

Lighting trends reveal state of the dark sky cloak: light at night and its ecological impacts in Aotearoa New Zealand

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Abstract: Artificial light at night (ALAN) exposes many organisms to increased night-time radiance and disrupts natural cycles that have cued the physiology and ecology of plants and animals throughout their evolutionary history. Here, we use satellite data to quantify spatiotemporal trends of ALAN in Aotearoa New Zealand between 2012–2021 and review the literature of the ecological impacts of ALAN. Our results show that the night-time light environment is changing rapidly in Aotearoa New Zealand: while the vast majority (95.2%) of the country had no direct emissions of ALAN, the lit surface area increased by 37.4% (from 3.0% to 4.2%) between 2012 and 2021. A total of 4694 km² of the country experienced increased brightness (median increase of 87%) over the decade. In contrast, 886 km² became less bright (median decrease 33%), mainly in urban centres where absolute brightness remains high. Our estimated increases in ALAN extent and brightness are underestimates as satellite imagery does not capture sky glow, nor the full extent of the light spectrum emitted by increasingly common light emitting diodes. Impacts of ALAN on the flora and fauna of Aotearoa New Zealand were identified from 39 pieces of literature, with most focussing on behavioural responses in avifauna, mammals, and insects. ALAN is an understudied environmental pollutant, as > 31% of the records described general observations rather than experimental or observational studies and literature describing impacts on groups including herpetofauna and marine mammals was absent, as were studies quantifying impacts on population size, species interactions, or ecosystem functions. At ALAN's current rate of increase, Aotearoa New Zealand is in danger of losing its cloak of darkness, resulting in increased negative environmental impacts. Greater awareness and targeted ecological research are proposed to stimulate change towards minimising ALAN and mitigating the impacts of light emitted into the nocturnal environment.

Introduction

Artificial light at night (ALAN) has transformed the way we live and work outdoors after dark. However, ALAN can adversely impact human wellbeing (Royal Society - Te Apārangi 2018), diminish the aesthetics of the night sky (Royal Commission on Environmental Pollution 2009), and limit celestial observations (Zielinska-Dabkowska & Xavia 2021) for astronomers and indigenous groups with close cultural ties to the night sky (Harris et al. 2013). Moreover, a growing body of evidence indicates that ALAN is an emerging threat to ecological systems. Research clearly demonstrates that ALAN not only disrupts the physiology and behaviour of many organisms, but also alters species abundance and distribution, species interactions and ecosystem functioning (Sanders et al. 2021). These effects span terrestrial, freshwater, and marine ecosystems (Gaston et al. 2013). Altering nocturnal light levels is referred to as light pollution, while ecological light pollution refers to the way that ALAN disrupts the regular cycles of organisms and the natural processes to which species contribute (Gaston et al. 2013).

The widespread use of ALAN in modern society has

exposed much of the earth's surface to night-time radiance that exceeds natural levels. The surface of the earth that is affected by ALAN increased by an average of 2.2% per annum between 2012 and 2016 and there were large differences across regions and between countries (Kyba et al. 2017). The natural nightscape can be altered by ALAN through direct emissions and/or through the scattering of such emissions, resulting in skyglow that can be visible for > 100 km from the source of emission. Globally, in 2019, 26.5% of land area showed direct emissions, while skyglow was modelled to affect 46.9% of the terrestrial surface (Cox et al. 2022). In Aotearoa New Zealand, based on satellite imagery of ALAN emissions in 2014 and skyglow modelling, it has been estimated that more than 97% of the population live under skies that are at least somewhat affected by artificial light at night, and that the eyes of approximately 5% of the country's population never switch to night vision (Falchi et al. 2016).

The global transition from high-pressure sodium (HPS) to light-emitting diode (LED) light sources has brought additional concerns around ecological impacts. As LED lights contain a broad wavelength spectrum and a strong peak in the blue part of the spectrum, they may substantially increase the magnitude

of effects on species that are sensitive to specific wavelengths (Davies et al. 2013; Longcore et al. 2018). Global data estimates that 19.6% of birds, 16.6% of reptiles, 93.3% of amphibians, 14.1% of fish, 64.4% of invertebrates, and all bat species are nocturnal (Hölker et al. 2010). These species are likely to be particularly sensitive to changes in lighting conditions (Hölker et al. 2010), though diurnal species can also experience negative impacts, as a direct result of exposure to ALAN or through indirect impacts on nocturnal species (Gomes et al. 2021; Vardi-Naim et al. 2022). While the number of nocturnal species in Aotearoa New Zealand is not quantified, we have a high level of endemism and our unique flora and fauna may be particularly impacted by the spread of ALAN. Despite this, the impacts of ALAN in this country have received very limited attention in the scientific literature (Farnworth et al. 2018).

To-date, only one study has assessed the prevalence of ALAN in Aotearoa New Zealand and this was focused on a local scale across a relatively short timeframe. McNaughton et al. (2022) measured ground-based levels of night sky brightness around Auckland between 2015 and 2017 using a lensed Sky Quality Meter. Across the three-year period, the measured sky brightness did not change and modelled skyglow did not fully mask the lunar cycle (i.e. nights with a full moon were brighter than the skyglow). However, in areas of ecological importance (i.e. Significant Ecological Areas, Outstanding Natural Features, and Outstanding Natural Landscapes) lying within 15 km of the city centre, night skies were predicted to be at least 10-fold brighter than natural levels (McNaughton et al. 2022). The accessibility of satellite data to quantify ALAN permits a broader scope of research opportunities and allows a comprehensive review of changes in ALAN across Aotearoa New Zealand.

Here we address two aims: (1) to describe the spatial and temporal patterns of ALAN in Aotearoa New Zealand, and (2) to summarise the known impacts of ALAN for New Zealand flora and fauna. To do so, we (1) use night light satellite imagery between 2012–2021 to describe the trends in extent and brightness of direct ALAN emission, identifying areas that experience potential effects of ALAN, and (2) summarise the published literature on the impacts on species and communities that have been described in Aotearoa New Zealand to date and place it within the context of impacts observed globally. Our study is the first to describe, in detail, trends in ALAN and to compile all literature on the impacts of ALAN on the flora and fauna of Aotearoa New Zealand. Our intention is that our work provides a foundation to support the development of future research directions and relevant mitigation measures for ALAN in Aotearoa New Zealand.

Methods

Artificial night-time light

We assessed trends in ALAN between 2012–2021 in Aotearoa New Zealand by using data from the Visible Infrared Imaging Radiometer Suite (VIIRS) on the Suomi National Polar-orbiting Partnership satellite. We used the masked median dataset (V.2 VNL time), which consists of cross-calibrated annual composites that are created from monthly data and have been processed to screen out clouds, stray light, ephemeral lights, and background (non-lights) data (Elvidge et al. 2021). Data are freely available from the Payne Institute for Public Policy under the Colorado School of Mines (<https://eogdata.mines.edu/products/vnl/>).

The VIIRS records the radiance of artificial night-time light emissions (in nanowatt per square centimetre per steradian $\text{nW cm}^{-2} \text{sr}^{-1}$) at a spatial resolution of 15 arc-seconds. The dataset was masked to the New Zealand terrestrial area, transformed, and resampled to New Zealand Transverse Mercator projection in ArcMap 10.6. This resulted in equal area pixels of 250×250 m resolution.

Change in lit surface area

To assess change in the extent of lit surface area over the study period, we first selected a brightness threshold. Any pixel with a value above the threshold was considered 'lit' in each annual dataset. Although there is no known threshold after which artificial light becomes biologically relevant, ecological impacts have been noted at very low light levels (Alaasam et al. 2021; Hölker et al. 2021). In addition, the VIIRS dataset is a global product, and detecting the most relevant light emitting sources, such as small settlements, is best determined using relevant local thresholds (C. Elvidge, NOAA National Geophysical Data Center, pers. comm). We visually inspected the yearly imagery overlayed on daytime satellite imagery of Aotearoa New Zealand and found that areas of VIIRS brightness levels that were greater than $0.25 \text{ nW cm}^{-2} \text{sr}^{-1}$ clearly corresponded with the locations of small-scale settlements or infrastructure. Hence, we determined the change in extent of lit area over the 10 year period by assessing the number of pixels with any night light in annual images (hereafter 'lit surface area'), using a background darkness threshold of $0.25 \text{ nW cm}^{-2} \text{sr}^{-1}$ (Elvidge et al. 2021).

For each year, we summed the pixels that contained brightness levels above the threshold to calculate the lit surface area. To estimate the annual increase in lit surface area across Aotearoa New Zealand, we then fitted linear, exponential, and log-linear gaussian models to the annual time series and compared model fits using the Akaike Information Criterion (AIC; Anderson & Burnham 2004) and the stats package of R 4.1.1 (R Core Team 2021). The linear model fitted the data best, closely followed by the log-linear model ($\Delta\text{AIC} < 0.3$, suggesting that both models were supported; see Appendix S1 in Supplementary Material). Due to uncertainty over the ideal detection threshold for ALAN, we conducted a sensitivity analysis to assess how the overall change in lit surface area depended upon the darkness threshold used, by setting the threshold at regular intervals between brightness levels 0.1 and $1.0 \text{ nW cm}^{-2} \text{sr}^{-1}$ and replicating the above analysis (Appendix S1).

Change in brightness

To evaluate changes in brightness, we assessed temporal trends in radiance for each pixel using the Theil-Sen slope. This is a robust, non-parametric method of simple linear regression that is commonly used to analyse timeseries data (Wilcox 2010). We tested whether there was a significant change over time, using the *kendallTrendTest* function in the EnvStats package in R. This is a non-parametric test for a monotonic trend based on Kendall's tau statistic (Millard 2013). We classed pixels as having a significant change in brightness over time if the Kendall test was significant and the modelled brightness of the pixel exceeded the darkness threshold in the decade studied. We visualised the results in ArcMap 10.6. To support description of the spatiotemporal patterns of ALAN, we separately assessed changes in brightness across different categories along the urban-rural gradient. We used the *exact_extract* function in

the `exactextractr` package in R (Baston 2022) to tabulate the areas of significant change (increase or decrease) according to the 2021 Urban Rural classification (Statistics New Zealand 2021). This classification groups the country into areas that share common urban or rural characteristics, and it separately identifies urban areas (representing densely developed spaces that include residential, commercial, and other urban land uses), rural settlements, other rural areas and water bodies.

To express the relative rate of brightness change, we estimated the brightness ratio between 2021 and 2012 for each of the individual pixels using the estimated Theil-Sen intercept and slope (rather than the respective annual observations, which show stronger fluctuations). For pixels that started off in 2012 as dark (i.e. $0 \text{ nW cm}^{-2} \text{ sr}^{-1}$ or close) and then became brighter, ratios are infinite or artificially high. Pixels with estimated values of $< 0.25 \text{ nW cm}^{-2} \text{ sr}^{-1}$ at the start of the period were set to that threshold value, prior to calculating the ratio. Although this approach reduced issues with very large and infinite estimates, it would have produced somewhat conservative estimates of the brightness ratio. In particular, those pixels that started dark and became brighter to only just above the darkness threshold, now showed a brightness ratio of (close to) 1. Rather than calculating the mean, which may be biased by extreme changes, we calculated the median ratio of brightness change for pixels that experienced significant change (i.e. either increased or decreased).

Impacts of ALAN on the flora and fauna of Aotearoa New Zealand

We examined the literature for studies investigating the impacts of light pollution on the flora and fauna of Aotearoa New Zealand. Specifically, we searched ScienceDirect for articles published until 1 September 2023 using the following search statement: (“New Zealand” AND (“light pollution” OR “artificial light at night” OR “night light” OR “night-light” OR “nightlight”)). We screened the abstracts of the 317 resulting articles for papers that had studied flora or fauna. We also conducted the same search in Google Scholar and screened the first 500 results. We then used snowballing to find other relevant articles by reviewing the cited literature in the articles found. Although we acknowledge that we may have missed articles or reports, we do not anticipate that effects on specific plant or animal taxa are less likely to be captured using this method.

We included peer reviewed papers, personal communications mentioned within peer reviewed papers, grey literature reports, and theses within the results. We did not include species

management plans that consider the impact of lighting on native species (e.g. bat management plans produced by consultancies), as these plans can be subject to confidentiality clauses and are not always publicly available. We also did not include media releases from newspapers, magazines, or other popular literature about species affected by ALAN. Publications that used passive light traps for the purposes of collecting species unrelated to studying the impacts of ALAN were also excluded. Grey literature and theses that examined species responses to ALAN were only included if related publications (i.e. those presenting data from thesis or report chapters) were not available. Studies on both native and non-native species in Aotearoa New Zealand were considered within the review, although studies that were conducted overseas on native New Zealand plants and animals were excluded (e.g. Aulsebrook et al. 2020 on black swans in Australia).

Literature was categorised by the type of evidence-base, i.e. ‘observational study’, ‘experiment’, ‘general observation’, or ‘literature review’. Research where lighting conditions were experimentally manipulated (i.e. lighting was added to a system and a control treatment was available) was classed as an ‘experiment’, irrespective of whether it occurred in a laboratory or in the field. Research where the assignment of the light treatment was not influenced, i.e. research that utilised streetlighting already in place to collect data for modelling or to make behavioural observations, was classed as an ‘observational study’. Behaviour observed *in situ* (rather than within an experiment or observational study) was classed as a ‘general observation’. General observations also included those recorded as personal communications within published literature. Publications containing a compilation of (inter) national literature to infer how ALAN could potentially impact New Zealand species were classed as a ‘literature review’.

