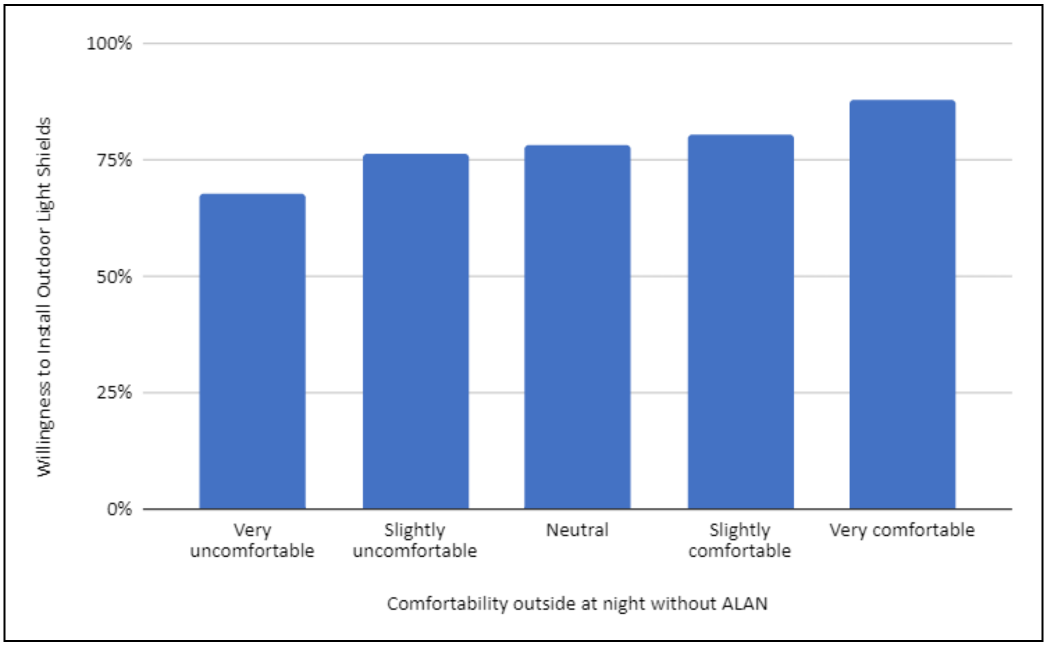

Figure 36 | Comfortability outside at night without artificial light and the willingness of respondents to install outdoor light shields to reduce the impacts of ALAN. Higher comfort levels are related to greater willingness to install the shields. (n=453)

Participant stargazing frequency and night sky appreciation was also found to have a significant relationship with participants willingness to install outdoor lighting shields ($p=0.0044$, $n=362$), change electronics to warmer toned light ($p=0.0016$, $n=336$), and change outdoor lights to warmer tones ($p=0.0031$, $n=354$). More frequent night sky appreciation was positively related to willingness to implement three of the suggested ALAN reduction methods (Figure 37). These findings align with the existing literature which points to night sky appreciation and willingness to reduce light pollution being positively correlated. Another study has previously identified that those who brought enhanced viewing equipment to a night sky event were roughly 10% more likely to be willing to pay to reduce light pollution (Mitchell et al., 2017). We may expect that those who have invested in night sky viewing equipment view the night sky more frequently.

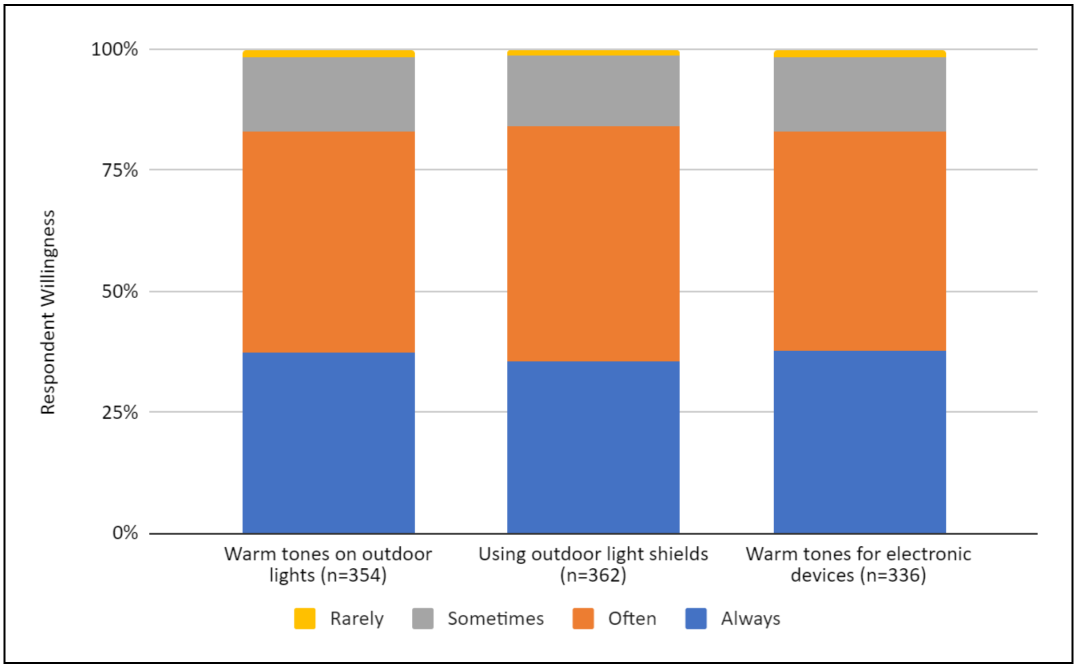

Figure 37 | Number of respondents willing to make ALAN reduction modifications and their frequency of night sky appreciation. Those who more frequently admire the night sky are more likely to use outdoor light shields and change electronics and outdoor lights to warm tones.

This relationship between night sky appreciation frequency and willingness to apply residential ALAN reduction measures appears stronger than between darkness comfort and willingness and similar to the relationship between overall concern around ALAN and these reduction measures. Switching electronics and outdoor lights to warmer tones were both significantly related to ALAN concern levels and night sky appreciation, possibly suggesting that these two may be linked and that individual concern about ALAN is rooted in appreciation for naturally dark skies.

Support for ALAN reduction was also studied by asking participants if they would be willing to support several ALAN reduction methods at commercial and municipal levels. The reduction measures suggested included outdoor light shielding, installation of motion sensor triggered lights, transitioning to warm toned outdoor lights, and turning off outdoor lights. Participants responded overwhelmingly in favor of supporting these reduction measures with over 75% of respondents preferring that all four suggested reduction methods be implemented at both commercial and municipal levels (Figure 38). This indicates that the respondents were not only interested in seeing ALAN reduction at their own homes, but also on a community level across town buildings and local businesses. This public support of commercial and municipal reduction supports findings from a 2013 study in which commercial lighting was the second most commonly noted source of light pollution (Lyytimäki & Rinne, 2013). Respondents are noticing the contribution that businesses and municipalities are making to ALAN and would like to see it reduced.

