

1 Why artificial light at night should be a focus for global change research in the
2 21st century

3 **Running head:** Artificial light is a global change issue

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11 environment interrelationships.

12 **Opinion**

13 Abstract

14 The environmental impacts of artificial light at night have been a rapidly growing field of global
15 change science in recent years. Yet light pollution has not achieved parity with other global change
16 phenomena in the level of concern and interest it receives from the scientific community, government
17 and non-governmental organisations. This is despite the globally widespread, expanding and changing
18 nature of night-time lighting; and the immediacy, severity and phylogenetic breadth of its impacts. In
19 this opinion piece, we evidence ten reasons why artificial light at night should be a focus for global
20 change research in the 21st century. Our reasons extend beyond those concerned principally with the
21 environment, to also include impacts on human health, culture and biodiversity conservation more
22 generally. We conclude that the growing use of night-time lighting will continue to raise numerous
23 ecological, human health and cultural issues, but that opportunities exist to mitigate its impacts by
24 combining novel technologies with sound scientific evidence. The potential gains from appropriate
25 management extend far beyond those for the environment, indeed it may play a key role in
26 transitioning towards a more sustainable society.

27 Introduction

28 While artificial light at night (ALAN) has been a long established man-made disturbance (Longcore
29 and Rich, 2004), the number of studies documenting its ecological and human health impacts has
30 grown dramatically in the last decade (Figure 1). Collectively, this body of research now highlights
31 the pervasiveness of ALAN's impacts across a broad array of biomes, ecosystems, species and
32 behaviours. The measured biological responses occur at intensities and spectra of artificial light that
33 are currently encountered in the environment, and the global distribution of night-time lighting means
34 that it is likely already having widespread impacts in marine, freshwater and terrestrial habitats around
35 the world.

36

37 While ALAN research has gained notable momentum in recent years it is yet to achieve notoriety
38 among environmental scientists as a driver of global change. Here, we argue that ALAN should be a
39 focus for global change research in the 21st century. Our argument is broken down into ten points that
40 highlight the global extent of ALAN; the geographic scale of its influence; the potential to reverse its
41 environmental impacts; the rise of new human-environment conflicts with emerging lighting
42 technologies; its evolutionary novelty; the diverse array of species now known to be affected; the
43 extreme sensitivity of organisms to light; impacts on human health; cultural impacts on human-
44 environment interrelationships; and the feasibility of solutions. While we do not assert that ALAN is
45 any more important than other global change phenomena, we draw comparisons where they help
46 highlight the need for greater parity of concern.

47

48 **Globally widespread**

49 As with greenhouse gas emissions, ALAN is a globally widespread environmental pollutant. It is
50 estimated that 23% of the land surface between 75°N and 60°S (Falchi *et al.*, 2016), is exposed to
51 artificial skyglow (artificial light that is scattered in the atmosphere and reflected back to the ground).
52 This is comparable to the area of global ice-free land converted to either pasture or cropland,
53 estimated to be 35% in the year 2000 (Klein Goldewijk *et al.*, 2011). The degree of exposure

54 increased in all global terrestrial ecosystems between 2008 and 2012, with those important for
55 biodiversity conservation often most affected (Bennie *et al.*, 2015b). Exposure to ALAN is not limited
56 to terrestrial environments, with current best estimates indicating that 22% of the worlds' coastal
57 regions (Davies *et al.*, 2014) are experiencing some degree of artificial illumination and 20% of
58 marine protected areas are exposed across their entire range (Davies *et al.*, 2016). The amount of
59 artificial light is also increasing in 13,061 terrestrial protected areas across Europe, Asia and South
60 and Central America (Gaston *et al.*, 2015a), and 1,687 (14.7%) of the worlds marine protected areas
61 (Davies *et al.*, 2016). Given that more than 95% of global population increases are projected to occur
62 in the cities of economically developing countries over the next 50 years (Grimm *et al.*, 2008), and
63 levels of light pollution are closely associated with population density and economic activity
64 (Gallaway *et al.*, 2010), ALAN will continue to expand both in spatial extent and intensity throughout
65 the 21st century without intervention.

66

67 **Sphere of influence**

68 Artificial light arises from point sources (municipal, industrial, commercial and residential), giving
69 the impression that its impacts on the environment are highly localised. Indeed the majority of studies
70 into the ecological impacts of ALAN quantify responses to direct lighting (Gaston *et al.*, 2015b).
71 Artificial sky-glow increases the sphere of ALAN's potential influence far beyond a patch of habitat
72 in the vicinity of a street light (Kyba & Hölker, 2013, Falchi *et al.*, 2016). Numerous taxa are adapted
73 to make use of spatial and temporal patterns of natural sky brightness at intensities equivalent to or
74 less than those created by artificial sky-glow (Naylor, 1999, Moore *et al.*, 2000, Dacke *et al.*, 2013,
75 Last *et al.*, 2016, Warrant & Dacke, 2016), suggesting that lights in urban centres will have impacts in
76 environments tens to hundreds of kilometres away. A dung beetle navigating its landscape using the
77 Milky Way could, for example, become disorientated by artificial skyglow from a city tens or perhaps
78 even hundreds of kilometres away (Kyba *et al.*, 2013), an effect comparable to a moth becoming
79 disorientated by a street light hundreds of metres away (van Grunsven *et al.*, 2014).