Results

ALAN trend, 2012–2021

Change in lit surface area

In 2012, just over 3.0% of Aotearoa New Zealand’s terrestrial extent was brighter than the set threshold. By 2021, lit surface area had increased by an estimated annual increment of $338 \pm 55 \text{ km}^2$ to 4.2% of the terrestrial extent. The modelled average expansion of surface area experiencing ALAN emissions was 37.4% across the decade and the average annual increase was estimated as 3.2% (Fig. 1). For 95.2% of Aotearoa

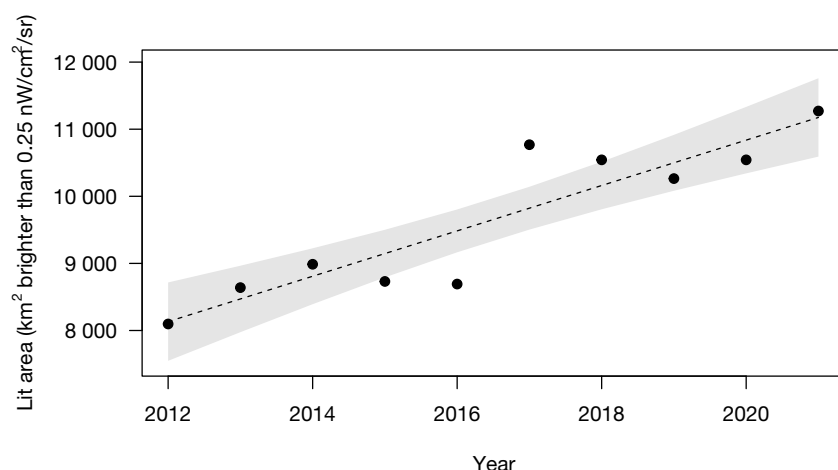


Figure 1. Change in lit surface area across Aotearoa New Zealand between 2012–2021, as represented by emissions of artificial light at night detected by VIIRS satellite imagery. The dotted line represents the linear trend model (shaded area represents 95% confidence interval). Over the decade, the extent of lit surface area (brightness levels $> 0.25 \text{ nW cm}^{-2} \text{ sr}^{-1}$) increased by approximately 37.4%.

New Zealand, VIIRS satellite imagery did not detect any ALAN emissions (i.e. it was darker than the radiance threshold for the whole decade).

Change in brightness

Between 2012 and 2021, a total of 4694 km² of terrestrial Aotearoa New Zealand saw a significant increase in the brightness of ALAN emissions, whereas 886 km² became significantly darker (Fig. 2). Pixels that became significantly brighter showed absolute increases between 0.005 and 6.310 nW cm⁻² sr⁻¹ annually, with a median relative brightness increase of 87% over the decade. Areas that decreased in brightness did so by between -3.967 and -0.006 nW cm⁻² sr⁻¹

annually, with a median decrease in brightness of 33% over the 10 years (Appendices S2 and S3). Most of the increase in brightness occurred in the urban-rural category 'Other rural areas' (Fig. 2, Table 1), which comprises the areas located outside urban areas or rural settlements (including land used for agriculture and forestry, conservation areas, and regional and national parks). The strongest rates of increase in direct emissions mainly occurred at a small scale (< 1 km²) and were often related to industrial development (Appendix S2).

Decreases in brightness were pronounced in major and large urban centres, together accounting for 43.8% of decreased extent (Fig. 2, Table 1). However, the absolute levels of brightness in those areas remained higher than in most other

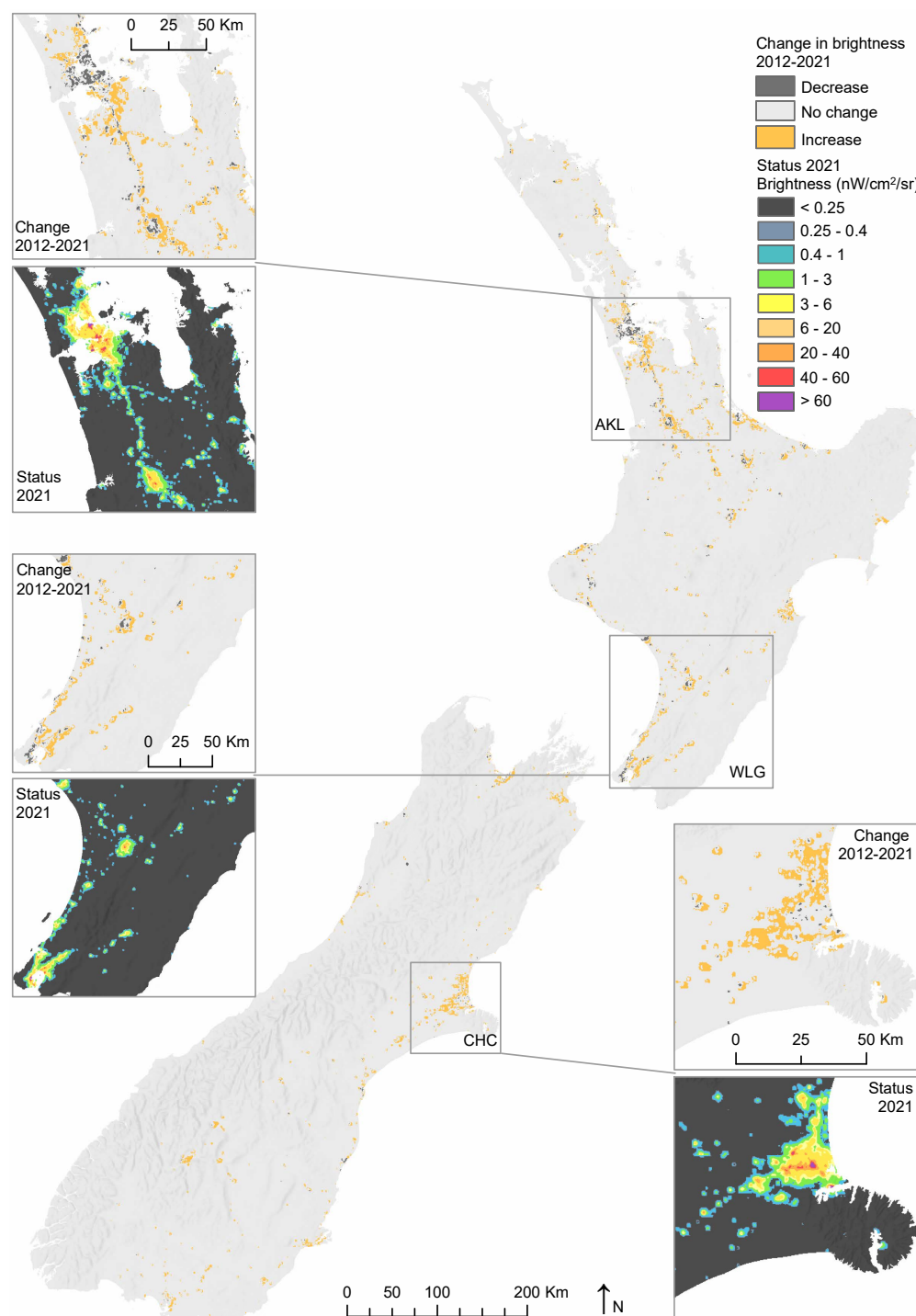


Figure 2. Map detailing areas of significant increase (orange) and decrease (black) in the brightness of direct emissions of artificial light at night (nW cm⁻² sr⁻¹) between 2012–2021, as represented by VIIRS satellite imagery. Inserts show details around Auckland (AKL), Wellington (WLG) and Christchurch (CHC) for the change in brightness and the brightness status in 2021 (see Appendices S2 and S3 for maps showing the average annual rate of change and the status in 2021 respectively).

Table 1. Changes in brightness of direct emission of artificial light at night (ALAN; as determined by VIIRS satellite imagery between 2012–2021) classified by urban-rural categories (Statistics New Zealand 2021). The table represents, for each urban-rural category, the summed area of pixels with a significant decrease, no change, or a significant increase, and the percentage of the grand total of each change type that occurred within each urban-rural category (in brackets). The table also shows the percentage of the areal extent of each urban-rural category that showed a decrease or increase in brightness.

Urban ¹ -rural category	Significant decrease in brightness (km ²) (% of area) ²	No change in brightness (km ²) ²	Significant increase in brightness (km ²) (% of area) ²	% of urban-rural category with significant brightness change	
				Decrease	Increase
Major urban area	281 (31.7%)	797 (0.3%)	332 (7.1%)	19.9	23.5
Large urban area	107 (12.1%)	446 (0.2%)	171 (3.6%)	14.8	23.6
Medium urban area	71 (8.0%)	281 (0.1%)	172 (3.7%)	13.5	32.8
Small urban area	131 (14.8%)	691 (0.3%)	282 (6.0%)	11.9	25.5
Rural settlement	41 (4.6%)	1184 (0.5%)	199 (4.2%)	2.9	14
Rural other	243 (27.4%)	254 592 (97.2%)	3458 (73.7%)	0.1	1.3
Inland water	3 (0.3%)	3152 (1.2%)	52 (1.1%)	0.1	1.6
Inlet	6 (0.7%)	403 (0.2%)	20 (0.4%)	1.4	4.7
Oceanic	3 (0.3%)	345 (0.1%)	8 (0.2%)	0.8	2.2
Grand total ³	886 (100%)	261 891 (100%)	4694 (100%)	0.3	1.8

¹Urban areas were subdivided by population size: major > 100 000 residents; large 30 000–99 999; medium 10 000–29 999; and small 1000–9999.

²The first number represents the total area (summed number of pixels, expressed in km²) over which the type of brightness change (significant decrease, no change or significant increase) was detected for each urban-rural category; the number in brackets describes the percentage of the grand total of each change type that occurred within that urban-rural category.

³For the grand total, the total area of Aotearoa New Zealand's land surface over which the type of brightness change (significant decrease, no change or significant increase) was detected is noted in km², together with the percentage of the country's land surface this represents.

locations (Appendix S3). Areas on the urban peripheries often experienced an increase in brightness (see inserts of Auckland, Wellington, and Christchurch in Fig. 2; Appendices S2, S3).

Impacts of ALAN on the flora and fauna of Aotearoa

The impacts of ALAN on the flora and fauna of Aotearoa New Zealand were collated across 39 pieces of literature (Table 2), comprising 22 peer reviewed articles, ten grey literature studies, four theses and three personal communications contained within peer reviewed papers. Out of the 39 works, 36% were classed as experiments, 31% as general observations, 23% as observational studies, and 10% as literature reviews. Some studies assessed impacts on more than one species group. Overall, avifauna were the most frequently represented taxonomic group ($n = 17$), followed by mammals ($n = 12$), invertebrates ($n = 9$), fish ($n = 4$) and plants ($n = 1$). Literature describing impacts on herpetofauna or marine mammals was absent. The vast majority of studies focused on organism behavioural responses to ALAN (in particular phototaxis, i.e. movement in response to light, either towards the source of light, positive phototaxis, or away from it, negative phototaxis). One study modelled changes in population size based on expert-elicited vital rates estimates (Fischer et al. 2023), but to date, the impact of ALAN on population size, species interactions, ecosystem functioning, or ecosystem services has not been experimentally assessed.

Discussion

Trends of light pollution in Aotearoa

Our data revealed that the extent and brightness of emissions of ALAN in Aotearoa New Zealand is growing rapidly. Although

our night-time environment remains relatively dark compared with other countries, and 95% of the country's surface area is not affected by direct emission of ALAN, the total surface area of Aotearoa New Zealand that is lit has increased by 37.4% to more than 11 000 km². The lit surface area has grown much faster than the expansion of the country's built-up area (comprised of urban, suburban and rural settlements, and industrial areas), which grew by only 3.2% between 2012 and 2018 (LCDB5.0; Manaaki Whenua 2020). We found that the expansion of ALAN emissions was concentrated in rural areas that are outside settlements in Aotearoa New Zealand (Table 1), as has been found globally (Cox et al. 2022). The illuminated surface area in Aotearoa New Zealand is also growing faster than the global average, i.e. a 3.2% increase per annum between 2012–2021 compared with the global average increase of 2.2% per annum between 2012–2016 (Falchi et al. 2016; Kyba et al. 2017). Moreover, 4694 km² of the country significantly increased in brightness (with a median increase of 87%), whereas only 886 km² experienced a decrease in emission brightness (median decrease of 33%). These decreases were particularly noticeable in urban centres, where absolute brightness has remained high.

Despite the capability of satellite imagery to quantify lit surface area and changes in emission brightness across Aotearoa New Zealand, the data likely underestimates the changes observed by humans and other ground-based organisms. This is because the data represent direct emissions of ALAN only and (1) did not incorporate estimates of skyglow, (2) may not accurately capture emission characteristics associated with new technology, and (3) did not capture organisms' viewpoints (see below). Using > 50 000 citizen science observations, Kyba et al. (2023) recently estimated a 9.6% annual increase in night sky brightness in major cities around the world between 2011

Table 2. Summary of the literature examining the ecological impacts of artificial light at night (ALAN) in Aotearoa New Zealand, detailing the species (group) studied, type of evidence and publication, as well as process studied, methodology used, and reported impact. HSP: high pressure sodium, LSP: low pressure sodium, LED: light emitting diode, UV: ultra-violet; MH: metal halide.

Species (group) studied	Type of evidence	Process studied	Summary of method	Impact of artificial light at night (ALAN)	Reference	Publication type
Plants						
Pōhutukawa/iron tree (<i>Metrosideros excelsa</i>)	General observation	Phenology (flowering)	Observation mentioned in peer reviewed paper.	Trees next to streetlights flower more profusely than trees between them.	Bennie et al. (2016)	Pers. comm. from J. Beggs in peer reviewed paper
Invertebrates						
Tree wētā (<i>Hemideina thoracica</i>) and cave wētā (Rhaphidophoridae)	Experiment	Behaviour (phototaxis)	Visitation of illuminated sites vs dark control sites.	Both species visited lit sites less often than dark sites. For tree wētā, this effect was sex-dependent: males but not females avoided illuminated sites.	Farnworth et al. (2018)	Peer reviewed paper
Introduced longhorn beetles (<i>Arhopalus ferus</i>) and bark beetles (<i>Hylurgus ligniperda</i> ; <i>Hylastes ater</i>)	Experiment	Behaviour (phototaxis)	Catch rate in light traps baited with different colours (yellow, red, green, white, UV-black light, and UV-black-light-blue).	UV lights trapped significantly more of the three study species and non-target species (dominated by Lepidoptera, then Hymenoptera, Diptera, Coleoptera). Yellow light was the least attractive.	Pawson et al. (2009)	Peer reviewed paper
Huhu beetle (<i>Prionoplus reticularis</i>) and introduced longhorn beetle (<i>Arhopalus ferus</i>)	Experiment	Behaviour (phototaxis)	Catch rate of beetles in light traps baited with UV light (to attract) and yellow light from LPS and HPS and white light from MH lighting fixtures to deter, compared with a control.	UV traps were highly attractive to beetles. Yellow LPS and HPS lights were poor attractants. Target beetle species differed in phototaxis to MH lights. Observations during the study noted greater insect flight activity surrounding MH lights, especially Lepidoptera and non-target Coleoptera.	Pawson and Watt (2009)	Peer reviewed paper
Moths (<i>Dumbletonius unimaculatus</i> ; <i>Aenetus virescens</i> ; <i>Wiseana signata</i> ; <i>Aoraia dinodes</i> ; <i>Aoraia enysii</i>)	General observation	Behaviour (phototaxis)	Observation mentioned in peer reviewed paper.	Moths exhibited fatal attraction to lighting, with male <i>A. dinodes</i> and <i>A. enysii</i> particularly attracted.	Dugdale (1994)	Peer reviewed paper
Caddisflies (Trichoptera)	Experiment	Behaviour (phototaxis)	Catch rates in paired light traps with 3000 vs 6500 K in a light-naïve waterway (Hawdon River) and 4000 vs 5650 K in an urban waterway (Avon River), respectively.	More caddisflies and lepidoptera were captured using 6500 K compared with 3000 K, and using 5650 K compared with 4000 K.	Schofield (2021)	Thesis
Flying insects, including Coleoptera, Diptera, Hymenoptera, Lepidoptera and Thysanoptera	Experiment	Behaviour (phototaxis)	Catch rate at HPS vs 4000K LED; and dark control vs 2700, 3000, 3500, 4000, 5000 and 6500 K LED.	LED lamps attracted more flying invertebrates on average than HPS lamps. LED colour temperature did not affect invertebrate attraction.	Pawson and Bader (2014)	Peer reviewed paper

Table 2. Continued.