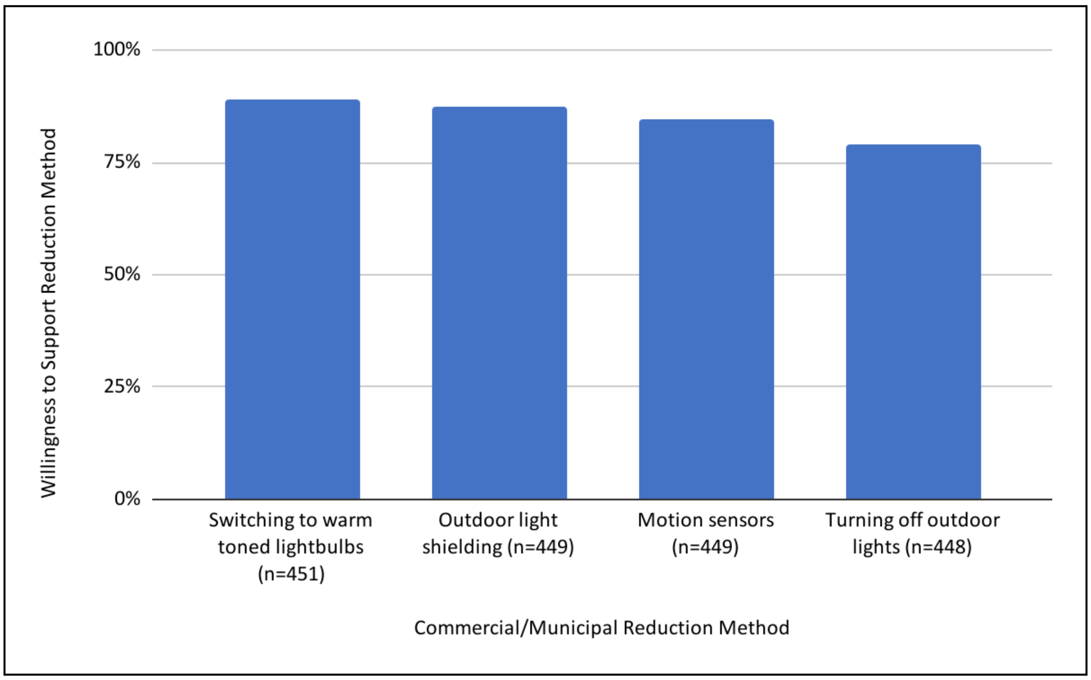

Figure 38 | Respondent's willingness to support the application of several ALAN reduction measures at both the commercial and municipal level. Support surpassed 75% for each of the suggested reduction methods.

The final measure used to identify support for the reduction of ALAN across the Outer Banks was participant's willingness to support placing ALAN informational materials in rental properties so that visitors to the area are more well-informed on the issue. There was high support of this initiative, evidenced by 80.5% of respondents expressing their approval. Seasonal and year-round residents expressed slightly higher approval than visitors, who more commonly responded with "I don't know" (20.5%) (Figure 39). It is possible that some visitors felt like they were not in a position to have an opinion on supporting any sort of local effort to present renters with ALAN informational materials. However, if that was the case, it would be interesting to know how those visitors would feel about receiving educational materials upon arrival to the place that they were staying during their visit.

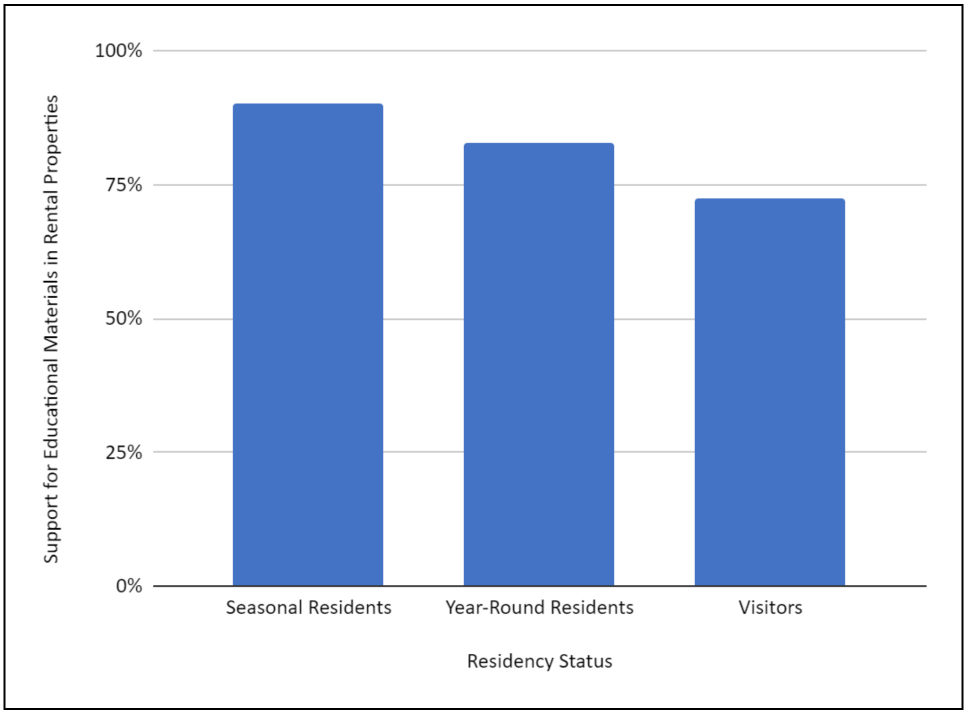

Figure 39 | Support for the placement of educational materials within rental properties compared to the residency status of respondents. Visitors were less likely to support the educational materials plan than seasonal and year-round residents. (n=449)

It is possible that many visitors did not feel as tied to this location and as properly informed about the topic of ALAN in the Outer Banks as many residents do. This may cause hesitancy in the conviction of their responses since they aren't sure how their opinions may affect the area and those who live in the Outer Banks seasonally or year-round. Additionally, higher frequencies of night sky appreciation seemed to point to a higher likelihood of support for the educational material initiative with a higher proportion of respondents who said they view the night sky "often" or "always" supporting the education materials idea than those who rarely view the night sky (Figure 40). This result is reasonable considering those who care more about being able to view the night sky would most likely be more inclined to support actions that would promote its natural darkness. There is little existing research that investigates relationships between educational materials support and variables such as night sky appreciation and residential status, so these relationships should continue to be studied in order to better understand what influences public support of an initiative such as this.

