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A proposed methodology for defining the criteria of 'Good Environmental Status' for artificial light at night in marine waters

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ABSTRACT

There is now a growing recognition internationally that the impacts of Artificial Light at Night (ALAN) on marine biodiversity require regulation. How ALAN should be regulated and what constitutes 'Good Environmental Status' (GES) for underwater ALAN remain open questions that if resolved would accelerate the integration of ALAN management into existing policy instruments. In the European Union, interpretations of Descriptor 11 of the Marine Strategy Framework Directive (MSFD) - 'Introduction of Energy' - have historically focused exclusively on underwater noise. As a result, no formal targets, thresholds or assessment structures currently exist for marine light pollution across EU Member States. Building on the methodological precedent established by the D11 Technical Group on Underwater Noise, we evaluate the applicability of a multi-indicator and Level of Onset of Adverse Biological Effects (LOBE) approach to defining GES for ALAN. Adopting a precautionary stance, we recommend 0.1 $\mu W\,m^{-2}$ as a provisional LOBE threshold, based on the most light-sensitive marine taxa currently documented. This threshold is applied to define a classification system (nil to high exposure risk) for two different ecosystems separately (pelagic and benthic), and calculate aggregate exposure risk scores that describe the status of a defined geographic area. Application of these criteria across European Regional Seas reveals pronounced spatial variability, with the highest exposure concentrated in coastal zones, enclosed seas and regions with dense infrastructure. The proposed framework provides a coherent, operational methodology for assessing ALAN under the MSFD and establishes a foundation for future threshold-setting, monitoring and mitigation worldwide.

1. Introduction

Research investigating the ecological impacts of artificial light at night (ALAN) emissions into the sea has grown exponentially over the last decade (Marangoni et al., 2022; Tidau et al., 2021). Prior to 2014, the known impacts were restricted to seabird strike mortality events on ships at sea, and the disorientation of sea turtle hatchlings (Davies et al., 2014; Depledge et al., 2010). The known impacts of artificial light at night now span a broad array of marine species and ecosystems (Marangoni et al., 2022).

Globally, 22% of the world's coastlines are impacted by light pollution nightly (Davies et al., 2014). Light from coastal cities is sufficiently bright for biologically important light pollution to be detectable in adjacent seabed habitats (Smyth et al., 2022; Davies et al., 2020), such that 1.6 million kilometres squared of the world's exclusive economic zones are exposed to this biologically important light pollution to a depth of at least 10 m (Smyth et al., 2021). Marine ecosystems will be increasingly exposed to ALAN over the 21st century, as coastal populations continue to rise (Reimann et al., 2023).

The rapid growth in use of Light Emitting Diode (LED) lighting over

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the last 14 years has, in particular, exacerbated the exposure of marine ecosystems to coastal and offshore ALAN. LED's have grown from 2% of the global lighting market in 2012 to 48% in 2019, and are forecast to reach 87% by 2030 (Zissis et al., 2021). Although described as broad spectrum 'white' lights, the emission spectra of many phosphor coated LEDs contain a prominent blue spectral peak (Davies & Smyth, 2018). This blue light penetrates further in seawater compared to previous lighting technologies, increasing the depth of biologically important ALAN from tens to hundreds of metres (Davies & Smyth, 2018, Davies et al., 2020). The blue peak is also closely aligned with the wavelengths at which many marine species are evolutionarily adapted to utilise natural light cues (Davies and Smyth, 2018, Davies et al., 2020). Some of the most globally important biological phenomena taking place in the oceans are guided by information contained within light signals from the moon and sun (Naylor, 2005; Hayes, 2003; Naylor, 1999). These include Diel Vertical Migration, the largest migration of biomass on the planet (Hayes, 2003), and synchronised broadcast spawning in corals (Lin et al., 2021; Kaniewska et al., 2015; Babcock et al., 1986). These and numerous other biological processes in the oceans have been shown to be disrupted by the expansion of ALAN and widespread adoption of LEDs in coastal developments, shipping, fisheries and offshore infrastructure (Davies et al., 2023; Ayalon et al., 2021; Berge et al., 2020; Ludvigsen et al., 2018).

Despite the prevalence and increasingly well documented impacts of ALAN in the oceans, policy that sets targets for managing artificial light emissions into the sea remains lacking (Marangoni et al., 2022). This is despite the scientific community calling for a review of the legislation surrounding the management of ALAN in marine contexts for more than a decade (Davies et al., 2014, 2016), including within European legislative instruments.

The Marine Strategy Framework Directive (Directive 2008/56/EC), for example, is intended to protect the marine environment by ensuring that all EU marine waters achieve Good Environmental Status (GES) across eleven qualitative descriptors. The MSFD is implemented through national legislatures in EU member states. Underwater light pollution is a form of energy and it is encompassed under Descriptor 11 of the MSFD "*Introduction of energy, including underwater noise, is at levels that do not adversely affect the marine environment.*" While underwater noise was explicitly mentioned, the intention was for the descriptor to cover all forms of energy input including light and electromagnetic radiation. This was later evidenced in Commission Decision 2010/477/EU on 'criteria and methodological standards on good environmental status of marine waters' as follows:-

> "*Together with underwater noise, which is highlighted throughout Directive 2008/56/EC, other forms of energy input have the potential to impact on components of marine ecosystems, such as thermal energy, electromagnetic fields and light.*"

The Commission however recognised that substantial knowledge gaps precluded the introduction of GES for other forms of energy stating that:-

> "*Additional scientific and technical progress is still required to support the further development of criteria related to this descriptor, including in relation to impacts of introduction of energy on marine life …*"

Commission Decision 2010/477/EU was later repealed by Commission Decision 2017/848/EU to lay down criteria and methodological standards on good environmental status of marine waters and specifications and standardised methods for monitoring and assessment, which stated that for Descriptor 11:-

> "*Criteria relating to other forms of energy input (including thermal energy, electromagnetic fields and light) and criteria relating to the environmental impacts of noise are still subject to further development.*"

Descriptor 11 has so far been interpreted by most member states and national legislative instruments to refer exclusively to underwater noise pollution. The pre-Brexit implementation of the UK Marine Strategy, for example, made no reference to light pollution or electromagnetic radiation under Descriptor 11 (UK Marine Monitoring and Assessment Strategy, 2019).