Species (group) studied	Type of evidence	Process studied	Summary of method	Impact of artificial light at night (ALAN)	Reference	Publication type
Ground insects (Formicidae, Blattidae, Orthoptera), Aranae flying insects (Diptera, Coleoptera, Hemiptera, Hymenoptera)	Observational study	Behaviour (activity, phototaxis)	Activity of ground insects (tracking tunnels) and catch rate of spiders and flying insects (sticky traps at 2.5 m high) before and after streetlight retrofit from HPS to LED. LED were 4000 K and dimmed to 50% between 23:30 and 06:00.	Ground insect activity was more likely under LED than HPS; no effect of LED vs HPS for any of the five orders of insects at 2.5 m high.	McNaughton et al. (2021)	Peer reviewed paper
Glow worms (<i>Arachnocampa luminosa</i>)	General observation	Behaviour (phototaxis)	Observation mentioned in peer reviewed paper.	Glow worms were disturbed by lighting.	Meyer-Rochow (2007)	Peer reviewed paper
Squid (Oegopsina)	Literature review	Behaviour (phototaxis)	International literature was used to infer likely effects of lights from a proposed iron sands extraction and processing vessel at South Taranaki Bight.	Internationally, squid are attracted to high-intensity lights used on squid-fishing vessels. Given relatively modest lights from the proposed processing vessel, effects were considered to be relatively small.	Thompson (2013)	Grey literature
Birds						
Ruru (<i>Ninox novaeseelandiae</i>)	Observational study	Vocalisation	Number of syllables vocalised per hour between sunset and sunrise were counted on audio recordings at five LED retrofit sites and five control HSP sites. LED were 4000 K and dimmed to 50% between 23:30 and 06:00.	No effect on vocalisation was detected.	McNaughton et al. (2021)	Peer reviewed paper
North Island brown kiwi (<i>Apteryx mantelli</i>)	Experiment	Behaviour (movement)	Assessed preference in captive kiwi for light colour (blue, yellow, red or green) and light intensity was using choice tests.	Light colour did not affect the amount of time that kiwi spent in different parts of an enclosure, but birds spent significantly more time in areas with lower light intensity.	Grant (2012)	Thesis
North Island brown kiwi (<i>Apteryx mantelli</i>)	Experiment	Chronobiology	Assessed how indoor brooder light intensity affects the timing of outdoor emergence times of juvenile kiwi.	Kiwi housed in darker brooder boxes emerged significantly earlier than kiwi housed in brighter brood boxes.	Grant (2012)	Thesis
Urban birds Native: tūī (<i>Prothemadera novaeseelandiae</i>), silvereye (<i>Zosterops lateralis</i>) Exotic: common myna (<i>Acridotheres tristis</i>)	Observational study	Chronobiology	Initiation of dawn song and cessation of dusk song from audio recording of bird song before and after streetlight retrofit from HPS to LED,	Mynas started singing later after retrofit. Tūī started singing later too, but only in some months. No effect on silvereye was detected. No impact on cessation of dusk song for any of	McNaughton et al. (2021)	Peer reviewed paper

Table 2. Continued.

Species (group) studied	Type of evidence	Process studied	Summary of method	Impact of artificial light at night (ALAN)	Reference	Publication type
			compared with lights remaining HPS. LED were 4000 K and dimmed to 50% between 23:30 and 06:00.	the three species was observed.		
Urban birds Native: tūī (<i>Prosthemadera novaeseelandiae</i>), silvereye (<i>Zosterops lateralis</i>), grey warbler (<i>Gerygone igata</i>) Exotic: sparrow (<i>Passer domesticus</i>), Eurasian blackbird (<i>Turdus merula</i>), common myna (<i>Acridotheres tristis</i>), starling (<i>Sturnus vulgaris</i>), spotted dove (<i>Spilopelia chinensis</i>), song thrush (<i>Turdus philomelos</i>), Eastern rosella (<i>Platycercus eximius</i>), goldfinch (<i>Carduelis carduelis</i>), rock pigeon (<i>Columba livia</i>)	Observational study	Community composition	Using monthly street-facing garden bird counts, before and after streetlight retrofit from HPS to LED, compared with lights remaining HPS, species richness, relative abundance and community composition were assessed. LED were 4000 K and dimmed to 50% between 23:30 and 06:00.	10% more species were detected overall, and 15% more introduced species were recorded after LED retrofit. No effect on native species richness was observed. Of the 12 most common birds, native grey warbler (<i>Gerygone igata</i>) and introduced rock pigeon (<i>Columba livia</i>) increased in abundance after retrofit. No response was detected for other species. Retrofit did not significantly alter community composition.	McNaughton et al. (2021)	Peer reviewed paper
Southern black-backed gull (<i>Larus dominicanus</i>)	General observation	Behaviour (foraging)	Peer reviewed paper documenting behavioural observations under ALAN.	Unusual nocturnal feeding behaviour was observed around lit wood-processing sites and sawmills whereby ALAN increased time spent foraging.	Pugh and Pawson (2016)	Peer reviewed paper
Southern black-backed gull (<i>Larus dominicanus</i>)	General observation	Behaviour (foraging)	Observation mentioned in grey literature.	Black-backed gulls used streetlights on the Auckland motorway as perches to enhance foraging opportunities, including predation on threatened banded dotterels (<i>Charadrius bicinctus</i>). Shielding, dimming, or turning off lights provided immediate mitigation without a lag phase.	Simcock et al. (2022)	Grey literature
Whenua Hou diving petrel (<i>Pelecanoides whenuahouensis</i>)	Observational study	Individual exposure to ALAN	Cumulative exposure of Whenua Hou diving petrels to floodlights was estimated by combining nightly vessel counts and probability of floodlight use near the breeding colony with number of petrel commutes and duration of phenophases.	Modelling suggests that adults commuted out of the nesting area approximately 100 times per breeding period, resulting in tens of thousands of trips past vessels using floodlights within any given breeding period.	Fischer et al. (2021)	Peer reviewed paper

Table 2. Continued.

Species (group) studied	Type of evidence	Process studied	Summary of method	Impact of artificial light at night (ALAN)	Reference	Publication type
Whenua Hou diving petrel (<i>Pelecanoides whenuahouensis</i>)	Literature review	Behaviour (phototaxis); Population size	A working group conveyed objectives fundamental to Whenua Hou Diving petrel recovery and identified eleven potential conservation strategies, including two relating to light pollution, for which consequences were predicted by expert elicitations of vital rates.	Vessel-based light at night within the vicinity of colonies disorientated commuting birds and resulted in collisions and subsequent mortalities. Population size was modelled using expert estimated vital rates under mitigation strategies of (1) reducing vessel-based light pollution and (2) implementing light curfews. Both strategies were estimated to result in increased population sizes.	Fischer et al. (2023)	Peer reviewed paper
Cook's petrel (<i>Pterodroma cookii</i>)	General observation	Behaviour (phototaxis)	Observation mentioned in grey literature.	Fall out was observed in the Auckland central business district and east coast settlements between the city and Leigh.	Gaskin and Rayner (2017)	Grey literature
Cook's petrel (<i>Pterodroma cookii</i>)	Observational study	Mortality (cause of death)	Necropsies determined injuries and cause of death of 19 grounded birds that were treated at an avian rehabilitation centre but did not survive.	70% of Cook's petrels had head trauma, internal bleeding, and/or wounds as the main causes of death. Most birds were healthy other than the collision injuries, suggesting that disorientation from light pollution may cause collisions with anthropogenic structures.	Heswall et al. (2023)	Peer reviewed paper
Westland petrel (<i>Procellaria westlandica</i>)	General observation	Behaviour (phototaxis)	Observation mentioned in grey literature.	Fall out was observed by lights at Punakaiki, Westport, Greymouth and Hokitika.	Wilson (2016)	Grey literature
Fairy prion (<i>Pachyptila turtur</i>)	Experiment	Behaviour (phototaxis)	Abundance, flight behaviour (i.e. turning towards camera/light) and the number of grounded birds were compared across a dark control and three LED colour treatments (red, low power amber, high power amber, low power white, and high power white) imitating fishing vessel lighting set up on land and at sea.	A greater number of birds were recorded flying towards the camera or turning into beams of white light compared to other colours. There was also a tendency for more grounded birds under white light. The at-sea set up had a small sample size and showed no differences.	Goad et al. (2023)	Grey literature
Hutton's shearwater (<i>Puffinus huttoni</i>)	Observational study	Behaviour (phototaxis)	Data from community-based rescue campaigns and systematic searches over two years assessed the spatial distribution of fallout locations in relation to artificial light.	> 90% of bird recoveries were within lit areas. High densities of lights and high wattage lights may influence fall out but only partly explained the spatial distribution.	Deppe et al. (2017)	Peer reviewed paper

Table 2. Continued.

Species (group) studied	Type of evidence	Process studied	Summary of method	Impact of artificial light at night (ALAN)	Reference	Publication type
Hutton's shearwater (<i>Puffinus huttoni</i>), Grey-faced petrel (<i>Pterodroma macroptera gouldi</i>)	General observation	Behaviour (phototaxis)	Peer reviewed paper documenting behavioural observations under ALAN.	Observations of fledglings attracted to light at night. The author proposes that attraction could be because chicks are fed bioluminescent prey when young, and may then use light as a feeding cue.	Imber (1975)	Pers. comm. by N. Hellyer and D. Stack in peer reviewed paper
Sea birds of Northern Aotearoa: Cook's petrels (<i>Pterodroma cookii</i>); Buller's shearwater (<i>Ardenna bulleri</i>); flesh-footed shearwater (<i>Puffinus carneipes</i>)	Literature review	Behaviour (phototaxis)	Inference based on international literature review	Disorientation by light at night is common in seabirds, sometimes resulting in fall out. Fledgelings appear to be more vulnerable. Authors inferred that lighting on coastlines and vessels around Auckland and Hauraki gulf region may put seabirds at risk.	Whitehead et al. (2019)	Grey literature
Buller's shearwater (<i>Ardenna bulleri</i>); common diving petrel (<i>Pelacanoides urinatrix</i>); sooty shearwater (<i>Ardenna grisea</i>); fluttering shearwater (<i>Puffinus gavia</i>); white-faced storm petrel (<i>Melagodroma marina</i>); grey-faced petrel (<i>Pterodroma macroptera</i>); Cook's petrel (<i>Pterodroma cookii</i>)	Observational study	Behaviour (phototaxis)	Three years' worth of data of grounded seabirds taken to a wildlife rescue facility were correlated with characteristics (including night sky brightness) of grounding locations.	More fallout occurred in areas with higher light pollution (e.g. the Central Business District in Auckland). Most species experienced similar levels of grounding across urban and rural areas although black petrels and grey-faced petrels tended to be grounded in rural areas, whereas Cook's petrel tended to be grounded in urban areas. Seasonal differences occurred across species.	Heswall et al. (2022)	Peer reviewed paper
Broad-billed prion (<i>Pachyptila vittata</i>); Chatham petrel (<i>Pterodroma axillaris</i>); Chatham Island taiko (<i>Pterodroma magentae</i>); fairy prion (<i>Pachyptila turtur</i>); Whenua Hou diving petrel (<i>Pelecanoides whenuahouensis</i>); flesh-footed shearwater (<i>Puffinus carneipes</i>); sooty shearwater (<i>Ardenna grisea</i>)	Observational study	Behaviour (phototaxis)	Light-based geolocators on 179 individuals of seven native seabird species were used to estimate the location and frequency of exposure to night-time light events between October 2008 and November 2019.	Species differed in their rates of exposure to ALAN, ranging from 11% of 27 tagged Chatham Island taiko to 57% of 14 fairy prions. Median duration of light events showed that Chatham petrels were exposed to light much longer than Chatham Island taiko, fairy prions and Whenua Hou diving petrels.	Petterson (2022)	Grey literature
General seabird species	Literature review	Behaviour (phototaxis)	International literature and deck strike data from New Zealand waters between 2005–2010 was used to infer effects of light from a proposed iron sands extraction and processing vessel at South Taranaki Bight.	Avian attraction to high-intensity vessel lighting (particularly in poor weather conditions) may result in deck strikes. Vessel lighting may also attract prey (fish, squid), that may attract seabirds. Key attractant for reported deck strikes in New Zealand	Thompson (2013)	Grey literature

Table 2. Continued.