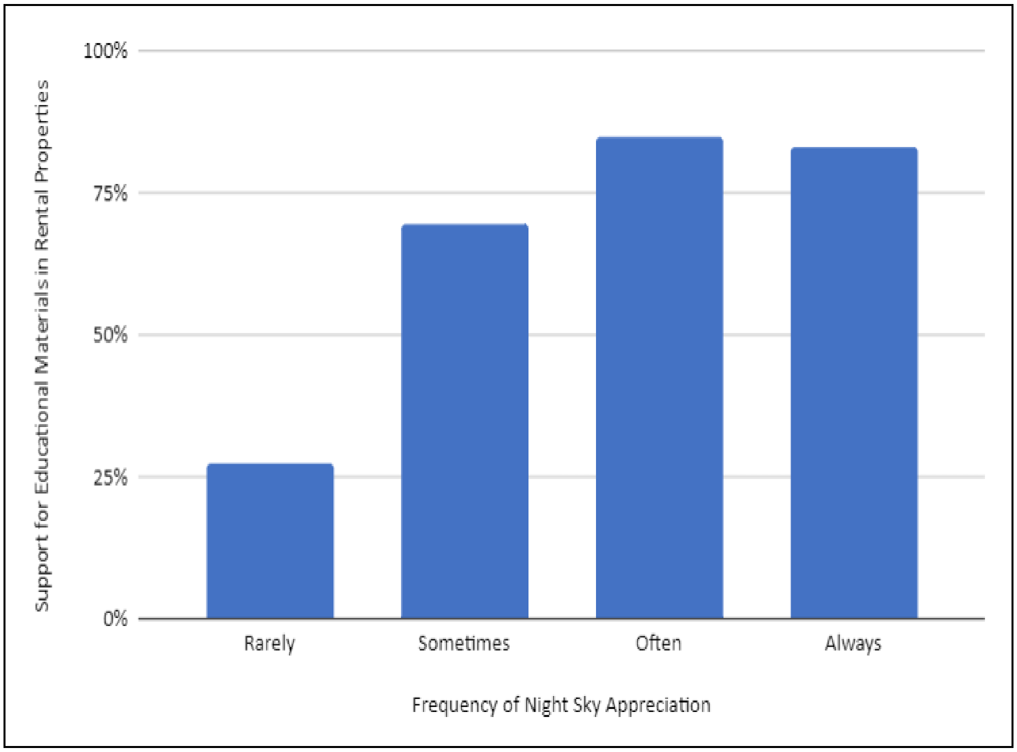

Figure 40 | Support for the placement of educational materials within rental properties compared to respondents frequency of night sky appreciation. Those who appreciated the night sky more frequently had greater approval of the education initiative. (n=456)

5. Results & Discussion of Natural Science versus Social Science

The natural and social sciences are important to look at separately but a few interesting parallels are to be seen throughout the variables. We overlaid the social science variables with our annual mean satellite-based ALAN by town because the satellite-based dataset is a more robust indicator of ALAN patterns across the Outer Banks as opposed to our beach-based data, which was taken over a much shorter period of time.

5.1. Relationship Between Extinguishing Exterior Lights and ALAN

The average time residents turned off their exterior lights was compared with the satellite-based ALAN means from September through November 2022 (Fig. 41). The ALAN means from 2022 September through November were used because they are the closest proxy for the timing of the survey. Figure 41 reveals no specific connection between the average time when town residents turn off exterior lights and where the most ALAN was measured. Importantly, the data about the timing of extinguishing exterior lights only includes residential properties. It is unknown when or if exterior lights on commercial, municipal, or other types of properties are extinguished. Even where residents are conscious of the problems associated with artificial light and extinguishing outdoor lights, their efforts may not be enough to reduce ALAN levels and help resolve the problems associated with artificial light if businesses and municipal properties are large contributors to the ALAN.

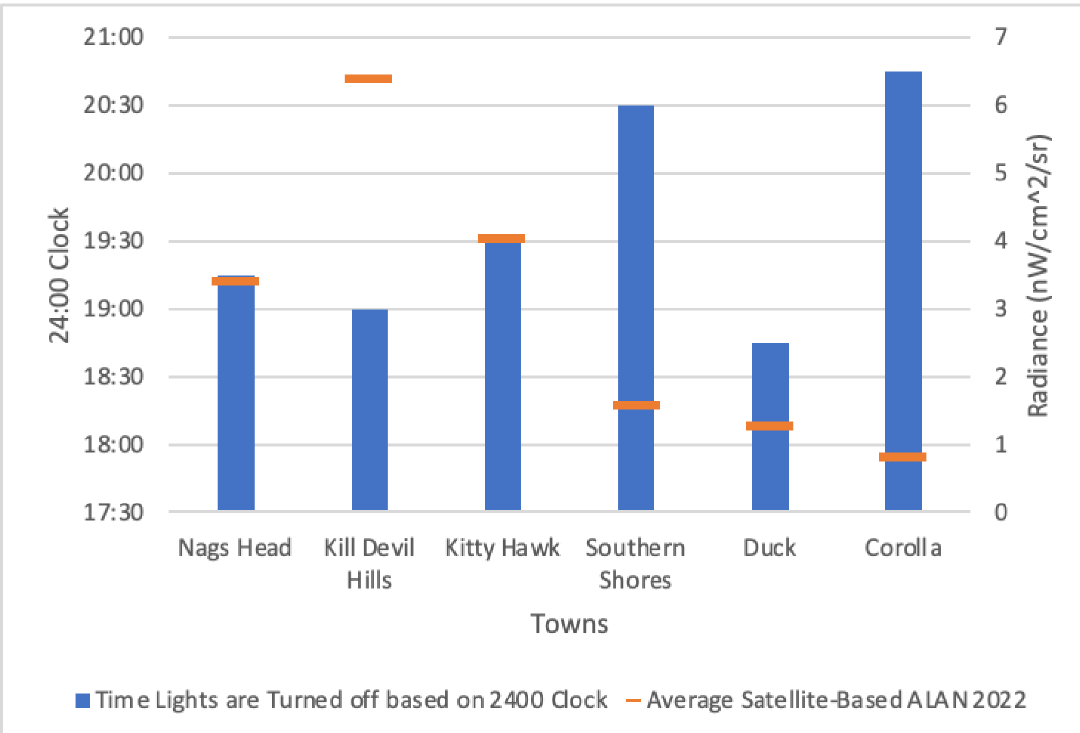

Figure 41 | Comparison of mean average (2022) radiance (nW/cm^2/sr; satellite-based ALAN) from September-November 2022 to the average time residents of the Outer Banks turned off their exterior lights.

5.2. Relationship Between Perceived and Observed Impact of ALAN on Sea Turtles

We compared turtle activity (false crawl plus nesting) to survey respondents' perceived effect of ALAN on sea turtles. To do this, we summed total turtle activity per town and then calculated the percentage of respondents in that town who perceived the threat to be highly negative or negative. We also calculated the percent of respondents who chose other options such as "has no effect", "positively", and "highly positively", however, these percentages were around 1% so were omitted from Figure 42. Regardless of the amount of turtle activity in a town, there is a strong consensus among respondents that there is a highly negative or negative effect of ALAN on sea turtles (Fig. 42). This shows that people are consistently aware of the impact of

ALAN on turtles, suggesting that it is possible for the known negative impacts of ALAN to become common knowledge among communities. As research continues to show the impacts of ALAN, it is important that the results are shared with the public to then become common knowledge.