80

81 While ALAN can be misconstrued as being a highly localised anthropogenic stressor, climate
82 warming is likewise misrepresented as globally widespread in its occurrence. Like ALAN,
83 ecologically relevant warming occurs at more localised spatial scales (Hannah *et al.*, 2014) (Figure 2),
84 and is influenced by variable topographical features such as slope and aspect that create refuges where
85 rates of warming are reduced (Bennie *et al.*, 2008, Maclean *et al.*, 2016). The ecological impacts of
86 climate change - like light pollution – are therefore likely to be spatially heterogeneous for organisms
87 with low mobility, but more widespread for taxa that depend on large scale movements for their
88 survival and reproduction. In the case of both stressors, population impacts on the former species are
89 manifest foremost through the loss and fragmentation of suitable habitat (Hannah *et al.*, 2014), while
90 impacts on the latter species are manifest via direct effects on population demography (Gaston &
91 Bennie, 2014).

92

93 **Lag effects**

94 Abating future rises in global temperatures constitutes one of the most significant challenges facing
95 humanity in the 21st century. Yet even if all fossil fuel combustion ceased with immediate effect, the
96 recovery of atmospheric CO₂ concentrations, global temperatures, ocean pH and oxygen
97 concentrations to pre-industrial levels would take hundreds to thousands of years (Frolicher *et al.*,
98 2014, Frölicher & Paynter, 2015, Mathesius *et al.*, 2015), and there is the very real possibility that
99 temperatures would continue to rise in the medium term (Frolicher *et al.*, 2014). By contrast, globally
100 widespread artificial light can be ‘switched off’ instantaneously. There would be no lag effect on the
101 physical environment following such an event, allowing the biological environment to immediately
102 begin the recovery process. While such a scenario would likely prove controversial, recent
103 technological advances present tangible ways of mitigating the ecological impacts of artificial light at
104 night (see reason ten). Failure to abate the environmental consequences of a man-made disturbance
105 using available viable solutions, would not inspire confidence in our ability to solve the apparently
106 insurmountable challenges posed by global climate change phenomena.

107

108 The rise of LEDs

109 Light-Emitting Diodes (LEDs) have grown from a 9% share of the lighting market in 2011 to 45% in
110 2014, and are forecast to reach 69% by 2020 (Zissis & Bertoldi, 2014). Their rising popularity stems
111 from the variety of colours that LEDs can be tailored to produce, their improved energy efficiency
112 over alternative electric light sources, and ability to produce ‘white’ light that is aesthetically pleasing
113 and provides enhanced visual performance (Schubert & Kim, 2005, Pimputkar *et al.*, 2009). Whilst
114 LEDs are often advocated for their potential to reduce global CO₂ emissions, and the ability to tailor
115 their spectra to avoid unwanted environmental impacts (see ‘Feasibility of solutions’), environmental
116 scientists and human health experts have raised concerns about the broad-spectrum light (Davies *et*
117 *al.*, 2013, Macgregor *et al.*, 2014), and prominent short wavelength peak (Haim & Portnov, 2013,
118 Haim & Zubidat, 2015) that the commonly used white models emit (Figure 3).

119

120 Firstly, the broad range of wavelengths emitted by white LEDs likely enables organisms to perform
121 colour guided behaviours at night that were previously only possible during the day (Davies *et al.*,
122 2013). A range of intra and interspecific interactions could be affected including foraging (for
123 example seeking nectar rich flowers), predation (ability to locate and successfully capture prey),
124 sexual communication (ability to locate, identify and assess the fitness of conspecifics through visual
125 displays) and camouflage (ability to avoid detection by predators). Nocturnal species may find
126 themselves competing for resources with diurnal species where such interactions had previously not
127 existed (Macgregor *et al.*, 2014), and differences in the sensitivity of animal visual systems to white
128 LED light spectra could change the balance of species interactions (Davies *et al.*, 2013). Some
129 alternative lighting technologies also emit light across a broad range of wavelengths (for example
130 Metal Halide and Mercury Vapour lighting, Figure 3), however the energy efficiency of LEDs makes
131 them the lighting of choice in the 21st century, and as such research should focus on how any
132 unforeseen deleterious impacts can best be mitigated.

133

134 Secondly the short wavelength peak emitted by white LEDs coincides with the wavelengths to which
135 many biological responses are known to be sensitive. Many invertebrate behaviours (Cohen &
136 Forward, 2009, Gorbunov & Falkowski, 2002, Haddock *et al.*, 2010, van Langevelde *et al.*, 2011)
137 and the melatonin response (West *et al.*, 2011) are sensitive to short wavelengths of light (between
138 350 and 500nm), and some studies have demonstrated that white LED lighting has a greater impact on
139 short wavelength sensitive responses compared to alternative lighting technologies (Pawson & Bader,
140 2014).

141

142 Thirdly, because LEDs illuminate a broad range of wavelengths, they have the potential to affect a
143 greater variety of biological responses that are sensitive to specific wavelengths of light. To give one
144 example, while many invertebrate behaviours and the melatonin response are most sensitive to short
145 wavelength light, the phytochrome system in plants – which is associated with the timing of
146 flowering- is sensitive to red/far red light (660 and 720nm) (Bennie *et al.*, 2016). Using broad
147 wavelength light sources such as white LEDs therefore risks affecting more biological responses
148 across a greater variety of taxa than using narrow wavelength light sources such as low pressure
149 sodium lighting (Gaston *et al.*, 2012).

