**Primary Research Article**

**Title:** Biologically relevant artificial light at night on the seafloor

**Running title:** Ecological light pollution on the seafloor

Thomas W. Davies1,2, David McKee3, James Fishwick4, Svenja Tidau1,2 and Tim Smyth4

1School of Biological and Marine Sciences, University of Plymouth, Drake Circus, Plymouth, UK, PL4 8AA

2School of Ocean Sciences, Bangor University, Menai Bridge, Anglesey, UK, LL59 5AB

3Physics Department, University of Strathclyde, 107 Rottenrow, Glasgow, Scotland, G4 0NG

4Plymouth Marine Laboratory, Prospect Place, Plymouth, Devon, UK, PL1 3DH

Corresponding author: thomas.w.davies@plymouth.ac.uk, +44 (0) 1752 584 733

# Abstract

Rapid urbanisation is resulting in increased nocturnal illumination of the world’s coastlines by artificial light at night. Coupled with the transition towards broad spectrum LED lighting rich in short wavelengths that penetrate deeper in seawater, this global social and technological revolution is likely elevating the nighttime exposure of coastal seafloor habitats to light pollution. A pivotal question remains unanswered in establishing the likely ecological impacts of rising light pollution in marine ecosystems: Does sufficient light from anthropogenic sources reach the seafloor to stimulate biological responses? Using a combination of mapping, and radiative transfer modelling utilising in situ measurements of optical seawater properties, we quantified artificial light exposure at the sea surface, beneath the sea surface, and at the sea floor of an urbanised temperate estuary bordered by an LED lit city. By empirically defining critical thresholds above which blue, green and red artificial light can be considered biologically relevant, we calculated the three-dimensional seafloor area exposed to ecological light pollution across contrasting tidal states and meteorological conditions. Up to 76% of the three-dimensional seafloor area was exposed to biologically relevant light pollution. Exposure to green wavelengths was highest, while exposure to red wavelengths was nominal. Cloud cover increased sea surface exposure to artificial light, which coupled with tidal fluctuations created a highly variable artificial light environment for marine organisms. We conclude that globally widespread light pollution from coastal cities results in biologically relevant artificial light exposure on the seafloor of adjacent coastal habitats. A comprehensive understanding of the consequences of illuminating seafloor ecosystems globally is urgently needed.

# Introduction

The potential for artificial light at night (ALAN) to reshape the ecology of marine habitats is increasingly recognised (Davies et al., 2014; Zapata et al., 2019), and an emergent focus of research (Becker et al., 2012a; Bolton et al., 2017; Davies et al., 2015; Ludvigsen et al., 2018; Pulgar et al., 2019). Artificial light can be detected above 22% of the world’s coasts nightly (Davies et al., 2014), and will dramatically increase as coastal human populations more than double by year 2060 (Neumann et al., 2015).

Given the low levels of artificial light that likely reach the seafloor, it seems intuitive to suggest that light pollution is not a concern in marine ecosystems. Marine organisms are however, evolutionary adapted for detecting natural light of low intensity, distinct spectra and regular cycles. To give some examples, *Calanus* copepods undergo diel vertical migration to depths of 50m guided only by variations in moonlight intensity during the Arctic winter (Båtnes et al., 2013; Last et al., 2016); the larvae of some sessile invertebrates move and identify suitable settlement locations guided by light levels equivalent to moonless overcast nights (Crisp & Ritz, 1973); and polychaete worms, corals and echinoderms synchronise broadcast spawning events using monthly and annual variations in lunar light intensity (Naylor, 1999). In-water radiative transfer modelling reveals that the larval and adult stages of zooplankton, tropical corals and temperate marine organisms are likely to respond to artificial sky glow (light scattered in the atmosphere and reflected back to the ground) down to depths of 70m, and to waterside street lighting down to 100m (Davies & Smyth, 2018). These predictions are corroborated in part by recent observations of zooplankton avoiding research vessel lights at depths >80m (Ludvigsen et al., 2018). Given the extreme sensitivity of these animals to light, and the extent of ALAN across coastal regions (Davies et al., 2014), large areas of seafloor habitat adjacent to urbanised coastlines are likely experiencing light pollution levels that are detectable to marine organisms and, as a consequence, impacting marine ecosystems.