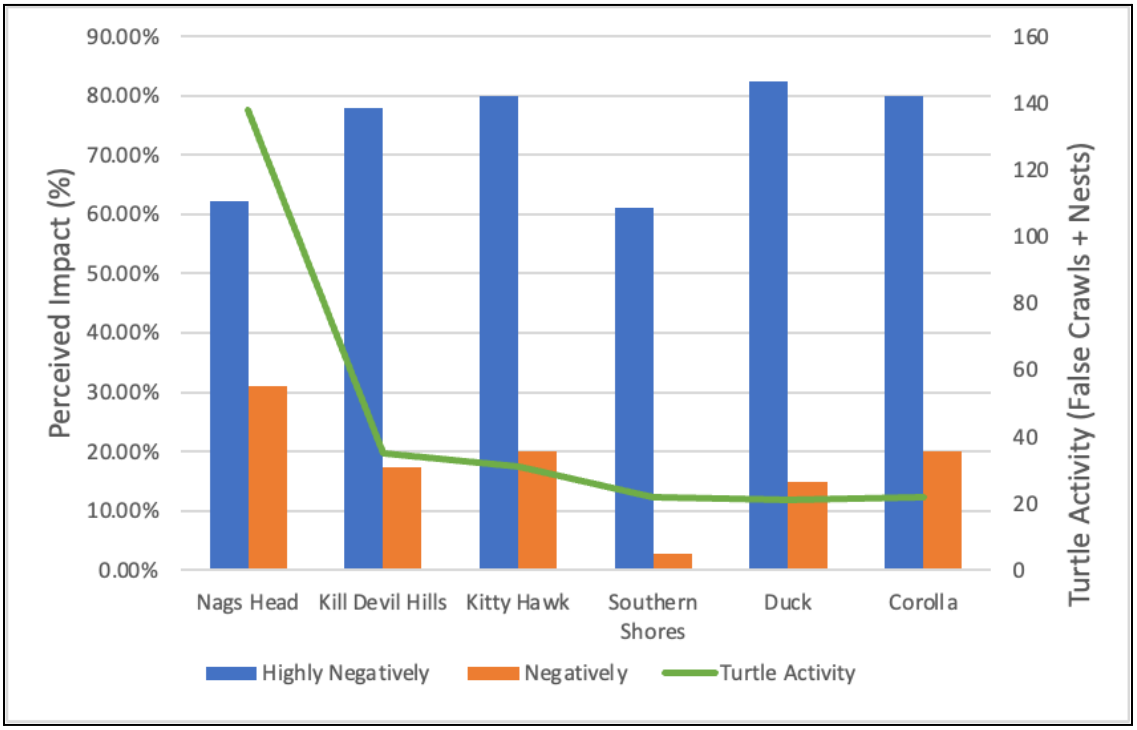

Figure 42 | Relationship between the perceived impact of ALAN on sea turtles and the turtle activity in each town on the Outer Banks. This graph goes from the southernmost town in our survey (Nags Head) to the northernmost (Corolla).

5.3. Relationship Between Level of Concern About ALAN and Observed ALAN by Town

We compared the level of concern about ALAN indicated by respondents to our survey to mean satellite-based ALAN from 2014-2022 by town (Figure 43). Survey respondents indicated their level of concern about ALAN on a scale ranging containing the following responses: I'm very concerned about it, I'm concerned about it, I'm not sure, I'm slightly concerned about it, I'm not concerned about it at all. We measured the percentage of respondents from each town who indicated they were either "concerned" or "very concerned" about ALAN. We then overlaid the mean ALAN measured by satellites from 2014-2022. We observed Duck and Corolla/Currituck to have the highest percentage of residents with these concern levels and the lowest average ALAN levels. This may be because the high percentage of residents that are concerned about ALAN are making decisions that limit light in those areas. We observed a direct relationship between respondents' concern and average ALAN levels in Nags Head, Kill Devil Hills, and Kitty Hawk. We saw that in these towns, the percentage of respondents indicating they were concerned or very concerned about ALAN corresponded with observed mean ALAN; the town with the highest ALAN was the town with the highest percentage of respondents concerned about it. One explanation for this could be that the experience of living with ALAN results in concern about it.

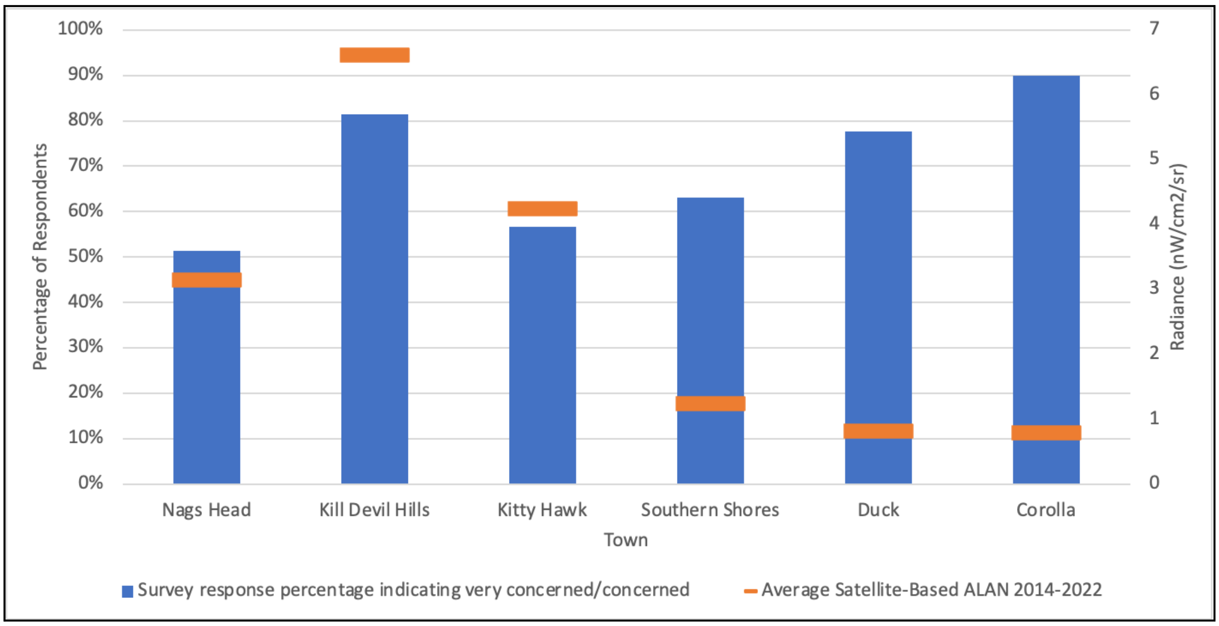

Figure 43 | Percentage of Residents who Indicated they were Concerned/very Concerned about Artificial Light at Night and average satellite-based measurements of ALAN of Each Town from 2014-2022

5.4. Relationship Between Knowledge Score and Observed ALAN by Town from 2014-2022

According to Figure 44, towns with lower average satellite-based values such as Corolla, Duck, and Southern Shores tend to have slightly higher average knowledge scores. For instance, Corolla's satellite-based mean ALAN for 2014-2022 was 0.79 nW/cm^2/sr, whereas Kill Devil Hills' is higher, with a value of 6.55 nW/cm^2/sr. Inversely, Corolla has a higher knowledge score of 6.5, whereas Kill Devil Hills has one of 6.1. This slight difference in knowledge scores could be due to the policies put in place in the northern towns. For instance, in Duck, "light fixtures must be opaque on top so that light is spread below and around but not above"(American Legal Publishing, 2023). Policies like these could contribute to the towns' residents knowing more about the ALAN and its consequences, leading places with lower levels of ALAN to know more about the topic.