150

151 Fourthly, the improved energy efficiency offered by LEDs may encourage growth in the amount of
152 artificial light produced around the world. This ‘rebound effect’ can be observed in historical lighting
153 trends (see Kyba *et al.* 2014), and partly explains why aesthetic and decorative lighting installations
154 are now increasingly seen in municipal centres, on monuments, bridges and waterfront developments.

155

156 Finally, improvements in the energy efficiency of LED lighting coupled with the production
157 efficiency of solar cells is resulting in a rapid growth in off grid lighting installations, typically in
158 remote regions containing previously artificial light naive ecosystems (Mills & Jacobson 2007,
159 Adkins *et al.*, 2010, Dalberg Global Development Advisors 2013). The greatest ecological impacts of
160 ALAN over the next 50 years will likely occur in these previously artificial light naive regions, with
161 an ecology not previously shaped by night-time lighting.

162

163 **Evolutionary novelty**

164 Organisms have evolved with large scale fluctuations in atmospheric CO₂, climate temperatures and
165 ocean pH throughout history, while sudden changes to natural light regimes are unprecedented over
166 evolutionary time-scales. The harmonic movements of the earth, moon and sun provide reliable cues
167 to which many biological events are now highly attuned (Kronfeld-Schor *et al.*, 2013).

168 The ability of organisms to rapidly adapt to the introduction of ALAN through behavioural, genetic or
169 epigenetic changes is likely to be far more limited than for climate warming due to the unprecedented
170 nature of this change (Swaddle *et al.*, 2015). Further, the scattered growth of artificial lighting around
171 the world is a significant barrier to predicting where organisms will be able to seek out suitably dark
172 habitats in the future, and identifying where to allocate dark corridors that enable such migrations to
173 happen. While challenging, identifying where species need to go to survive climate warming, and how
174 they get there, is made simpler by the predictability of regional climatic shifts (for example poleward
175 migrations by land and sea, and upward migrations in high altitude regions) (Hannah *et al.*, 2007).

176

177 **Diversity of biological responses**

178 ALAN is now known to cause a plethora of environmental impacts from altering organism physiology
179 to changing the structure of ecological communities. The diversity of taxa affected continues to grow
180 and now includes birds (Kempnaers *et al.*, 2010, Dominoni, 2015), bats (Rydell, 1992, Stone *et al.*,
181 2009), sea turtles (Witherington, 1992, Kamrowski *et al.*, 2012), marsupials (Robert *et al.*, 2015),
182 rodents (Bird *et al.*, 2004), anurans (Hall, 2016); freshwater and marine fish (Becker *et al.*, 2012,
183 Riley *et al.*, 2013, Brüning *et al.*, 2015); moths (Frank, 1988, Wakefield *et al.*, 2015); beetles, spiders,
184 harvestmen, woodlice and ants (Davies *et al.*, 2012, Davies *et al.*, 2017); branchiopod (Moore *et al.*,
185 2000), amphipod (Davies *et al.*, 2012, Davies *et al.*, 2015, Navarro-Barranco & Hughes, 2015) and
186 copepod (Davies *et al.*, 2015) crustaceans; polychaete worms, colonial ascidians, and hydrozoans
187 (Davies *et al.*, 2015); corals (Kaniewska *et al.*, 2015), and terrestrial plants (Bennie *et al.*, 2015a,
188 Bennie *et al.*, 2016, French-Constant *et al.*, 2016). The documented impacts include those on animal

189 communication (Kempnaers *et al.*, 2010, van Geffen *et al.*, 2015), reproductive development
190 (Dominoni *et al.*, 2013, Hansen *et al.*, 1992), the timing of reproduction (Kaniewska *et al.*, 2015,
191 Robert *et al.*, 2015), orientation (Frank, 1988, Witherington, 1992), habitat selection (Davies *et al.*,
192 2012, Davies *et al.*, 2015), predator avoidance (Wakefield *et al.*, 2015), predation pressure (Rydell,
193 1992, Becker *et al.*, 2012, Bolton *et al.*, 2017), circadian disruption (Brüning *et al.*, 2015, Raap *et al.*,
194 2015, Raap *et al.*, 2016), plant phenology (Bennie *et al.*, 2015a, Bennie *et al.*, 2016, French-Constant
195 *et al.*, 2016), and ecosystem services (Lewanzik & Voigt, 2014, Knop *et al.* 2017).