The growing use of white Light Emitting Diodes (LEDs) - forecast to account for up to 80% of the global lighting market share by 2022 (Bertoldi, 2018) - will likely exacerbate the prevalence and impacts of artificial light in marine ecosystems**.** Compared to older lighting technologies, LEDs emit more short wavelength light that: i) penetrates deeper into seawater [the spectral signature from land being detectable on coral reefs at 30m depth (Tamir et al., 2017)]; and ii) many marine organisms are most sensitive to (Båtnes et al., 2013; Gorbunov & Falkowski, 2002; Marshall et al., 2015). Given the pace at which LEDs are being adopted in coastal cities around the world, an understanding of the prevalence of ‘biologically relevant’ artificial light pollution, i.e. irradiances sufficient to elicit responses in marine organisms living in seafloor habitats is urgently needed.

We surveyed the spatial and spectral distribution of ALAN across an urbanised temperate estuary using a combination of radiative transfer modelling and mapping accounting for in situ measured optical seawater properties. By presenting high resolution maps of ALAN at the sea surface and on the seafloor, we provide the first evidence that biologically relevant light pollution is likely to be globally widespread in coastal marine habitats.

# Methods

## Surveying ALAN

We surveyed the spatial distribution of sea surface ALAN across Plymouth Sound and the Tamar Estuary, UK (50.358°, -4.169°) two connected coastal water bodies that are home to the largest naval port in Western Europe and a predominantly LED lit city of more than 240,000 people. Predicted night time sky brightness across the survey area on clear moon free nights ranged from 0.26 mCd m-2 to 2.56 mCd m-2 (Falchi et al., 2016) (Figure S1). Sea surface spectral irradiances of broadband blue (400-500nm), green (495-560nm) and red (620-740nm) artificial light were surveyed on four consecutive nights from 03/06/2018 to 06/06/2018 aboard R.V. Plymouth Explorer (Figure S1). Surveys were conducted during astronomical night, when the moon was below the horizon. Cloud conditions (recorded at each station or every 10 minutes during transit) were variable (0-8 Okta), with observations classified as cloudy (5-8 Okta), or clear (0-3 Okta) for data processing and analysis.

GPS and time stamped irradiances were measured every 10 seconds along a continuous transect linking ninety pre-allocated sampling stations (Figure 1) using a Spectrosense 2+ data logger fitted with a multispectral irradiance sensor (Skye Instruments Ltd). Each measurement was recorded from 1m above the sea surface to avoid detecting upwardly emitted light from the port and starboard navigation lights which remained on to ensure the vessel was visible at night in close proximity to a busy military port.

The inherent optical properties (IOPs) of the water column (absorption and scattering of light by, for example algae, sediments and coloured dissolved organic matter) play a critical role in determining the propagation of artificial light in seawater. We accounted for them by quantifying the sub-surface in-water optical properties (IOPs) at 43 station locations using a pole mounted Wet Labs BBFL2 which measures backscatter (bb) at 532 nm, chlorophyll fluorescence calibrated as chlorophyll concentration (mg m-3) and fluorescence due to coloured dissolved organic matter (fCDOM). The instrument was held just below the surface for a period of three minutes, using a 1Hz sampling rate, to enable a representative amount of data (*n*>180) to be collected.

## Mapping sea surface irradiances

All spatial data manipulation was carried out in QGIS version 3.2.2. Data processing was carried out separately for data collected under cloudy and clear conditions such that the influence of cloud on the extent and intensity of artificial light could be established. Continuous recordings of artificial light irradiances logged during transit at variable speeds resulted in highly uneven sample densities. To remove the leverage of densely sampled regions, data were first resampled across a 100m resolution, 100m diameter circular buffered grid overlaid across the survey region. The median blue, green and red irradiance values falling within each buffered grid point were then extracted and interpolated to 10m resolution sea surface irradiance maps by kriging using an exponential semi-variogram model.

## Correcting for background sky brightness

The resulting rasters were corrected for natural background irradiance using the intercept of the relationships between interpolated broadband red, green and blue irradiances and predicted night sky brightness (mCd m-2) from the New World Atlas of Night Sky Brightness [(Falchi et al., 2016); obtained from http://dataservices.gfzpotsdam.de/contact/showshort.php?id=escidoc:1541893&contactform] which were extracted for pre-allocated sampling stations for both x and y data (Figure S2). These relationships were quantified using quantile regression on the median to reduce the leverage of irradiances recorded under direct light sources including bridge and port lights (Figure S2). The night sky brightness data were supplied corrected for natural background lighting from the stars and Milky Way, hence the intercept of these relationships can be taken as irradiance in the absence of artificial light and was subtracted from the surface irradiance maps to correct for natural background light sources.

