

Rhian Jenny Bek

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**Investigating the impact of artificial night lighting on
the common European glow-worm,
Lampyris noctiluca (L.) (Coleoptera: Lampyridae)**

Professor John Altringham
Faculty of Biological Sciences
University of Leeds
LS2 9JT

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1. ABSTRACT

The flight-to-light behaviour of insects to artificial night lighting is a well-documented phenomenon which, when coupled with increasing global light pollution, poses significant ecological problems. The attraction of male common European glow-worms (*Lampyris noctiluca*) to street lights was investigated along a road within the Great Orme Country Park, Llandudno, North Wales. In collaboration with Conwy County Borough Council, the lamp type of 12 street lights was altered over the 2014 mating season (June and July) with each lamp having two lighting conditions, both lasting a month. Lamps were either Low Pressure Sodium (LPS), High Pressure Sodium (HPS), Light-Emitting Diode (LED) or switched off. Transect counts were used to assess male attraction to the different lights. LPS lights attracted the most males (556 out of the total 564, 98.5%), more than any other lamp type ($p < 0.01$). No males were found under lights which were LED or switched off. Only 8 (1.5%) males were counted under the single HPS lamp during the study. A Zero-Inflated Poisson regression model revealed that the LPS lamps were significant predictors of the number of males ($p < 0.01$), as was lamp number (position) and daily rainfall (both $p < 0.05$). Date and mean temperature were found not to be contributing factors in the model (both $p > 0.05$). From what is known of insect vision, the LPS lamps must have been the most visible in terms of their spectral output to male *L. noctiluca* and therefore most attractive to them. LED lights on the other hand were no more likely to attract glow-worms than lights that were switched off. No strong conclusions could be made of HPS lamps due to the small sample size. Ideally artificial night lighting should be minimised but where this is not possible, LED lights are preferred as they attract fewer male *L. noctiluca* than LPS lamps. However, organisms respond differently to particular wavelengths of light and therefore in ecologically sensitive areas, finding a light spectra which is suitable for all is difficult. Light pollution mitigation strategies should therefore also limit the amount and duration of light, if the impacts of artificial night lighting on biodiversity are to be reduced successfully.

2. INTRODUCTION

This project investigates the impact of artificial night lighting on males of the common European glow-worm, *Lampyrus noctiluca* (Linnaeus, 1767). Glow-worms are beetles (order: Coleoptera) in the Lampyridae family, which includes fireflies. Females of the species are flightless and bioluminescent during the breeding season (June and July) in order to attract a flying non-bioluminescent male. The populations and ranges of glow-worms in Great Britain are declining and light pollution has been implicated as a contributing factor (Tyler, 2002). A literature review on light pollution has been undertaken, with particular emphasis on the impacts of artificial night lighting on nocturnal insects. Recommendations for reducing light pollution are given as well as details on the characteristics of different types of street lights - the source of artificial night lighting investigated in this study.

2.1. Light Pollution

Light pollution is the alteration of natural night-time light levels by the introduction of artificial light (Falchi *et al.*, 2011) and occurs on a global scale (Figure 1). There are three main types of light pollution; skyglow, light intrusion and glare. All of these have been increasing globally at an average of 6% per annum (Hölker *et al.*, 2010), due to the excessive 'need' for night lighting in response to population growth, increasing economic prosperity and industrial development (Eisenbeis & Hänel, 2009).



Figure 1. World atlas of global light pollution. Brighter areas indicate where there is relatively more light pollution. Europe, North America and East Asia have some of the highest levels of light pollution in the world. From: International Astronomical Union, 2014 (www.iau.org/public/themes/light_pollution).

On a landscape scale, light pollution can result in skyglow, a phenomenon argued to be one of the most dramatic anthropogenic modifications to the Earth's biosphere (Kyba & Hölker, 2013). Skyglow occurs when artificial light projects upwards and is scattered by aerosols in the atmosphere. Light is then reflected back down to Earth and colours the sky, reducing stellar visibility (Kyba & Hölker, 2013). Light intrusion is the unwelcome spilling of light into areas not intended to be lit, for example into back gardens and bedroom windows. Glare is caused by light that is spilled from a light source and causes discomfort, distraction or an inability to see what the light is meant to be illuminating (Mizon, 2012).

While skyglow is often an unavoidable consequence of outdoor artificial night lighting, what can be controlled however, is the ratio of useful light to wasted light, which depends on lamp design (Kyba *et al.*, 2014). Limiting the amount of light emitted above the horizontal can greatly reduce the spill of light contributing to skyglow, while shielding and re-angling can reduce intrusion and glare.

