Article title: Light pollution: A landscape-scale issue requiring cross-realm consideration

Authors: Mariana Mayer-Pinto[1], Theresa M. Jones[2], Stephen E. Swearer[3], Kylie A. Robert[4], Damon Bolton[5], Anne E. Aulsebrook[6], Katherine A. Dafforn[7], Ashton L. Dickerson[8], Alicia M. Dimovski[9], Nikki Hubbard[10], Lucy K. McLay[11], Kellie Pendoley[12], Alistair G.B. Poore[13], Michelle Thums[14], Nikolas J. Willmott[15], Kaori Yokochi[16], Emily K. Fobert[17]

Affiliations: Centre for Marine Science and Innovation, Evolution and Ecology Research Centre, School of Biological, Earth and Environmental Science, University of New South Wales, Sydney, NSW 2052, Australia[1], School of BioSciences, University of Melbourne, Parkville, VIC 3010, Australia[2], National Centre for Coasts and Climate (NCCC), School of BioSciences, University of Melbourne, Parkville, VIC 3010, Australia[3], Department of Ecology, Environment & Evolution, La Trobe University, Melbourne, VIC 3086, Australia[4], School of BioSciences, University of Melbourne, Parkville, VIC 3010, Australia; Department of Behavioural Ecology and Evolutionary Genetics, Max Planck Institute for Ornithology, Seewiesen 82319, Germany[5], Department of Earth and Environmental Sciences, Macquarie University, North Ryde, NSW 210 Australia[6], Agriculture Victoria Research, Bundoora, VIC 3083, Australia[7], Pendoley Environmental Pty Ltd, 12A Pitt Way, Booragoon, WA 6154, Australia[8], Australian Institute of Marine Science, Indian Ocean Marine Research Centre, University of Western Australia, Crawley, WA 6009, Australia[9], Centre for Integrative Ecology, School of Life and Environmental Sciences, Deakin University, Burwood, VIC 3125, Australia[10], School of BioSciences, University of Melbourne, Parkville, VIC 3010, Australia; College of Science and Engineering, Flinders University, Bedford Park, SA 5042, Australia[11]

Orcid ids: 0000-0001-9679-7023[1]

Contact e-mail: m.mayerpinto@unsw.edu.au

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Professor Dan Osborn
Editor-in-Chief
UCL Open: Environment

Dear Professor Osborn,

Please find our manuscript entitled '**Light pollution: A landscape-scale issue requiring cross-realm consideration'**, by M. Mayer-Pinto and collaborators, which we would like you to consider for publication in *UCL Open: Environment*.

Artificial light at night (ALAN) is expected to profoundly impact most ecosystems on the planet by disrupting a fundamental driver of and evolutionary processes: natural light cycles. ALAN is an emergent global stressor and affects approximately one-quarter of the planet. It can impact a wide range of organisms and habitats as well as multiple realms. Terrestrial (including air and land), marine, and freshwater realms are inherently linked through ecological, biogeochemical and/or physical processes. Nevertheless, current management practices for light pollution rarely consider connectivity between realms.

Here, we discuss the ways in which ALAN can have cross-realm impacts and provide case studies for each example discussed. We identify three main ways in which ALAN can affect two or more realms: 1) through impacts on species that have life cycles and/or stages on two or more realms, such as diadromous fish that cross realms during ontogenetic migrations and many terrestrial insects that have juvenile phases of the lifecycle in aquatic realms; 2) impacts on species interactions that occur across realm boundaries, and 3) impacts on transition zones or ecosystems such as mangroves and estuaries.

We consider the consequences of taking a single-realm approach to light pollution management and propose a framework for cross-realm management of ALAN, incorporating both theoretical and empirical considerations. We then discuss current challenges and potential solutions to increase the uptake of a cross-realm approach for light pollution management. Given ALAN is projected to increase in all three realms in response to continuing human population growth, cross-realm management will be critical for ensuring the ongoing resilience of ecosystems.

We believe this critical and timely article will be of broad interest to the readers of *UCL Open: Environment* and fills important gap in the research.

On behalf of the authors, I can confirm that none of the manuscript has been previously published or is being considered for publication in any other journal or a book. The authors have seen the manuscript and agree to its submission for publication.

Yours Sincerely,

Dr Mariana Mayer Pinto
Scientia Senior Lecturer
Centre of Marine Science and Innovation; Evolution & Ecology Research Centre
School of Biological, Earth and Environmental Sciences
University of New South Wales, Sydney NSW 2052

Light pollution: A landscape-scale issue requiring cross-realm consideration

Mayer-Pinto M.[1*]; Jones T.M.[2]; Swearer S.E. [3]; Robert K.A.[4]; Bolton D.[1]; Aulsebrook A.E. [2,5]; Dafforn K.A. [6]; Dickerson A.L. [2]; Dimovski A.M.[4]; Hubbard N.[1]; McLay L.K.[7,]; Pendoley, K. [8], Poore, A.G.B.[1]; Thums, M.[9], Willmott N.J.[2]; Yokochi K.[10] & Fobert E.K.[2,11]

[1] Centre for Marine Science and Innovation, Evolution and Ecology Research Centre, School of Biological, Earth and Environmental Science, University of New South Wales, Sydney, NSW 2052, Australia

[2] School of BioSciences, University of Melbourne, Parkville, VIC 3010, Australia

[3] National Centre for Coasts and Climate (NCCC), School of BioSciences, University of Melbourne, Parkville, VIC 3010, Australia

[4] Department of Ecology, Environment & Evolution, La Trobe University, Melbourne, VIC 3086, Australia

[5] Department of Behavioural Ecology and Evolutionary Genetics, Max Planck Institute for Ornithology, Seewiesen 82319, Germany

[6] Department of Earth and Environmental Sciences, Macquarie University, North Ryde, NSW 2109, Australia

[7] Agriculture Victoria Research, Bundoora, VIC 3083, Australia

[8] Pendoley Environmental Pty Ltd, 12A Pitt Way, Booragoon, WA 6154, Australia

[9] Australian Institute of Marine Science, Indian Ocean Marine Research Centre, University of Western Australia, Crawley, WA 6009, Australia

[10] Centre for Integrative Ecology, School of Life and Environmental Sciences, Deakin University, Burwood, VIC 3125, Australia

[11] College of Science and Engineering, Flinders University, Bedford Park, SA 5042, Australia

* corresponding author: m.mayerpinto@unsw.edu.au

ABSTRACT

Terrestrial, marine, and freshwater realms are inherently linked through ecological, biogeochemical and/or physical processes. An understanding of these connections is critical to optimise management strategies and ensure the ongoing resilience of ecosystems. Artificial light at night (ALAN) is a global stressor that can profoundly affect a wide range of organisms and habitats and impact multiple realms. Despite this, current management practices for light pollution rarely consider connectivity between realms. Here we discuss the ways in which ALAN can have cross-realm impacts and provide case studies for each example discussed. We identified three main ways in which ALAN can affect two or more realms: 1) impacts on species that have life cycles and/or stages on two or more realms, such as diadromous fish that cross realms during ontogenetic migrations and many terrestrial insects that have juvenile phases of the lifecycle in aquatic realms; 2) impacts on species interactions that occur across realm boundaries, and 3) impacts on transition zones or ecosystems such as mangroves and estuaries. We then propose a framework for cross-realm management of light pollution and discuss current challenges and potential solutions to increase the uptake of a cross-realm approach for ALAN management. We argue that the strengthening and formalisation of professional networks that involve academics, lighting practitioners, environmental managers and regulators that work in multiple realms is essential to provide an integrated approach to light pollution. Networks that have a strong multi-realm and multi-disciplinary focus are important as they enable a holistic understanding of issues related to ALAN.