The loss of any reference to ALAN when the MSFD was translated into national instruments had two profound consequences. Firstly, there was no formal policy frameworks that necessitated its regulation; and secondly, it has remained largely unrecognised among environmental agencies and international governance structures including the OSPAR commission, Helsinki Commission and The Barcelona Convention, where action plans and monitoring programmes for underwater noise pollution are now common (OSPAR, 2025; HELCOM, 2021).

Recent years have seen a renewed interest in managing light pollution above and below water with pivotal policy briefs, developments and management guidelines emerging from the European Commission (European Commission), the International Union for the Conservation of Nature (Welch et al., 2024), the Convention on Migratory Species (Convention on Migratory Species, 2024), Fisheries and Oceans Canada (Bundy et al., 2025), the Australian (DCCEEW, 2023) and New Zealand (Lohrer et al., 2024) governments, and the Great Barrier Reef Marine Park Authority (Great Barrier Reef Marine Park Authority 2024). These recent policy developments suggest that Descriptor 11 of the MSFD should fully integrate ALAN as part of the upcoming MSFD review. To facilitate the deeper integration of marine ALAN regulation into EU policy frameworks however, there is an identified need to develop a viable methodology for quantifying the criteria of 'Good Environmental Status' for ALAN in marine waters.

To date, no attempt has been made to define the criteria of 'Good Environmental Status' (GES) for ALAN in EU waters. Here, we present the first proposed methodological approach to defining GES for ALAN. To achieve this, we review the available methodologies for defining GES of ALAN in the context of the only other D11 pollutant for which these have been defined, underwater noise. Next, we recommend a framework for defining GES for ALAN. Finally, we review how this framework translates into GES for ALAN across EU waters.

2. Defining GES for ALAN: A brief methodological appraisal

In 2010, the European Commission established the Technical Group on Underwater Noise (TG Noise) under the Common Implementation Strategy for the MSFD. This brought together experts from EU Member States, and the regional seas conventions to harmonise approaches for monitoring and assessing underwater noise. The group proposed two indicators, continuous low-frequency noise from shipping, and impulsive noise for which criteria of Good Environmental Status could be defined (Commission Decision 2017/848/EU). In 2022 TG Noise put forward options for threshold values for continuous (Borsani et al., 2023) and impulsive noise (Sigray et al., 2023).

Given that underwater noise has been the focus of MSFD Descriptor 11 over the last decade, we use the adopted approach as a framework against which GES for ALAN might be developed. The approach was underpinned by two management positions of relevance to ALAN. The first was the decision to apply a dual threshold approach (i.e., the design of separate thresholds for continuous versus impulsive underwater noise). The second was the decision to base the threshold setting on the concept of the least observable biologically adverse effect (LOBE).

2.1. The dual threshold approach

TG Noise proposed two indicators of underwater noise pollution for which GES thresholds could be independently defined. These were continuous noise from shipping, and impulsive noise from pile driving and underwater explosives (Borsani et al., 2023; Sigray et al., 2023). The dual threshold approach recognised spatial and temporal variability in the nature of noise exposure underwater. Implicit in the concept was that the area exposed to shorter duration impulsive noise could be larger

than longer duration continuous noise in order for GES to be met.

ALAN can be categorised in numerous ways. Most commonly in the scientific community, a distinction is made between direct ALAN that is experienced in close proximity to sources of artificial illumination, and artificial sky glow which is the collective light from many sources (for example a town or city) that is scattered in the atmosphere and reflected back to the ground (Kyba et al., 2011). Artificial skyglow is more geographically widespread but less bright in comparison to direct exposure in close proximity to streetlights for example (Kyba et al., 2017; Falchi et al., 2016). The distinction is useful, because the primary mechanism of impact differs between the two. Direct light pollution disrupts information contained in light regimes from the moon and the sun, while artificial skyglow disrupts information contained in moonlight regimes only. Applying threshold concepts aligned with the precautionary principle, such as LOBE, however, negates the need to carry this distinction through into management, as impacts on lunar guided processes form the basis of deciding where such thresholds are exceeded.

Like underwater noise pollution, ALAN also occurs continuously or intermittently. The classification of the two pollutants into continuous or impulsive is however very different due to the permanence of land-based ALAN sources. In aquatic contexts, continuous sources of illumination through the night include coastal developments (where part-night lighting is not used), offshore infrastructure and decorative lighting (Marangoni et al., 2022; Davies et al., 2014). Intermittent sources include shipping and light fisheries which are more transient by comparison (Davies et al., 2014).

An important distinction between ALAN and underwater noise is the technologies most likely to be used for mapping and monitoring exposure. For underwater noise, monitoring is almost always conducted *in situ*. While this is possible for ALAN, remote sensing products offer broader geographic scope at sufficient spatial resolution of insight for regional decision making (Smyth et al., 2021; Hänel et al., 2018; Falchi et al., 2016). When quantifying GES across regional seas for example, products like the 'Global Atlas of Artificial Light at Night Under the Sea' (Smyth et al., 2021, 2024) present an 'off the shelf' tool that can be readily accessed by marine managers. Such products can be made temporally explicit, by for example accounting for monthly variability in optical water properties, or the expansion or contraction of artificial lighting as detected by satellite remote sensing products. Critical to this approach, however, is that ephemeral sources of ALAN are typically filtered out from such products, allowing GES to be quantified only for continuous sources (Falchi et al., 2016). ALAN arising from shipping and other temporary sources can be measured *in situ*, or using raw level 1 satellite imagery, however there is little reason to distinguish differing thresholds for ephemeral and fixed ALAN sources for the purposes of quantifying GES. The threshold value beyond which ALAN can be considered good, is just as relevant to a vessel moored off the coast as it is to the port and harbour infrastructure where it might dock.