Therefore lighting technicians and landscape planners have a key role to play in reducing light pollution which, as this review will reveal, has damaging and wide reaching impacts on biodiversity that need to be mitigated through the design, planning and use of good lighting practices.

2.2. Impacts of Light Pollution

The increasing level of light pollution has fuelled research into the effects of artificial night lighting on a wide range of organisms including mammals, reptiles, amphibians, invertebrates and plants. This review consolidates research on these impacts, with particular focus on the effects of street lighting on glow-worms.

2.2.1. Humans

There is substantial support for the negative effect that artificial night lighting can have on humans. Many reports document disrupted sleep due to light intrusion into bedroom windows (Mizon, 2012). This can result in the suppression of nocturnal melatonin secretion by the pineal gland (Lewy *et al.*, 1980). Melatonin has a vital role in the regulation of circadian rhythms (Cajochen *et al.*, 2003) and a deficiency in melatonin has been linked to a rise in the risk of cancer, especially female breast cancer (Reiter *et al.*, 2007). The disturbance of biological clocks, melatonin synthesis and the elevated risks of cancer as a result of irregular light is known as chronodisruption (Erren & Reiter, 2009), which clearly has serious implications for human health. Furthermore, discomfort and reduced visibility from glare, especially from

blue-rich lighting (Zuchlich *et al.*, 2005), are particularly dangerous when driving and should be addressed in outdoor lighting (International Dark-Sky Association, 2010).

2.2.2. Wildlife

Artificial light that alters the natural patterns of light and darkness in ecosystems is known as ecological light pollution (Longcore and Rich, 2004). There are four main effects on wildlife; attraction to light, avoidance of light, photoperiodism effects and spectral responses (The Royal Commission on Environmental Pollution, 2009).

Some organisms are adapted to navigating in a dark environment and use natural light in orientation. For example, sea turtle hatchlings, such as those of the loggerhead turtle (*Caretta caretta*), move in the brightest direction, which on naturally-lit beaches is the sea. However, hatchlings are often attracted to artificial lights on light-polluted beaches, making them susceptible to dehydration and predation (Florida Marine Research Institute, 2000).

Migrating birds can become disoriented when artificial lights disrupt the visual cues from the horizon, which they use to navigate (Herbert, 1970). Exposure to artificial light at night can result in birds reducing speed, changing direction, hovering and circling. Once attracted, birds can become 'trapped' at light sources such as lighthouses, ships and control towers, and are likely to die from exhaustion, predation or collision (Gauthreaux Jr. & Belser, 2006).

The behaviour of song-birds is closely linked to lighting cues and so artificial lighting can affect their photoperiodism (response to the length of day or night). Kempenaers *et al.*, (2010) compared dawn singing times in five species of forest song-bird. Males near street lights started singing significantly earlier in the morning than males in other parts of the forest, thus disrupting their natural diurnal cycle.

Artificial lights can fragment habitats for bat species that avoid lit areas, thus excluding them from good foraging and roosting habitats (Altringham, 2011). Furthermore, the attraction of insects to lights (discussed in the next section) has been exploited by some species of bats, which has led to improvements in foraging success. However, light intolerant species such as the lesser horseshoe bat (*Rhinolophus hipposideros*) may be being outcompeted by the fast-flying, light tolerant pipistrelle (*Pipistrellus pipistrellus*), resulting in changes to community structure (Arlettaz *et al.*, 2000).

The cumulative effects of the behavioural changes induced by artificial night lighting on individuals, competition, predation and population structure have the potential to disrupt important ecosystem functions if the intrusiveness of light at night is not reduced.

2.2.3. Insects

The flight-to-light behaviour of insects is a well-studied phenomenon which disturbs their ecology and causes high mortality (Eisenbeis, 2006). Flight, navigation, vision, migration, dispersal and mating can all be negatively impacted upon resulting in lit areas having a much poorer insect fauna than darker landscapes (Frank, 1988).

Eisenbeis (2006) details three main ways that artificial night lights attract and impact upon insects; the 'fixation' effect whereby insects are unable to escape the zone of attraction around lights. Here insects may orbit the light endlessly until they are caught by predators or fall to the ground exhausted. They might also die immediately by flying into the hot glass of the lamp or become dazzled and immobilised. Secondly, the 'crash barrier' effect involves the disturbance of an insect's long-distance movement (e.g. migration) by lights encountered along the flight path, which then fixates them. Lastly, the 'vacuum cleaner' effect describes how insects are sucked out of habitat areas (for example while foraging), as if by a vacuum and drawn to their deaths.