Species (group) studied	Type of evidence	Process studied	Summary of method	Impact of artificial light at night (ALAN)	Reference	Publication type
General seabird species	Experiment	Behaviour (phototaxis)	Abundance and flight behaviour (i.e. turning towards camera/light) of seabirds in response to lights of different types (LED, halogen and fluorescent), brightness (high and low), and colour (white, red and green) were assessed in land-based and sea-based trials.	waters is suggested to be vessel lighting. Lights from proposed iron sands vessel is expected to pose a relatively low risk to seabirds utilising the marine environment, due to relatively far distance from closest seabird colony. No difference in seabird attraction was observed between light treatments, although only small sample sizes were obtained.	Lukies et al. (2019)	Grey literature
Fish						
Inanga (<i>Galaxias maculatus</i>)	Experiment	Physiology; Survival	Fitness-related traits (swimming performance, body size, flexion stage and growth rate) and survival were assessed for larvae (whitebait, inanga) reared in captivity under different nocturnal lighting conditions (14-hr dark night vs 24-hr light).	ALAN did not significantly influence swimming performance, flexion stage, body size or survival rate. However, larvae reared under ALAN developed accelerated otolith growth rates.	O'Malley (2023)	Thesis
Common river galaxias (<i>Galaxias vulgaris</i>) and upland bullies (<i>Gobiomorphus breviceps</i>)	General observation	Behaviour (phototaxis)	Observations mentioned in peer reviewed paper.	Laboratory observations noted that both species of fish were disturbed after lights were switched on during nocturnal periods and that fish would change their positions within tanks.	Cadwallader (1975)	Peer reviewed paper
New Zealand common triplefin (<i>Forsterygion lapillum</i>)	Experiment	Physiology; Behaviour (reproduction)	Laboratory experiment measured fitness-related traits (body condition, body size, growth) and reproductive behaviour and clutch size after exposing fish to three 12-hr night treatments fully dark, or with a dimmed or regular lunar cycle) and a 24-hr artificial light treatment.	Body condition was not affected by light treatment. The relationship between body size and growth differed by sex and light treatment: in the 24-hr light treatment, the relationship between body size and growth rate was positive for males, but negative for females. Fish in the 24-hr light and dark at night treatments were more likely to reproduce than those in the lunar treatment, and fish in the 24-hr	Barclay (2023)	Thesis

Table 2. Continued.

Species (group) studied	Type of evidence	Process studied	Summary of method	Impact of artificial light at night (ALAN)	Reference	Publication type
New Zealand common triplefin (<i>Forsterygion lapillum</i>)	Experiment	Survival; Physiology	Laboratory experiment examined photos of fish egg clutches to determine if hatching success, offspring eye development, total development, and the portion of development taken to synthesise eyes was shaped by exposure to nocturnal illumination (three 12-hr night treatments: dark, or with a dimmed or regular lunar cycle; and a 24-hr artificial light treatment.	light treatment tended to lay more eggs than those in the 12-hr dark at night control. Light treatment did not impact the length or structure of development. Hatching success did not differ between the light treatments but in the lunar treatments, clutches that hatched during the new moon had higher success than those hatching during full moon.	Barclay (2023)	Thesis
General marine fish	Literature review	Behaviour (phototaxis)	International literature was used to infer effects of light from a proposed iron sands extraction and processing vessel at South Taranaki Bight.	Vessel lights may attract plankton and fish, and result in more schooling behaviour of small fish, in turn altering feeding behaviour of larger predatory fish. Since vessel lights only illuminate the extent of nocturnal illumination of the water surrounding the boat, the effects of light from the proposed extraction vessel were considered to be “localised”.	Thompson (2013)	Grey literature
Mammals						
Lesser short-tailed bat (<i>Mystacina tuberculata</i>)	General observation	Behaviour (phototaxis)	Observation mentioned in peer reviewed paper.	Lesser short-tailed bats were observed near the lights of fishing boats anchored approximately 200 m off Codfish Island.	Daniel and Williams (1984)	Peer reviewed paper
Long-tailed bat (<i>Chalinolobus tuberculatus</i>)	General observation	Mortality	Observation mentioned in peer reviewed paper.	Two long-tailed bats were found outside a house in Hazelburn appearing as though they had been chewed. Cause of death was not sighted but bats were believed to have been killed by a domestic cat while feeding on moths attracted to an outside light.	Daniel and Williams (1981)	Peer reviewed paper
Long-tailed bat (<i>Chalinolobus tuberculatus</i>)	Observational study	Behaviour (activity)	Bat detectors were used to assess presence and absence of bat calls	Bat activity significantly increased with distance from the city centre	Le Roux and Le Roux (2012)	Grey literature

Table 2. Continued.

Species (group) studied	Type of evidence	Process studied	Summary of method	Impact of artificial light at night (ALAN)	Reference	Publication type
Long-tailed bat (<i>Chalinolobus tuberculatus</i>)	Observational study	Behaviour (activity)	at 62 green space habitats in Hamilton City. Number of calls were used to infer activity. Transects were surveyed using bat detectors to determine presence within urban habitats of Hamilton City. Number of calls were used to infer activity.	and human activity (i.e. combined roading, lighting and housing). Activity was highest in habitats where there were fewest houses, roads, and streetlights. A higher density of streetlights was correlated with a decrease in activity of long-tailed bats.	Dekrout et al. (2014)	Peer reviewed paper
Long-tailed bat (<i>Chalinolobus tuberculatus</i>)	General observation	Behaviour (foraging)	Observation mentioned in peer reviewed paper.	Long-tailed bats were seen feeding on moths around streetlights near Borland Lodge, Fiordland.	Smith et al. (2017)	Pers. comm. by D. Smith in peer reviewed paper
Long-tailed bat (<i>Chalinolobus tuberculatus</i>)	Observational study	Behaviour (activity)	Baseline activity of long-tailed bats and illumination levels were monitored for two years prior to the Southern Links road development project in Hamilton. Number of calls were used to infer activity.	The highest bat activity rates occurred at sites with low light (≤ 0.5 average lux), suggesting that long-tailed bats may avoid areas with higher light levels or use them less frequently.	Borkin and Smith (2019)	Grey literature
Long-tailed bat (<i>Chalinolobus tuberculatus</i>)	Literature review	Behaviour (activity); Mitigation of road effects (including light)	Literature review summarising the potential impacts of road lighting on bats and outlining mitigation measures proposed by consultancies for the Waikato Expressway infrastructure project and a pedestrian bridge.	Impacts as per other studies listed in Table 2, though the review specifically noted that the proposed mitigation measures for infrastructure projects did not include any activities that would determine the success of the mitigation strategies for bats (e.g. monitoring bat activity, behaviour or population rates).	Jones et al. (2019)	Peer reviewed paper
Long-tailed bat (<i>Chalinolobus tuberculatus</i>)	Experiment	Behaviour (activity); Chronobiology	Bat detectors were installed at two neighbouring sites: one dark control and one site with 4000K LED flood lights. Lights were on for four consecutive nights and then off for four nights over 10 weeks. Number of calls were used to infer activity, and timing of nightly first detection was assessed.	During lit nights, there were fewer bat detections (less activity), and mean nightly first detection times were c. 2 hours later. There were no significant differences at the dark control site for the same period.	Schamhart et al. (2023)	Peer reviewed paper

Table 2. Continued.

Species (group) studied	Type of evidence	Process studied	Summary of method	Impact of artificial light at night (ALAN)	Reference	Publication type
House mouse (<i>Mus musculus</i>)	Experiment	Behaviour (foraging)	Two experiments (one performed in the laboratory and one performed at an ecosanctuary in the Waikato Region) examined the Giving-Up Densities (GUDs) of house mice under light and dark conditions.	Mice removed fewer seeds (i.e. had higher GUDs), spent less time foraging, and made fewer visits at illuminated foraging patches.	Farnworth et al. (2016)	Peer reviewed paper
Ship rat (<i>Rattus rattus</i>)	Experiment	Behaviour (foraging and movement)	Behaviour of wild ship rats was assessed within a large, outdoor “U maze” under either illuminated or dark conditions. Five foraging-related behaviours and seven movement-related behaviours were studied.	Light at night had no effect on foraging behaviour, but significantly affected movement behaviours (e.g. rats made fewer visits to the maze and reduced exploration and speed of movement within the maze when lit). The total time males spent within the illuminated maze was significantly less than females.	Farnworth et al. (2019)	Peer reviewed paper
Ship rat (<i>Rattus rattus</i>)	Experiment	Behaviour (activity)	Trail cameras were used to investigate rodent visitation to sections of fencing at a Waikato ecosanctuary that were either illuminated or dark.	Presence of lighting did not alter the number of visits made by ship rats to sites along ecosanctuary fencing.	Farnworth et al. (2020a)	Peer reviewed paper
Small mammals (hedgehogs <i>Erinaceus europaeus</i> ; rats <i>Rattus</i> spp.; and house mouse <i>Mus musculus</i>)	Observational study	Behaviour (activity)	Activity at tracking tunnels was monitored during a streetlight retrofit from HPS to LED. LED were 4000 K and dimmed to 50% between 23:30 and 06:00.	No significant difference in likelihood of activity was detected between LED and HPS lighting.	McNaughton et al. (2021)	Peer reviewed paper

and 2022. These observations contrast starkly with previous estimates based on satellite imagery from 2012–2016 (approx. 1.8% total radiance growth per year, Kyba et al. 2017). In addition to a sampling bias due to sampling in cities, this discrepancy was at least partly attributed to the satellites' inability to discern the blue light emitted by LEDs (Falchi & Bará 2023; Kyba et al. 2023). Short wavelength (blue) light also scatters more strongly during its transit through the atmosphere, compared with long-wavelength light. A small increase in blue light can therefore have a disproportionately large impact on skyglow, even at long distances from the source (Barentine et al. 2020) and this effect was observed by citizen scientists but not measured by satellites. Our study assessed direct ALAN emissions using satellite imagery and it was beyond the scope of the current study to include estimates of skyglow. Skyglow can be estimated through a zenith modelling approach, as implemented in the world atlas of artificial night sky brightness that was constructed using VIIRS satellite imagery from 2014 (Falchi et al. 2016). These same estimates are also presented as the national indicator of Artificial Sky Brightness (Statistics New Zealand 2018).

As none of the widely used satellite technologies can currently detect the full visible spectrum of light (Mander et al. 2023), it is difficult to quantify the extent of ALAN and changes in emission or sky brightness after the transition to LED. Given that our results rely on satellite-derived data and do not incorporate skyglow, the extent and trends of ALAN outlined within this paper are a conservative estimate. Since 2015, the New Zealand Transport Agency Waka Kotahi and the National Land Transport Fund have supported territorial authorities around the country to replace existing older streetlights with LED lighting, meaning that the conversion to LED street lighting has accelerated in the past decade. As of January 2023, approximately 84% of public street lighting was LED (c. 393 000 out of c. 481 000 public luminaires; EC, unpubl. data) and the corrected colour temperature (CCT) of most luminaires is at least 4000 K (78% at 4000 K and an additional 1% that range up to 6000 K, based on the c. 372 000 LED luminaires of which the temperature is known; EC, unpubl. data). The majority of public streetlighting is therefore relatively rich in the blue part of the spectrum, which is not accurately captured by current satellite technology. Therefore, the decrease in brightness observed in many major urban centres (Fig. 2) is likely to be at least partly explained by this change in spectrum of installed luminaires and its imperfect representation in the satellite imagery. The LED conversion of streetlighting is unlikely to have caused an increase in the surface area that is lit (as seen in Fig. 1). In contrast, trends in emission brightness depicted within this paper may be associated with LED conversion. Increases in brightness are likely the result of new and additional lighting installations (Kyba et al. 2017), while decreases are likely due to a combination of the bias in satellite-based methodology and increased shielding of LED luminaires compared with prior installations.

Modern conversions to LED increasingly use luminaires that incorporate shielding to reduce light spill and light trespass. Improved shielding for recently installed LEDs will have contributed to reduced upward emitted radiance across the country. However, the relative contribution of true decreases in brightness (i.e. through shielding) and methodological bias remains unknown, as both occur simultaneously when conversion to LED is undertaken. LED lights are also more easily dimmed than older types of lamps (Levin et al. 2020). Retrofitting public streetlighting to LED lights can therefore

result in a significant reduction in full-spectrum sky brightness (Barentine et al. 2020). Most street lighting installed in Aotearoa New Zealand in recent years is now capable of using (or being retrofitted with) a central management system that allows control of individual streetlights (e.g. on or off, or reducing the brightness at specific times), which may reduce environmental impacts. The benefits of dimming streetlighting at times of low usage extend to non-ecological realms and include reduced costs due to lower energy requirements, decreased CO₂ emissions, and increased lifespan of luminaires. Dimming has not yet been implemented at any significant scale beyond the city of Auckland (EC, unpubl. data), and while other available technologies (e.g. including lighting controlled by motion-sensing) are being implemented in commercial or private spaces, they are also yet to be implemented widely in public areas.

Importantly for ecological studies, satellite imagery of light at night does not capture organisms' viewpoints (Mander et al. 2023). In addition to upward emissions (partially) captured by satellites and scattered light resulting in skyglow, most organisms' view of the night sky is also affected by light that is emitted horizontally (e.g. from ultrabright LED billboards and illuminated building façades) and may not be shielded by natural vegetation (e.g. under tree canopies, Gaston et al. 2021). In-situ sky brightness measurements with Sky Quality Meters have a better representation of the spectrum than satellite derived measures, but do not sufficiently capture changes in sky brightness when the colour spectrum changes at the same time (Sánchez de Miguel et al. 2017; Mander et al. 2023). As an alternative, photographs taken from the International Space Station (freely accessible via the Gateway of Astronaut Photography of the Earth; <https://eol.jsc.nasa.gov>) have been used after calibration, to determine trends in night light over cities (Sánchez de Miguel et al. 2019). While available for several large cities around the world, unfortunately, the number of photographs of Aotearoa New Zealand at night is insufficient to allow trend analyses using this data source. Investments in technology are required to better capture, and regularly report on, trends in sky brightness around Aotearoa New Zealand, including skyglow, and in such a way that it encompasses ecologically relevant information, including the full spectral distribution (Mander et al. 2023). We acknowledge that streetlights are not the only emission sources of artificial light into the environment. Internationally, streetlights are estimated to contribute between 14–21% to satellite-derived ALAN (Kuechly et al. 2012; Kyba et al. 2021), and less to ground-based measurements of skyglow (Barentine et al. 2020). The advent of LED lighting, associated technology (e.g. solar power, with cheaper running costs), and new applications (e.g. lit billboards on bus stops and façades around urban centres) has expanded the use of outdoor lighting beyond the public sector. To protect nocturnal ecology, it is therefore crucial to also focus on investing in technology to capture light emissions and implement legislative changes beyond streetlights, across all municipal, industrial, commercial, and residential light emitting sources (Gaston et al. 2021; Kyba et al. 2021).