The nature of the habitat exposed to ALAN is arguably the most distinguishing feature that justifies a multi threshold approach. ALAN enters the marine environment from above the water's surface in most cases. Excepting the intertidal, pelagic species are therefore the first to be exposed to ALAN (Berge et al., 2020; Ludvigsen et al., 2018). The global atlas of artificial light at night under the sea quantifies ALAN exposure as the depth to which biologically important light pollution penetrates the ocean (Smyth et al., 2021, 2024). While this metric simplifies the otherwise complex problem of determining and comparing exposure levels at the sea surface and across multiple depths, it assumes an infinitely deep ocean. Benthic habitats occur at variable depths not accounted for by the atlas. ALAN arising from offshore infrastructure in deeper waters may have profound impacts on the pelagic ecosystem, while insufficient quantities reach to the seafloor to impact benthic habitats. This distinction should be made when quantifying GES.

2.2. Level of onset of adverse biological effects

The Level of Onset of Adverse Biological Effects (LOBE) concept was pivotal in defining GES for underwater noise (Borsani et al., 2023; Sigray et al., 2023). It is the sound level above which an adverse biological effect on an indicator species is expected to occur. While 'adverse' is a subjective definition, examples are given such as disturbance leading to avoidance of an area. TG Noise used studies of underwater noise impacts to categorise different sources of impulsive underwater noise into 'Very low', 'Low', 'Medium', 'High', 'Very High'. For continuous underwater noise, a single value for LOBE is not yet defined. Instead, TG Noise recommends LOBE values should be set by member states based on indicator species and evidence-based studies.

Within TG Noise, there was an expectation that there will always be areas where LOBE is exceeded at least for some of the time. The duration of exposure above LOBE became a critical dimension for quantifying GES due the ephemeral nature of all underwater noise sources. As discussed above however, the distinction between permanent and temporary that was made for noise does not translate to ALAN sources, nor is it useful for defining LOBE intensities that if exceeded constitute impact. As we explore later, the spatial and temporal extent over which ALAN exceeds LOBE constitutes severity of impact and hence GES, while LOBE itself can be specified and fixed.

A metric akin to LOBE was previously used to quantify the threshold irradiance of ALAN that can be considered biologically important (Davies et al., 2020). This was derived following the precautionary principle as the minimum amount of white light that elicits diel vertical migration in *Calanus* copepods, 0.1 $\mu W\,m^{-2}$ (Davies et al., 2020). This value was later used to quantify the depth of biologically important light pollution across the world's oceans (Smyth et al., 2024) and has been suggested as a quantifiable metric for measuring the depth of the photic zone (Davies and Smyth, 2025). The value is extremely conservative due to the high sensitivity of *Calanus* copepods to light. They can respond to moonlight at depths greater than 50 m (Båtnes et al., 2013). This LOBE value is therefore likely to be inclusive for most species light sensitivities (Table 1) and is considered to be the best option when deciding threshold values using the precautionary principle.

Ideally, LOBE would be a representative measure derived from the minimum light sensitivities of many species across a broad array of phyla (Davies & Smyth, 2025). The list of taxa for which minimum light sensitivities have been quantified is however too small, phylogenetically restricted and dominated by pelagic species and early life stages (Table 1).

Quantifying LOBE using a representative measure such as a mean or median across such a small number of species would allow taxonomic imbalances to dominate the setting of the threshold. The lack of any meaningful representation of benthic taxa also means any definition of LOBE using a dual threshold approach for ALAN should be refined in the future as datasets improve. Clearly, there is a need for more fundamental research into the sensitivity of marine organisms to light. In the absence of this, we recommend retaining the precautionary approach and applying the inclusive measure of 0.1 $\mu W\,m^{-2}$ originating from a white light source. The application of this LOBE threshold in benthic and pelagic contexts will however differ because: i) ALAN passes through pelagic ecosystems to reach benthic ecosystems hence exposure is generally higher in the former; ii) in coastal regions benthic systems can be highly exposed during periods of tidal emersion, and iii) pelagic ecosystems are three-dimensional with ALAN varying across depths for every geographical position.

3. A framework for defining GES of ALAN

In this section we will apply LOBE as identified above to determine risk matrices for Pelagic and Benthic marine habitats. To avoid confusion, we do not refer to this as a dual threshold approach, while acknowledging that the principle of applying different thresholds to

Table 1
Minimum light sensitivities of marine taxa used for defining LOBE of ALAN.