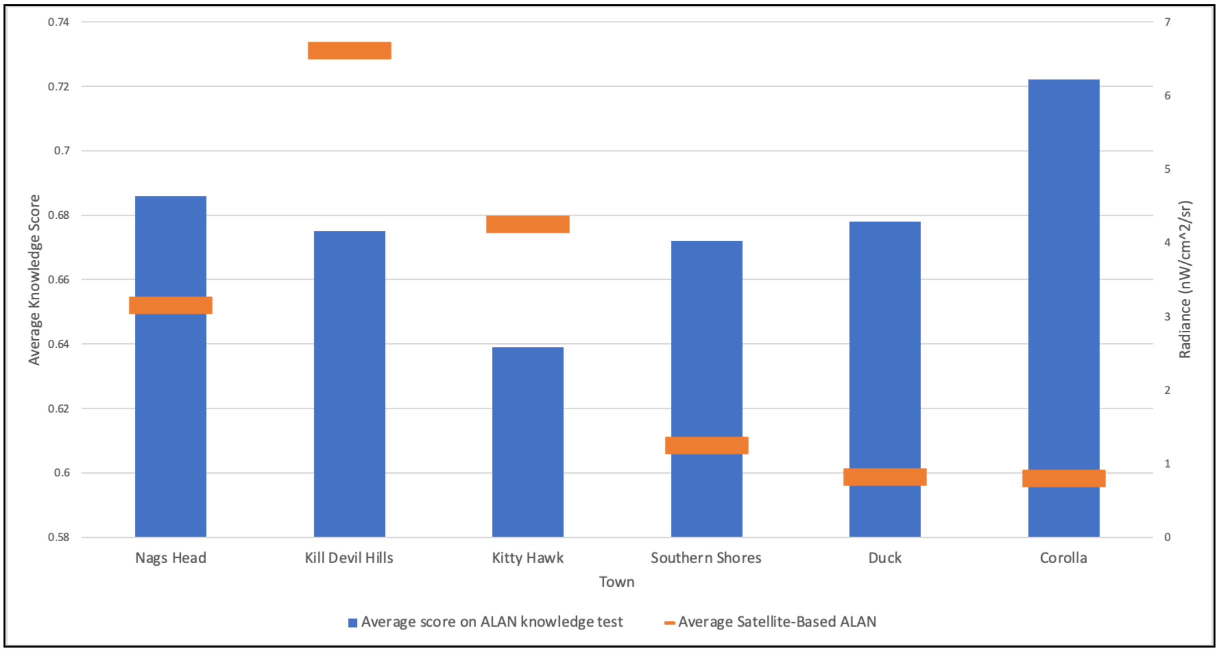

Figure 44 | Average Knowledge Concerning ALAN per Town Compared to Average 2014-2022 ALAN values per Town.

6. Conclusion

The significant findings of our natural science and social science research highlights the importance of current and continued research on ALAN in coastal communities. Our conclusions contribute to a better understanding of how ALAN has changed over time and space on the Outer Banks, how these changes impact sea turtle activity, and what those living on the Outer Banks know and believe about ALAN. We hope these findings are useful to individuals, businesses, and local governments on the Outer Banks, especially as our findings suggest darkness is decreasing and that there is overwhelming support for ALAN reductions on the Outer Banks.

Although our study site and survey sample were limited in scope and magnitude, we feel our results were significant enough to assert the following claims: increasing ALAN is resulting in a loss of darkness across the Outer Banks. Sites along the Outer Banks that were the brightest in 2014 remained the brightest sites in 2022 and sites that were the darkest in 2014 were the darkest in 2022. The Sky Quality Meter (SQM) showed similar trends to using the VIIRS satellite dataset, suggesting the SQM, an easy and inexpensive method for measuring ALAN, is also accurate. We found that light does play a role in false crawls, but does not play a role in nesting. We are unsure why we saw this pattern but some factors we considered were whether a threshold needed to be met, if another variable had greater influence than light, and if our sample size was great enough to show a pattern in turtle behavior.

Our research on ALAN in North Carolina's Outer Banks contributes to a wider body of knowledge on spatio-temporal light trends and its impact on one organism: sea turtles. In the future, we suggest collecting and analyzing ALAN levels over a greater spatio-temporal scale using more consistent on-the-ground measurement collection, and consideration of more coastal organisms. In this study, we focused only on sea turtles, but believe other organisms, such as seabirds and invertebrates may be impacted by ALAN. Through our study, we found that the use of a Sky Quality Meter (SQM) was an accurate and cost-effective form of monitoring ALAN levels. Future research could involve using SQM devices to participate in community science and keep track of how ALAN is changing in the Outer Banks.

Based on our survey of Outer Banks residents and visitors, , we came away with several conclusions. First and foremost, we found that the majority (~70%) of both residents and visitors were concerned about ALAN levels on the Outer Banks. Additionally, respondents perceived ALAN to negatively affect all the factors surveyed, with overwhelmingly negative perceptions of ALAN on star-gazing and sea turtles. Conversely, there was a positive perception of ALAN on safety at night. Ultimately, these concerns translated to a willingness by nearly all respondents, regardless of resident status, to support individual, commercial, and municipal lighting reduction measures.

After analyzing the results of this study, we would like to offer some examples of policy measures that can be used by municipal governments to reduce ALAN in the Outer Banks. One measure that can be used to reduce ALAN is to establish a curfew for when lights need to be turned off at night. This can be established for both residential and commercial/municipal buildings so that businesses who require lights to operate can continue to do so. Another measure would be to require that outdoor lights be fully shielded for all newly constructed and future buildings. By placing shields over lights, light can be directed towards the ground where it is needed while reducing light pollution being put into the night sky. In our survey, we polled respondents about introducing an initiative to place educational materials in rental houses about ALAN. This type of program can be used by a municipal government on a larger scale. An educational initiative that informs citizens about the effects of ALAN could be a useful tool for municipal governments to increase awareness and knowledge of ALAN. This could also motivate residents and visitors to take individual actions to reduce ALAN. One final measure that could reduce ALAN in the Outer Banks is to establish a requirement for the amount of lumen output or foot candle output that lights can emit in newly constructed and future buildings. For municipalities that already have established requirements for light output, they can continue to decrease the amount of output that can be emitted by new lights.

References

Beaudet, C., Tardieu, L., & David, M. (2022). Are citizens willing to accept changes in public lighting for biodiversity conservation? *Ecological Economics*, *200*, 107527. https://doi.org/10.1016/j.ecolecon.2022.107527.

