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Ecological light pollution: Consequences for the aquatic ecosystem

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Abstract
Light Pollution is a growing concern for man and the environment. As awareness of the issue grows, various studies reveal its hitherto unnoticed effects on various organisms and ecological processes. The aquatic ecosystem has not been untouched by its influence either, and although much research is still required in the field, an attempt has been made to compile studies and reviews on the effects of Ecological Light Pollution on the world under water. Light has both direct and indirect influences on aquatic systems, and some possible consequences on various aspects of aquatic ecology have been extrapolated from existing studies. It has been attempted to bring attention to some implications that Ecological Light Pollution may have for the aquatic communities, and the aspects that require further investigation for a better understanding of the consequences of increased artificial illumination for entire aquatic ecosystems.

Keywords: Artificial light at night, benthos, ecological light pollution, nekton, plankton

1. Introduction

Light pollution can be defined as the alteration of natural light levels in the night environment by artificial light [1]. Increased artificial illumination has led to changes in the cycles of light and dark in the environment. This artificial light alters the spatial, temporal and spectral characteristics of the photic environment, creates a patchy light environment in illuminated areas, contributing to sky glow, resulting in illumination after sunset and creating spectra different than natural light [2]. The effects of light pollution and its components, such as Polarized Light Pollution and Artificial Light at Night consist of both overt as well as subtle influences on ecosystems and individual organisms. The responses to these stressors exist from the level of the individual to that of the entire ecosystem, and include physiological and behavioural responses in individuals, altered patterns of predation and competition, restructuring of food webs and changes in natural nutrient cycling patterns [3].

2. Ecological Light Pollution

The term “Ecological Light Pollution” describes artificial illumination that can alter natural patterns of light and dark in ecosystems [4]. Light is used both as a resource and a means of receiving information about the environment by organisms [2]. Thus any alterations in the natural regimes of light and dark would affect the way this resource is utilized. Excess irradiance can prove damaging for photosynthetic organisms, through the production of by-products and reactive intermediates [5]. In animals, artificial light may result in responses involving orientation or disorientation, attraction, fixation and repulsion; habitat quality change and disruption of natural rhythms by affecting the neuro-endocrine system [6]. The term ‘Polarized Light Pollution (PLP)’ is used to describe the effects of artificial light on the use of light and its direction of polarization by animals as a source of information [7].

Aquatic Ecosystems are also exposed to artificial light as a result of growing anthropogenic activities both in the water bodies and on their shores and banks, and it is important to pay attention to how artificial light changes the natural state of these ecosystems and their communities.

2.1. The Underwater Light Climate

The nature and conditions in different aquatic habitats creates differences in how light affects various processes and the organisms there.

Absorption of the red spectrum by pure water itself leaves wavelengths of the blue spectrum available to be utilized for photosynthesis. Suspended solids as well as detritus also contribute to absorption and scattering, although they're not very wavelength-specific. The photosynthetic pigments of both phytoplankton and macrophytes also contribute to absorption. Phytoplankton contributes to the phenomenon of scattering as well [8]. The specific absorption of wavelengths in aquatic systems depends on whether light is absorbed by gilvin and tripton, or by pure water. In oligotrophic systems, blue light penetrates the farthest. The high gilvin and tripton content of eutrophic bodies causes a shift to the red part of the spectrum [9].

2.2. Dissolved Nutrients

Nutrients in water are used by photoautotrophs, which in turn sustain grazers and higher trophic levels. Increased light availability enhances Nitrogen fixation by benthic algae, thus exerting an influence on the nutrient composition of aquatic environments by causing shifts between N-limiting and P-limiting conditions [10]. Nutrient assimilation is also affected by light-dark cycles, and continuous lighting can result in higher nutrient uptake from nutrient-rich waters [11]. Artificial light also alters grazing behaviour of zooplankton, resulting in a top-down regulation of available nutrients in the water [12].

2.3. Primary Producers and Photoinhibition

Although light is necessary for primary production by photoautotrophs, excessive irradiance can cause over excitation of the photoactive centres and thus damage the photosynthetic machinery of primary producers. Excess excitation energy accumulation caused by excessive illumination can result in an increased longevity of singlet chlorophyll, which is converted to triplet chlorophyll, which can react with ground state triplet oxygen molecules, converting them to highly reactive singlet molecules [5]. Thus these organisms employ 'Photoinhibition', which is the light-induced, reversible retardation of photosynthesis [13]. Non-Photochemical-Quenching works as a feedback loop which relies on the activation of violaxanthin de-epoxidase in response to absorption of excess photons [5]. The phenomenon has been observed in many aquatic species, including diatoms, cyanobacteria, various algae and seaweeds, and symbiotic algae in corals [14-17].

2.4. Plankton Communities

Plankton, a food source for various aquatic organisms, play a crucial role in important processes of population dynamics of various species, including the recruitment of economically important fish such as the Atlantic Cod through match-mismatch mechanisms [18]. Since the phytoplankton community is dependent on light and utilize irradiation to produce food, they are affected by changes in light quality and availability in water, mainly through changes in pigments and photosynthetic machinery and processes [19, 20]. ALAN has also been shown to have effects on the ash-free mass and gross primary productivity of diatoms [21]. Though the effect of excess irradiance on phytoplankton is exerted through photoinhibition, it varies across habitats as estuarine diatoms display a greater capability for photoprotection than coastal and oceanic species [22].