Group	Taxon	Life stage	Habitat	Response	Threshold Light Sensitivity (μW m^{-2})	Reference
Arthropoda	*Calanus* spp.	Adult (f)	Pelagic	Phototaxis (-ve), DVM	0.102	Båtnes et al. (2013)
	Calanus spp.	Adult (m)	Pelagic	Phototaxis (-ve), DVM	1.02	Båtnes et al. (2013)
	Pleuromamma xiphias	Adult	Pelagic	Phototaxis (-ve), DVM	0.261	Buskey et al. (1989)
	Semibalanus balanoides	Larvae	Pelagic	Phototaxis (varied)	0.101	Crisp and Ritz (1973)
	Eusergestes arcticus	Adult	Pelagic	Abdominal flexion	36.2	Myslinski et al. (2005)
	Meganyctiphanes norvegica	Adult	Pelagic	Abdominal flexion	3.62	Myslinski et al. (2005)
	Pasiphaea multidentata	Adult	Pelagic	Abdominal flexion	3.62	Myslinski et al. (2005)
	Uca spp.	Megalope	Pelagic	Phototaxis (-ve)	3.62	Tankersley et al. (1995)
	Callinectes sapidus	Larvae	Pelagic	Phototaxis (+ve)	362	Forward et al. (1995)
	Pleuromamma gracilis	Adult	Pelagic	Phototaxis (-ve), DVM	50.7	Buskey et al. (1989)
	Pontella karachiensis	Adult	Pelagic	Phototaxis (-ve)	678	Manor et al. (2009)
Chordata	*Ascidia mentula*	Larvae	Pelagic	Phototaxis (-ve)	217	Svane and Dolmer (1995)
	Ascidia callosa	Larvae	Pelagic	Change in swimming	2170	Young and Chia (1985)
	Hippoglossus hippoglossus	Larvae	Pelagic	Phototaxis (+ve)	2010	Naas and Mangor-Jensen (1990)
	Cyanea capillata	Larvae	Pelagic	Phototaxis (-ve)	72500	Svane and Dolmer (1995)
	Polyandrocarpa zorritensis	Larvae	Pelagic	Phototaxis (+ve)	130000	Forward et al. (2000)
	Pyura chilensis	Larvae	Pelagic	Phototaxis (-ve)	3620000	Manríquez and Castilla (2007)
	Polyandrocarpa zorritensis	Larvae	Pelagic	Phototaxis (+ve)	1050000	Forward et al. (2000)
Annelida	*Spirobranchus giganteus*	Larvae	Pelagic	Phototaxis (+ve)	362000	Marsden (1986)
	Phragmatopoma caudata	Larvae	Pelagic	Phototaxis (+ve)	688	McCarthy et al. (2002)
	Serpula vermicularis	Larvae	Pelagic	Phototaxis (-ve)	2170000	Young and Chia (1982)
	Galeolaria caespitosa	Larvae	Pelagic	Phototaxis (-ve)	3620000	Marsden (1988)
Porifera	*Amphimedon queenslandica*	Larvae	Pelagic	Phototaxis (-ve)	217000	Leys and Degnan (2001)
Platyhelminthes	*Prosthecereaeus crozieri*	Larvae	Pelagic	Phototaxis (+ve)	66700	Johnson and Forward (2003)

DVM = Diel Vertical Migration.

different situations where relevant has been adopted from the approach used by TG Noise. Instead, we adopt the term 'multi-indicator' approach.

3.1. Pelagic ecosystems criteria

Risk mapping for ALAN is defined using the Global Atlas of Artificial Light at Night under Sea (Smyth et al., 2024). The global atlas quantifies ALAN exposure as the depth to which biologically important ALAN penetrates in the water column in metres (critical depth: Z_c). This depth threshold was determined using the proposed value of LOBE of 0.1 μW m^{-2}, derived from the light sensitivity of *Calanus* copepods to 'white' light. The original intention was to use the quartiles over which Z_c varies to define four levels of exposure, Nil, Slight, Moderate and High Impact. The logarithmic nature of the ALAN exposure distribution however meant that this classification system would not be representative of biological impacts arising from ALAN exposure. Therefore, an alternative classification was proposed (Table 2).

Within this classification system:-

- Nil exposure occurs where biologically important ALAN (0.1 μW m^{-2}) is not exceeded beneath the sea surface.
- Low exposure occurs where biologically important ALAN (0.1 μW m^{-2}) penetrates to a depth of 1m.
- Medium exposure occurs where biologically important ALAN (0.1 μW m^{-2}) penetrates to depths of 1-10 m.
- High exposure occurs where biologically important ALAN (0.1 μW m^{-2}) penetrates to depths of greater than 10 m.

The logarithmic nature of the revised classification system accounts for the exponential decay of light with depth, minimising the over-representation of locations in lower exposure categories and the underrepresentation of those in higher exposure categories. This system removes the complexity of needing to estimate ALAN exposure across multiple critical depths. Instead, it provides a single easily interpretable metric of exposure 'the depth of biologically important ALAN' across a four-level category system that can be applied using existing open-source datasets (https://aquaplan.eofrom.space/) to quantify GES for ALAN in EU waters.

Table 2
Proposed threshold criteria for defining GES of ALAN in pelagic ecosystems based on the depth of biologically important light pollution (0.1 μW m^{-2}), Z_c.

Threshold depth (m)	Exposure risk category	Exposure risk score
0	Nil	1
$0 < Z_c \leq 1$	Low	2
$1 < Z_c \leq 10$	Medium	3
$10 < Z_c$	High	4

3.2. Benthic ecosystem criteria

The development and application of risk matrices for benthic ecosystems requires a sufficient number of benthic species for which LOBE has been quantified in response to ALAN. Currently the phylogenetic range and number of species that LOBE has been quantified for in response to white light is not sufficient to produce a scientifically robust alternative to the threshold of LOBE proposed for pelagic ecosystems (Table 1). Following the precautionary approach, and in the absence of a reliable alternative, we recommend that a cut off of 0.1 μW m^{-2} is used define ALAN impact in benthic ecosystems.

Unlike in pelagic ecosystems, however, benthic habitats occupy a unique depth at each point in space. This makes it feasible and pragmatic to define LOBE thresholds based on ALAN irradiance experienced at the seafloor, rather than a metric like *Zc* which is representative of the depth at which a threshold value of ALAN occurs. This raises the question of how the remaining thresholds in a four-tier categorical system should be defined. The logarithmic distribution of species threshold sensitivities to light provides a logical framework for defining these categories which is also reflected in the criteria proposed for pelagic ecosystems. Given that 0.1 μW m^{-2} defines whether ALAN is present in sufficient quantities to give rise to biological impacts, a logarithmic classification system is proposed in which tiers are defined across orders of magnitude (Table 3).

Within this classification system:-

- Nil exposure occurs where ALAN irradiance on the seafloor is less than 0.1 μW m^{-2}.
- Low exposure occurs where ALAN irradiance on the seafloor is greater than or equal to 0.1 μW m^{-2}, but less than 1 μW m^{-2}.