## Seafloor Bathymetry

A 10m resolution Mean Sea Level (MSL) bathymetry map for the region was obtained from the Channel Coastal Observatory (www.channelcoast.org) datasets and converted to depth at Mean High Water Spring (MHWS) and Mean Low Water Spring (MLWS) tide using the local Vertical Offshore Reference Frames.

## Modelling ALAN propagation in seawater

Sea surface broadband red, green and blue irradiances under cloudy and clear conditions, and depths at MHWS and MLWS were extracted across a 50m resolution point grid to define the input parameters of a hydrological optics model [HYROLIGHT (Mobley, 1995)] of dowelling irradiance at the sea surface [*Ed(0)*], scalar irradiance just below the sea surface [*Eo(0-)*], and scalar irradiance at the seabed as function of tide [*Eo(MHWS)*, *Eo(MLWS)*], depth, sea-surface irradiance, wavelength and inherent optical sea water properties. For areas of seabed exposed during low tide (MLWS), the value of *Eo(MLWS)* wasset to *Ed(0)*. The measured IOPs were interpolated onto the same 10m resolution grid and extracted in the same way as for the sea surface irradiances, and used to model optical properties of the water column (Figure S2).

For *Ed(0)*, the broadband surface spectral irradiances were defined as blue (400-500nm), green (495-560nm) and red (620-740nm). The sky radiance distribution was modelled as uniform for both cases of cloud cover conditions (i.e. *Ed(0)* is totally diffused). For the in-water radiance distribution [*Eo(0-)*, *Eo(MHWS)*, *Eo(MLWS)*], four inherent optical property (IOP) components were included in the model, these being pure-water, chlorophyll, CDOM and particulates. Spectral absorption and scatter for pure water was taken from Smith & Baker (1981) and used a pure water phase function (Mobley, 1994) for the angular light distribution. Spectral absorption due to chlorophyll was modelled using chlorophyll concentration (Morel & Maritorena, 2001), and was assumed to be non-scattering. CDOM spectral absorption was determined using the CDOM fluorescence measurements together with the approach of Kowalczuk, Zablocka, Sagan & Kuliński (2010) and assumed to be non-scattering. Spectral particulate backscattering was derived from the bb(532nm) interpolated field measurements using a power law relationship (Smyth et al., 2006) and the phase function of Ptezold (1972). The resulting 10m resolution map resulted in 22,231 discrete points with inputs of above surface irradiance (3 wavelengths) and in-water IOPs to be run at two cloud cover conditions. Each discrete point also had two extracted water column depths of the height of MHWS and MLWS, resulting in three depths the HYDROLIGHT model was run at: sub-surface (0.01 m), MHWS and MLWS tide depth. The HYDROLIGHT model was run on a Linux workstation for a total of 133386 cases (total run time 10 hours), and values of the scalar irradiances in blue, green and red spectrum were extracted at these three depths for each of the discrete points.

## Estimating seafloor exposure to ‘biologically relevant’ ALAN

Since thresholds of biologically relevant ALAN are taxon specific and can only be based on the limited number of taxa for which sensitivities have been quantified, a definition of these is inevitably somewhat subjective. Here, we define ‘biologically relevant’ artificial light in marine waters as irradiances equal to or greater than the minimum detectable blue (0.19 µW m-2), green (0.75 µW m-2) and red (149 µW m-2) irradiances that elicit diel vertical migration in adult female *Calanus* copepods (Båtnes et al. 2013). *Calanus* copepods are globally widespread and known to be extremely sensitive to light (Last et al., 2016) and have been empirically demonstrated to react to sea surface artificial illumination at depths >80m (Davies & Smyth, 2018; Ludvigsen et al., 2018). In addition, the threshold sensitivities of *Calanus* copepods have been quantified separately for blue, green, and red light (Båtnes et al., 2013). Original values provided in Photosynthetic Photon Flux Density (PPFD, µmol photons m-2 s-1) for wavelengths (λ) of 455nm (blue), 525nm (green) and 640nm (red) were converted to irradiances (µW m-2) using [λ x (8.359 x 10-6) x PPFD] x 106 where λ is given in metres.

Having defined the threshold blue, green, and red broadband irradiances that can be considered biologically relevant, we calculated the three-dimensional seafloor area within the survey region exposed to biologically relevant blue, green, and red artificial light during MLWS and MHWS under clear and cloudy conditions using the raster surface area calculator in GRASS GIS.