KEY-WORDS: ALAN, artificial light at night, light pollution, multi-disciplinary, adaptive management, ecological connectivity.

INTRODUCTION

Artificial light at night (ALAN) is a widespread anthropogenic pollutant that is rapidly increasing in intensity and global distribution. The most current estimates suggest that more than 80% of the human population, and nearly a quarter of the global land area, are exposed to light-polluted skies (Falchi et al. 2016). Consequently, ALAN is reaching most ecosystems globally, with the potential for profound impacts. At its core, ALAN alters natural light-dark cycles, disrupting a key driver of ecological and evolutionary processes (Gaston et al. 2014, Hopkins et al. 2018). Emergent research has linked the presence of ALAN to altered physiology of plants (Bennie et al. 2016) and animals (Dominoni et al. 2013) shifts in activity patterns, behaviours, reproduction and survival of animals (Robert et al. 2015, Sanders et al. 2020); disruption of trophic and non-trophic species interactions (Bennie et al. 2015, Gaston et al. 2017); and, significant changes to the structure of ecological communities (Davies et al. 2015, Hölker et al. 2015). The importance and severity of potential impacts of this stressor are increasingly recognised across multiple taxa, habitats and/or ecosystems (Sanders et al. 2020) and there is an increased desire to devise management strategies to minimise ecological impacts of ALAN.

A major challenge with mitigating the impacts of ALAN is that, while it is a global environmental pollutant (Falchi et al. 2016) that damages ecological systems (Sanders et al. 2020), it is also central to the functioning of modern human society (Edensor 2017). However, beyond natural systems, ALAN can pose public health risks (Pauley 2004) and is energetically and economically costly (Gallaway et al. 2010). Strategies to address the ecological challenges posed by ALAN therefore need to be interdisciplinary, involving researchers (e.g. ecologists, physiologists, social scientists, physicists), managers or regulators (e.g. local councils and government agencies), and practitioners (e.g. urban planners, developers, health specialists, and lighting professionals). While interdisciplinary frameworks have been developed to foster collaboration among researchers, managers and practitioners to better manage urban lighting (e.g. Pérez Vega et al. 2021), they are largely applied within an individual realm (i.e. terrestrial (including land and air), freshwater or marine), rather than considering the potential for light pollution to transcend multiple realms or operate at the realm interface. Current management practices for light pollution do not consider connectivity between realms. Although realms are often considered as separate entities, they are intrinsically linked through ecological, biogeochemical and/or physical processes. Where these linkages are compromised, ecosystem functioning and services might be affected and systems can become less biodiverse and less resilient to change (Beger et al. 2010, Field and Parrott 2017). The lack of a multiple-realm integrated approach means outcomes of practices are limited, at best, to small-scale, localised and/or temporary benefits (Threlfall et al. 2021).

In this paper, we review examples where ALAN affects two or more realms, directly and/or indirectly. We use the term ‘realm’ as defined by Bugnot et al. (2019), to encompass a group of ecosystems that share common physical and ecological attributes (e.g. the marine realm includes all ecosystems present below the high tide mark while the terrestrial realm includes both air and land). We discuss the consequences of taking a single-realm approach to light pollution management and present a framework to help bridge this gap, incorporating both theoretical and empirical considerations. We also discuss existing challenges and hurdles to studying and managing light pollution. Given ALAN is projected to increase in all three realms in response to continuing human population growth (Kyba et al. 2017), cross-realm management will be critical for ensuring the ongoing resilience of ecosystems (Threlfall et al. 2021).

Impacts of ALAN on two or more realms

Mitigating the impacts of ALAN and prioritising conservation actions requires consideration of the fundamental interactions among multiple realms (e.g. terrestrial, marine and freshwater) (Beger et al. 2010). Realms may be linked through ecological, biogeochemical, or physical processes (or combinations of these), including the movement of organisms, materials and energy between ecosystems and realms; this link is broadly referred to as ecological connectivity (Taylor et al. 1993). Shifts in ecological connectivity through the disruption of daily, seasonal or cyclic movement of organisms or resources will likely have consequences across multiple realms. For example, changes to predation and foraging behaviours at the level of the individual or community (e.g. species diversity and richness) can have cross-realm implications due to trophic cascades and linked changes in ecosystem function through nutrient cycling or pollination. This is particularly true if the organisms involved typically function across realm boundaries. Similarly, individual-level shifts can have cross-realm ecological consequences if the species in question has life histories or migratory patterns that traverse multiple realms, such as the two case studies we discuss below, salmon (freshwater juveniles, marine adults) and secondarily aquatic insects (aquatic juveniles, terrestrial adults).

ALAN-driven impacts include changes in the phenology, growth form and resource allocation of plants (Bennie et al. 2016), as well as the behaviour, physiology, distribution and survival of animals (Brüning et al. 2011, Perkin et al. 2014, Bolton et al. 2017, Fobert et al. 2019, Willmott et al. 2019, Aulsebrook et al. 2020). Mechanisms driving such impacts, which could then directly or indirectly affect other realms, include changes in the flux of inorganic and organic material. Changes in oxygen and nutrient fluxes, for example, can potentially directly impact land, sea and freshwater habitats (Hölker et al. 2015, Grubisic et al. 2017). Indirect effects can be driven by bottom-up or top-down processes. Bottom-up processes occur when effects on primary producers (e.g. algae or autotrophic microbes) affect populations at higher trophic levels through changes in resource availability. For example, an increase or reduction in the diversity and abundance of aquatic insects due to ALAN is expected to have implications for terrestrial consumers that rely on aquatic prey, such as spiders, birds and bats (Baxter et al. 2005, Zapata et al. 2019). Alternatively, changes may be driven by top-down processes, arising from impacts on, for example, the survival or behaviour of herbivores and/or predators. Consequences of such changes are varied and dependent on the magnitude of change, but may result in loss of biodiversity (Bowyer et al. 2005).

ALAN is also likely to have cross-realms consequences if the effects occur within ecosystems that link multiple realms – i.e. transitional zones – such as estuaries and coastal wetlands, which are at the intersection of freshwater, marine, and terrestrial realms. Such zones, and the organisms that inhabit them, tend to be disproportionally affected by ALAN, because urban settlements where ALAN is prevalent, are often developed near waterways (Kummu et al. 2011).

Rapid changes in the environment, such as those caused by ALAN, can alter environmental cues used by many animals to select optimal habitats that maximise their fitness (Hale and Swearer 2016, Swearer et al. 2021). Such ‘ecological traps’ can promote disruptions or alterations in the movement patterns of organisms, resulting in increased risk of mortality and/or shifts in trophic interactions (Schlaepfer et al. 2002), with potential implications for multiple realms. Examples that have major consequences for species in multiple realms include turtle hatchlings crawling inland towards artificially-lit beach fronts instead of heading seaward (Witherington and Bjorndal 1991), or once reaching the ocean, swimming towards lights on water such as on boats, piers or other nearshore infrastructure (Thums et al. 2016, Wilson et al. 2018). This can have serious implications for the health of seagrass meadows, with likely flow-on effects on the diversity supported by these important habitats (e.g. Hernández and van Tussenbroek 2014). Similarly, terrestrial insects can fall for these ecological traps if they attempt to land or lay eggs on impervious concrete surfaces that reflect light and thus are mistaken for water (Horváth et al. 2009). This failure to lay eggs in the appropriate habitat can impact offspring survival with cross-realm impacts. While ecological traps do not inherently have cross-realm impacts, the impacts of ecological traps created by ALAN can cross realm boundaries if it disrupts species interactions or movements that occur across more than one realm (see Box 1).