Impacts of ALAN on the flora and fauna of Aotearoa New Zealand

Our literature review revealed some pronounced responses by native organisms to ALAN (Table 2, Fig. 3). Broad themes of light's impact on each species group emerged from the studies and representative summaries of the findings are presented below. Nonetheless, our literature search only retrieved a small



Figure 3. Artificial light at night (ALAN) from local sources (e.g. streetlights) or diffuse sources in the distance (skyglow) can impact the physiology, behaviour, phenology, and fitness of various taxonomic groups. Positively phototactic taxa are attracted to ALAN (including caddisflies, Trichoptera, and huhu beetles *Prionoplus reticularis*), while negatively phototactic taxa avoid ALAN (such as cave wētā, Rhaphidophoridae, male Auckland tree wētā *Hemideina thoracica*, and long-tailed bats *Chalinolobus tuberculatus*). ALAN can also obscure natural nocturnal light sources used in navigation and disorientate seabirds and cause fall-out (e.g. fairy prions *Pachyptila turtur*, and Hutton's shearwaters *Puffinus huttoni*). ALAN can alter circadian or seasonal patterns. For example, *Metrosideros excelsa*, pōhutukawa trees near streetlights have been observed to flower more profusely than those further away from lights. Characteristics of the light perceived by taxa (e.g. intensity and colour composition) may affect the circadian responses. For example, changing high-pressure sodium streetlighting to LED fixtures coincided with indigenous tūī (*Prosthemadera novaeseelandiae*) and exotic common myna (*Acridotheres tristis*) starting their dawn chorus later in the morning. The extent to which these changes affect species interactions (e.g. between predators and prey, plants and their pollinators, parasites and their hosts) has not yet been studied in Aotearoa New Zealand. Textures modified from Creative Commons Attribution 2.0 Generic licensed images.

number of publications that directly studied the impacts of nocturnal lighting, emphasising that ALAN is an understudied pollutant in Aotearoa New Zealand. Based on global studies, we expect that there is potential for other ecological impacts of ALAN on native flora and fauna beyond those presented here.

Plants

Empirical studies examining the impact of ALAN on plants in Aotearoa New Zealand are absent. The only mention in the literature, to our knowledge, is the observation of pōhutukawa (*Metrosideros excelsa*) flowering more profusely next to compared with between streetlights (Jacqueline Beggs, pers. comm. in Bennie et al. 2016). However, it is likely that the responses of New Zealand plants towards ALAN are similar to those demonstrated in international studies (Bennie et al. 2016). For example, exposure to ALAN alters the timing of key phenological phases (e.g. budburst and flowering; French-Constant et al. 2016), extends the growing seasons of deciduous species (Meng et al. 2022), and affects plant growth form, resource allocation, and community composition (Bennie et al. 2015, 2016, 2018).

Lighting from streetlights and digital billboards has already been observed to delay leaf senescence in Aotearoa New Zealand (Fig. 4), and critical interactions between native

plants and insects may also be affected by exposure to ALAN. For example, international studies show that ALAN can alter invertebrate behaviour and aggregations at plants and therefore modify herbivory (Crump et al. 2021; Murphy et al. 2022; Cieraad et al. 2023), pollination (Knop et al. 2017; Boom et al. 2020; Giavi et al. 2021), and seed dispersal (Giavi et al. 2020). Exploring how light alters species interactions is an essential research direction that will contribute to understanding how the impacts of ALAN on primary producers pervade through ecosystems.

Invertebrates

Research on insects dominated the literature on invertebrate responses to ALAN in Aotearoa New Zealand, with only a single report on a non-insect invertebrate (squid; Thompson 2013). Experimental studies typically investigated the characteristics of lighting fixtures (e.g. colour temperature or wavelength of light) that contribute to positive phototaxis (i.e. attraction to light), though Farnworth et al. (2018) examined ALAN from an evolutionary perspective and hypothesised that aversion of ALAN by wētā (Orthoptera: Rhaphidophoridae, Anostomatidae) may occur to mitigate predation risk. Attraction to lamps of different types and colours appeared to be species-specific (Pawson et al. 2009; Pawson & Bader



Figure 4. Light emitted at night can delay the onset of leaf senescence. (a) a birch (*Betula* sp.) shows senescence only of leaves not directly adjacent to a streetlight in Darfield, Canterbury, and (b) light emitted from digital billboards within the Hamilton city centre delays senescence on the light-exposed side of a liquid amber tree (*Liquidambar styraciflua*). Photo credits: (a) Pauline and Brian Loader; (b) BF.

2014; McNaughton et al. 2021). Species also responded differently depending on the colour temperature of white light. For example, Pawson and Bader (2014) did not detect a significant difference between the abundance of terrestrial invertebrates that were attracted to lights ranging between 2700 and 6500 K CCT, whereas forthcoming research found a difference in attraction between 2700 K and 6000 K for some aquatic invertebrate taxa (M. Greenwood, NIWA, pers. comm.; Schofield 2021).

Collectively, these studies emphasise that the expanse of ALAN into Aotearoa New Zealand's nocturnal niche has the potential to negatively affect invertebrates, but our understanding of the specific mechanisms (i.e. altered predation, competition, or movement) driving any detrimental impacts is limited. Globally, ALAN has been proposed as a driver of insect declines and it impacts a diverse suite of insect taxa (Owens & Lewis 2018) by modifying their development, movement, foraging, and reproductive behaviour (Owens et al. 2019). Collision, overheating, dehydration, and predation have already been observed internationally in response to invertebrate attraction to ALAN (Yoon et al. 2010; Minnaar et al. 2015) and Aotearoa New Zealand's native species may experience similar consequences. The impacts of ALAN may also differ between sexes. For example, observations within Aotearoa New Zealand literature suggest that light attracted male puriri moths (*Aenetus virescens*), male sand porina (*Wiseana signata*), and male ghost moths (*Aoraia dinodes*, *A. enysii*) (Dugdale 1994), whereas male tree wētā avoided illuminated sites (Farnworth et al. 2018). Given that moths and tree wētā display sexual differentiation in their responses to ALAN, a sex bias in the impacts of ALAN on these native species may occur (Farnworth et al. 2018).

Invertebrates maintain many key ecosystem services and the expansion of illuminated area across New Zealand

landscapes has the potential to cause broader impacts across ecological systems. For example, the positive phototaxis exhibited by native moths could indicate that their ecological services may be severely limited by ALAN, especially given that light has affected pollination networks elsewhere (Knop et al. 2017; Boom et al. 2020; Giavi et al. 2021). This is particularly concerning given the limited knowledge on the importance of moths as nocturnal pollinators of native plants (Buxton et al. 2018). Similarly, the role that wētā play in seed dispersal and predation (Duthie et al. 2006; Wyman et al. 2011; Larsen & Burns 2012) may also be impacted by the increased area illuminated by ALAN. Food webs are also likely to be affected due to invertebrate responses to lighting. For example, the interruption of aquatic invertebrate drift with ALAN may alter food resources for fish (Zapata et al. 2019) and changes in aquatic invertebrate oviposition and emergence patterns due to ALAN may impact terrestrial ecosystem functioning (Manfrin et al. 2017). Further research examining the impact of ALAN on invertebrates and their interactions would benefit Aotearoa New Zealand by enabling the development of appropriate strategies to mitigate any adverse effects.

Fish

To our knowledge, only two studies have specifically examined the impacts of ALAN on native fish in Aotearoa New Zealand to date. Larvae of threatened endemic inanga (*Galaxias maculatus*) that were reared under ALAN demonstrated accelerated otolith growth rates compared to larvae reared under dark nocturnal lighting cycles (O'Malley 2023). ALAN also altered triplefin (*Forsterygion lapillum*) reproductive behaviour, with more eggs laid after exposure to illumination (Barclay 2023). Observations that *Galaxias vulgaris* and *Gobiomorphus breviceps* were disturbed by light (Cadwallader 1975) also indicate that ALAN is likely to alter the behaviour

of nocturnal fish. However, given the lack of literature, the extent of ALAN impacts on fish remains unclear. Despite < 8% of global studies that examine ALAN responses being on fish (reviewed in Bassi et al. 2022), some consistent effects have become apparent. For example, ALAN alters the daily activity patterns of fish, including foraging, migration, and reproductive behaviour (Nightingale et al. 2006). ALAN can also induce chemical changes, such as increased hormone levels (Gairin et al. 2022), and alter physiological performance, including increased oxygen consumption (Pulgar et al. 2019). The behavioural and physiological responses of fish towards ALAN may be particularly strong, given that fish already demonstrate clear behavioural changes in response to moonlight (Shima et al. 2021, 2022).

It is likely that Aotearoa New Zealand's native fish are impacted by exposure to ALAN, but confirmatory research in the field is required. In addition, responses by fish are often studied in artificial environments, with short term additions of low lighting intensities (Bassi et al. 2022). Much less is known about the impacts of ALAN on fishes within natural environments and therefore further research should prioritise understanding the influence of ALAN in complex habitats that contain competition or predation (Bassi et al. 2022). For example, light has been proposed as affecting the success of fish passage (Franklin et al. 2018) and the addition of ALAN to waterways may impact native fish movement. Constraints on fish passage can disrupt vital connections between the habitats that are required for fish to complete their lifecycles, thereby impeding natural population dynamics. Freshwater and estuarine habitats are exposed to nocturnal lighting from terrestrial sources (i.e. housing, streetlighting, public amenities, etc.) while marine environments experience lighting from coastal developments and offshore sources such as fishing boats, offshore oil platforms, shipping vessels, and cruise ships (Davies et al. 2014). Examining the impacts of exposure to lighting from both terrestrial and marine sources is essential, as more than half of New Zealand's native fish are diadromous and spend part of their life cycle at sea (McDowall 1998).

Birds

For native avifauna, research to date has centred on documenting how individual species change their vocalisation, orientation, and foraging behaviours in response to ALAN. Light at night has been shown to alter the timing of behaviours, including feeding by black-backed gulls *Larus dominicanus* (Pugh & Pawson 2016) and delaying the onset of dawn song for common myna *Acridotheres tristis* and tūi *Prosthemadera novaeseelandiae* after conversion from high-pressure sodium to LED lighting (McNaughton et al. 2021). Furthermore, ALAN also disrupts avian orientation and navigation behaviour particularly for coastal sea birds. A phenomenon known as fall out occurs when terrestrial lighting disorients seabirds: when forced to land, the birds are unable to take off again and become vulnerable to predation, vehicle collisions, or starvation (Rodriguez et al. 2017). Attraction to ship lighting, which results in grounding and birds often having to be assisted to take off, is known as deck strike. In Aotearoa New Zealand, fall out and deck strike of several seabird species has been observed, including Hutton's shearwaters *Puffinus huttoni*, Cook's petrels *Pterodroma cookii*, Westland petrels *Procellaria westlandica*, and Whenua Hou diving petrels *Pelecanoides whenuahouensis* (Deppe et al. 2017; Waugh & Wilson 2017; Whitehead et al. 2019; Fischer et al. 2021; Gaskin 2021; Heswall et al. 2022, 2023). Some instances have involved numerous individuals, for example,

in 2019 there was a major deck strike of several hundred fairy prions *Pachyptila turtur* from Stephen's Island after an illuminated fishing vessel passed by the breeding colony (K. Middlemiss, Department of Conservation, pers. comm.).

In addition to altering the behaviour of individuals, emerging evidence shows that ALAN of different types can also change avian community dynamics by altering species richness, relative abundance, and community composition of birds. For example, after a LED retrofit in Auckland city, introduced avian species richness increased by 15%; and the abundance of native grey warbler *Gerygone igata* and introduced rock pigeon *Columba livia* increased by 2.3 and 5.5 times respectively (McNaughton et al. 2021).

Studies that investigate the consequences of behavioural changes caused by ALAN are vital because they enable the broader ecological impacts to be understood. For example, internationally, exposure to ALAN has changed the timing or repertoire of behaviours of birds and while clear survival benefits were recorded for some species, there were adverse effects for others (Richard et al. 2021). Although some urban bird species profit by exploiting insects attracted to light (Robertson et al. 2010), ALAN may cause other species to accelerate their reproductive behaviour and miss the peak availability of food for feeding their young (Kempnaers et al. 2010; Dominoni et al. 2013).

While the impacts present in international studies highlight the importance of further research within an Aotearoa New Zealand context, the existing literature indicates a need to reduce the attractiveness of at-sea vessels. Given that Aotearoa New Zealand has the highest number of endemic seabirds in the world (33 species only breed here; Croxall et al. 2012), minimising potential attraction and follow-on population level impacts could make an important contribution towards species conservation (Fischer et al. 2023). Furthermore, the behaviour of birds that migrate at night, including many seabirds and waders, is also likely to be affected by ALAN, not only in Aotearoa New Zealand but also elsewhere along their migration routes (Burt et al. 2023). Specific consideration should also be given to iconic nocturnal avifauna that are managed within developed areas (e.g. little spotted kiwi *Apteryx owenii* within Zealandia, an urban ecosanctuary), so that any negative impacts of ALAN can be minimised for threatened terrestrial species.

Mammals

Our literature review revealed that the impacts of ALAN on Aotearoa New Zealand's two species of native terrestrial mammal have been significantly understudied. Understanding the impacts and effects of ALAN on the long-tailed bat *Chalinolobus tuberculatus* and the lesser short-tailed bat *Mystacina tuberculata* and is essential given their legal threat status (Nationally critical', and ranging from 'At Risk' to 'Threatened' depending on the sub-species, respectively; O'Donnell et al. 2022) and their propensity to reside in urban areas with associated high light levels. Currently, there are no experimental or observational studies that examine responses to ALAN by lesser short-tailed bats. Lesser short-tailed bats have been observed approximately 200 m off-shore near lit vessels (Daniel & Williams 1984), but whether this reflects attraction to lights is unknown. However, they may be deterred by light, as during attempts at filming lesser short-tailed bats feeding on nectar of *Dactylanthus taylorii* in Pureora Forest Park, bats did not visit flowers that were illuminated by visible light (2500–2700 K), but did visit flowers lit with infra-red light (K. Borkin, Department of Conservation, pers. comm.).

Similarly, on Hauturu-o-toi, lesser short-tailed bats avoided illuminated pōhutukawa during attempts to film feeding behaviour, but they continued to forage on directly adjacent inflorescences that remained in the dark (D. Pattemore, Plant & Food Research, pers. comm.).