Bedrosian, T. A., & Nelson, R. J. (2017). Timing of light exposure affects mood and brain circuits. *Translational Psychiatry*. https://doi.org/10.1038/tp.2016.262.

Bennie, J., Davies, T. W., Duffy, J. P., Inger, R., & Gaston, K. J. (2014). Contrasting trends in light pollution across Europe based on satellite observed night time lights. *Scientific Reports (Nature Publisher Group), 4*, 3789. doi:https://doi.org/10.1038/srep03789.

Cleary-Gaffney, M., Espey, B., Coogan, A. N. (2022). Association of perceptions of artificial light-at-night, light-emitting device usage and environmental noise appraisal with psychological distress, sleep quality and chronotype: A cross sectional study. *Heliyon*, 8 (11). https://doi.org/10.1016/j.heliyon.2022.e11284.

Coetzee, B. W. T., Smit, I. P. J., Ackermann, S., & Gaston, K. J. (2023). The impacts of artificial light at night in africa: Prospects for a research agenda. *South African Journal of Science, 119*(3), 13-19. doi:https://doi.org/10.17159/sajs.2023/13988.

Coogan, A. N., Cleary-Gaffney, M., Finnegan, M., McMillan, G., González, A., Espey, B. (2020). Perceptions of light pollution and its impacts: Results of an Irish citizen science survey. *International Journal of Environmental Research and Public Health,* 17(15), 5628. https://doi.org/10.3390/ijerph17155628.

Crawford, D. L. (1991). Light pollution – a problem for all of us. International Astronomical Union Colloquium, 112, 7–10. https://doi.org/10.1017/S0252921100003572.

Dare County, NC. Www.darenc.gov. https://www.darenc.gov/.

Elvidge, C. D., Baugh, K. E., Zhizhin, M., & Hsu, F.-C. (2013). Why VIIRS data are superior to DMSP for mapping nighttime lights. Proceedings of the Asia-Pacific Advanced Network, 35(0), 62. https://doi.org/10.7125/APAN.35.7.

Elvidge, C. D., Zhizhin, M., Ghosh, T., Hsu, F.-C., & Taneja, J. (2021). Annual time series of global viirs nighttime lights derived from monthly averages: 2012 to 2019. Remote Sensing, 13(5), 922. https://doi.org/10.3390/rs13050922.

Davies, T. W., & Smyth, T. (2017). Why artificial light at night should be a focus for global change research in the 21st century. *Global Change Biology*, *24*(3), 872–882. https://doi.org/10.1111/gcb.13927.

Duck Outdoor Lighting Ordinance, North Carolina. § 156.133 (2021).

Falchi, F., Cinzano, P., Elvidge, C. D., Keith, D. M., & Haim, A. (2011). Limiting the impact of Falchi, F., Cinzano, C., Elvidge, C., Keith D., Haim, A., (2011) light pollution on human health, environment and stellar visibility. *Journal of Environmental Management*, *92*(10), 2714–2722. https://doi.org/10.1016/j.jenvman.2011.06.029.

Floodlight cover. (n.d.). Retrieved December 12, 2023, from https://theshedplace.org/projects/metal/floodlight/index.php.

Fobert EK, Burke da Silva K, Swearer SE. (2019) Artificial light at night causes reproductive failure in clownfish. Biol. Lett.15:20190272. http://dx.doi.org/10.1098/rsbl.2019.0272.

Gaston, K. J., Davies, T. W., Bennie, J., & Hopkins, J. (2012). Reducing the ecological consequences of night-time light pollution: options and developments. *The Journal of applied ecology*, *49*(6), 1256–1266. https://doi.org/10.1111/j.1365-2664.2012.02212.x.

Gaston K, Sánchez De Miguel A. (2022). Environmental Impacts of Artificial Light at Night. *Annu. Rev. Environ. Resour. 2022. 47:373–98.* https://doi.org/10.1146/annurev-environ-112420-014438.

Hillger, D., Kopp, T., Lee, T., Lindsey, D., Seaman, C., Miller, S., Solbrig, J., Kidder, S., Bachmeier, S., Jasmin, T., & Rink, T. (2013). FIRST-LIGHT IMAGERY FROM SUOMI NPP VIIRS. *Bulletin of the American Meteorological Society, 94*(7), 1019-1029. http://libproxy.lib.unc.edu/login?url=https://www.proquest.com/scholarly-journals/first-light-imagery-suomi-npp-viirs/docview/1428261654/se-2.

Hochard, J. P., Hamilton, S., & Barbier, E. B. (2019). Mangroves shelter coastal economic activity from cyclones. Proceedings of the National Academy of Sciences, 116(25), 12232–12237. https://doi.org/10.1073/pnas.1820067116.

Houser, K. W. (2021, August 4). Ethics and Fallacies of Human-Centric Lighting and Artificial Light at Night. *The Journal of the Illuminating Engineering Society.* https://www.tandfonline.com/doi/pdf/10.1080/15502724.2021.1951021.

Huss, A., van Wel, L., Bogaards, L., Vrijkotte, T., Wolf, L., Hoek, G., Vermeulen, R. Shedding some light in the dark– A comparison of personal measurements with satellite-based estimates of exposure to light at night among children in the Netherlands. *Environmental Health Perspectives*, 127(6). https://doi.org/10.1289/EHP3431.

Jones, T.L., Baxter, M. A. J., & Khanduja, V. (2013). A quick guide to survey research. *The Annals of the Royal College of Surgeons of England, 95(1): 5-7.* Doi: 10.1308/003588413X13511609956372.

Kamrowski, R. L., Sutton, S. G., Tobin, R. C., & Hamann, M. (2015). Balancing artificial light at night with turtle conservation? Coastal community engagement with light-glow reduction. Environmental Conservation, 42(2), 171–181. https://doi.org/10.1017/S0376892914000216.

Katie E. Hillyer, David J. Beale, Jeffrey S. Shima. (2021). Artificial light at night interacts with predatory threat to alter reef fish metabolite profiles, Science of The Total Environment, 769, https://doi.org/10.1016/j.scitotenv.2020.144482.

Kelleher, A., Cox, L., Decelles, M., & Puch, S. (2021). The Bright Darkness: Assessing Public Attitudes Towards Light Pollution in Princeton, MA and Recommending Approaches to Mitigation. *Worcester Polytechnic Institute.*

Kramer, N., Tamir, R., Galindo-Martínez, C. T., Wangpraseurt, D., & Loya, Y. (2023). Light pollution alters the skeletal morphology of coral juveniles and impairs their light capture capacity. *Marine Pollution Bulletin*, *193*. https://doi.org/https://doi.org/10.1016/j.marpolbul.2023.115212.

Lyytimäki, J., & Rinne, J. (2013). Voices for the Darkness: Online Survey on Public Perceptions on Light Pollution as an Environmental Problem. Journal of Integrative Environmental Sciences, 127–139. https://doi.org/10.1080/1943815X.2013.824487.