The magnitude of each of these effects depends on the background illumination created by moonlight and other light-polluting sources (Eisenbeis & Hänel, 2009). It is estimated that a third of flying insects that are attracted to street lights will die as a result (Eisenbeis, 2006).

The wavelength of light can also determine the degree of attraction. Ultraviolet (UV), green and blue light, which have high frequencies and short wavelengths, are best discriminated by most insects and are therefore most attractive to them (Bruce-White & Shardlow, 2011). The distance over which insects have been attracted to light varies from 3 to 30 metres, depending on intensity (Frank, 2006).

An analysis by Davies *et al.*, (2012) concluded that invertebrate community composition is affected by the proximity to street lighting, noting that both flying and ground-dwelling invertebrates were affected by an increase in predators and scavengers under the lights. Furthermore, these impacts can occur at higher levels of biological organisation than previously thought.

2.2.4. Glow-worms

There are two species of glow-worm in Great Britain, the common European glow-worm, *Lampyrus noctiluca* (Linnaeus, 1767), the focus of this study, and the lesser European glow-worm, *Phosphaenus hemipterus* (Goeze, 1777). *L. noctiluca* is the more common of the two, being found across Great Britain, albeit in small, often isolated populations and is also wide spread across Europe and Asia (Tyler, 2002). Glow-worms are typically found inhabiting

areas with a mixture of open grassland and some form of cover (Tyler, 2002), such as road and path verges, gardens and heathlands.

Both males and females at all life stages have the ability to glow to varying extents but it is the adult females which are characteristically bioluminescent during the summer breeding season in order to attract a mate. The bioluminescent reaction, which uses the enzyme luciferase to catalyse the oxidation of luciferin, produces a bright yellow-green light. It is extremely energy efficient, wasting less than 2% energy as heat (McElroy & DeLuca, 1978).

L. noctiluca are extremely sexually dimorphic. Males are capable of flight and have two well-developed wings, protected by dark brown elytra. Females cannot fly and have segmented bodies with the light organ on the underside their abdomens (Figure 2). To find a mate, the male typically flies approximately one metre above the ground and scans the grass below. Males are not strong fliers and are vulnerable to the effects of wind and rain (Gardiner, 2011).



Figure 2. a) Female *L. noctiluca* on a leaf blade, twisting to reveal the underside of the abdomen, b) the female light organ, with the characteristic pattern of two bands and two dots, c) male *L. noctiluca* gathered on a rock under a street light. Photos a) and b) by R. Bek, 2014, photo c) by J. Cox, 2014.

Anecdotal reports indicate that populations of *L. noctiluca* are declining (Tyler, 1986, 2004). Habitat loss and fragmentation, pollution and climate change are all likely to be contributing to this decline (Gardiner, 2007). Light pollution may also be having a considerable impact, due to the use of bioluminescence in mating (Tyler, 2002).

The eyes of *L. noctiluca* have separate green and blue photoreceptors (Booth *et al.*, 2004). Males show preference for the green light that bioluminescent females emit ($\lambda_{\max}=555$) but

excitation of the blue receptors can impair this preference (Booth *et al.*, 2004). This implies that other wavelengths of light, particularly short wavelengths (blue and UV) can disrupt the male's response to the bioluminescent females.

However, studies on North American fireflies in the genus *Photinus* (Coleoptera: Lampyridae), which share the same photic niche as *L. noctiluca* (night-active as opposed to dusk-active), indicate that males are insensitive to wavelengths of light below 500 nm (Buck, 1937; Schwalb, 1961; Lall & Worthy, 2000). Therefore short wavelengths may in fact elicit no response at all.

Schwalb (1961) found that male *L. noctiluca* exhibited positive phototaxis to light intensities up to approximately 200 lux and any further increase in intensity elicited either no response or a negative one. Therefore bright artificial night lighting could be wrongly perceived as a colony of glowing females by the males, hindering mating success if the males remained under the streetlights and were exposed to predation (Tyler, 2002).