196

197 While those impacts on survival and reproductive success highlight that ALAN is likely causing
198 widespread population losses for a variety of taxa, no population-level effects have so far been
199 reliably demonstrated. This is in part because satellite images of night-time lights are not available in
200 sufficiently high spatial resolution for inferences to be drawn regarding impacts on species
201 populations that can be variable on the scale of tens to hundreds of metres (Elvidge *et al.* 2007).
202 Disentangling the effects of street and residential lighting from those of urbanisation and land use
203 change is challenging, since all of these explanatory variables likely contributes to population declines
204 but all co-vary. Analyses using higher resolution images from the international space station (capable
205 of identifying individual roads), may yield further insights, but tend to be focused on cities,
206 preventing comparisons from being drawn across sufficiently large spatial scales. Recent
207 developments in hemispherical photography allow 'biologically relevant' artificial skyglow to be
208 mapped from ground level across thousands of square kilometres (Luginbuhl *et al.*, 2009, Zoltan,
209 2010), better enabling ecologists to quantify its impacts on populations of organisms that utilize
210 celestial patterns of sky brightness, but perhaps not the population effects of direct lighting.
211 Techniques to model the distribution of artificial light across towns and cities have also been
212 developed (Bennie *et al.* 2014), however such models can be computationally expensive and have not
213 yet been applied to the question of whether direct lighting has an impact on organism populations.
214 Before After Control Impact (BACI) experiments have the potential to provide insights into the long-
215 term responses of sessile species populations and those mobile taxa with <1km home ranges, however
216 the finances and time required to implement them at appropriate spatial and temporal scales make this

217 approach less feasible in a limited funding environment. For now, quantifying the population level
218 impacts of ALAN remains one of the most important and challenging problems facing ecologists
219 working in this area.

220

221 **Sensitivity of biological responses**

222 Many organisms are extremely sensitive to natural light, utilizing light cues as dim as the Moon and
223 the Milky Way to orientate themselves, navigate landscapes and identify conspecifics and resources at
224 night (Ugolini *et al.*, 2005, Dacke *et al.*, 2013, Last *et al.*, 2016, Warrant & Dacke, 2016). Perhaps
225 most striking is the growing number of documented responses to white LEDs in marine systems
226 (Gorbunov & Falkowski, 2002, Davies *et al.*, 2015, Navarro-Barranco & Hughes, 2015, Bolton *et al.*,
227 2017), where species are both adapted to utilize short wavelengths that penetrate deeper in seawater,
228 and are incredibly sensitive to natural light. Examples of this extreme sensitivity include copepods
229 (*Calanus* sp.) that undergo diel vertical migration to depths of 50m guided only by variations in
230 moonlight intensity during the arctic winter (Båtnes *et al.*, 2013, Last *et al.*, 2016); sessile invertebrate
231 larvae that move and identify suitable settlement locations guided by light levels equivalent to
232 moonless overcast nights (Thorson, 1964, Crisp & Ritz, 1973); and polychaete worms, corals and
233 echinoderms that synchronise broadcast spawning events using monthly and annual variations in lunar
234 light intensity (Naylor, 1999). Many of these responses are clearly sensitive enough to be affected
235 both by direct lighting and artificial skyglow (Figure 4), and indeed such impacts have been
236 demonstrated for zooplankton diel vertical migration in freshwater ecosystems (Moore *et al.*, 2000).
237 Given the spatial extent of artificial skyglow in coastal regions (Davies *et al.*, 2014, Falchi *et al.*,
238 2016), the disproportionate importance of these regions for global biogeochemical cycles [coastal
239 zones account for 30% of global ocean primary production but only 10% of global ocean surface area
240 (Wollast, 1998)], and the role of diel vertical migration in maintaining these cycles (Hays, 2003), it is
241 not unreasonable to surmise that ALAN could have detectable effects on ocean carbon and nutrient
242 budgets in the near future.

243

244 Impacts on human health

245 In 2007, The World Health Organisation classified shift work that disrupted human circadian rhythms
246 as a probable human carcinogen (International Agency for Research on Cancer, 2007). While this
247 classification is primarily associated with shift work, exposure to ALAN has been linked to a variety
248 of health disorders in people through the same circadian disruption mechanism. These include sleep
249 disorders, depression, obesity, and the progression of some cancers (Cajochen *et al.*, 2011, Haim &
250 Portnov, 2013, Chang *et al.*, 2014, Keshet-Sitton *et al.*, 2015). The prominent peak of blue
251 wavelength light emitted by LEDs is of increasing concern, since it occurs at the most effective
252 frequency for suppressing the production of melatonin (West *et al.*, 2011, Haim & Zubidat, 2015), a
253 hormone released by the pineal gland that regulates sleep wake cycles and acts as an antioxidant. Over
254 the last decade, LEDs have become a ubiquitous feature of human life, and can be found in street,
255 residential, commercial and aesthetic lighting installations, laptops, televisions, e-readers, smart
256 phones and tablets. Late evening exposure to LED light from handheld devices has been linked to
257 circadian disruption of sleep wake cycles, and alertness and cognitive performance during the day
258 (Cajochen *et al.*, 2011, Chang *et al.*, 2014).

259

260 The extent to which outdoor lighting impacts human health is yet to be reliably determined. While
261 epidemiological studies have found correlations between the amount of outdoor lighting and some
262 health effects (Kloog *et al.*, 2008, Koo *et al.*, 2016), as with ecological patterns they are limited by the
263 inferences that can be drawn from satellite images (Defence Meteorological Satellite Programme
264 Operational Line Scan) with insufficient spatial resolution (5km) to differentiate exposure to ALAN
265 from other factors that co-vary across city districts at fine spatial scales (Elvidge *et al.* 2007, Kyba,
266 2016). The need for higher resolution images or novel approaches that can disentangle the effects on
267 both ecology and human health of multiple urban pollutants that co-vary is clear, although individual
268 level sensors can also reveal important impacts of daily light exposure on circadian disruption and
269 stress (Figueiro *et al.* 2017). A more recent analysis using higher resolution (0.75km) images from the
270 Visible Infrared Imaging Radiometer Suite (VIIRS) on board the Suomi National Polar-orbiting

271 Partnership satellite has revealed a significant association between ALAN and breast cancer incidence
272 in the Greater Haifa Metropolitan Area in Israel (Rybnikova & Portnov, 2016). This analysis
273 accounted for several potential co-varying explanatory factors, but not noise pollution, and
274 atmospheric pollution explicitly.