Three observational studies and one experimental study suggest that long-tailed bats may also be deterred by light. Three observational studies in Hamilton found that long-tailed bat activity decreased in areas with more streetlights or brighter illumination (Le Roux & Le Roux 2012; Dekrout et al. 2014; Borkin & Smith 2019). Recent experimental research showed that bat activity (defined as the number of ultrasonic calls captured by recording devices) started approximately two hours later and was reduced overall on nights when 4000 K lights were on, compared to unlit nights (Schamhart et al. 2023). However, elsewhere, anecdotal observations of long-tailed bats feeding around lighting suggest attraction to light (Daniel & Williams 1981; D. Smith, pers. comm. in Smith et al. 2017). International research suggests that species-specific responses to ALAN may be driven by differences in flight speed, habitat use, and foraging strategies (Voigt et al. 2021). Changes in behaviour may occur in the presence of ALAN due to altered foraging opportunities, increased perceived risks of predation (particularly by owls *Ninox novaeseelandiae* and cats *Felis catus*, Daniel & Williams 1981, 1984), or by masking environmental cues that prompt roost emergence (Mariton et al. 2022). Given that ALAN can disturb the system that some moths (Lepidoptera: Geometridae) use to detect ultrasonic calls made by bats while feeding (Wakefield et al. 2015; Dickerson et al. 2023), ALAN may increase predation success by bats and provide short-term foraging advantages, which may explain attraction to lighting by some bat species overseas (Rydell 1992; Blake et al. 1994). However, ALAN has also delayed the emergence of other species from their daytime roosts, with subsequent impacts on individual growth rates (Boldogh et al. 2007).

Improved understanding of the mechanisms behind behavioural change and determining net fitness impacts would aid our knowledge of whether ALAN is contributing to population declines. For example, if bats tend to avoid ALAN, this may mean that their nocturnal commuting routes are lengthened and preferred foraging areas are no longer available for use. Increases in the illuminated area of Aotearoa New Zealand may therefore further increase energetic costs for bats while also reducing available foraging time. Sustained avoidance of ALAN may culminate in negative effects on body condition and reproductive ability (Smith et al. 2017). Addressing ALAN's long-term impacts is vital for developing effective strategies to avoid or mitigate the impacts of ALAN on bats (Jones et al. 2019), particularly for management plans.

The remaining studies on mammals consistently demonstrated that ALAN alters the behaviour of pest rodent species. The presence of light at night strongly reduced the movement and foraging activity of rodents, which was hypothesised to originate from the increased level of predation risk that nocturnal prey species perceive under illumination (Farnworth et al. 2016, 2019, 2020a). Increases in the illuminated area across Aotearoa New Zealand may reduce small mammal activity at lit sites and act as a barrier to movement through the landscape (Farnworth et al. 2016), though the avoidance behaviour of rodents may depend on the size of the illuminated area (Farnworth et al. 2020b; McNaughton et al. 2021). Of concern is that light-sensitive native species residing in dark fragments in urban habitats

may experience increased predation if city lighting drives pest species towards the remaining dark urban refuges. Internationally, the importance of darkness within networks of interconnected habitats (dark infrastructure) is increasingly being recognised as a way to guarantee natural rhythms and processes, including movement and migration (Sordello et al. 2022).

Future research directions on the ecological impacts of ALAN in Aotearoa New Zealand

Local literature on the ecological impacts of ALAN indicate that the responses of native species mostly align with those described in international literature (Longcore et al. 2018; Sanders et al. 2021), however developing species-specific mitigation measures requires knowledge of many variables that are currently unknown (e.g. visual perception of the species involved and factors affecting this perception, as well as sensitivity to lighting characteristics including wavelength, timing and intensity). While a variety of taxa in Aotearoa New Zealand would benefit from investments into additional research on the impacts of ALAN, there are no studies on native herpetofauna and marine mammals, despite impacts of ALAN having been demonstrated overseas (Perry et al. 2008). Furthermore, only single studies with anecdotal observations of the responses to ALAN of plants, non-insect invertebrates, and short-tailed bats have been published. Changes in behaviour have been the focus of most studies, and examining fitness and population-level consequences are vital next steps.

The impacts of ALAN on broader ecological connections between species and communities have not been the focus of any study in Aotearoa New Zealand, yet this is crucial to assess cascading impacts, including on ecosystem functioning and services (e.g. pollination, herbivore control, etc.). The potential for light to interact with other sensory pollutants, invasive species impacts (e.g. predators; Farnworth et al. 2020b; Shima et al. 2022), and global change stressors (Hölker et al. 2021) may heighten responses to ALAN in both terrestrial and aquatic environments, and also requires attention. Any future studies should ensure that the characteristics of the light emissions that are reported encompass ecologically relevant information, including the full spectral distribution (Mander et al. 2023).

Compared to other types of emissions, ALAN emissions may be a relatively easy environmental problem to solve (McDermott 2023). The simplest approach to managing pollution from ALAN is to prevent areas from being lit in the first place (Gaston et al. 2012). If that is not possible, there are clear and straightforward principles that reduce light spill into surrounding areas, including reducing the spatial and temporal occurrence of ALAN, limiting its intensity, and reducing the use of shorter-wavelength lighting (Longcore et al. 2018; Commonwealth of Australia 2023). These options for mitigating the impacts of ALAN also require further investigation (Gaston et al. 2015; Davies & Smyth 2018; Mayer-Pinto et al. 2020; Hölker et al. 2021). For example, transitioning from HPS to LED lighting has also enabled the dimming of Auckland's public streetlights for much of the night, and this may have contributed to fewer reported environmental impacts compared with cities experiencing similar transitions elsewhere (McNaughton et al., 2022). However, no study of ALAN from Aotearoa New Zealand has yet directly applied a dose-response experimental design (i.e. quantifying impacts at more than two levels of brightness under the same conditions, or determining a low brightness threshold at which there are no observed impacts) and only

one study has assessed differential responses to more than two spectra of lights (Pawson & Bader 2014). Even globally, very few studies have combined dimming and part-night lighting to better understand the thresholds of light avoidance or other impacts on species, communities, and ecosystems (Jägerbrand & Bouroussis 2021).

Aotearoa New Zealand is in a privileged position compared to other countries in the world, with much of our country still cloaked in darkness today. However, lit areas are expanding into the rural landscape and towards (protected) natural areas, with the potential to impact a greater proportion of species, communities, and ecosystem functions. The encroachment of ALAN into ecologically valuable areas, including protected and significant natural areas and rare and threatened ecosystems, warrants urgent investigation. In addition, even a partial overlap of a species' habitat with illuminated area or skyglow may be of concern. This is particularly the case for highly mobile and threatened species, such as bats, or species that spend their night-time or a crucial life stage in places that are (temporarily) lit. However, we lack knowledge on which life stages may be particularly vulnerable, the extent to which the fauna of Aotearoa New Zealand is nocturnal, and the mechanisms that may render even diurnal species vulnerable to impacts as a result of exposure to ALAN (Gomes et al. 2021; Vardi-Naim et al. 2022). Moreover, if ALAN deters species, leading to accumulation of individuals into adjacent dark areas, this can affect species interactions and ecosystem functioning beyond the lit area. Such patterns have been shown in insect-plant interactions, but are hypothesised to occur more widely (Giavi et al. 2020).

Implications

Global drivers of biodiversity loss are often difficult to change. However, in contrast to other stressors, mediating the impacts of light pollution at local and landscape scales is feasible in the short-term. Despite the opportunities that LEDs and associated technology offer to help stem light pollution (e.g. shielding, spectral options and automated controls), the overall emission of light at night continues to increase in Aotearoa New Zealand, as it has globally (Falchi & Bará 2023). At the current rate of increase of ALAN, the country is in danger of losing its cloak of darkness. Local literature on the ecological impacts of ALAN indicate that the responses of native species mostly align with those described in international literature (Longcore et al. 2018; Sanders et al. 2021), including disruption of daily or annual cycles and changed patterns of behaviour, activity and movement, but species-specific nuances may hold the key to successful mitigation. Without intervention, further increases in ALAN may contribute towards breaking down ecosystem functions and services and increasing existing concerns about social and cultural impacts.

Progress is being made towards voluntary best-practice guidelines and standards across several sectors. For example, mitigation standards have been developed to reduce light-induced vessel strikes of seabirds with commercial fishing vessels (Ministry for Primary Industries et al. 2023), there are existing guidelines for the cruise industry (Department of Conservation n.d.), and recognition of ecological impacts is supported by the lighting industry (Lighting Council New Zealand & Illuminating Engineering Society of ANZ 2022). New Zealand is also party to the United Nation's convention on the conservation of migratory species, which has endorsed light pollution guidelines for wildlife (Commonwealth of Australia 2023). However, voluntary

adoption of guidelines and standards is unreliable and not sufficient to stem the current rate of erosion of the dark sky in Aotearoa New Zealand. Some lighting ordinances exist at local levels (mostly related to Dark Sky Reserve designations; Zielinska-Dabkowska & Xavia 2021); however, emissions of light at night are not regulated at a larger scale. To protect the natural darkness of the sky and reduce environmental impacts, it is important that best-practice guidelines and standards around the emission of light at night are further encouraged and that regulation is developed in Aotearoa New Zealand (e.g. following examples of nationwide legislation in Croatia, France, and Slovenia; Jägerbrand & Bouroussis 2021).

We can be optimistic that technologies already exist to minimise ALAN and mitigate impacts, and that more innovative solutions will be created in the future. While the societal challenge of reducing the impacts of light at night must also consider the benefits that light provides to humans, there is a general lack of public awareness on the extent, increase, and negative consequences of ALAN, so community engagement will be crucial to elevate social license for voluntary and regulated mitigation strategies. Perhaps most importantly, we must continue to build a body of scientific evidence that can inform the design of mitigation strategies that effectively reduce the impact of ALAN on the native flora and fauna of Aotearoa New Zealand.

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Author contributions: EC conceived the idea and conducted the data analysis. EC and BF developed the idea and wrote the manuscript.

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References

- Alaasam VJ, Kernbach ME, Miller CR, Ferguson SM 2021. The diversity of photosensitivity and its implications for light pollution. *Integrative and Comparative Biology* 61(3): 1170–1181.
- Anderson D, Burnham K 2004. *Model selection and multi-model inference*. 2nd edn. New York, Springer Verlag. 488 p.

- Aulsebrook AE, Lesku JA, Mulder RA, Goymann W, Vyssotski AL, Jones TM 2020. Streetlights disrupt night-time sleep in urban black swans. *Frontiers in Ecology and Evolution* 8: 131.
- Barclay J 2023. Effects of nocturnal illumination on fitness-related traits of the New Zealand common triplefin (*Forsterygion lapillum*). Unpublished MSc thesis. Victoria University, Wellington, New Zealand.
- Barentine JC, Kundracik F, Kocifaj M, Sanders JC, Esquerdo GA, Dalton AM, Foott B, Grauer A, Tucker S, Kyba CCM 2020. Recovering the city street lighting fraction from skyglow measurements in a large-scale municipal dimming experiment. *Journal of Quantitative Spectroscopy and Radiative Transfer* 253: 107120.
- Bassi A, Love OP, Cooke SJ, Warriner TR, Harris CM, Madliger CL 2022. Effects of artificial light at night on fishes: A synthesis with future research priorities. *Fish and Fisheries* 23(3): 631–647.
- Baston D 2022. exactextractr: Fast Extraction from Raster Datasets using Polygons. (Version 0.9.1). <https://cran.r-project.org/web/packages/exactextractr/index.html>
- Bennie J, Davies TW, Cruse D, Inger R, Gaston KJ 2015. Cascading effects of artificial light at night: resource-mediated control of herbivores in a grassland ecosystem. *Philosophical Transactions of the Royal Society B-Biological Sciences* 370(1667): 20140131.
- Bennie J, Davies TW, Cruse D, Gaston KJ 2016. Ecological effects of artificial light at night on wild plants. *Journal of Ecology* 104(3): 611–620.
- Bennie J, Davies TW, Cruse D, Bell F, Gaston KJ 2018. Artificial light at night alters grassland vegetation species composition and phenology. *Journal of Applied Ecology* 55(1): 442–450.
- Blake D, Hutson AM, Racey PA, Rydell J, Speakman JR 1994. Use of lamplit roads by foraging bats in southern England. *Journal of Zoology* 234(3): 453–462.
- Boldogh S, Dobrosi D, Samu P 2007. The effects of the illumination of buildings on house-dwelling bats and its conservation consequences. *Acta Chiropterologica* 9: 527–534.
- Boom MP, Spoelstra K, Biere A, Knop E, Visser ME 2020. Pollination and fruit infestation under artificial light at night: light colour matters. *Scientific Reports* 10: 18389.
- Borkin K, Smith D 2019. Baseline acoustic monitoring of long-tailed bats for the Southern Links roading project, Hamilton 2017 and 2018. Contract Report No. 4192d. Rotorua, Wildlands. 38 p.
- Burt CS, Kelly JF, Trankina GE, Silva CL, Khalighifar A, Jenkins-Smith HC, Fox AS, Frstrup KM, Horton KG 2023. The effects of light pollution on migratory animal behavior. *Trends in Ecology & Evolution* 38(4): 355–368.
- Buxton MN, Anderson BJ, Lord JM 2018. The secret service – analysis of the available knowledge on moths as pollinators in New Zealand / Te pepe huna – he tātarihaka o te mātauraka rakahau ki kā pepe hai whakaaia ki Aotearoa me Te Waipounamu. *New Zealand Journal of Ecology* 42(1): 1–9.
- Cadwallader PL 1975. A laboratory study of interactive segregation between two New Zealand stream-dwelling fish. *Journal of Animal Ecology* 44(3): 865–875.
- Cieraad E, Strange E, Flink M, Schrama M, Spoelstra K 2023. Artificial light at night affects plant-herbivore interactions. *Journal of Applied Ecology* 6(3): 400–410.
- Commonwealth of Australia 2023. National light pollution guidelines for wildlife, version 2.0. <https://www.dcceew.gov.au/sites/default/files/documents/national-light-pollution-guidelines-wildlife.pdf> (Accessed 1 September 2023)
- Cox DTC, Sánchez de Miguel A, Bennie J, Dzurjak SA, Gaston KJ 2022. Majority of artificially lit Earth surface associated with the non-urban population. *Science of The Total Environment* 841: 156782.
- Croxall JP, Butchart SHM, Lascelles B, Stattersfield AJ, Sullivan B, Symes A, Taylor P 2012. Seabird conservation status, threats and priority actions: a global assessment. *Bird Conservation International* 22(1): 1–34.
- Crump MC, Brown C, Griffin-Nolan RJ, Angeloni L, Lemoine NP, Seymoure BM 2021. Effects of low-level artificial light at night on Kentucky bluegrass and an introduced herbivore. *Frontiers in Ecology and Evolution* 9: 732959.
- Daniel MJ, Williams GR 1981. Long-tailed bats (*Chalinolobus tuberculatus*) hibernating in farm buildings near Geraldine, South Canterbury. *New Zealand Journal of Zoology* 8(3): 425–430.
- Daniel MJ, Williams GR 1984. A survey of the distribution, seasonal activity and roost sites of New Zealand bats. *New Zealand Journal of Ecology* 7: 9–25.
- Davies TW, Smyth T 2018. Why artificial light at night should be a focus for global change research in the 21st century. *Global Change Biology* 24(3): 872–882.
- Davies TW, Bennie J, Inger R, Ibarra NH, Gaston KJ 2013. Artificial light pollution: are shifting spectral signatures changing the balance of species interactions? *Global Change Biology* 19(5): 1417–1423.
- Davies TW, Duffy JP, Bennie J, Gaston KJ 2014. The nature, extent, and ecological implications of marine light pollution. *Frontiers in Ecology and the Environment* 12(6): 347–355.
- Dekrout A, Clarkson B, Parsons S 2014. Temporal and spatial distribution and habitat associations of an urban population of New Zealand long-tailed bats (*Chalinolobus tuberculatus*). *New Zealand Journal of Zoology* 41(4): 285–295.
- Department of Conservation n.d. Seabirds landing on ships. Advice sheet. <https://www.doc.govt.nz/contentassets/6d5226329ba841bb92ad4b73d35baa28/seabirds-on-cruise-ships-advice-sheet.pdf> (Accessed 1 September 2023)
- Deppe L, Rowley O, Rowe LK, Shi N, McArthur N, Gooday O, Goldstien SJ 2017. Investigation of fallout events in Hutton's shearwaters (*Puffinus huttoni*) associated with artificial lighting. *Notornis* 64: 181–191.
- Dickerson AL, Hall ML, Jones TM 2023. Effects of variation in natural and artificial light at night on acoustic communication: a review and prospectus. *Animal Behaviour* 198: 93–105.
- Dominoni D, Quetting M, Partecke J 2013. Artificial light at night advances avian reproductive physiology. *Proceedings of the Royal Society B: Biological Sciences* 280(1756): 20123017.
- Dugdale JS 1994. Hepialidae (Insecta: Lepidoptera). *Fauna of New Zealand* 30: 1–194.
- Duthie C, Gibbs G, Burns KC 2006. Seed dispersal by weta. *Science* 311(5767): 1575–1575.
- Elvidge CD, Zhizhin M, Ghosh T, Hsu F-C, Taneja J 2021. Annual time series of global VIIRS nighttime lights derived from monthly averages: 2012 to 2019. *Remote Sensing* 13(5): 922.
- Falchi F, Bará S 2023. Light pollution is skyrocketing. *Science*