Table 3
Proposed threshold criteria for defining GES of ALAN in benthic ecosystems based on the irradiance (I) of artificial light at night experienced on the seafloor.

Threshold Irradiance I (μW m^{-2})	Exposure risk category	Exposure risk score
$0.1 > I$	Nil	1
$0.1 \leq I < 1$	Low	2
$1 \leq I \leq 10$	Medium	3
$10 \leq I$	High	4

- Medium exposure occurs where ALAN irradiance on the seafloor is greater than or equal to 1 μW m^{-2}, but less than 10 μW m^{-2}.
- High exposure occurs where ALAN irradiance on the seafloor is greater than or equal to 10 μW m^{-2}.

This classification defines 'Low' exposure risk at ALAN irradiances that would impact 15% of the biological responses reported in Table 1, 'Medium' exposure risk at ALAN irradiances that would impact 30% of the biological responses reported in Table 1, and 'High' exposure risk at ALAN irradiances that would impact 100% of the biological responses reported in Table 1.

4. Quantifying GES for ALAN in EU waters

Here, we have outlined a proposed set of criteria to be considered to

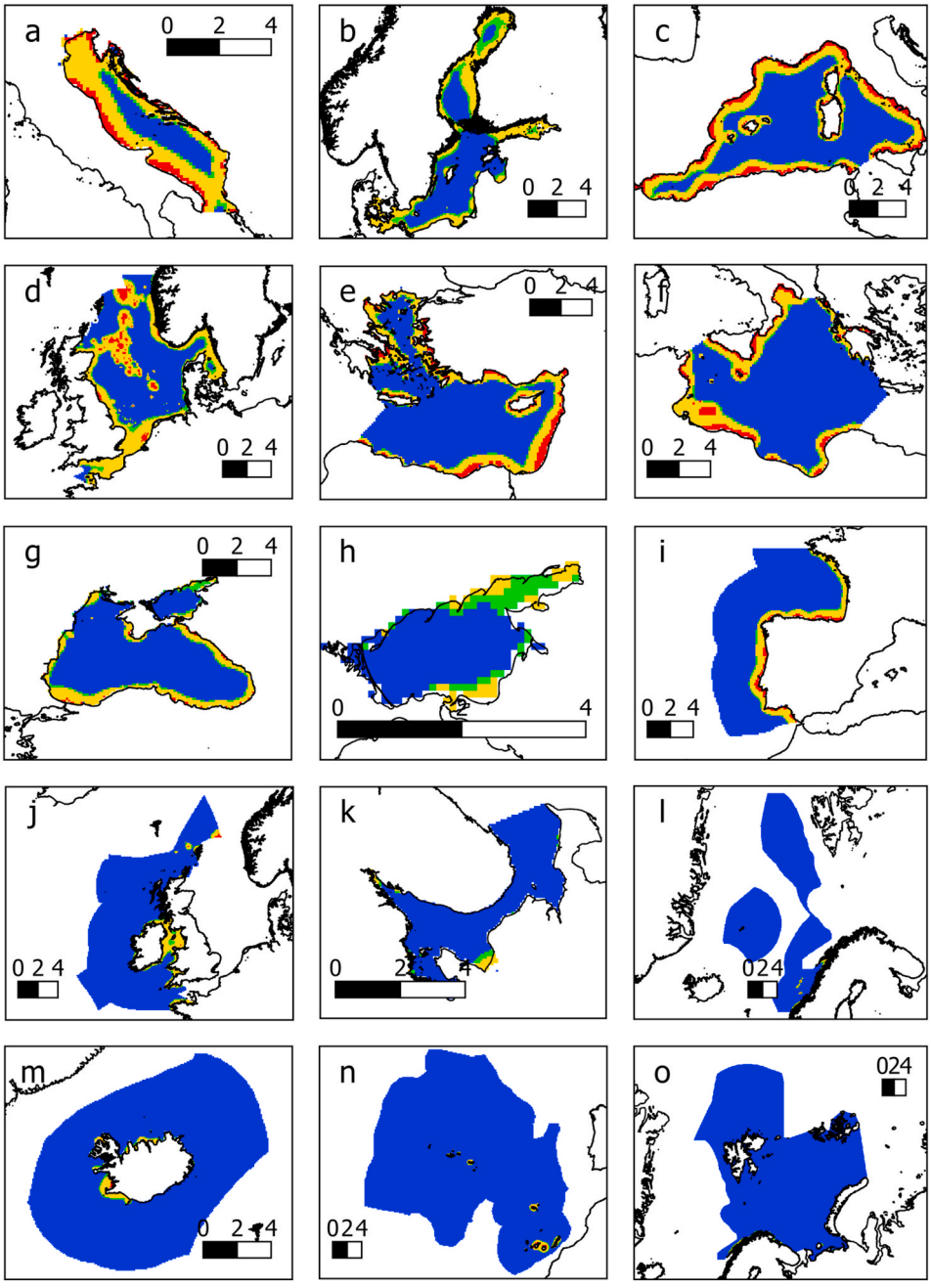

Fig. 1. Exposure risk of Pelagic ecosystems to ALAN across European Sea Regions. Sea Regions are ordered from the highest (a) to the lowest (n,o) mean weighted exposure risk scores. a) Adriatic Sea; b) Baltic Sea; c) Western Mediterranean Sea; d) Greater North Sea; e) Aegean-Levantine Sea; f) Ionian Sea and the Central Mediterranean Sea; g) Black Sea; h) sea of Azov; i) Bay of Biscay and the Iberian Coast; j) Celtic Seas; k) White Sea; l) Norwegian Sea; m) Iceland Sea; n) Barents Sea; o) Macaronesia. Exposure Risk Categories are colour coded as: Blue = Nil; Green = Low; Amber = Medium; Red = High.

measure Good Environmental Status of ALAN in EU waters. We do not however go so far as to define which level of the proposed 4 tier classification systems constitutes 'Good'. As with TG noise, we acknowledge that defining such a threshold is complex and requires a multi-stakeholder approach to be successfully implemented. The nature of GES is also yet to be established. Whether GES should reflect a single category level within the four-tier system, the proportion of a given region or habitat exposed to a given tier (or combination of tiers), or a mean exposure across a region are all viable approaches that the EU and member states would likely consider in applying such criteria. Here, we lay out the methodological approach for defining the criteria by which GES should be quantified as opposed to recommending exactly what GES should be. In the following section we explore the implications of these criteria for setting GES across EU Sea regions. As in section 3, pelagic habitats and benthic habitats are dealt with separately, applying the threshold criteria outlined in Tables 2 and 3 respectively.