Based on the above, we have identified three broad 'ways' where there is evidence, or likelihood, of ALAN- related cross-realm impacts; they operate by impacting: 1) species that move across realms, through life cycles and/or stages or migratory patterns that occur in two or more realms, such as diadromous fish and many insects, as well as marine reptiles, mammals (e.g. seals) and birds (e.g. penguins and albatross) that are tied to land for breeding and/or resting; 2) species interactions, such as predator-prey interactions, that occur across realm boundaries; and 3) transitioning zones or ecosystems such as coastal wetlands and estuaries, which inherently link realms. The impacts of ALAN on these cross-realm linkages can be further altered or exacerbated if light pollution is acting as an ecological trap (see Box 1). Below, we provide examples or case studies, where possible, stating observed or inferred/likely effects of ALAN, and discuss their cross-realm consequences.

1) Impacts on species with life cycles/stages across two or more realms

The life cycles of many organisms occur in two or more realms. Examples include animals whose juveniles are aquatic while adults are predominantly marine or terrestrial, or marine animals that breed on land or in freshwater systems. Impacts of ALAN on any one stage are, therefore, predicted to have carry-over effects on subsequent life-stages, consequently impacting different realms. We use two case studies to illustrate this, one on salmon (Salmonidae) and the other gives a broader overview of secondarily aquatic insects, such as dragonflies and mayflies.

Case study 1 – Salmon, a vector of energy and nutrients across realms

Salmon, including the Atlantic (*Salmo salar*) and Pacific Salmon (*Oncorhyncus* spp.), are anadromous fish, meaning they spend their juvenile phase (e.g. alevins, fry, and parr) in rivers, before migrating to the ocean as smolts (1-3 yr old juveniles that are physiologically adapted for sea water) to feed, grow, and mature. Adults then return to freshwater systems for spawning (Figure 1). ALAN has demonstrable impacts on several life-stages of salmons including fry (Riley et al. 2013, Riley et al. 2015) and smolts (Riley et al. 2012). For example, emergence of juvenile Atlantic salmon in streams is usually mediated by environmental cues, such as presence of predators (Jones et al. 2003). Fry are highly vulnerable to predation, and synchronous emergence can increase their chances of survival (Brännäs 1995). ALAN associated with human populations along river systems is linked to asynchronous nocturnal emergence, disrupted dispersal and decreased weight of fry in the freshwater realm (Riley et al. 2013). This has knock-on effects for population recruitment and predation risk given that both synchronous nocturnal emergence and dispersal are posited as predator avoidance mechanisms (Riley et al. 2013). At the smolt stage in the marine realm, ALAN associated with aquaculture practices, for example, can alter the vertical movement of salmon, causing trade-offs between preferred light and temperature levels, feeding, and risk perception (Oppedal et al. 2011). Furthermore, a field experiment showed that smolt populations exposed to ALAN from streetlights presented altered migratory behaviour, potentially impacting their fitness and/or predation risk (Riley et al. 2012), with likely consequences for the total biomass of fish surviving to the ocean life-stage.

In addition to the direct impacts on salmon, these fish are important vectors in transporting energy and nutrients between the ocean, freshwater and terrestrial environments (Gende et al. 2002); therefore, impacts in one environment will likely have cross-realm consequences (Figure 1). For example, migrating adult salmon serve as a food resource for terrestrial wildlife as they travel upstream to spawn. Bears alone move up to 90% of all salmon biomass to land, sometimes hundreds of meters from their stream of origin (Reimchen 2000). Salmon-derived minerals and nutrients are further spread in the terrestrial environment through bear urine and faeces as these mammals move throughout the riparian and upland forests (Hilderbrand et al. 1999). Salmon also support freshwater systems by providing nutrients from their carcasses following spawning (Juday et al. 1932) and play an important role in the marine food-web during their migratory stage to the sea (Gende et al. 2002). Therefore, efforts to mitigate the impacts of ALAN on salmon, that are solely focused in one realm may be ineffective and economically wasteful if impacts from/in other realms are not considered.

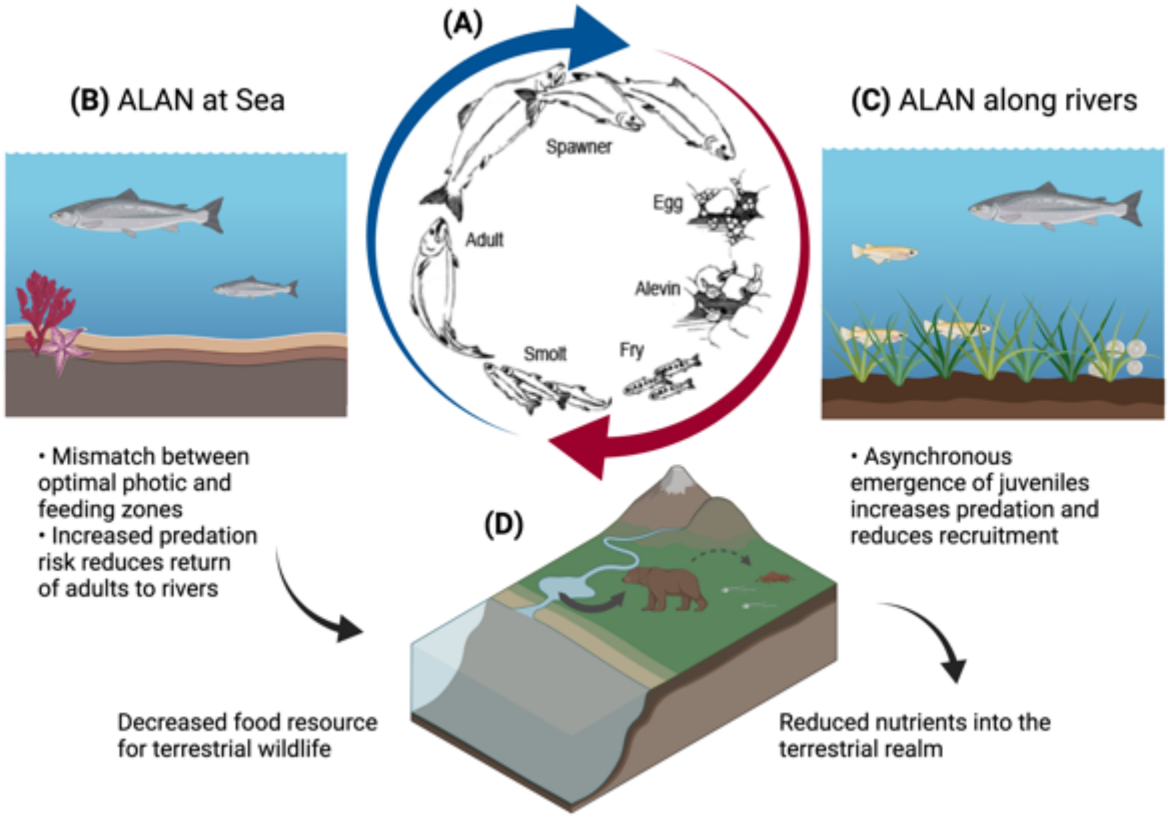

Figure 1 - Schematic figure showing the potential cross-realms impacts of ALAN due to effects on different life stages in salmon species. (A) Salmon spend their juvenile phase in rivers before migrating to sea to grow and mature. To complete their life cycle they must return to the river to spawn. (B) ALAN at sea alters vertical movement of fish resulting in a mismatch between preferred light levels and optimal feeding zones. Additionally, ALAN results in increased predation of fish at sea and hence a decrease in adults returning to rivers. (C) ALAN along rivers disrupts synchronous emergence of juveniles resulting in increased predation which then reduces the recruitment of smolts out to sea. This reduction in adults returning to rivers and smolts migrating to sea results in trophic effects in both realms. (D) Illustrates one trophic effect in the terrestrial environment with reduced food resources for bears resulting in reduced nutrients into the terrestrial environment. Image created with BioRender.com.