MacMillan, G. (2015). Preserving our Night-time Skies: An exploratory study on the impact of light pollution and the potential for a new dark-sky site in County Mayo, Ireland [Dissertation]. Galway-Mayo Institute of Technology, Mayo Campus.

Marangoni, L. F. B., Davies, T., Smyth, T., Rodríguez, A., Hamann, M., Duarte, C., Pendoley, K., Berge, J., Maggi, E., & Levy, O. (2022). Impacts of artificial light at night in marine ecosystems—A review. Global Change Biology, 28(18), 5346–5367. https://doi.org/10.1111/gcb.16264.

McMahon, O., Smyth, T. & Davies, T. W. (2022). Broad spectrum artificial light at night increases the conspicuousness of camouflaged prey. *Journal of Applied Ecology*, 59, 1324–1333. https://doi.org/10.1111/1365-2664.14146**.**

Mendoza-González, G., Martínez, M. L., Lithgow, D., Pérez-Maqueo, O., & Simonin, P. (2012). Land use change and its effects on the value of ecosystem services along the coast of the Gulf of Mexico. *Ecological Economics*, *82*, 23–32. https://doi.org/10.1016/j.ecolecon.2012.07.018.

Mitchell, D. M., Gallaway, T., & Olsen, R. (2017). Estimating the willingness to pay for dark skies. International Journal of Research in Engineering and Technology, 06(15), 18–24. https://doi.org/10.15623/ijret.2017.0615004.

Morgan-Taylor, M., & Kim, J. T. (2016). Regulating artificial light at night: A comparison between the south korean and english approaches. *International Journal of Sustainable Lighting*, *18*, 21–31. https://doi.org/10.26607/ijsl.v18i0.18.

North Carolina Natural Heritage Program Online Data Search. [December 10, 2023]. Department of Natural and Cultural Resources, Division of Land and Water Stewardship, Raleigh, NC. Available at: www.ncnhp.org.

Salvador Bará, Fabio Falchi, Raul C. Lima, Martin Pawley. (2021). Keeping light pollution at bay: A red-lines, target values, top-down approach, *Environmental Challenges*, 5(1), 100212, ISSN 2667-0100, https://doi.org/10.1016/j.envc.2021.100212.

Salvador, B. & Fabio F. (2023). Artificial light at night: a global disruptor of the night-time environment *Phil. Trans. R. Soc. B*3782022035220220352 http://doi.org/10.1098/rstb.2022.0352.

Schroer, S., & Hölker, F. (2014). Light pollution reduction. *Handbook of Advanced Lighting Technology*, 1–17. https://doi.org/10.1007/978-3-319-00295-8_43-1 *Who speaks for the night? The regulation of light pollution in the 'Rights of Nature' legal framework |*

International Journal of Sustainable Lighting. (2021). https://www.lightingjournal.org/index.php/path/article/view/104.

Schulte-Römer, N., Meier, J., Dannemann, E., & Söding, M. (2019). Lighting Professionals versus Light Pollution Experts? Investigating Views on an Emerging Environmental Concern. Sustainability, 11(6), 1696. https://doi.org/10.3390/su11061696.

Schroer, S., Huggins, B. J., Azam, C., & Hölker, F. (2020). Working with Inadequate Tools: Legislative Shortcomings in Protection against Ecological Effects of Artificial Light at Night. *Sustainability*, *12*(6), 2551. MDPI AG. http://dx.doi.org/10.3390/su12062551.

Small, C. & Nicholls, R.J. (2003) A global analysis of human settlement in coastal zones. *Journal of Coastal Research*, 19, 584–599.

United Nations, Department of Economic and Social Affairs, Population Division (2018). The World's Cities in 2018—Data Booklet (ST/ESA/ SER.A/417). https://www.un.org/en/development/desa/population/publications/pdf/urbanization/the_worlds_cities_in_2018_data_booklet.pdf.

Wahl, S., Engelhardt, M., Schaupp, P,. Lappe, C,. Ivanov V. (2019) The inner clock—blue light sets the human rhythm J. Biophot. (2019), 10.1002/jbio.201900102.

Wang, T., Kaida, N., & Kaida, K. (2023). Effects of outdoor artificial light at night on human health and behavior: A literature review. Environmental Pollution, 323. https://www-sciencedirect-com.libproxy.lib.unc.edu/science/article/pii/S0269749123003238?via%3Dihub.

Zhiyong Hu, Hongda Hu, Yuxia Huang. (2023). Association between nighttime artificial light pollution and sea turtle nest density along Florida coast: A geospatial study using VIIRS remote sensing data. Environmental Pollution 239. https://doi.org/10.1016/j.envpol.2018.04.021.

Zielińska-Dabkowska, K.M., Xavia, K., Bobkowska, K. (2020). Assessment of Citizens' Actions against Light Pollution with Guidelines for Future Initiatives. *Sustainability*, 12(2), 4997. https://www.mdpi.com/2071-1050/12/12/4997.

Zubidat, A. E., & Haim, A. (2017). Artificial light-at-night – a novel lifestyle risk factor for metabolic disorder and cancer morbidity. Journal of Basic and Clinical Physiology and Pharmacology, 28(4), 295–313. https://doi.org/10.1515/jbcpp-2016-0116.

APPENDIX

Appendix A: Social Science Survey

You are invited to participate in a research study by the UNC Outer Banks Field Site students in partnership with the Coastal Studies Institute: *Artificial Light at Night in the Outer Banks* (UNC-CH IRB# 23-1625).

The purpose of this study is to understand perceptions about artificial light at night among Outer Banks residents and visitors. Participation in the study involves completing a survey that will ask you questions about your knowledge, experiences, and opinions about artificial light at night, as well as questions about yourself, such as age and gender. It will take about 10 minutes to complete this survey. The research and research results will not benefit you personally, and the only risk of the study is the possible breach of confidentiality, but we will be diligent to handle all data securely. All data will be stored on a secure network. If you choose to participate, the information you provide will never be connected with your name or any other identifiable information. Data may be made public or used for future research and teaching purposes, but your identity will always remain confidential. Your participation is voluntary. You may withdraw at any time, and you may choose not to answer any questions. Choosing not to participate will not affect any relationship you may have with UNC.

Thank you for your participation! If you have any questions about our research or team, feel free to contact Linda D'Anna, our instructor, at 252-475-5457 or ldanna@email.unc.edu. If you have any questions or concerns about your rights as a research subject, please contact UNC Chapel Hill's Institutional Review Board at 919-966-3113 or IRB_subjects@unc.edu.

Do you consent to take this survey?

___ Yes
___ No

We're interested in seeing what people already know about artificial light at night and its impacts. If you're not sure of an answer, make your best guess. If you don't have a guess, you can answer with "I don't know".