- 379(6629): 234–235.
- Falchi F, Cinzano P, Duriscoe D, Kyba CCM, Elvidge CD, Baugh K, Portnov BA, Rybnikova NA, Furgoni R 2016. The new world atlas of artificial night sky brightness. *Science Advances* 2(6): e1600377.
- Farnworth B, Innes J, Waas JR 2016. Converting predation cues into conservation tools: the effect of light on mouse foraging behaviour. *PLOS ONE* 11(1): e0145432.
- Farnworth B, Innes J, Kelly C, Littler R, Waas JR 2018. Photons and foraging: Artificial light at night generates avoidance behaviour in male, but not female, New Zealand weta. *Environmental Pollution* 236: 82–90.
- Farnworth B, Meitern R, Innes J, Waas JR 2019. Increasing predation risk with light reduces speed, exploration and visit duration of invasive shiprats (*Rattus rattus*). *Scientific Reports* 9: 3739.
- Farnworth B, Innes J, Kelly C, Waas JR 2020a. Who's in the hood? Assessing a novel rodent deterrent at pest fencing in New Zealand. *New Zealand Journal of Zoology* 47(3): 220–232.
- Farnworth B, Innes J, Davy M, Little L, Cave V, Waas JR 2020b. Antipredator responses of ship rats to visual stimuli: combining unimodal predation cues generates risk avoidance. *Animal Behaviour* 168: 149–157.
- French-Constant RH, Somers-Yeates R, Bennie J, Economou T, Hodgson D, Spalding A, McGregor PK 2016. Light pollution is associated with earlier tree budburst across the United Kingdom. *Proceedings of the Royal Society B - Biological Sciences* 283: 20160813.
- Fischer JH, Debski I, Taylor GA, Wittmer HU 2021. Consistent offshore artificial light at night near the last breeding colony of a critically endangered seabird. *Conservation Science and Practice* 3(9): e481.
- Fischer JH, Parker KA, Kenup CF, Davis T, Bull S, Pera-Leask E, Ryan H, Witehira M, Cole RA, Taylor GA, Debski I, Ewen JG 2023. Decision analysis for seabird recovery: Navigating complexity across ecosystems, balancing competing values and bridging spaces between research and implementation. *Journal of Applied Ecology* 60(8): 1720–1733.
- Franklin P, Gee E, Baker C, Bowie S 2018. Final New Zealand fish passage guidelines. NIWA Client Report No. 2018019HN <https://niwa.co.nz/sites/niwa.co.nz/files/Final%20NZ%20Fish%20Passage%20Guidelines%20with%20Cover%20Page%2014-12.pdf> (Accessed 1 September 2023)
- Gairin E, Dussenne M, Mercader M, Berthe C, Reynaud M, Metian M, Mills SC, Lenfant P, Besseau L, Bertucci F, Lecchini D 2022. Harbours as unique environmental sites of multiple anthropogenic stressors on fish hormonal systems. *Molecular and Cellular Endocrinology* 555: 111727.
- Gaskin CP ed. 2021. State of our seabirds 2021 - Seabird ecology, research and conservation for the wider Hauraki Gulf / Tikapa Moana / Te Moananui-ā-Toi region. Auckland, New Zealand, Northern New Zealand Seabirds Charitable Trust. 154 p.
- Gaskin CP, Rayner MJ 2017. Seabirds of the Hauraki Gulf – Natural history, research and conservation. Auckland, Hauraki Gulf Forum. 145 p.
- Gaston KJ, Davies TW, Bennie J, Hopkins J 2012. Review: Reducing the ecological consequences of night-time light pollution: options and developments. *Journal of Applied Ecology* 49(6): 1256–1266.
- Gaston KJ, Bennie J, Davies TW, Hopkins J 2013. The ecological impacts of nighttime light pollution: a mechanistic appraisal. *Biological Reviews* 88(4): 912–927.
- Gaston KJ, Visser ME, Hölker F 2015. The biological impacts of artificial light at night: the research challenge. *Philosophical Transactions of the Royal Society B-Biological Sciences* 370(1667): 6.
- Gaston KJ, Ackermann S, Bennie J, Cox DTC, Phillips BB, Sánchez de Miguel A, Sanders D 2021. Pervasiveness of biological impacts of artificial light at night. *Integrative and Comparative Biology* 61(3): 1098–1110.
- Giavi S, Blösch S, Schuster G, Knop E 2020. Artificial light at night can modify ecosystem functioning beyond the lit area. *Scientific Reports* 10(1): 11870.
- Giavi S, Fontaine C, Knop E 2021. Impact of artificial light at night on diurnal plant-pollinator interactions. *Nature Communications* 12(1): 1690.
- Goad D, Middlemiss K, Cieraad E, Duke K, Bell H, Maris V 2023. Light mitigation: Reducing vessel interactions with seabirds. <https://www.doc.govt.nz/globalassets/documents/conservation/marine-and-coastal/marine-conservation-services/reports/202223-annual-plan/mit2022-06-lighting-mitigation-final-report.pdf> (Accessed 1 September 2023)
- Gomes E, Rey B, Débias F, Amat I, Desouhant E 2021. Dealing with host and food searching in a diurnal parasitoid: consequences of light at night at intra- and trans-generational levels. *Insect Conservation and Diversity* 14(2): 235–246.
- Grant RK 2012. The effect of light on the behaviour of captive brown kiwi *Apteryx mantelli*; Implications for captive management. Unpublished MSc thesis. Massey University, Palmerston North, New Zealand.
- Harris P, Matamua R, Smith T, Kerr H, Waaka T 2013. A review of Māori astronomy in Aotearoa-New Zealand. *Journal of Astronomical History and Heritage* 16(03): 325–336.
- Heswall A-M, Miller L, McNaughton EJ, Brunton-Martin AL, Cain KE, Friesen MR, Gaskett AC 2022. Artificial light at night correlates with seabird groundings: mapping city lights near a seabird breeding hotspot. *PeerJ* 10: e14237.
- Heswall A-M, Dominguez A, Aotearoa B, Road A, Wijaya B, Cain K 2023. Why did they die? Analysing the cause of death of grounded seabirds lodged at an avian rescue centre in Auckland, New Zealand. *Notornis* 70: 124–134.
- Hölker F, Wolter C, Perkin EK, Tockner K 2010. Light pollution as a biodiversity threat. *Trends in Ecology and Evolution* 25(12): 681–682.
- Hölker F, Bolliger J, Davies TW, Giavi S, Jechow A, Kalinkat G, Longcore T, Spoelstra K, Tidau S, Visser ME, Knop E 2021. 11 pressing research questions on how light pollution affects biodiversity. *Frontiers in Ecology and Evolution* 9: 767177.
- Imber MJ 1975. Behaviour of petrels in relation to the moon and artificial lights. *Notornis* 22: 302–306.
- Jägerbrand AK, Bouroussis CA 2021. Ecological impact of artificial light at night: effective strategies and measures to deal with protected species and habitats. *Sustainability* 13(11): 5991.
- Jones C, Borkin K, Smith D 2019. Roads and wildlife: the need for evidence-based decisions; New Zealand bats as a case study. *New Zealand Journal of Ecology* 43(2): 3376.
- Kempnaers B, Borgström P, Loës P, Schlicht E, Valcu M 2010. Artificial night lighting affects dawn song, extra-pair siring success, and lay date in songbirds. *Current Biology*

- 20(19): 1735–1739.
- Knop E, Zoller L, Ryser R, Gerpe C, Horler M, Fontaine C 2017. Artificial light at night as a new threat to pollination. *Nature* 548(7666): 206–209.
- Kuechly HU, Kyba CCM, Ruhtz T, Lindemann C, Wolter C, Fischer J, Hölker F 2012. Aerial survey and spatial analysis of sources of light pollution in Berlin, Germany. *Remote Sensing of Environment* 126: 39–50.
- Kyba CCM, Kuester T, Sanches de Miguel A, Baugh K, Jechow A, Hölker F, Bennie J, Elvidge CD, Gaston KJ, Guanter 2017. Artificially lit surface of Earth at night increasing in radiance and extent. *Science Advances* 3: e1701528.
- Kyba CCM, Ruby A, Kuechly H, Kinzey B, Miller N, Sanders J, Barentine J, Kleinodt R, Espey B 2021. Direct measurement of the contribution of street lighting to satellite observations of nighttime light emissions from urban areas. *Lighting Research & Technology* 53(3): 189–211.
- Kyba CCM, Altıntaş YÖ, Walker CE, Newhouse M 2023. Citizen scientists report global rapid reductions in the visibility of stars from 2011 to 2022. *Science* 379(6629): 265–268.
- Larsen H, Burns KC 2012. Seed dispersal effectiveness increases with body size in New Zealand alpine scree weta (*Deinacrida connectens*). *Austral Ecology* 37(7): 800–806.
- Le Roux DN, Le Roux NN 2012. Hamilton City Bat Survey 2011–2012. Report prepared by Kessels & Associates Ltd for Project Echo. <https://www.waikatoregion.govt.nz/services/publications/hamilton-city-bat-survey-2011-2012/> (Accessed 1 September 2023)
- Levin N, Kyba CCM, Zhang Q, Sánchez de Miguel A, Román MO, Li X, Portnov BA, Molthan AL, Jechow A, Miller SD, Wang Z, Shrestha RM, Elvidge CD 2020. Remote sensing of night lights: A review and an outlook for the future. *Remote Sensing of Environment* 237: 111443.
- Lighting Council New Zealand, Illuminating Engineering Society of ANZ 2022. Joint LCNZ-IESANZ Position Statement: ‘Good Lighting and Dark Skies - a Pathway to Progress’. <https://irp.cdn-website.com/edcb35af/files/uploaded/Good%20Lighting%20and%20Dark%20Skies%20-%20Joint%20Position%20Statement%20%28FINAL%29%20-%2016%20March%202022.pdf> (Accessed 1 September 2023)
- Longcore T, Rodríguez A, Witherington B, Penniman JF, Herf L, Herf M 2018. Rapid assessment of lamp spectrum to quantify ecological effects of light at night. *Journal of Experimental Zoology Part A: Ecological and Integrative Physiology* 329(8–9): 511–521.
- Lukies K, Gaskin CP, Gaskett A, Heswall AG, Gulley K, Friesen M 2019. Lighting adjustments to mitigate against deck strikes/vessel impacts. Final report prepared by Northern New Zealand Seabird Trust for the New Zealand Department of Conservation No. MIT2019- 03. <https://www.doc.govt.nz/globalassets/documents/conservation/marine-and-coastal/marine-conservation-services/reports/201920-annual-plan/mit2019-03-lighting-adjustments-to-mitigate-against-deck-strikes-final-report.pdf> (Accessed 1 September 2023)
- Manaaki Whenua—Landcare Research. (2020). LCDB v5.0—Land Cover Database version 5.0, Mainland New Zealand. <https://iris.scinfo.org.nz/layer/104400-lcdb-v50-land-cover-database-version-50-mainland-new-zealand/> (Accessed 1 September 2023)
- Mander S, Alam F, Lovreglio R, Ooi M 2023. How to measure light pollution—A systematic review of methods and applications. *Sustainable Cities and Society* 92: 104465.
- Manfrin A, Singer G, Larsen S, Weiß N, van Grunsven RHA, Weiß N-S, Wohlfahrt S, Monaghan MT, Hölker F 2017. Artificial light at night affects organism flux across ecosystem boundaries and drives community structure in the recipient ecosystem. *Frontiers in Environmental Science* 5: 2017.00061.
- Mariton L, Kerbiriou C, Bas Y, Zanda B, Le Viol I 2022. Even low light pollution levels affect the spatial distribution and timing of activity of a “light tolerant” bat species. *Environmental Pollution* 305: 119267.
- Mayer-Pinto M, Dafforn K, Fobert E 2020. Knowledge exchange to improve research and management of the impacts of artificial light at night. *Austral Ecology* 45(8): 1059–1061.
- McDermott A 2023. Light pollution is fixable. Can researchers and policymakers work together to dim the lights? *Proceedings of the National Academy of Sciences* 120(27): e2309539120.
- McDowall RM 1998. Driven by diadromy: Its role in the historical and ecological biogeography of the New Zealand freshwater fish fauna. *Italian Journal of Zoology* 65: 73–85.
- McNaughton EJ, Beggs JR, Gaston KJ, Jones DN, Stanley MC 2021. Retrofitting streetlights with LEDs has limited impacts on urban wildlife. *Biological Conservation* 254: 108944.
- McNaughton EJ, Gaston KJ, Beggs JR, Jones DN, Stanley MC 2022. Areas of ecological importance are exposed to risk from urban sky glow: Auckland, Aotearoa-New Zealand as a case study. *Urban Ecosystems* 25(1): 273–284.
- Meng L, Zhou Y, Román MO, Stokes EC, Wang Z, Asrar GR, Mao J, Richardson AD, Gu L, Wang Y 2022. Artificial light at night: an underappreciated effect on phenology of deciduous woody plants. *PNAS Nexus* 1(2): pgac046.
- Meyer-Rochow VB 2007. Glowworms: a review of *Arachnocampa* spp. and kin. *Luminescence* 22(3): 251–265.
- Millard SP 2013. EnvStats: An R Package for Environmental Statistics (Version 2.3.0). [R]. <https://cran.r-project.org/web/packages/EnvStats/index.html>
- Ministry for Primary Industries, Department of Conservation, Fisheries New Zealand 2023. Mitigation standards to reduce light-induced vessel strikes of seabirds with New Zealand commercial fishing vessels. <https://www.mpi.govt.nz/dmsdocument/56320-Mitigation-Standards-to-Reduce-Light-induced-Vessel-Strikes-of-Seabirds-with-New-Zealand-Commercial-Fishing-Vessels> (Accessed 1 September 2023)
- Minnaar C, Boyles JG, Minnaar IA, Sole CL, McKechnie AE 2015. Stacking the odds: light pollution may shift the balance in an ancient predator–prey arms race. *Journal of Applied Ecology* 52(2): 522–531.
- Murphy SM, Vyas DK, Sher AA, Grenis K 2022. Light pollution affects invasive and native plant traits important to plant competition and herbivorous insects. *Biological Invasions* 24(3): 599–602.
- Nightingale B, Longcore T, Simenstad CA 2006. Artificial night lighting and fishes. In: Rich C, Longcore T eds. *Ecological consequences of artificial night lighting*. Washington DC, Island Press. Pp. 257–277.
- O'Donnell C, Borkin K, Christie J, Davidson-Watts I, Dennis G, Pryde M, Michel M. Conservation status of bats in Aotearoa New Zealand, 2022. *New Zealand Threat*