4.1. Quantifying GES for ALAN in pelagic ecosystems

The exposure criteria outlined in Table 2 was used to classify the Global Atlas of Artificial Light Under the Sea according to the suggested four tier classification of exposure risk. An interactive version of the resulting layer is available from https://aquaplan.eofrom.space/. The pre-classified layer used here was extracted for a representative month of June 2019, when satellite derived measures of water clarity are considered reliable (due to the solar zenith angle) at latitudes in excess of 60° North. This timeframe ensured that exposure risk could be quantified for northern seas. The exposure risk map was downloaded from https://rsg.pml.ac.uk/thredds/ncss/grid/combined_alan_and_noise_risk/dataset.html on 12/11/2025. The supplied data were approximately 10 km resolution.

Individual exposure risk maps were created for each of the European Regional Seas by clipping the global map to regional sea polygons obtained from https://data.europa.eu/data/datasets/51035cd2-3dea-4b39-94c7-e53946603c2a?locale=en on 24/01/2023 (Fig. 1). The choice of metric by which exposure risk and hence GES is measured is critical. Quantifying exposure as a percentage of area, or using mean weighted exposure scores allows the size of the area to have undue influence due to the coastal nature of ALAN. Regions with large areas classified as high risk end up with low percentages because of their large size. Using such metrics would allow GES to be easily met by simply increasing the area considered.

An alternative approach might quantify exposure risk within bands at set distances from the coast. Such an approach would make percentage scores for the area falling within each classification comparable within each band between regions that are bounded by land, and those that have a single land border. It would also limit the influence of area on exposure risk.

We calculated the exposure risk scores across four bands representing different distances from European coastlines. The bands used were reflective of the spatial resolution of the data (10 km), and the exponential decay of light from its source. These were chosen as 0-10 km, 10-50 km, 50-100 km, and >100 km (Table 4). Buffering highly complex coastlines can be computationally inefficient. To improve speed without compromising accuracy, islands less that 25 km^2 were removed from land polygons, and the coastlines simplified to 1 km resolution prior to buffering. The percentage of pixels within each strip that were classified in each ALAN exposure category was calculated separately for each sea region (Table 4). Mean weighted exposure risk scores were also calculated for each coastline band (Table 4).

Considering exposure risk to ALAN within defined bands of distance from European coastlines allows important contextual details to be identified and acted on. For example, it is evident that for all European Regional Seas the 10 km strip of sea immediately adjacent to the coast is most impacted by ALAN. Exposure to ALAN beyond 100 km from the coast is nil for all regional seas, with the exception of the Greater North

Table 4
Exposure risk of Pelagic ecosystems to ALAN, broken down by distance from the coast and sea region.

Region	Distance from coast	Percentage of sea region area exposed to each ALAN exposure category				Mean weighted risk score
		Nil	Low	Medium	High	
Adriatic Sea	**0-10 km**	2	0	43	56	4
	10-50 km	17	7	62	14	3
	50-100 km	50	9	41	0	2
	>100 km	96	4	0	0	1
Baltic Sea	**0-10 km**	12	8	79	2	3
	10-50 km	30	13	57	0	2
	50-100 km	69	18	14	0	1
	>100 km	91	4	4	0	1
Western Mediterranean Sea	**0-10 km**	4	0	22	73	4
	10-50 km	20	5	55	20	3
	50-100 km	71	6	22	0	2
	>100 km	99	1	0	0	1
Greater North Sea	**0-10 km**	11	5	75	9	3
	10-50 km	21	10	67	2	3
	50-100 km	60	11	28	1	2
	>100 km	71	4	20	5	2
Aegean-Levantine Sea	**0-10 km**	16	4	42	37	3
	10-50 km	52	6	33	9	2
	50-100 km	81	4	15	0	1
	>100 km	99	0	1	0	1
Ionian Sea and the Central Mediterranean Sea	**0-10 km**	9	1	38	52	3
	10-50 km	37	6	47	10	2
	50-100 km	87	2	9	1	1
	>100 km	98	0	1	1	1
Black Sea	**0-10 km**	29	11	50	10	2
	10-50 km	48	12	39	1	2
	50-100 km	94	2	3	0	1
	>100 km	100	0	0	0	1
sea of Azov	**0-10 km**	48	21	31	0	2
	10-50 km	75	17	8	0	1
	50-100 km	100	0	0	0	1
	>100 km	na	na	na	na	na
Bay of Biscay and the Iberian Coast	**0-10 km**	2	0	49	49	3
	10-50 km	13	6	68	13	3
	50-100 km	69	9	22	0	2
	>100 km	100	0	0	0	1
Celtic Seas	**0-10 km**	37	7	54	2	2
	10-50 km	64	7	29	0	2
	50-100 km	93	1	5	0	1
	>100 km	99	0	1	0	1
White Sea	**0-10 km**	82	6	11	0	1
	10-50 km	95	3	2	0	1
	50-100 km	100	0	0	0	1
	>100 km	100	0	0	0	1
Norwegian Sea	**0-10 km**	19	2	62	18	3
	10-50 km	49	8	42	1	2
	50-100 km	94	3	3	0	1
	>100 km	100	0	0	0	1
Iceland Sea	**0-10 km**	52	6	36	6	2
	10-50 km	80	4	16	0	1