1. How informed do you feel you are about artificial light at night and its impacts?
    a. Not at all
    b. Very little
    c. Some
    d. Moderately
    e. Very well

2. Which one of the following can be considered a form of light pollution?
    a. Moonlight reflecting off the ocean
    b. Fireflies flashing
    c. Streetlight shining in a bedroom window
    d. I don't know

3. Studies have shown that artificial light at night is associated with which of the following health concerns in humans? (select all that apply)
    a. Disrupted circadian rhythms
    b. Scoliosis
    c. Cancer
    d. Obesity
    e. Mood disorders
    f. I don't know

4. The following statements are about artificial light at night. If you believe the statement is true, please indicate "TRUE". If you believe the statement is false, please indicate "FALSE". If you don't have an answer, please indicate "I DON'T KNOW."

	TRUE	FALSE	I DON'T KNOW
a. Blue light is more disruptive to organisms at night than other colors of light.			
b. Artificial light at night increases visibility of the night sky.			
c. Artificial light at night affects sea turtles' ability to find the ocean after hatching.			

5. In your opinion, how does artificial light at night affect each of the following?

	Highly negatively	Negatively	Has no effect	Positively	Highly Positivel y	Unsure/ Don't know
Human health						
Sea turtles						
Shorebirds						
Greenhouse gas emissions						
Sleep patterns						
Energy consumption						
Personal safety						
Star gazing						

6. What is your overall opinion about artificial light at night in the Outer Banks?
   a. I'm not concerned about it at all
   b. I'm slightly concerned about it
   c. I'm concerned about it
   d. I'm very concerned about it.
   e. I'm not sure

7. What light source(s), if any, do you find necessary at night?
   a. Interior residential (bedrooms, hallways, etc.)
   b. Exterior residential (porch light, driveway lights, etc.)
   c. Commercial (shop signs, buildings with lights on past close, etc.)
   d. Gas stations
   e. Public buildings
   f. Street lighting
   g. Car headlights
   h. Parking lots
   i. Other (please fill in) __________________

8. To what extent do you find each of the following light sources to be disruptive during the night where you live or stay in the Outer Banks?

	Not at all	Slightly	Moderately	Excessively
Interior residential (bedrooms, hallways, etc.)				
Exterior residential (porch light, driveway lights, etc.)				
Commercial (shop signs, buildings with lights on past close, etc.)				
Gas stations				
Public buildings				
Street lighting				
Car headlights				
Parking lots				

9. At about what time are the majority of exterior lights turned off at your place of residence in the Outer Banks? If they are never turned off, write NA.

    _____ pm

10. How comfortable are you being outside at night without artificial light?
    a. Very uncomfortable
    b. Slightly uncomfortable
    c. Neutral
    d. Slightly comfortable
    e. Very comfortable

11. How often do you look at or appreciate the stars or night sky?
    a. Never
    b. Rarely
    c. Sometimes
    d. Often
    e. Always

12. The following is a list of methods for reducing artificial light at night in the Outer Banks. Indicate whether you would be willing to support each method for commercial light fixtures, municipal light fixtures, both types of fixtures, or neither type of fixture.

	Commercial	Municipal	Both	Neither
Shielding outdoor light fixtures to limit misdirected light				
Motion sensors for outdoor lights				
Turning off outdoor lights after midnight				
Switching to lightbulbs with warm tones				

13. Would you be willing to support an initiative to provide educational materials in rental properties about artificial light at night?

14. Which of the following actions would you be willing to take as an individual to reduce artificial light at night at your residence? (select all that apply)
    a. Turning off outdoor lights when they're not needed or before I go to sleep.
    b. Using blinds and curtains at nighttime.
    c. Switching electronic devices' from blue light to warmer toned light
    d. Shielding outdoor lighting to direct the light downwards
    e. Switching outdoor lighting to warm tones instead of cool tones
    f. Installing motion sensors for outdoor lights
    g. Using dimmers for outdoor lights
    h. None of the above.

15. Please indicate your level of agreement with the following statement:
    Artificial light at night in the Outer Banks should be reduced.
    a. Strongly disagree
    b. Disagree
    c. Neutral
    d. Agree
    e. Strongly agree

A few questions about you to help us analyze responses:

16. Are you a resident or visitor to the Outer Banks?
    a. Resident year-round (8-12 months of year)
    b. Resident seasonally (3-7 months of the year)
    c. Visitor

17. What town do you live in or are you staying in?: ___________________

18. What is your age? _____

19. What is your gender identity?
    a. Woman
    b. Man
    c. Non-binary/non-conforming
    d. Prefer not to respond

20. What is the highest level of education that you have completed?
    a. Less than high school diploma
    b. High school graduate
    c. Two-year college degree
    d. Four-year college degree
    e. Graduate or professional degree
    f. Trade or technical school or certification

Thank you for offering your time to this survey! This survey was created by Outer Banks Field Site students from UNC Chapel Hill who are in the Outer Banks for the fall semester. We are conducting research about how artificial light at night affects sea turtles, how accurately satellite imagery measures artificial light at night, and public opinions on artificial light at night. If you are interested in the results of this survey and our related research, you are welcome to attend our presentation at the Coastal Studies Institute on Roanoke Island in room 262 on **Tuesday, December 12th at 6pm**!

ANSWER KEY for QUESTIONS

Q: Which one of the following can be considered a form of light pollution?
- Moonlight reflecting off the ocean
- Fireflies flashing
- Streetlight shining in a bedroom window
- I don't know

A: STREETLIGHT SHINING IN A BEDROOM WINDOW. Light pollution is defined as the inappropriate or excessive use of artificial light by the International Dark-Sky Association. Artificial light that is unwanted or unintended, like a streetlight shining in a bedroom window, is a kind of light pollution known as trespass. Other forms of light pollution are sky glow (light sent upward directly or reflected and scattered), glare (excessive brightness that reduces visibility), and clutter (over-illuminated clusters of light such as signage or advertising).

Q: Studies have shown that artificial light at night is associated with which of the following health concerns in humans? (select all that apply)
- Disrupted circadian rhythms
- Scoliosis
- Cancer
- Obesity
- Mood disorders
- I don't know

A: SCOLIOSIS. Depending on the type of artificial light, its intensity and duration of exposure, the effects of artificial light at night can vary. Artificial light at night can have several negative effects on humans, including: disruption of the body's natural circadian rhythms, which regulate sleep and wake cycles (which can contribute to obesity); altered hormone production, which is important for sleep and overall health; potentially increased risk of certain cancers, increased risk in the transmission of vector-borne diseases, and contribution to mood disorders like depression and anxiety.

Blue light is more disruptive to organisms at night than other colors of light. TRUE
When it comes to artificial light at night, blue light is generally more disruptive to organisms at night, as it has a higher wavelength and thus causes disruption in the body's natural sleep-wake cycle.

Artificial light at night increases visibility of the night sky. FALSE
Artificial light at night can negatively impact people's ability to view the night sky because light pollution from urban areas that is reflected towards the sky can obscure the night sky and make it difficult to see stars and other objects in the sky.

Artificial light at night affects sea turtles' ability to find the ocean after hatching. TRUE
Newly hatched sea turtles are drawn to the natural light of the moon and stars over the ocean, but artificial lights from buildings and streets near the beach can disorient them and lead them away from the ocean, making it harder for them to survive.

Appendix B: Social Science Flyer