# Results

The broadband blue, green and red irradiances of dowelling artificial light at the sea surface [*Ed(0)*], scalar irradiance just below the sea surface [*Eo(0-)*], and scalar irradiance at the seabed as a function of tide [*Eo(MHWS)*, *Eo(MLWS)*] are presented for cloudy and clear conditions in figures 1 and 2. The sea surface of the whole of the lower reaches of the Tamar estuary and Plymouth Sound (36km2) were exposed to blue, green and red artificial light during both cloud conditions (Figure 1D, H, L; Figure 2D, H, L). Cloudy conditions amplified the sea surface irradiance of blue artificial light by a factor of two on average (mean = 2.12, min = 0.53, max = 4.46), green artificial light by a factor of three (mean= 2.64, min= 0.61, max= 3.83), and red artificial light by a factor of three (mean = 2.75, max = 4.74, min = 0.80) over the survey region. Green artificial light penetrated deepest in the water column compared to the blue and red bands during MHWS in both cloudy (Figure 1E) and clear (Figure 2E) conditions (Table 1). Exposure to green artificial light on the seafloor during MHWS under cloudy conditions (5-8 Okta) was three times greater than blue, and seven times greater than red artificial light; and under clear conditions (0-3 Okta) three times greater than blue, and five times greater than red (Table 1). Tidal retreat increased average seafloor exposure to blue, green and red artificial light by a factor of three (mean = 3.4, min = 1, max = 6.4), two (mean = 2.2, min = 1, max = 3.6), and thirteen (mean = 12.9, min = 1, max = 40.0) respectively during both cloud conditions.

The three-dimensional surface area of biologically relevant blue, green and red artificial light on the sea floor is presented in figures 3 and 4 for cloudy and clear conditions respectively. Biologically active green artificial light was most prevalent, with 76% and 46% of the sea floor in the survey region exposed during MLWS tide under cloudy and clear conditions respectively (Figure 3C, Figure 4C). This area was reduced during MHWS tide to 61% and 32% under cloudy and clear conditions respectively (Figure 3G, Figure 4G). Biologically active blue artificial light at night was also prevalent, with 70% and 43% of the sea floor in the survey region exposed during MLWS tide under cloudy and clear conditions respectively (Figure 3B, Figure 4B). This area was also reduced during MHWS tide to 49% and 23% under cloudy and clear conditions respectively (Figure 3F, Figure 4F). Biologically active red artificial light at night was least prevalent, with 0.4% of the sea floor in the survey region exposed during MLWS tide under both cloud conditions (Figure 3D, Figure 4D). This area was further reduced during MHWS tide to <0.1% under both cloud conditions (Figure 3H, Figure 4H).



**Figure 1. The spatial distribution of artificial light at night across Plymouth Sound and the Tamar Estuary, UK in cloudy conditions (5-8 Okta).** Modelled scalar irradiances (µW m-2) are given for Blue (400-500nm, A-D), Green (495-560nm, E-H), and Red (620-740nm, I-L) light on the seabed during Mean High Water Spring (MHWS) tide (A,E,I), Mean Low Water Spring (MLWS) tide (B,F,J), and immediately beneath the water surface (C,G,K). Measured planar irradiances are given for light incident on the sea surface (D,H,L). The coordinate reference system is OSGB 1936/British National Grid. Land is given by solid grey regions, the survey extent by dashed grey lines.



**Figure 2. The spatial distribution of artificial light at night across Plymouth Sound and the Tamar Estuary, UK under in clear conditions (0-3 Okta).** Modelled scalar irradiances (µW m-2) are given for Blue (400-500nm, A-D), Green (495-560nm, E-H), and Red (620-740nm, I-L) light on the seabed during Mean High Water Spring (MHWS) tide (A,E,I), Mean Low Water Spring (MLWS) tide (B,F,J), and immediately beneath the water surface (C,G,K). Measured planar irradiances are given for light incident on the sea surface (D,H,L). The coordinate reference system is OSGB 1936/British National Grid. Land is given by solid grey regions, the survey extent by dashed grey lines.