Case study 2 - Aquatic insects (with terrestrial adults)

Secondarily aquatic insects - those with an aquatic egg and juvenile phase and a terrestrial adult phase - are proposed as ideal bioindicators to assess the impact of cross-realm (aquatic and terrestrial) environmental change due to their sensitivity to anthropogenic stressors (Villalobos-Jimenez et al. 2016). However, there is an overall lack of direct evidence for how impacts in any one of these realms can influence others. Moreover, there is surprisingly little information regarding the specific impact of ALAN on the independent life history stages of secondarily aquatic insects: in the largest review of urban impacts on dragonflies, ALAN was not even included (Villalobos-Jimenez et al. 2016). Nevertheless, the overall life-history knowledge we have on these organisms, coupled with the current existing information on ALAN impacts on insects and their habitats more broadly, allows us to infer/hypothesise likely cross-realms impacts. For instance, the effect of variation in moonlight on adult insect activity has been long documented (Williams and Singh 1951) and it is well recognised that artificial lighting is attractive to adult insects, with this behaviour being commonly exploited when trapping potential pests (Shimoda and Honda 2013). Furthermore, increasing evidence suggests that artificial light at night will have multiple negative consequences for stream and riparian habitats (Perkin et al. 2011). Therefore, we discuss ways in which ALAN is likely to have cross-realms impacts through effects on both the terrestrial and aquatic life stages of secondarily aquatic insects.

Ecologically, dragonflies, mayflies and mosquitoes are classic examples of secondarily aquatic insects that have a relatively short terrestrial adult phase and a protracted aquatic egg and larval phase. The transition from the juvenile aquatic environment to the terrestrial adult environment is varied and taxon-specific. For example, prior to their final moult, dragonfly nymphs typically move up out of the water (usually at night) onto a branch or other structure where they eclose and emerge as air-breathing terrestrial adults. Mosquitoes remain in the aquatic environment emerging directly into the terrestrial environment as adults, typically remaining at the surface to allow their wings to dry and harden. Mayflies are hemi-metabolous and thus do not have a pupal stage, instead they either emerge into the terrestrial environment as a winged subadult (or sub-imago) and then rapidly moult to adults.

The mechanisms that promote ALAN-specific cross-realm impacts for secondarily aquatic insects are varied. Point sources of ALAN close to streams or water bodies may change patterns of dispersal (geographic or temporal; Manfrin et al. 2017) and/or act as ecological traps for newly emerging adults (Eisenbeis et al. 2006, Perkin et al. 2011). Such behaviours may lead individuals away from the aquatic environment required for mating and egg laying (Eisenbeis et al. 2006, Perkin et al. 2011) and into an environment where the risk of predation is increased (Davies et al. 2012). Some species (e.g. dragonflies) are also positively polarotactic, using horizontally polarized light to locate suitable water bodies for mating and egg laying (Kriska et al. 2009). In areas with anthropogenic sources of polarised light (asphalt surfaces, vertical glass and even vehicles) these behaviours can be disrupted leading surviving adults to aggregate and females to oviposit on suboptimal non-aquatic surfaces where juvenile survival is reduced or non-existent (Horváth et al. 2014). Similar effects are documented for mayflies and caddisflies, whose attraction to anthropogenic sources of polarised light at night can reduce reproductive success and increase risk of predation by light-attracted insectivores, such as birds, lizards or spiders (Robertson et al. 2010, Szaz et al. 2015).

Assuming eggs are laid in a body of water, the protracted aquatic juvenile phase may be vulnerable to the impact of ALAN. Evidence from other insects suggests aquatic juveniles may be directly attracted to external light sources, leading to shifts in foraging or other activity patterns (Kühne et al. 2021), which may result in increased predation risk (Manfrin et al. 2018). Prolonged juvenile exposure to ALAN may also negatively impact growth, development and survival, as shown in crickets (*Teleogryllus commodus*) (Durrant et al. 2018) or reduce fecundity (McLay et al. 2017, Willmott et al. 2018). Finally, ALAN may have indirect impacts by promoting shifts in the aquatic community structure, reducing availability of prey (Hölker et al. 2015). Ultimately, the degree to which exposure to ALAN results in selection of particular juvenile phenotypes that survive to the adult stage (Hopkins et al. 2018). The impact this has on juvenile or adult life history decisions, including flight to light behaviour is unknown. Nevertheless, impacts are expected. Hence, such knowledge is critical if we are to understand the fitness consequences for species, such as secondarily aquatic insects, that cross multiple realms and their knock-on effects.

2) Impacts on species interactions that involve two or more realms

To date, most studies on ALAN focus on the evolutionary and ecological consequences of ALAN at the level of the individual or population within a single realm (e.g. terrestrial, Sanders et al. 2020). However, the loss of, or changes in, species within a system can affect an entire cross-realm network, through altered competition and/or food-web interactions, with unpredictable consequences for communities, ecosystems (Eklöf and Ebenman 2006) and other, connected, realms (Bugnot et al. 2019). Below, we highlight two case studies where observed or inferred effects of ALAN for one species or group are expected to affect multiple realms through species interactions and knock-on effects.

Case study 3 - Fishing bats: terrestrial mammals specialised for feeding in aquatic ecosystems

Worldwide, there are 16 species of fishing or trawling bats (e.g. from the genus *Myotis*). This group has ecological and foraging specialisations that make them reliant on both terrestrial and aquatic realms (Campbell 2011). Fishing bats roost in caves, aqueducts, bridges, tunnels and tree cavities in the vicinity of water sources (Campbell 2009, Gorecki et al. 2020) and forage exclusively on aquatic prey using their feet to trawl the surface of water for fish and aquatic insects (Dwyer 1970, Law and Urquhart 2000, Campbell 2007). An emerging issue facing fishing bats that depend on surface foraging in waterways is the shifts in the aquatic prey behaviour driven by ALAN. Such shifts often result in changes in the distribution and behaviour of prey, which affect the bats' ability to forage (Figure 2). Fishing and trawling bats cannot detect submerged prey (Suthers 1965) and instead rely on echolocation of water surface irregularities created by fish and aquatic invertebrates (Thompson and Fenton 1982). Light is a critical cue for diel vertical migration: during the day, aquatic invertebrates (potential prey items) move downwards from the water's surface to deeper water, while during the night, prey move upwards to the surface (Perkin et al. 2011, Mehner 2012). Darkness is also a cue for the emergence of adult aerial invertebrates from the aquatic realm (Manfrin et al. 2017). Under ALAN, nocturnal vertical migration of invertebrates to the surface is reduced and fishing bats are limited in their ability to detect their aquatic prey. This reduction in foraging is compounded by the absence of smaller fish which in the presence of ALAN hide in the shadows.

To understand the impacts of ALAN on waterways, consideration of the direct impacts of ALAN on movement patterns of resident aquatic species, as well as the direct and indirect impacts on terrestrial species that feed on those aquatic species is required. For example, fishing bats appear to be light averse and actively avoid lit areas, possibly due to increased risk of predation (Straka et al. 2016), which reduces their ability to capitalise on the increased emergence of some aquatic insects and the attraction of aerial invertebrates to lights. Accordingly, experimental research highlights a reduction in recorded feeding attempts when waterways are lit (Haddock 2019), suggesting they are unable to switch prey resources to take advantage of the abundance of aerial insects attracted to the light source.