Responses of zooplankton to light include photokinesis, phototaxis, polarotaxis, and photophobic responses [23]. ALAN can affect zooplankton distributions in the water column as well as the diel migrations and grazing behaviour. Urban Light Pollution was shown to cause a decrease in both amplitude and magnitude of diel vertical migrations of *Daphnia* in Lake Waban and limit their grazing on algae, thus having further implications on the water quality of the lake [12]. Arctic zooplankton communities also show strong light-escape responses to artificial light [24]. Since these vertical migrations are also a means of escaping predators [25], alteration in this behaviour may result in changes in the feeding behaviour of planktivorous species.

Since the plankton exert an influence on the aquatic environment through important bottom-up and top-down processes [26-27], it is important to study how our need for artificial lighting inadvertently affects the plankton communities in natural water bodies.

2.5. Benthic Biofilm and Macroinvertebrate Communities

Benthic biofilms are composed of algae, cyanobacteria, heterotrophic bacteria, fungi as well as micro- and meio-fauna, all dependent on each-other and playing a role in the succession of the community [28, 29]. Light affects benthic algae differently than phytoplankton, and is more limiting in its role than nutrients for them. Light plays an important role in regulating the C:N ratio and biomass in periphytic communities, which then regulates the biomass of the macroinvertebrates that feed on them [30]. Therefore it is important to understand how the natural cycles of light and dark and any anthropogenic alterations thereof affect the microphyotobenthic communities.

Diatoms from microphytobenthic biofilms employ vertical migration in response to excess illumination. When vertical migration is inhibited, these diatoms show photoinhibition [31]. ALAN can also alter benthic community structure, causing an increase in photoautotroph abundance in aquatic sediments, accompanied by decreased nocturnal respiration [32]. In sub-alpine streams, ALAN has been shown to have an impact on early periphytic community composition, resulting in changes in the proportion of cyanobacteria and diatoms in the spring and autumn respectively, and also causing a decrease in biomass of the autotrophs in both seasons [33]. Benthic invertebrates depend on light intensity and wavelength as cues for settlement [34], and changes in light quality may alter the benthic invertebrate community structure both directly [35] and indirectly. Since these communities also have great significance in aquatic food webs, it is possible that artificial light may have more profound effects on the community composition of natural water bodies through its influence on planktonic and benthic communities.

2.6. Nekton Communities

The free-swimming organisms of aquatic habitats include invertebrates, fishes, amphibians, reptiles and mammals. Each of these organisms needs light for different purposes, and responds differently to any alterations in the natural patterns of light and dark.

The effects of PLP are seen across various groups of insects, crustaceans, birds, amphibians, reptiles and fish. PLP causes alterations in habitat selection, reproductive behaviour, navigation and orientation responses, and foraging and predation behaviour [7]. The orientation responses and their magnitude varies across different groups- aquatic insects are more vulnerable to artificial lighting, and are easily attracted to streetlights and light bulbs, which affects their dispersal across the aquatic habitat [36].

Light intensity can limit foraging behaviour of amphibians, as many species of frogs and toads cease foraging activities when exposed to enhanced illumination [37]. The breeding behaviour of frogs is negatively affected by artificial lights, as male frogs produce fewer calls to potential mates and move more frequently when exposed to artificial light. These modified reproductive behaviours can have consequences for reproductive success and recruitment of a species [38]. Turtles are especially vulnerable to the disorientation effects of artificial lights, which affect their nesting behaviour. Hatchlings often find it difficult to find their way to the sea on artificially lit beaches, resulting in mortality due to exhaustion and predation [39-41].
Light is an important factor affecting feeding, migration and schooling behaviours of fish and the responses of fish to illumination vary across individuals, species, age or life stages and habitats [42]. Artificial lights are known to affect migratory behaviour of various fish, including the European Eel [43] and Atlantic Salmon [44]. Predators of migratory fish, such as seals, use the light-shadow boundary created by artificial lights to increase their hunting efficiency [45]. These phenomena can severely affect the recruitment of migratory species. Continuous exposure to artificial light can alter behaviour and energy expenditure of fish exhibiting parental care, affecting the parental care, nest guarding behaviour and efficiency of such species [46].

2.7. Community Structure and Food Web Ecology
Light availability and penetration are important in determining the dominant primary producers in an aquatic habitat. Light availability, rather than nutrient availability plays a significant role in determining the primary productivity of nutrient-poor lakes [47]. The retention of leaves by deciduous plants [48] may have implications for the nutrient input into aquatic habitats and consequently the metabolism of the ecosystem itself [3]. Such changes in allochthonous inputs of organic matter can have great implications for habitats such as headwater streams, where shredders and collectors process this Coarse Particulate Organic Matter into Fine Particulate Organic Matter for use by organisms in the lower reaches of rivers [49]. Artificial lighting can alter the structure of stream communities and their ecosystem function by altering reciprocal stream-riparian invertebrate fluxes [50]. Different intensities of artificial light have different effects on the efficiency of different organisms, and the level of ALAN exposure has been shown to influence the strength of top-down control in insect food webs [51].

3. Conclusion
The effects of Ecological Light pollution vary across different communities, and also across habitats for similar organisms. Since its effects start with covert physiological alterations that result in behavioral changes and then ultimately in alterations in community assemblages which have further implications in aquatic habitats through top-down and bottom-up control mechanisms, it is necessary to study the processes behind these. ELP has the potential to alter population structures by affecting recruitment of species and thus have consequences that go beyond individual organisms and species to affect entire food webs and water and sediment quality as well. It is therefore necessary to study the responses of different communities to ELP and devise methods to reduce its impact on the aquatic environment.

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