In contrast, when investigating the effect of street lighting in a rural village in Switzerland, Ineichen & Rüttimeann (2012) found that *L. noctiluca* males avoided illuminated areas and that the light interfered with the ability of males to locate females. Furthermore, Bird & Parker (2014) concluded that very low levels of light pollution interfered with phototaxis, with no males being attracted to female-mimicking light traps when background illumination exceeded 0.18 lux. Therefore artificial night lighting might 'wash out' the glow of the females, hindering the ability of males to find a mate (Longcore & Rich, 2004).

There has been some investigation into the effects of light pollution on females since the onset of bioluminescence occurs only after light levels have decreased below a critical threshold (Driesig, 1975). Studies have suggested that sexual appetency was disturbed at 80 lux and females ceased glowing at 500 lux (Schwalb, 1961). Even lower light levels of just 1 lux have been enough to delay reproductive behaviours (Driesig, 1975). More recent studies however show that artificial light does not interfere with the duration of bioluminescence (Bird & Parker, 2014) or the distribution of females within a street lamp-lit landscape (Ineichen & Rüttimeann, 2012).

Therefore artificial night lighting may have a number of different impacts on *L. noctiluca* populations. This study will focus on males and the literature indicates that they are affected either by artificial lights attracting them away from glowing females, or by making it difficult for them to perceive female bioluminescence against background illumination. The effects of light pollution on the breeding, mating success and population levels in field conditions however, is under-studied and unknown (Bruce-White & Shardlow, 2011).

2.3. Street Lighting and Lamp Type

It is estimated that there are approximately 90 million street lights in Europe, of which 7.5 million are in the UK (Mizon, 2012). Street lights are a major cause of light pollution (Eisenbeis & Hänel, 2009) mainly due to excessive or unnecessary lighting, as well as poor design. This means a high proportion of light is wasted, contributing to skyglow and light intrusion (Figure 3).

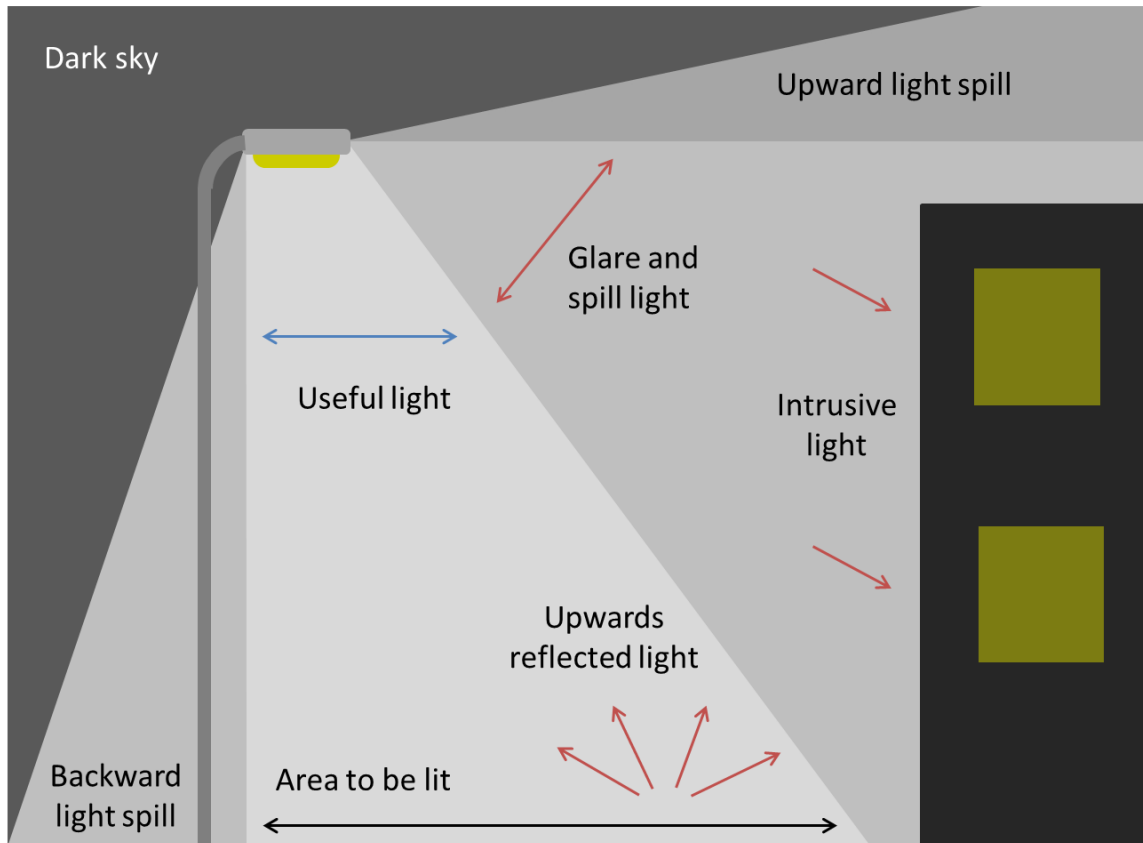


Figure 3. The useful (blue arrow) and wasted (red arrows) light from a street light. Adapted from: The Royal Commission on Environmental Pollution (2009).