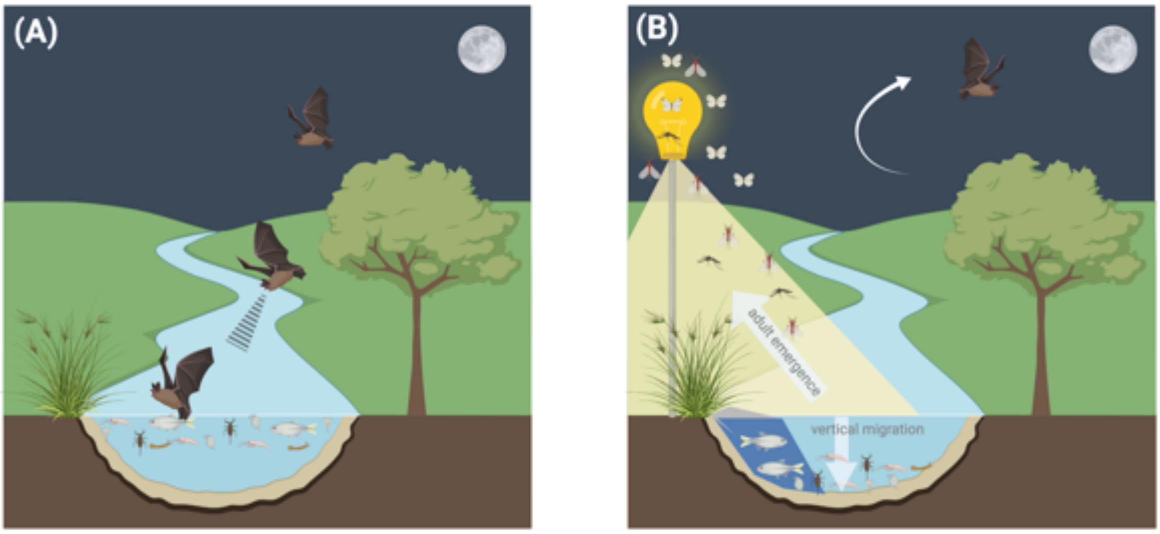

Figure 2 - (A) Schematic figure depicting the aquatic ecosystem with fishing bats under natural light (B) and how artificial light at night influences prey species. As artificial light is introduced, aquatic prey species migrate into shadows, sediment or to greater depths, making them unavailable to bats. Additionally, some aquatic insects emerge as aerial adult forms that are attracted to light. Fishing bats avoid lit areas and cannot switch foraging strategies to take advantage of the new aerial prey that is attracted to lights. Image created with BioRender.com.

Case study 4 – Shifting energy flows between realms via impacts on orb-web spiders and aquatic insect communities

Resource exchange from terrestrial to aquatic realms is an intrinsic facet of riparian habitats (Baxter et al. 2005). Spiders are important predators in riparian zones and can obtain more than 50% of their nutrition from aquatic sources, especially insects (Collier et al. 2002). Therefore, effects of ALAN on the diversity, abundance and distribution of spiders (both free-living and web-building), and/or the community of aquatic insects in riparian zones can alter cross-realm fluxes, with important regional and global implications for both terrestrial and aquatic realms (Manfrin et al. 2017). The consequences of these effects of ALAN depend on the time-scale considered and may be sex-specific. For example, short-term (two-month) exposure to ALAN increased the abundance and body mass of riparian long-jawed orb weavers (family Tetragnathidae) (Parkinson et al. 2020). These effects were more pronounced for females compared to males and were concordant with greater numbers of prey items captured in spider webs under ALAN compared to webs under natural night-time conditions. However, a comparable but longer-term study (one year) found that although spider density initially increased (as in the previous study), there was a long-term decrease in spider density, as well as a decrease in the emergence of aquatic insects (Meyer et al. 2013). Together, these studies suggest that aggregation of predators and prey around ALAN can increase predation on emerging aquatic insects and so reduce the transfer of biomass from aquatic to terrestrial systems through riparian zones. Concurrently, this would shift biomass from dark areas into artificially illuminated areas and dramatically shift the distribution, overall abundance, and diversity of insect communities reducing their abundance as prey (Perkin et al. 2014, Manfrin et al. 2017, Parkinson et al. 2020). Therefore, by altering both the abundance and predation success of terrestrial predators, as well as the distribution and abundance of aquatic prey, ALAN can drive shifts in predator-prey interactions across realm boundaries, altering flows of energy between aquatic and terrestrial systems, with important consequences for both realms.

3) Impacts on transition zones

Estuaries and coastal wetlands are critical transition zones that link freshwater habitats with marine and terrestrial environments (Levin et al. 2001). These zones perform important ecological functions such as nutrient cycling and regulation of water and nutrient fluxes between realms (Levin et al. 2001). Riparian zones are also at the interface of terrestrial and aquatic systems and support high biodiversity, as well as key ecosystem functions through biogeochemical cycling (Naiman and Decamps 1997). Therefore, impacts of light pollution on these critical transition zones are likely to cross ecosystem boundaries, affecting two or more realms, with multiple consequences for multiple functions of ecosystems and the services they underpin.

Natural light at the air-water interface is a key factor linking terrestrial and aquatic realms. The amount of light that reaches the water surface in freshwater or coastal systems, depends on the surrounding terrestrial habitat: structurally complex terrestrial environments, such as forested riparian zones, reduce the amount and colour of light reaching the water surface (Endler 1993). Organisms also vary extensively in their sensitivities to multiple light properties (Gaston et al. 2012, Land and Nilsson 2012), and transition zones support several specialised species that have adapted to these complex lighting environments. For example, some estuarine fish species that can live in highly turbid waters with low ambient light levels due to high loads of suspended material, such as the flathead grey mullet (*Mugil cephalus*), have morphological traits that support dim-light (i.e. scotopic) vision, such as high rod density in the retina (Zapata et al. 2019). The freshwater three-spine stickleback (*Gasterosteus aculeatus*) also has highly specialised visual sensitivity important for mate selection in clear versus tannin-stained lakes (Boughman 2001). Due to their evolutionary history, organisms inhabiting transition zones may be more sensitive to the presence of ALAN that modifies the unique light environment in which they have evolved (Sullivan et al. 2019). A further problem is that transition zones tend to be disproportionally affected by ALAN, since many urban settings, where ALAN is prevalent, are developed near waterways (Kummu et al. 2011). Transition zones, therefore, are significant sites for understanding and managing cross-realm impacts of ALAN, both due to the vulnerability of organisms inhabiting these zones, and the prevalence of light pollution near waterways.

The orb web spiders and aquatic insects example outlined above (Case study 4) illustrates how shifts in the flow of resources in riparian zones – the interface between land and rivers or streams – can have impacts across multiple realms. Additionally, in their recent comprehensive review, Zapata et al. (2019) outlined a multitude of ways ALAN can affect estuaries and highlighted potential cross-realm implications. For example, ALAN-induced delays in the leaf fall of deciduous trees (Bennie et al. 2016) can in turn reduce the input of nutrients from leaf detritus into aquatic systems, causing potential shifts in the biogeochemistry of aquatic systems (Zapata et al. 2019). Sullivan et al. (2019) also recently demonstrated the impacts of ALAN on riparian systems through shifts in the community structure of invertebrates, consequently altering the flows of energy between aquatic and terrestrial systems. Given these direct examples and published review of the impacts of ALAN on transition zones and flow-on effects across realms, we have not provided case studies here to further illustrate this mechanism. Instead, we want to highlight the importance of prioritising transition zones for management actions to limit the impacts of light pollution across multiple realms.