(*continued on next page*)

Table 4 (*continued*)

Region	Distance from coast	Percentage of sea region area exposed to each ALAN exposure category				Mean weighted risk score
	50-100 km	97	2	1	0	1
	>100 km	100	0	0	0	1
Barents Sea	**0-10 km**	77	1	17	4	1
	10-50 km	92	2	6	0	1
	50-100 km	99	1	0	0	1
	>100 km	100	0	0	0	1
Macaronesia	**0-10 km**	11	3	49	37	3
	10-50 km	75	4	19	3	1
	50-100 km	100	0	0	0	1
	>100 km	100	0	0	0	1

Sea, where extensive offshore energy infrastructure increases exposure risk from nil to low. Mediterranean Sea regions are consistently classified as being medium or high exposure risk within 10 km of the coastline along with the Greater North Sea, the Baltic Sea, the Norwegian Sea, and the Bay of Biscay. Far-reaching impacts of ALAN are prevalent in the Adriatic, Western Mediterranean, Greater North Sea, and the Bay of Biscay with each classified as medium risk between 10 and 50 km distant from the shore.

4.2. Quantifying GES for ALAN in benthic ecosystems

Exposure risk to ALAN was quantified using the classification system laid out in Table 3, applied to a 1 km^2 resolution raster atlas of benthic seafloor irradiance generated using the same approach as for *Zc* in pelagic ecosystems (Smyth et al., 2021). Given the increase in depth and hence likely reduction in ALAN exposure at the seafloor as distance to the coast increases, a coastal zone risk scoring approach similar to that applied in Table 4 was used. The higher resolution of the data (1 km^2) and rapid drop off in exposure with distance both enabled and necessitated narrower coastal zone boundaries. The nearest band was defined using the resolution of the input data as 0-1 km, followed by a 1-5 km band, a 5-10 km band and a >10 km band.

It should be noted that while the nearest band is restricted to the spatial resolution of the input data, we anticipate that a lot of variability in ALAN irradiance occurs within the 1 km band that is not effectively captured using our approach. This is because the atlas is only representative of large-scale geographical exposure resulting from artificial sky glow. Within the 1 km band, direct exposure to ALAN at intensities far in excess of those in Table 3 frequently occur at fine spatial scales, for example in ports and harbours (Davies et al., 2020). Table 3 can still be used to define whether exposure is 'Nil' to 'High' in these situations, however ALAN irradiance should be quantified directly using *in situ* measurements.

Table 5 provides a breakdown of ALAN exposure risk at the seafloor by EU regional seas and coastal zone bands. Exposure risk was lower for benthic ecosystems compared to pelagic ecosystems, as ALAN has to pass through the water column where it is attenuated before reaching the sea floor. Seafloor bathymetry plays a substantial role in determining ALAN exposure for benthic ecosystems. Deeper ecosystems that lie further offshore are less exposed compared to shallower ecosystems further inshore. By quantifying exposure across coastal strips however, values can be influenced by steep and shallower bathymetric profiles.

The majority of impact is seen within 1 km of the coast, with half of European sea regions classified as Low or Medium risk using the mean weighted risk score criterion. A third of sea regions were classified as Low risk in the 1-5 km band. Benthic ecosystems close to The Bay of Biscay and the Iberian Coast are at highest risk of ALAN exposure compared to other sea regions, likely because of extensive coastal

Table 5
Exposure risk of Benthic ecosystems to ALAN, broken down by distance from the coast and sea region.

Region	Distance from coast	Percentage of seafloor area exposed to each ALAN risk category				Mean weighted risk score
		Nil	Low	Medium	High	
Adriatic Sea	**0-1 km**	39	27	29	5	2
	1-5 km	63	24	12	1	2
	5-10 km	94	5	0	0	1
	>10 km	100	0	0	0	1
Baltic Sea	**0-1 km**	36	40	21	3	2
	1-5 km	62	27	11	1	2
	5-10 km	90	8	2	0	1
	>10 km	99	1	0	0	1
Western Mediterranean Sea	**0-1 km**	31	27	33	9	2
	1-5 km	68	19	12	2	1
	5-10 km	98	2	0	0	1
	>10 km	100	0	0	0	1
Greater North Sea	**0-1 km**	44	29	23	4	2
	1-5 km	62	24	13	1	2
	5-10 km	89	9	2	0	1
	>10 km	100	0	0	0	1
Aegean-Levantine Sea	**0-1 km**	51	26	18	5	2
	1-5 km	80	13	6	1	1
	5-10 km	99	1	0	0	1
	>10 km	100	0	0	0	1
Ionian Sea and the Central Mediterranean Sea	**0-1 km**	35	30	29	6	2
	1-5 km	62	25	12	1	2
	5-10 km	94	5	0	0	1
	>10 km	100	0	0	0	1
Black Sea	**0-1 km**	58	29	12	1	2
	1-5 km	79	16	4	0	1
	5-10 km	99	1	0	0	1
	>10 km	100	0	0	0	1
sea of Azov	**0-1 km**	65	30	6	0	1
	1-5 km	79	19	2	0	1
	5-10 km	97	3	0	0	1
	>10 km	100	0	0	0	1
Bay of Biscay and the Iberian Coast	**0-1 km**	12	27	49	12	3
	1-5 km	49	27	22	2	2
	5-10 km	95	5	0	0	1
	>10 km	100	0	0	0	1
Celtic Seas	**0-1 km**	67	23	9	1	1
	1-5 km	81	14	4	0	1
	5-10 km	98	2	1	0	1
	>10 km	100	0	0	0	1
White Sea	**0-1 km**	89	9	2	0	1
	1-5 km	91	8	2	0	1
	5-10 km	96	4	0	0	1
	>10 km	100	0	0	0	1
Norwegian Sea	**0-1 km**	70	21	9	0	1
	1-5 km	84	12	3	0	1
	5-10 km	96	4	0	0	1
	>10 km	100	0	0	0	1
Iceland Sea	**0-1 km**	70	20	8	2	1
	1-5 km	84	13	3	0	1
	5-10 km	97	3	0	0	1
	>10 km	100	0	0	0	1
Barents Sea	**0-1 km**	70	20	10	0	1
	1-5 km	84	12	4	0	1
	5-10 km	96	4	1	0	1
	>10 km	100	0	0	0	1
Macaronesia	**0-1 km**	73	16	9	2	1
	1-5 km	94	4	2	0	1
	5-10 km	100	0	0	0	1
	>10 km	100	0	0	0	1