**Table 1.** Exposure to blue, green and red artificial light at night on the seafloor of Plymouth Sound and the Tamar Estuary during clear (0-3 Okta) and cloudy (5-8 Okta) conditions.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Waveband (nm) | Parameter | Cloud cover (Okta) | Irradiance (µW m-2) | | |
|  |  |  | Mean | Min | Max |
| 400-500 (Blue) | *Eo(MHWS)* | 0-3 | 0.89 | <0.1 | 250.6 |
| 495-560 (Green) | *Eo(MHWS)* | 0-3 | 2.6 | <0.1 | 453 |
| 620-740nm (Red) | *Eo(MHWS)* | 0-3 | 0.4 | <0.1 | 269.8 |
|  |  |  |  |  |  |
| 400-500 (Blue) | *Eo(MLWS)* | 0-3 | 3.2 | <0.1 | 606.4 |
| 495-560 (Green) | *Eo(MLWS)* | 0-3 | 6.2 | <0.1 | 872 |
| 620-740nm (Red) | *Eo(MLWS)* | 0-3 | 3.6 | <0.1 | 903.5 |
|  |  |  |  |  |  |
| 400-500 (Blue) | *Eo(MHWS)* | 5-8 | 1.8 | <0.1 | 122.6 |
| 495-560 (Green) | *Eo(MHWS)* | 5-8 | 5.8 | <0.1 | 349 |
| 620-740nm (Red) | *Eo(MHWS)* | 5-8 | 1.3 | <0.1 | 177.7 |
|  |  |  |  |  |  |
| 400-500 (Blue) | *Eo(MLWS)* | 5-8 | 6.1 | <0.1 | 608.8 |
| 495-560 (Green) | *Eo(MLWS)* | 5-8 | 13.6 | <0.1 | 957 |
| 620-740nm (Red) | *Eo(MLWS)* | 5-8 | 8.8 | <0.1 | 1124.9 |

*Eo* = Scalar irradiance

*MHWS* = Mean High Water Spring Tide

*MLWS* = Mean Low Water Spring Tide



**Figure 3.** The three dimensional area of seafloor exposed to ‘biologically active’ blue (B,F), green (C,G) and red (D,H) artificial light at night at Mean Low Water Spring (MLWS) and Mean High Water Spring (MHWS) tide in Plymouth Sound and the Tamar Estuary under cloudy conditions. Legend indicates bathymetric depth (m) at the given datums. White space within the survey region (dashed line) indicates exposure at ALAN irradiances below the biological threshold. Numbers inset indicate the percentage of the 3D seafloor region (A,E) exposed.



**Figure 4.** The three dimensional area of seafloor exposed to ‘biologically active’ blue (B,F), green (C,G) and red (D,H) artificial light at night at Mean Low Water Spring (MLWS) and Mean High Water Spring (MHWS) tide in Plymouth Sound and the Tamar Estuary under clear conditions. Legend indicates bathymetric depth (m) at the given datums. White space within the survey region (dashed line) indicates exposure at ALAN irradiances below the biological threshold. Numbers inset indicate the percentage of the 3D seafloor region (A,E) exposed.

# Discussion

Exposure to artificial light at night in marine habitats has been documented in few locations (although see Tamir et al., 2017), and the extent to which biologically relevant artificial light is prevalent on the seafloor has, to our knowledge, not been quantified anywhere in the world. Our results demonstrate that artificial light from coastal urban centres is widespread across the sea surface, sub surface and seafloor of adjacent marine habitats. The areas exposed are non-trivial. Up to 76% of the sea floor in the survey region was exposed to biologically relevant artificial light. Plymouth is one coastal city with a population of 240,000 people. Given that 75% of the world's megacities (populations >10 million) are now located in coastal regions (Luijendijk et al., 2018) and costal populations are projected to more than double by 2060 (Neumann et al., 2015), it is clear that biologically relevant light pollution on the seafloor is likely to be globally widespread and increasing in intensity and extent.

Manipulative experiments have already demonstrated that artificially illuminating marine organisms at night to intensities commonly encountered in the real world can alter the structure of marine ecosystems (Davies et al., 2015; Garratt et al., 2019), and trophic interactions between marine organisms (Bolton et al., 2017; Underwood et al. , 2017). The physiology, survival, reproduction and movement of marine fish (Becker et al., 2012; Pulgar et al., 2019; Szekeres et al., 2017), turtles (Kamrowski et al. 2012; Witherington & Bjorndal, 1991), birds (Dwyer et al., 2013), corals (Ayalon et al., 2019; Kaniewska et al., , 2015) and other invertebrates (Duarte et al., 2019; Manríquez et al., 2019) are all affected by night-time lighting. The documented effects are however, almost exclusively in response to illuminances that would be experienced in close proximity to bright light sources. Our results provide evidence that low sea surface artificial light irradiances caused by sky glow can result in biologically relevant exposure levels in seafloor habitats. Artificial sky glow extends the geographical influence of localised direct lighting to hundreds of kilometres (Falchi et al., 2016), suggesting that impacts on marine organisms may be widespread, and urgently need quantifying.