275

276 **Human-environment interrelationships**

277 In a recent analysis that combined high resolution night-time satellite images with atmospheric
278 dispersion models of artificial sky-glow, Falchi *et al.* (2016) estimated that more than 80% of the
279 worlds' population currently live under light polluted skies, such that the Milky Way is hidden from
280 one third of people alive today. This extraordinary change in our night-time environment escalated in
281 the developed world during the mid to late 20th century, and is now rapidly transforming the cultures
282 of billions in the developing world. The trend is concurrent with urbanisation [66% of the worlds'
283 population will reside in urban areas by 2050 (United Nations, 2014)], and it contributes to the
284 growing disconnect between people and nature that has become known as 'the extinction of
285 experience' (Miller, 2005). This growing disconnect undermines public support for conservation
286 issues by preventing individuals from connecting with, understanding, and forming attachments to the
287 natural world (Miller, 2005).

288

289 The extinction of experience is another of the great challenges facing humanity in the 21st century.
290 Miller (2005) argues it can be addressed by designing urban landscapes to facilitate 'meaningful
291 interactions with the natural world'. There is perhaps no more profound way in which people can
292 reconnect with nature, than giving them access to the Milky Way, and allowing them to experience
293 the natural rhythms of moonlight and sunlight that they are evolutionarily pre-adapted to synchronise
294 their physiology and behaviour with (Cajochen *et al.*, 2013, Wright Jr *et al.*, 2013). Like biodiversity
295 conservation however, pristine skies have become tourist attractions restricted to regions awarded
296 special status for their value to dark sky conservation (Collison & Poe, 2013, Rodrigues *et al.*, 2014,
297 Pritchard, 2017) where many in the developed world can no longer afford to reside or visit. Pritchard

298 (2017) argues that dark sky protection programmes also risk suppressing the economic and cultural
299 development of poorer nations in a way analogous to biodiversity conservation in the 20th century. In
300 her appraisal of NASA's 'City Lights' composite satellite image of the world's lights at night
301 (<http://earthobservatory.nasa.gov/Features/IntotheBlack/>) Pritchard (2017) warns against 'neo-
302 colonial approaches to the conservation of natural night-sky brightness'. While it is clear the
303 continued growth in artificial lighting risks perpetuating the disconnect between people and the
304 environment - and this will inevitably contribute to the concomitant shifting baseline in conservation
305 objectives (Pauly, 1995, Papworth *et al.*, 2009) – any intervention should seek to support the
306 modernisation of societies while retaining their connections with the natural world. Pritchard (2017)
307 describes achieving this balance as a 'new frontier in 21st century conservation'.
308

309 **Feasibility of solutions**

310 While the recent growth in LED lighting has raised concerns among environmental scientists and
311 human health experts, this technology offers lighting managers greater flexibility when it comes to
312 tailoring the timing, intensity and spectral power distribution of municipal lighting systems (Gaston,
313 2013, Davies *et al.*, 2017). Of the local authorities in England, 23% are engaged in permanent part-
314 night lighting schemes where street lights are turned off between midnight and 04:00 to 05:00 AM,
315 while 39% are engaged in permanent dimming schemes where lights are dimmed for at least some
316 period of the night (Campaign to Protect Rural England, 2014). Increasing constraints on local
317 authority budgets have incentivized the adoption of these lighting strategies in the wake of the 2008
318 global financial crash, however more often the reasons given for their implementation are improved
319 energy savings and reduced CO₂ emissions. Both dimming and part-night lighting are better enabled
320 by switching to LED, and introducing central management systems that use wireless communication
321 technology to programme individual street lights remotely.
322

323 The ecological benefits of dimming and part-night lighting are not yet well explored (although see
324 Azam *et al.*, 2015, Day *et al.*, 2015, Davies *et al.*, 2017). A recent emphasis in the ecological

325 literature has instead been on tailoring spectral power distributions to reduce known ecological
326 impacts (Pawson & Bader, 2014, Longcore *et al.*, 2015, Brüning *et al.*, 2016, Rivas *et al.*, 2015,
327 Spoelstra *et al.*, 2015, van Geffen *et al.*, 2015, Davies *et al.*, 2017), despite this approach being less
328 popular among lighting managers and engineers who often focus on the improved visual performance
329 offered by broad spectrum lighting as a key selling point. These studies collectively present an
330 inconsistent picture of whether spectral manipulation can be used to effectively mitigate the
331 ecological impacts of ALAN. This is partly because some studies compare narrow spectrum (for
332 example red, green and blue) light with broad spectrum light sources, while others either decrease the
333 amount of light occurring at wavelengths known to manifest certain ecological responses (usually
334 shorter wavelengths in the visible spectrum), or increase the amount of light occurring at wavelengths
335 that do not give rise to these responses (longer wavelengths in the visible spectrum). Even if a unified
336 approach were adopted in spectral manipulation experiments, it seems unlikely that a publically
337 acceptable light spectra that does not give rise to any ecological impacts can be developed, because
338 different species responses are evolutionarily adapted to utilize different wavelengths of light.