CHALLENGES AND PRACTICAL SOLUTIONS FOR RESEARCH AND MANAGEMENT OF ALAN

Several challenges exist that need to be addressed for the impacts of light pollution to be effectively understood and managed, both within and across realms. A major difficulty (and potential point of contention) encountered when dealing with cross-realm issues is determining the boundaries for management and governance (Pittman and Armitage 2016). For example, land-based sources of ALAN may indirectly influence the productivity of aquatic systems through its impact on nutrient inputs from terrestrial sources through e.g. changes in the leaf fall patterns of deciduous trees. In this case, areas are separated by physical and jurisdictional boundaries (e.g. land and coastal managers) and potentially social boundaries (different communities or social networks). Here, we propose a framework for cross-realm management, which builds on previous frameworks for conservation and management across-realms (e.g. Beger et al. 2010, Alvarez-Romero et al. 2015, Giakoumi et al. 2019, Threlfall et al. 2021), but with a specific focus on light pollution (Figure 3).

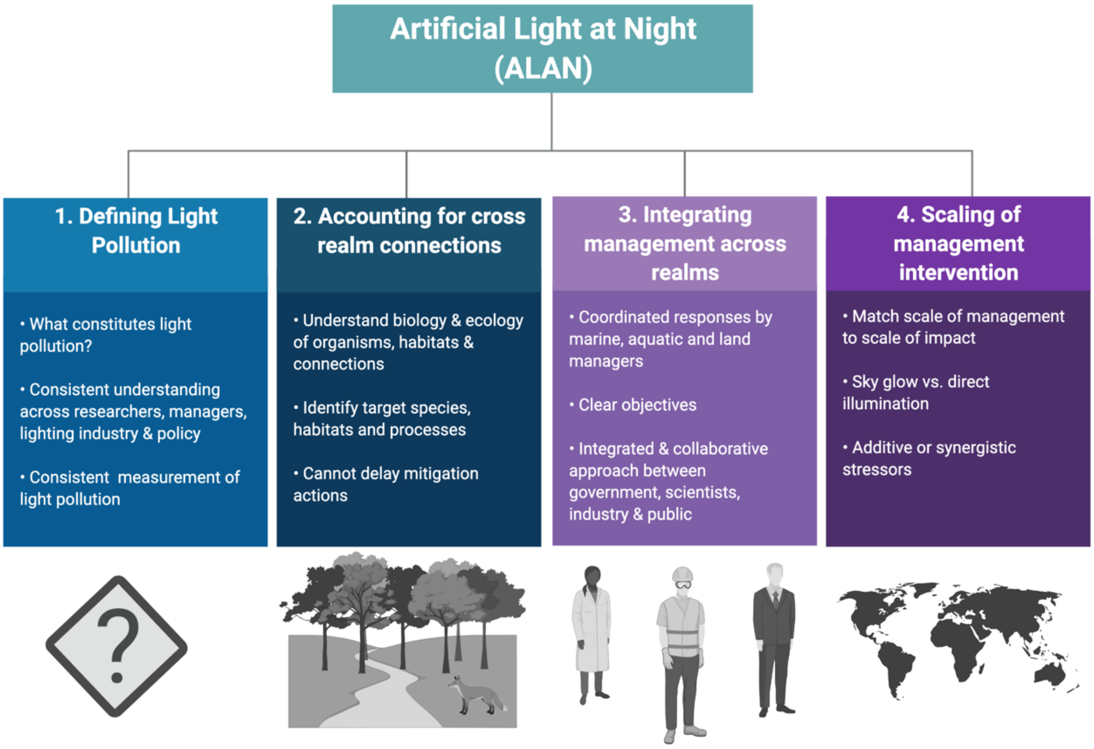

Figure 3 - Proposed framework to integrate cross-realms considerations into the study and management of light pollution. Image created with BioRender.com.

Challenges and practical solutions

1 - Defining light pollution

One of the main challenges for driving practical solutions to manage ALAN is agreeing to a collective understanding of how and when lighting should be defined as pollution (Schulte-Römer et al. 2019). Here, we define light pollution as light introduced into the environment by humans at intensities that are higher than the natural level at that time for the given environment and that has the potential to cause harm to humans and/or the environment. In a recent analysis, Schulte-Römer et al. (2019) found that light pollution experts (including scientists and managers) had a stronger and more consistent view of what constitutes light pollution than lighting professionals (such as lighting designers, urban planners and engineers). Importantly, however, both groups had very skewed views when considering potential issues caused by light in areas where it is ‘unwanted’, depending on the habitat or realm. Approximately 90% of light pollution experts (n = 89 respondents) considered light to be pollution when it obscures the visibility of stars, or when fixtures were installed close to observatories. In contrast, only 66% of those surveyed considered lighting as pollution when it was installed close to bodies of water, and, among lighting professionals, this dropped to only 17% (n = 67 respondents). These results highlight a common misconception, and a massive global problem, namely, that light is a ‘land’ problem rather than of fundamental significance for all ecosystems on earth. These findings also ignore the critical need for fluctuating light levels (both day and night) that have characterised the evolutionary history of that life. Therefore, the first steps to successfully managing light pollution within and across realms are to (i) raise awareness of the importance of fluctuating light regimes for ecological process; (ii) enhance understanding of the impacts of artificial light across all realms: terrestrial, freshwater and marine environments; (iii) broaden knowledge regarding the impact that light within one realm can have for biodiversity and ecosystem function within other realms and (iv) understand the ‘acceptable’ levels of ALAN for both the local ecological communities and society (i.e. trade-offs between ecological impacts and societal needs or desires). Critically, this needs to include multiple stakeholders, including the general public.

2 - Accounting for cross-realm connections

The next step in managing light pollution across realms is to understand the biology and ecology of organisms and habitats of interest and their potential linkages, so that management interventions can more fully account for connections across realms. Ideally, the extent of the impact of ALAN on target individuals, populations, habitats and systems, as well as the mechanisms driving these changes, will be well-known within and across realms. However, we acknowledge that, unfortunately, the current state of habitat degradation worldwide and rapid expansion of ALAN means that we cannot afford delaying mitigation actions until the impacts, or even the potential unintended risks of management interventions, are fully understood (Mayer-Pinto et al. 2019). Therefore, we need to keep gathering the - still much needed - scientific information on the effects of ALAN, within and across realms, while, at the same time, implementing local, regional and global best practice guidelines to prevent or lessen such impacts.

3 - Integrating management across realms

Another key issue with cross-realm management of light pollution is the lack of collaboration between different stakeholders and the existence of methodological disparities across realms. To address this, it is important to clearly specify the desired outcomes and to standardise approaches/methodologies regarding ALAN and its impacts across realms. The compartmentalisation that can exist within governance structures, such as within and between local, state/territory and federal government agencies often results in a lack of consistency in management decisions across realms. This can be due to poor communication, differing and potentially competing priorities and a lack of collaboration among the sectors and agencies responsible for planning and environmental protection in the different realms; a lack of spatial data on cross-realm processes; and difficulties arising in adapting existing decision-tools and coordinating different governance systems (Alvarez-Romero et al. 2015 and references therein).

There are some key general steps, as outlined by Alvarez-Romero et al. (2015), Bugnot et al. (2019) and Threlfall et al. (2021), among others, to successfully implement cross-realm management strategies. First and foremost, a clear objective is necessary, i.e. what are the desired outcomes? For issues pertaining to light pollution, these can include minimising the effects of ALAN on ecologically, culturally and/or commercially important target species/groups or a target area (e.g. a transition zone, migratory pathways or a protected area). This requires an integrated and collaborative approach with policy makers, regulators, scientists, lighting designers, developers and the general community, including First Nations People, so that potential conflicting interests are identified, and solutions are devised accordingly. Consequently, we need to not only unify terminologies and agree on desired outcomes (Webb 2012, Bugnot et al. 2019), but ideally, understand potential thresholds of 'acceptable' artificial light levels across different species and realms.