Satellite images have proved valuable for quantifying the exposure of the sea surface and coastal regions to night-time lighting (Aubrecht et al., 2008; Davies et al., 2014; Mazor et al., 2013; Zhao et al., 2018), however marine organism life histories play out in pelagic and benthic habitats that experience artificial light undetectable to satellite remote sensing technologies. Using a combination of sea surface mapping and radiative transfer modelling, we were able to produce high resolution (10m) maps of artificial light on the seafloor that captured: i) the effect of wavelength and locally relevant in situ optical water properties on the transmission of artificial light through seawater; ii) spatially variable seabed bathymetry which affects the path length of artificial light to the seafloor; iii) temporal variability in this path length due to local tidal conditions; iv) the natural background irradiance due to stars and the Milky Way; and v) the influence of cloud cover on the sea surface distribution of artificial light.

We are confident that our estimates are rigorously derived, and do not overestimate exposure to artificial light in the marine habitats of the survey region. They may however underestimate artificial light exposure for the following reasons, and as such should be considered conservative. Firstly, low irradiances recorded at the furthest extents of the survey region pushed the limits of our radiometers’ sensitivity. Consequently, we may have overestimated the natural background irradiances and in correcting for these, underestimated sea surface irradiances. Secondly, our seafloor irradiances account for the optical properties of a temperate estuarine water body during a snapshot in time, September 2018 during a phytoplankton (*Noctiluca Scintillans*) bloom. Water column concentrations of optically active constituents (chlorophyll, CDOM, particulates) are strongly seasonal, and even within seasons highly variable meteorological drivers such as precipitation, natural light history, wind-speed and temperature, can have a large bearing. The results presented here, although modelled using input measurements representative of those historically observed in this location (Smyth et al., 2010), may be an underestimate for times of the year where the water column is clearer.

Recent years have seen growing interest in manipulating LED light spectra to avoid wavelengths that give rise to undesirable ecological impacts (Brüning et al., 2016; Longcore et al., 2015; 2018). Other than a handful of notable examples (Rivas et al., , 2015), evidence of this strategy’s mitigation potential is lacking in marine ecosystems. Our results present a compelling case for using red artificial light at night in coastal installations to reduce exposure in marine habitats. Red light attenuates faster in water. Given this, it is unsurprising that 0.4% of the seafloor was exposed to biologically relevant red artificial light, compared to up to 70% and 76% blue and green artificial light respectively. The persistence of these attenuation differences in geological time means that many marine animals have also evolved maximum sensitivity at shorter wavelengths of their visual spectrum compared to terrestrial (Marshall et al., 2015). While the ecological benefits of applying spectral manipulation in terrestrial ecosystems remain uncertain (Davies & Smyth, 2018; Longcore et al., 2018), its application in aquatic habitats seems likely to produce favourable results. Nonetheless, red and amber light spectra guide developmental, behavioural and physiological processes in a number of marine organisms (Birklund & Wijsman, 2005; Duanmu et al., 2014; Mason & Cohen, 2012; Wijgerde et al., 2014), and it seems unlikely that switching to long wavelength emitting light sources or retrofitting existing luminaires with band pass filters will avoid the ecological impacts of artificial light altogether. The feasibility of adopting such approaches is also likely to prove highly contentious in maritime industries and communities. Alternative strategies including switching lights off, dimming or shielding lights, and preserving naturally dark seascapes should be given equal consideration in the design of coastal lighting installations (Davies & Smyth, 2018; Gaston et al., 2012).

The rapid urbanisation of global coastlines is increasing the exposure of marine waters to artificial light, including those regions of our oceans most valued by society (Davies et al., 2016). We conclude that artificial light pollution at the sea surface is sufficient to cause widespread exposure of the seafloor to biologically relevant light pollution. The transition of outdoor lighting to technologies rich in short wavelength light will exacerbate exposure levels on the seafloor. We suggest that broad spectrum LEDs should be considered an emerging threat to marine biodiversity that warrants urgent attention.

# Acknowledgements

The research leading to this publication was funded by National Geographic [grant number CP-116R-17 awarded to T.D., T.S. and D.M.]; and part funded by the European Regional Development Fund through the Welsh Government [grant number 80761-BU-134 awarded to T.D.], and the Natural Environment Research Council [grant numbers NE/S003533/1 awarded to T.D, T.S. and D.M].

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