339

340 Examples of this are abundant in the emerging literature on the ecological impacts of artificial light.
341 The number of beetle taxa aggregating under white LED lighting can be reduced by switching to
342 amber, but this has no discernible effect on the number of spider taxa that aggregate (Davies *et al.*,
343 2017). Many animal responses are sensitive to short wavelength light (van Langevelde *et al.*, 2011,
344 Rivas *et al.*, 2015, Spoelstra *et al.*, 2017), while phenological responses in plants are most sensitive to
345 the longer wavelengths recommended to avoid such effects (Bennie *et al.*, 2015a, Bennie *et al.*, 2016).
346 Male caterpillars of the moth *Mamestra brassicae* reared under green artificial light reached a lower
347 maximum mass, pupated earlier and obtained a lower pupal mass than those reared under red light
348 (van Geffen *et al.* 2014), while red light inhibited the attractiveness of a female pheromone lure to
349 more adult males of the winter moth *Operophtera brumata* than did green light (van Geffen *et al.*
350 2015).

351

352 Studies investigating the ecological benefits of part-night lighting have also highlighted that different
353 taxa respond in different ways (Azam *et al.*, 2015, Day *et al.*, 2015, Davies *et al.*, 2017), and the
354 adoption of part-night lighting schemes is often inhibited by a perception among political actors that
355 they lack popular support. There are both perceived and realised benefits of artificial light for society,
356 including in the areas of road safety, crime, and the economy (Gaston *et al.*, 2015c). The night time
357 economy in the UK, for example, was worth £67bn in 2016 (MAKE Associates, 2017), and accounted
358 for up to 27% of town and city centre turnover and 10% of most locations overall employment figure
359 in 2009 (VisitEngland, 2012).

360

361 While modern lighting technologies offer the potential to reduce the ecological impacts of ALAN,
362 identifying how this is best achieved is clearly complex. Studies are needed across a wide variety of
363 taxonomic groups and lighting approaches, to develop options that are both socially and ecologically
364 acceptable.

365

366 Conclusion

367 Research into the ecological, human health and societal consequences of ALAN is now growing
368 rapidly. Here, we have highlighted ten reasons why ALAN should, and likely will be a focus for
369 global change research in the 21st century. Most important to consider, is the notion that while ALAN
370 is having widespread and profound impacts on people and the environment, strategies for abating
371 them are already being explored. Solving the challenges posed by ALAN would not only improve
372 environmental and human health outcomes, but also enhance the human experience of nature and
373 change perceptions of the natural world in a way that facilitates the necessary transition towards a
374 more environmentally orientated and hence sustainable society. It would also inspire greater
375 confidence in our ability to tackle the problems posed by other global change phenomena. The
376 challenge now is identifying how best to address to the complex array of ecological, human health and
377 cultural problems presented by society's propensity for illuminating the night.

378

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383

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Figure 1. The trend in research outputs associated with light pollution and climate change since the year 2000. Bar heights represent the cumulative number of articles expressed as a percentage of the total number of articles published by the end of 2016; numbers are the cumulative number of articles published by the end of each year. Note that the total number of articles does not reflect the total number published in the research area, only the number returned from the search. The data were collected from a Web of Science search for phrases in article titles. The search phrases used for light pollution research outputs were "Light pollution" OR "Artificial Light at Night" OR "Nighttime lighting" OR "Night-time lighting" OR "Night time lighting" OR "Street Lighting" OR "LED lighting" OR "Light-emitting diode lighting". The search phrase for climate change was 'Climate change' and results were not refined by research area. The search for articles on light pollution was refined by research areas: (PLANT SCIENCES OR ORNITHOLOGY OR PSYCHOLOGY MULTIDISCIPLINARY OR ENVIRONMENTAL SCIENCES OR EVOLUTIONARY BIOLOGY OR PHYSICS APPLIED OR ENTOMOLOGY OR ENGINEERING ENVIRONMENTAL OR ECOLOGY OR URBAN STUDIES OR FISHERIES OR BIODIVERSITY CONSERVATION OR BIOLOGY OR PHYSICS MULTIDISCIPLINARY OR ZOOLOGY OR OCEANOGRAPHY OR GEOGRAPHY PHYSICAL OR GEOGRAPHY OR REMOTE SENSING OR PHYSIOLOGY OR MARINE FRESHWATER BIOLOGY OR PUBLIC ENVIRONMENTAL OCCUPATIONAL HEALTH).