Determining ALAN thresholds, however, requires standardised measurements of light *per se*. Currently, there is great inconsistency in instrumentation and light parameters within and across realms. Discrepancies in lighting measurements exist for valid and practical reasons – e.g. the measurement and instrument used needs to match the scale of both the light pollution being measured (i.e. direct source vs skyglow) and the ecological or biological response of interest (e.g. insect attraction to a street light vs bird migration). Moreover, as far as we know, there is not yet available affordable and easy-to-use instrumentation to adequately measure light levels under water. However, there is a clear and urgent need to standardise, where possible, the measurement of light pollution, so that outcomes are comparable and applicable across realms (see Box 3 for further discussion). It is important to note, however, that knowing relevant light 'levels' is not enough for effective management for ecological outcomes. At the extreme, any light that is not natural in its origin is likely to interfere with ecological process. Thus, perhaps of greater importance, we need to be able to measure and understand how light properties (including spectra and intensity) affect organisms and habitats in multiple realms. Standardising how and which properties of light are measured will facilitate communication of clear and specific recommendations (including biologically relevant thresholds) between researchers, practitioners and managers. This will permit informed decision making when taking into account potential impacts across different habitats and realms and the risks we are willing to take when night-time illumination is unavoidable and/or socially desirable.

4 - Scaling of management intervention

Ultimately, there is a need to match the scale of the management intervention to the scale of impact (Threlfall et al. 2021). Light pollution impacts occur at the landscape scale, and include impacts caused by sky glow, light scattered in the atmosphere (Cinzano et al. 2001, Falchi et al. 2016), and those caused by direct illuminance from light sources (e.g. streetlights). Impacts caused by direct illuminance are, in theory, easier to mitigate, than impacts caused by sky glow – which can be an issue even tens (and possibly hundreds) of kilometres from urban light sources (Gaston et al. 2012) and require management interventions at much larger, landscape level, scales to prevent or mitigate cross-realm impacts. For example, research has shown that light pollution can spill into otherwise protected areas up to 15 km from urban centres (McNaughton et al. 2021). Additionally, a recent study has highlighted the potential for synergistic interactions between sky glow and direct illuminance (Dickerson et al, unpublished data). Management actions therefore need to consider, whenever possible, multiple spatial scales to mitigate light pollution and avoid cross-realm impacts. Extensive examples on specific interventions and management strategies can be found in the literature (Gaston et al. 2012, DAWE 2020).

Light pollution is just one of a multitude of anthropogenic stressors associated with urbanisation (Dominoni et al. 2020), which can also cross realm boundaries. Therefore, management interventions should also consider potential additive or interacting impacts from multiple stressors (Hale et al. 2017). For example, ALAN and night-time warming have non-additive interactive effects on the predation of aphids by lady beetles, decreasing aphid population densities (Miller et al. 2017). Similarly, particular traits in birds can be impacted by both ALAN and noise pollution: light pollution is associated with advancement in reproductive phenology of several species of birds while noise decreased clutch size of closed-habitats (i.e. forests) birds (Senzaki et al. 2020). Interactive effects of stressors remain, however, poorly understood. Understanding, or at a minimum identifying, other stressors that may interact with or act simultaneously with ALAN will enhance cross-realm management outcomes. Moreover, climate change adds additional challenges to cross-realms studies since it increasingly modifies key land-sea ecological and social processes, therefore increasing the urgency for transboundary management initiatives.

CROSS-REALMS MANAGEMENT SUCCESS

There have been few examples of successful of management of ALAN which have resulted in a reduction of cross-realm impacts, and most of these examples involved management interventions that targeted a single species. Successful examples include the mitigation of impacts on shearwaters at Phillip Island, Melbourne (Rodríguez et al. 2014, Rodríguez et al. 2017) and on nesting marine turtles (discussed in more detail here). Marine turtles have complex life histories that cross marine and terrestrial realms, and are considered key indicators of ecosystem health (Haywood et al. 2019). In Australia, marine turtles are protected under environmental legislation. As light pollution can reduce the reproductive viability of turtle stocks by disrupting critical behaviour such as the ability of hatchling marine turtles to successfully reach the ocean (Witherington and Bjorndal 1991), all actions in Australia that involve artificial light that is likely to impact marine turtles must be referred for environmental assessment. Proponents must demonstrate, via formal risk assessments, how the impact of ALAN on all age classes of marine turtles will be mitigated and adaptively managed. Light in nearshore waters (e.g. boats on anchor, jetties, coastal lighting, etc), for instance, influence the offshore dispersal of hatchlings in the critical minutes and hours after they leave the beach. Attraction to artificial lights increases the time hatchlings spend crossing predator rich nearshore waters before reaching the safety of deep water offshore, thus increasing their vulnerability to predation (Harewood and Horrocks 2008, Thums et al. 2016, Wilson et al. 2018); and as predators are also attracted to the same lights, predation pressure can be high. Mitigation measures that benefit marine turtles have been summarised in the National Light Pollution Guidelines for Wildlife Including Marine Turtles, Seabirds and Migratory Shorebirds (DAWE 2020) and include management of the physical aspects of the light, such as intensity (lumen output), colour (wavelength) and elevation above dark horizons behind the beach, as well as the maintenance of dark zones between turtle nesting beaches and light sources, and shielding and targeting of light fixtures to avoid direct visibility and limiting sky glow (DAWE 2020). Given light pollution sources that can affect turtles can be both marine and terrestrial, management actions in both realms are likely required, with the collaboration of terrestrial and aquatic ecologists and lighting professionals (as occurred for the aforementioned turtle example), to successfully avoid terrestrial-aquatic impacts.

MITIGATING IMPACTS OF A BRIGHT FUTURE

There is increasing recognition that conservation and management strategies should be designed to account for cross-realm connections (e.g. Threlfall et al. 2021, Tulloch et al. 2021). A recent study developed a national-scale conservation framework that incorporated linkages among the marine, freshwater and terrestrial realms, to select protected areas for minimising the threats of both land-use and climate change (Tulloch et al. 2021). The cross-realm approach resulted in changes to both terrestrial and marine priorities compared to when connections among realms were not considered. The authors also argued that a cross-realm approach allowed the identification of potential trade-offs and opportunity costs of conservation versus ecological benefits, as well as the implementation of interventions with multiple objectives (such as habitat management and biodiversity protection) (Tulloch et al. 2021).

Increasing the uptake of a cross-realm management approach requires increased and improved communication between researchers, lighting practitioners, managers and regulators that work within and across different realms. The creation of professional networks is a great way to begin such conversations. In Australia, the Network for Ecological Research on Artificial Light (NERAL; www.neralaus.com) was established to provide a platform to connect researchers and practitioners working towards mitigating the impacts of light pollution within and across realms. NERAL is a professional network of academic scientists and consultants, with a wide range of expertise, including terrestrial and marine ecologists and physiologists, and managers from local and federal government agencies. A primary aim of the network is to increase communication between scientists and managers working on different species, habitats and/or realms. This will allow: 1) managers to easily access information crucial to developing and implementing interventions to prevent or mitigate light pollution impacts, and 2) researchers to identify management priorities and provide evidence-based information to shape management interventions. Networks that have a strong multi-realm focus such as NERAL are important, as they enable a more holistic understanding of issues related to ALAN. They can also provide an opportunity to develop standardised methods for measuring light so that the impacts can be compared across realms. This holistic approach can then be translated into the ongoing implementation of strategies to reduce impacts of ALAN across terrestrial, marine and freshwater realms.

BOX 1) LIGHT AS AN ECOLOGICAL TRAP

Ecological traps form when animals are attracted into poor-quality habitats where their fitness is compromised (Hale and Swearer 2016). ALAN can cause ecological traps by influencing both the habitat selection decisions of animals and their fitness consequences. The orb-web spiders and aquatic insect community case study presented here clearly illustrates this – the adult stages of aquatic insects are attracted to artificial light where they suffer higher mortality because of the high density of webs. This case study provides further evidence of how ecological traps caused by ALAN can impact on cross-realm linkages. In this case, ALAN strengthens the magnitude of cross-realm predator-prey interactions. Specifically, the higher attraction and mortality of aquatic insects leads to increased aquatic-to-terrestrial subsidy flux (e.g. Manfrin et al. 2017).