- Classification Series, Volume 41. Wellington, Department of Conservation. 18 p.
- O'Malley E 2023. The influence of nocturnal illumination on the development of early life history traits in inanga, *Galaxias maculatus*. Unpublished MSc thesis. Te Herenga Waka-Victoria University of Wellington, Wellington, New Zealand.
- Owens ACS, Lewis SM 2018. The impact of artificial light at night on nocturnal insects: A review and synthesis. *Ecology and Evolution* 8(22): 11337–11358.
- Owens ACS, Cochard P, Durrant J, Farnworth B, Perkin EK, Seymoure B 2019. Light pollution is a driver of insect declines. *Biological Conservation* 241: 108259.
- Pawson SM, Bader MK-F 2014. LED lighting increases the ecological impact of light pollution irrespective of color temperature. *Ecological Applications* 24(7): 1561–1568.
- Pawson SM, Watt MS 2009. An experimental test of a visual-based push–pull strategy for control of wood boring phytosanitary pests. *Agricultural and Forest Entomology* 11(3): 239–245.
- Pawson SM, Watt MS, Brockerhoff EG 2009. Using differential responses to light spectra as a monitoring and control tool for *Arhopalus ferus* (Coleoptera: Cerambycidae) and other exotic wood-boring pests. *Journal of Economic Entomology* 102(1): 79–85.
- Perry G, Buchanan B, Fisher R, Salmon M, Wise S 2008. Effects of artificial night lighting on urban reptiles and amphibians in urban environments. In: Mitchell JC, Jung Brown RE eds. *Herpetological Conservation*. Salt Lake City, Society for the Study of Amphibians and Reptiles. Pp. 239–256.
- Petterson D 2022. Estimating exposure of vulnerable seabird populations to offshore light pollution. <https://www.doc.govt.nz/our-work/conservation-services-programme/csp-resources-for-fishers/how-to-manage-marine-light-pollution/estimating-seabird-populations-to-offshore-light-pollution/> (Accessed 1 September 2023)
- Pugh A, Pawson S 2016. Artificial light at night potentially alters feeding behaviour of the native southern black-backed gull (*Larus dominicanus*). *Notornis* 63: 37–39.
- Pulgar J, Zeballos D, Vargas J, Aldana M, Manriquez PH, Manriquez K, Quijón PA, Widdicombe S, Anguita C, Quintanilla D, Duarte C 2019. Endogenous cycles, activity patterns and energy expenditure of an intertidal fish is modified by artificial light pollution at night (ALAN). *Environmental Pollution* 244: 361–366.
- R Core Team 2021. R: A language and environment for statistical computing. Vienna, Austria, R Foundation for Statistical Computing. <https://cran.r-project.org>
- Richard F-J, Southern I, Gigauri M, Bellini G, Rojas O, Runde A 2021. Warning on nine pollutants and their effects on avian communities. *Global Ecology and Conservation* 32: e01898.
- Robertson B, Kriska GY, Horvath V, Horvath G 2010. Glass buildings as bird feeders: urban birds exploit insects trapped by polarized light pollution. *Acta Zoologica Academiae Scientiarum Hungaricae* 56(3): 283–293.
- Rodriguez A, Holmes ND, Ryan PG, Wilson KJ, Faulquier L, Murillo Y, Raine AF, Penniman JF, Neves V, Rodriguez B, Negro JJ, Chiaradia A, Dann P, Anderson T, Metzger B, Shirai M, Deppe L, Wheeler J, Hodum P, Gouveia C, Carmo V, Carreira GP, Delgado-Alburquerque L, Guerra-Correa C, Couzi FX, Travers M, Corre ML 2017. Seabird mortality induced by land-based artificial lights. *Conservation Biology* 31(5): 986–1001.
- Royal Commission on Environmental Pollution 2009. Artificial light in the environment. London, Office of Public Sector Information. 43 p.
- Royal Society - Te Apārangi 2018. Blue light Aotearoa - Impacts of artificial blue light on health and the environment. Evidence summary. <https://www.royalsociety.org.nz/assets/Uploads/Blue-light-Aotearoa-evidence-summary.pdf> (Accessed 1 September 2023)
- Rydell J 1992. Exploitation of insects around streetlamps by bats in Sweden. *Functional Ecology* 6(6): 744–750.
- Sánchez de Miguel A, Aubé M, Zamorano J, Kocifaj M, Roby J, Tapia C 2017. Sky Quality Meter measurements in a colour-changing world. *Monthly Notices of the Royal Astronomical Society* 467(3): 2966–2979.
- Sánchez de Miguel A, Kyba CCM, Aubé M, Zamorano J, Cardiel N, Tapia C, Bennie J, Gaston KJ 2019. Colour remote sensing of the impact of artificial light at night (I): The potential of the International Space Station and other DSLR-based platforms. *Remote Sensing of Environment* 224: 92–103.
- Sanders D, Frago E, Kehoe R, Patterson C, Gaston KJ 2021. A meta-analysis of biological impacts of artificial light at night. *Nature Ecology & Evolution* 5(1): 74–81.
- Schamhart T, Browne C, Borkin KM, Ling N, Pattemore DE, Tempero GW 2023. Detection rates of long-tailed bats (*Chalinolobus tuberculatus*) decline in the presence of artificial light. *New Zealand Journal of Zoology*: 2245760.
- Schofield J 2021. Effects of LED light on adult caddisflies at two rivers in Canterbury, New Zealand. Unpublished Master thesis. University of Canterbury, Christchurch, New Zealand.
- Shima JS, Osenberg CW, Noonburg EG, Alonzo SH, Swearer SE 2021. Lunar rhythms in growth of larval fish. *Proceedings of the Royal Society B: Biological Sciences* 288(1942): 20202609.
- Shima JS, Osenberg CW, Alonzo SH, Noonburg EG, Swearer SE 2022. How moonlight shapes environments, life histories, and ecological interactions on coral reefs. *Emerging Topics in Life Sciences* 6(1): 45–56.
- Simcock R, Innes J, Samarasinghe O, Lambie S, Peterson P, Glen A, Faville N 2022. Road edge-effects on ecosystems: a review of international and New Zealand literature, an assessment method for New Zealand roads, and recommended actions. Waka Kotahi NZ Transport Agency research report. Wellington, Waka Kotahi NZ Transport Agency. 173 p.
- Smith D, Borkin K, Jones C, Lindberg S, Davies F, Eccles G 2017. Effects of land transport activities on New Zealand's endemic bat populations: reviews of ecological and regulatory literature. New Zealand Transport Agency Research Report No. 623. Rotorua, Wildlands Consultants Ltd. 249 p.
- Sordello R, Busson S, Cornuau JH, Deverchère P, Faure B, Guetté A, Hölker F, Kerbiriou C, Lengagne T, Le Viol I, Longcore T, Moeschler P, Ranzoni J, Ray N, Reyjol Y, Roulet Y, Schroer S, Secondi J, Valet N, Vanpeene S, Vauclair S 2022. A plea for a worldwide development of dark infrastructure for biodiversity – Practical examples and ways to go forward. *Landscape and Urban Planning* 219: 104332.
- Statistics New Zealand 2018. Artificial night sky brightness. <https://www.stats.govt.nz/indicators/artificial-night-sky-brightness> (Accessed 1 September 2023)

- Statistics New Zealand 2021. Urban-rural classification 2021. <https://datafinder.stats.govt.nz/layer/105158-urban-rural-2021-generalised> (Accessed 1 September 2023)
- Thompson DR 2013. Effects of ships lights on fish, squid and seabirds. Report prepared for Trans-Tasman Resources Ltd. <https://www.epa.govt.nz/assets/FileAPI/proposal/EEZ000004/Applicants-proposal-documents/0fc5f83116/EEZ000004-Effects-of-ships-lights-on-fish-squid-and-seabirds-NIWA-April-2013.pdf> (Accessed 1 September 2023)
- Vardi-Naim H, Benjamin A, Sagiv T, Kronfeld-Schor N 2022. Fitness consequences of chronic exposure to different light pollution wavelengths in nocturnal and diurnal rodents. *Scientific Reports* 12(1): 16486.
- Voigt CC, Dekker J, Fritze M, Gazaryan S, Hölker F, Jones G, Lewanzik D, Limpens HJGA, Mathews F, Rydell J, Spoelstra K, Zagmajster M 2021. The impact of light pollution on bats varies according to foraging guild and habitat context. *BioScience* 71(10): 1103–1109.
- Wakefield A, Stone EL, Jones G, Harris S 2015. Light-emitting diode street lights reduce last-ditch evasive manoeuvres by moths to bat echolocation calls. *Royal Society Open Science* 2(8): 150291.
- Waugh SM, Wilson K-J 2017. Threats and threat status of the Westland petrel. *Marine Ornithology* 45: 195–203.
- Whitehead EA, Adams N, Baird KA, Bell EA, Gaskin CP, Landers TJ, Rayner MJ, Russell JC 2019. Threats to seabirds of northern Aotearoa New Zealand. Auckland, Northern New Zealand Seabird Charitable Trust. 76 p.
- Wilcox R 2010. Fundamentals of modern statistical methods: Substantially improving power and accuracy. New York, Springer-Verlag. 249 p.
- Wilson K-J 2016. A review of the biology and ecology and an evaluation of threats to the Westland petrel *Procellaria westlandica*. West Coast Penguin Trust. <https://www.westcoastpenguintrust.org.nz/wp-content/uploads/2018/09/Westland-petrel-threats-report-June-2016-Kerry-Jayne-Wilson.pdf> (Accessed 1 September 2023)
- Wyman T, Trewick S, Morgan-Richards M, Noble A 2011. Mutualism or opportunism? Tree fuchsia (*Fuchsia excorticata*) and tree weta (*Hemideina*) interactions. *Austral Ecology* 36: 261–268.
- Yoon TJ, Kim DG, Kim SY, Jo SI, Bae YJ 2010. Light-attraction flight of the giant water bug, *Lethocerus deyrolli* (Hemiptera: Belostomatidae), an endangered wetland insect in East Asia. *Aquatic Insects* 32(3): 195–203.
- Zapata MJ, Sullivan SMP, Gray SM 2019. Artificial lighting at night in estuaries— Implications from individuals to ecosystems. *Estuaries and Coasts* 42(2): 309–330.
- Zielinska-Dabkowska KM, Xavia K 2021. Looking up to the stars. A call for action to save New Zealand's dark skies for future generations to come. *Sustainability* 13(23): 13472.

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Supplementary material

Additional supporting information may be found in the supplementary material file for this article:

Appendix S1. Methods and results for radiance threshold sensitivity analysis.

Appendix S2. Average annual rates of brightness change across Aotearoa New Zealand 2012–2021.

Appendix S3. Brightness map of Aotearoa New Zealand in 2021.

Appendix S4. Ratio of brightness 2021:2012.

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