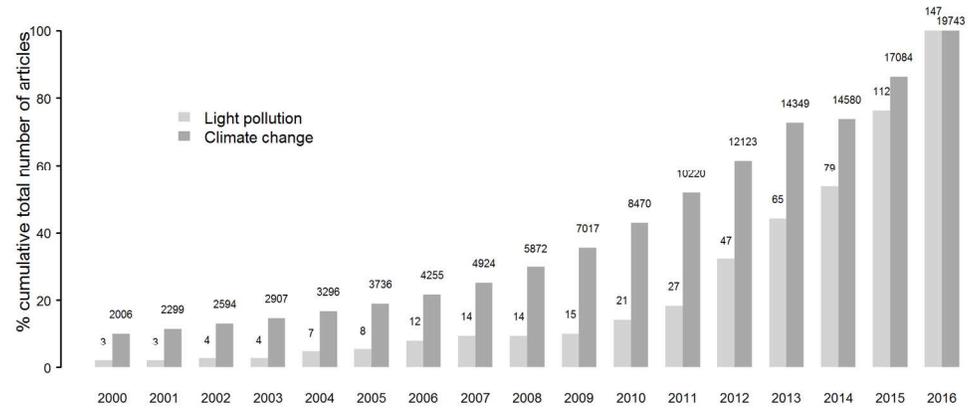
Figure 2. A comparison of fine scale spatial variability in environmental warming and artificial light at night on the Lizard peninsula, Cornwall, UK. A) The increase in the number of growing degree-days (a measure of a measure of change in growing season length expressed in °C Days) between 1977 and 2014 (100m resolution). Adapted with permission from Maclean *et al.* (2016). B) The distribution of artificial light across the same area (750m resolution) recorded from the VIIRS sensor on board the Suomi NPP satellite.

Figure 3. The potential ecological impacts of white Light Emitting Diode lighting compared to other light sources. Spectral power distributions are given for white Light Emitting Diode (LED),

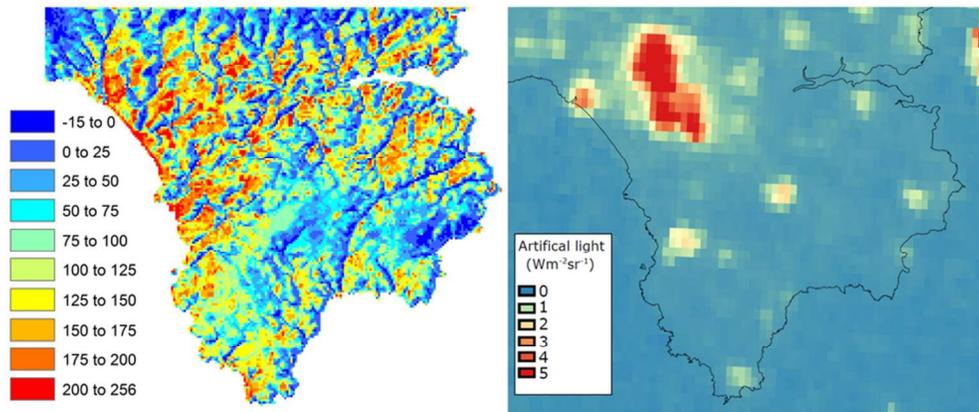
Low Pressure Sodium (LPS), High Pressure Sodium (HPS) and Metal Halide (MH) lights recorded using a MAYA 200 pro spectrometer from street lighting in Cornwall. The amount of light at each wavelength is standardised to relative intensity (radiant energy divided by the maximum radiant energy recorded at any wavelength for each light source) so that the relative distribution of radiant energy across the light spectrum can be compared for each light source. Grey arrows represent the wavelength range over which different types of biological response are expected/recorded. Dashed lines represent the range of wavelengths over which Mammal, Bird, Reptile, Insect, and Arachnid visual systems can detect light [adapted from Davies *et al.* (2013)].

Figure 4. The sensitivity of marine invertebrates to direct artificial light and artificial sky glow.

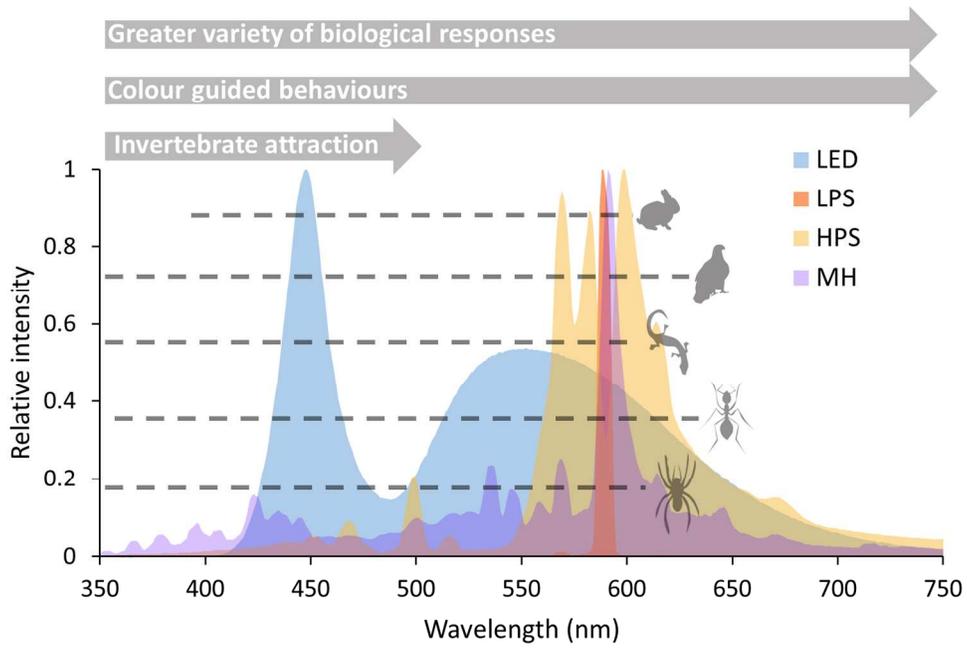
Solid lines represent the attenuation of scalar irradiance (between 400 and 700nm) with depth estimated using radiative transfer models under winter (**a & c**; Chlorophyll = 0.3mg m^{-3} uniform profile, wind = 5m s^{-1}) and spring (**b & d**; Chlorophyll = 5mg m^{-3} uniform profile, wind = 5m s^{-1}) water column properties. Models of scalar irradiance with depth are derived from spectral power distribution recorded from the spring high tide mark under a white LED street light on the Barbican in Plymouth (**a & b**), and artificial skyglow from predominantly white Metal Halide spectra recorded above Falmouth Harbour (**c & d**). Grey dashed lines indicate the maximum depth at which sufficient artificial light is available to perform species behaviours. SSS= Settlement Site Selection; PR=Polyp Retraction; LP=Larval Phototaxis; DVM=Diel Vertical Migration. Sensitivities to white light were calculated from experimentally derived values in existing literature (Crisp & Ritz, 1973, Young & Chia, 1982, Forward *et al.*, 1984, Svane & Dolmer, 1995, Tankersley *et al.*, 1995, Båtnes *et al.*, 2013, Gorbunov & Falkowski, 2002).