development. The Adriatic Sea, Baltic Sea, Greater North Sea and the Ionian and Central Mediterranean Seas are the next most exposed regions, with 'Low' risk scores extending to 5 km from the coast.

While Table 5 provides some insight into the distribution of ALAN risk in benthic ecosystems across large spatial scales, the resolution of the data is insufficient to make determinations of risk in the most impacted nearshore ecosystems. The need for higher resolution spatial data, and LOBE thresholds defined using relevant species sensitivities to light are critical knowledge gaps inhibiting progress towards more relevant criteria for GES of ALAN in nearshore benthic ecosystems. While the approach outlined here is useful and insightful for management of ALAN emissions into the sea, we would expect that the threshold criteria and outcomes would continue to be revised as more data becomes available.

5. Discussion

We provide the first comprehensive methodology for defining the criteria by which Good Environmental Status (GES) for Artificial Light at Night (ALAN) may be assessed in EU marine waters. By integrating scientific evidence, policy context and methodological precedents, we demonstrate both the urgency and feasibility of fully incorporating ALAN into the Marine Strategy Framework Directive under Descriptor 11.

The results confirm that ALAN is now a widespread and ecologically significant pressure on marine ecosystems in European Seas. Coastal and offshore lighting associated with urbanisation, and infrastructure introduces biologically relevant light into both pelagic and benthic habitats, disrupting fundamental processes such as diel vertical migration, larval settlement and reproductive synchrony (Davies et al., 2023; Marangoni et al., 2022). Despite this, ALAN remains unregulated within national MSFD implementations, creating a clear gap between scientific understanding and policy action.

Drawing on the approach developed for underwater noise, we evaluated the suitability of a LOBE-based framework for ALAN. While recognising important differences between the two stressors—particularly in their spatial and temporal persistence and monitoring requirements—we demonstrated that the core principles translate effectively. In the absence of comprehensive, taxonomically balanced sensitivity data, we recommend adopting a precautionary LOBE threshold of 0.1 $\mu W\,m^{-2}$, derived from the most light-sensitive marine taxa currently documented.

A key advance in our approach is the explicit differentiation between pelagic and benthic ecosystems in defining GES criteria. For pelagic systems, exposure is quantified using satellite-derived estimates of the depth to which biologically important ALAN penetrates the water column, producing a four-tier exposure classification that is regionally comparable and readily operational. For benthic ecosystems, where habitats occur at fixed depths, a parallel classification is proposed based on ALAN irradiance experienced at the seafloor. This benthic framework acknowledges both the attenuation of light through the water column and the current limitations of species-specific sensitivity data, while still enabling meaningful large-scale assessment.

Application of these criteria across European Regional Seas highlights strong spatial heterogeneity in exposure. Enclosed and densely populated seas, such as the Adriatic and parts of the Mediterranean, consistently show the highest exposure across both pelagic and benthic habitats. In contrast, open ocean regions generally exhibit low mean exposure, though coastal zones across all regions emerge as consistent hotspots of risk. For benthic ecosystems in particular, impacts are largely concentrated within the first kilometre from the coast, underscoring the importance of targeted nearshore management.

6. Conclusion

There are currently no defined criteria of 'Good Environmental Status' (GES) for ALAN in EU waters, limiting the ability of member states to understand its impacts and legislate to reduce them. Here, we described the first proposed methodological approach to defining GES for ALAN, borrowing and adapting concepts used for underwater noise where applicable. Applying this methodology to EU regional seas revealed novel insights about the current status and future management of ALAN.

Importantly, our approach does not prescribe what constitutes GES. Instead, it establishes the methodological basis upon which GES can be defined, recognising that final thresholds will require political agreement, stakeholder consultation and alignment with broader MSFD objectives. By providing a scientifically grounded, operational and adaptable framework, this outline methodology positions ALAN as a pressure that is now sufficiently mature for integration into future MSFD cycles and regional sea convention processes. Following more than fifteen years of elevated ALAN exposure in the sea due to the introduction of LED's and with an impending review of the MSFD, our approach demonstrates that effective and scientifically grounded management of marine light pollution can be achieved through existing policy instruments.

CRediT authorship contribution statement

Thomas W. Davies: Writing – review & editing, Writing – original draft, Methodology, Funding acquisition, Formal analysis, Conceptualization. **Olivia R. Rendon Thompson:** Writing – review & editing, Methodology, Conceptualization. **Benjamin O'Driscoll:** Visualization, Resources, Methodology, Data curation. **Rosalyn Seddon:** Writing – review & editing, Methodology, Conceptualization. **Elena Maggi:** Writing – review & editing, Project administration, Funding acquisition. **Francesca Rossi:** Writing – review & editing, Funding acquisition. **Junio Fabrizio Borsani:** Writing – review & editing. **Tim Smyth:** Writing – review & editing, Methodology, Funding acquisition, Conceptualization.

Data statement

The artificial light at night exposure risk atlas can be visualised and extracted from https://aquaplan.eofrom.space/. The global atlas of artificial light at night under the sea can be visualised and extracted from https://aquaplan.eofrom.space/, with raw data layers available from https://doi.pangaea.de/10.1594/PANGAEA.969081.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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