Artificial light can also interfere with the migratory behaviour of species that occupy different realms as part of their life cycle. A well-known example of this is the impact of ALAN on the dispersal behaviour of sea-turtle hatchlings. Nocturnally emerging hatchlings are attracted to artificial lighting from coastal development. Crawling towards an artificial light source can result in predation (Erb and Wyneken 2019), impair their ability to swim offshore (Lorne and Salmon 2007), leading to reduced rates of offshore migration and rates of transition between life stages (Wilson et al. 2019).

Lastly, ALAN could increase cross-realm rates of disease transmission due to its impact on vector biology, such as biting mosquitoes. For example, in a recent study by Fyie et al. (2021), artificial light masked natural daylength change which is the trigger for diapause, meaning mosquitos remained reproductively active for longer and produced more aquatic larvae. ALAN exposed mosquitos also had increased rates of blood feeding compared to control mosquitos. Given the preference for humans to associate with artificially lit environments at night, this suggests both changes in human and vector behaviour have resulted in a largely unrecognized ecological trap for humans.

BOX 2) CROSS-REALM EXPLOITATION OF RESOURCES USING ARTIFICIAL LIGHT AT NIGHT

Artificial light at night is known to attract and/or aggregate many organisms. This effect can be exploited by predator species within and across realms, if, for example, a terrestrial predator is exploiting an aggregation of aquatic organisms to a light source. One of the best cross-realm examples of how ALAN can be used to exploit resources is the use of artificial light by humans during night-time fishing.

The attraction of many fish and aquatic invertebrates to light has been known for thousands of years, and artificial light has been used by humans to improve fishing efficacy for centuries (Yami 1976). Light at night is known to attract small fish, insects and/or plankton, which in turn attract larger predatory fishes and invertebrates (Becker et al. 2013), or directly attracting target species through positive phototaxis, disorientation, or curiosity (Marchesan et al. 2005). Historically, humans exploited this behaviour by lighting a fire on a beach to attract fish into the shallows to facilitate harvest (e.g. by spearing or netting) (Yami 1976). Today, incandescent, fluorescent, metal halide, and LED above-water and underwater lights are used for artisanal and industrialized fishing practices worldwide to increase harvest (Solomon and Ahmed 2016, Nguyen and Winger 2019). In fact, certain fisheries cannot operate effectively without the use of lights, such as the squid jigging fishery. Jigging for squid dates back to antiquity in many parts of the world, however in the recent century, the addition of artificial light to jigging gear has substantially increased landings due to the effect of light at night on attracting and concentrating squid (Solomon and Ahmed 2016).

The effects of ALAN on fish attraction/aggregation are not lost on recreational fishers; recreational fishers often target artificially lit areas for night fishing, as they know certain target game species will follow baitfish into the illuminated areas (Cooke et al. 2017). Urbanization has led to an increase in artificial light installations in coastal areas, illuminating a substantial portion of shallow aquatic habitats at night (Davies et al. 2014, Davies et al. 2016), and has therefore created ample opportunities for recreational fishers to exploit artificial lighting (i.e. light pollution) to increase catch rates.

The increased harvest resulting from fishing practices using ALAN can lead to overfishing and increased rates of bycatch in a fishery which may can have negative impacts on fished populations (e.g. reduction in size and altered life-history traits) (Solomon and Ahmed 2016) and thus ecological consequences for the marine or freshwater realms (e.g. through trophic cascades). However, since responses to ALAN are species-specific, ALAN can be used by humans to both increase fishing harvest and reduce catch rates of different species. The use of artificial light has been recognized as a potential tool for bycatch reduction in commercial fisheries, and therefore ALAN can also be exploited to mitigate cross-realm impacts through minimizing effects of fishing on non-target organisms. Research on the use of artificial light to reduce bycatch has demonstrated varying levels of success (e.g. Hannah et al. 2015, Larsen et al. 2018, Lomeli et al. 2018) and is dependent on species of interest, light properties tested, and proper placement/location of (often LED) lights within the fishing gear. However, the use of artificial light to deter adult sea turtles has also proved to be effective (e.g. Wang et al. 2010, Virgili et al. 2018) resulting in LED lights now widely applied worldwide in pelagic gillnet fisheries to reduce sea turtle bycatch (Nguyen and Winger 2019). This positive use of artificial light demonstrates that with species-specific knowledge, it is possible to harness the effects of ALAN for positive impacts across realms.

BOX 3: DISCREPANCIES IN LIGHT MEASUREMENTS

A complicating factor influencing the ability of scientists to confidently predict the impact of light on a sensitive receptor is the lack of an agreed upon standard method for modelling, measuring and monitoring light or skyglow (e.g. Jechow and Hölker 2019, Jechow et al. 2019, Kalinkat et al. 2021). Instrument types and applications vary widely: instruments include luxmeters, spectrometers, and cameras which measure light emitted directly from a source or light reflected from a surface, from overhead looking down on the earth (satellite based) or from the ground looking up or horizontally across the landscape. Limitations include: restrictions in the wavelengths they measure (i.e. they do not measure all wavelengths across the entire visible spectrum), detection limits that are not low enough to measure sky glow or intensities that elicit a biological response, highly technical instruments requiring specialised knowledge to operate and maintain, and a wide range of different measurement units.

Arguably, many of the existent ‘disparities’ are due to the fact that different instruments are designed to measure different things, depending on the objectives of the users. For example, studies aiming to measure large-scale environmental effects due to sky glow will (and should) measure different variables (and consequently use different instruments) than studies which the primary aim is to evaluate the effects of street-light on a particular species of insect. Nevertheless, whenever possible, studies with similar objectives and/or operating at similar spatial scales, should try to standardise measurements. Crucially it is important to understand the operating limits of even the simplest instruments, as instruments can be misused or used for an inappropriate environment (Longcore et al. 2020). Similarly, the literature acknowledges that there are no conclusive intensity thresholds below which artificial light is not harmful to species and habitats (Schroer et al. 2020), and even the low intensity light characteristic of skyglow can affect organisms (Grubisic et al. 2019, Kupprat et al. 2020).

Attempts to compare or standardise measurements across realms adds further complications. For instance, while remote sensing techniques are commonly used as a best proxy to quantify the amount of artificial light at night on terrestrial systems, there are serious challenges associated with the use of this technology in water bodies/underwater (see the extensive discussion in Jechow and Hölker 2019). Furthermore, different disciplines often use different physical quantities and units for measuring light, creating confusion even among experts (Jechow and Hölker 2019). For instance, much of the existing data on the quantity and quality of light reaching both terrestrial and aquatic systems assess different physical parameters (spectral irradiance, illuminance); have used several different instruments to acquire measurements (e.g. SQM, luxmeter, spectrometer, digital camera); and, report outcomes using different measurement units (lux, candela, magnitudes, Watts). Therefore, as stated by Jechow and Hölker (2019), ‘there is no clear coherence between these measurements, although each of them was well designed and conducted’. Cross-realm assessment and management of light pollution is impeded by the discrepancies in measurements of light pollution across systems and disciplines. However, standardization of measurements across species level responses, systems, and realms of interest is incredibly challenging, as measurements currently generally differ for valid, practical reasons, such as the ecological and spatial scale of interest. This challenge highlights the value of cross-realm and cross-discipline networks for developing solutions that allow efficient conservation and management actions across species, habitats and realms.

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