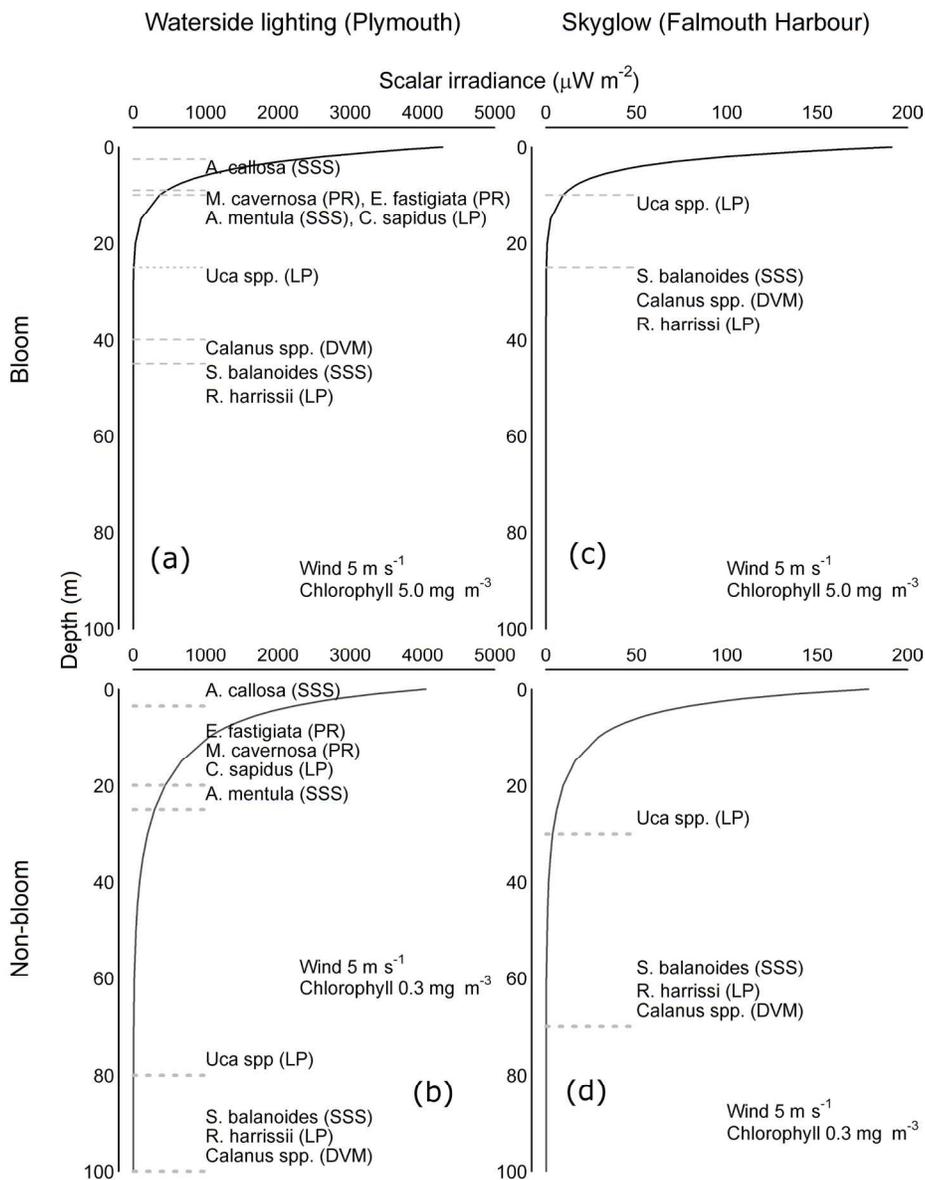
159x69mm (300 x 300 DPI)



80x37mm (300 x 300 DPI)



150x99mm (300 x 300 DPI)



179x231mm (300 x 300 DPI)