Recommendations to reduce light pollution include preventing areas from being artificially lit in the first place, limiting the duration of lights by switching them off or dimming them in off-peak hours, and the use of full cutoff luminaires to reduce the amount of ‘wasted’ light projected above the horizontal (Institution of Lighting Professionals, 2011).

The type of lamp used in a street light can determine the response of insects due to differences in intensity and spectral composition (van Langevelde *et al.*, 2011). The three types of lamp investigated in this study are low pressure sodium vapour lamps (LPS), high pressure sodium vapour lamps (HPS), and light-emitting diode lamps (LED). All lamps differ considerably in terms of their spectral output (Figure 4) and so are perceived differently by humans and are also likely to elicit different responses from *L. noctiluca* males.

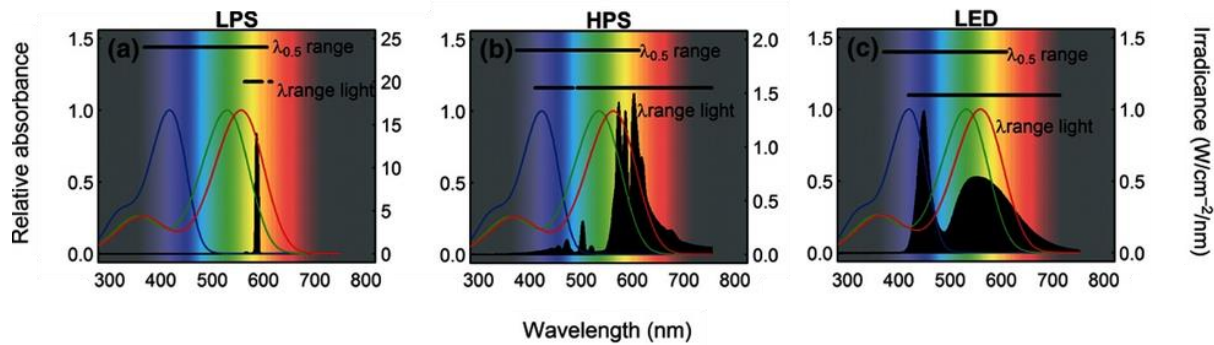


Figure 4. The spectral output (shaded black) of three types of street light, a) Low pressure sodium, b) High pressure sodium, c) Light-emitting diode and the approximate colour of the wavelengths as detected by human visual pigments (coloured background of plot). Blue, green and red coloured lines show the spectral peaks of the three visual pigments in the human visual system and the black horizontal lines show, λ range light = spectrum over which light is emitted from the lamp and $\lambda_{0.5}$ range = spectrum to which the human visual pigments are half maximally sensitive. Adapted from: Davies *et al.*, 2013.

Low Pressure Sodium: Low Pressure Sodium (LPS) lamps are gas-discharge lamps which use sodium in an excited state to produce light. They are widely used in street lighting because of their energy efficiency and absence of glare (Luginbuhl *et al.*, 2014). They produce light on a single wavelength (589.3 nm), which means that this narrow spectrum is likely to have fewer ecological impacts compared to a light with a broader range of wavelengths (Poiani *et al.*, 2014). However, this does mean that LPS lamps allow no colour rendering and makes humans almost completely colour blind at night (van Langevelde *et al.*, 2011).

High Pressure Sodium: High Pressure Sodium (HPS) lamps are also gas-discharge lamps which produce light in the same way as LPS lamps but on a wider range of wavelengths, allowing better colour rendition (Poiani *et al.*, 2014). They too are commonly used in street lighting due to their long life span and moderate energy consumption however they do emit some UV radiation (0.3%), which is known to be attractive to insects (Gaston *et al.*, 2012).

Light Emitting Diodes: Light Emitting Diodes (LEDs) are semiconductor light sources which are becoming more widely adopted thanks to their durability, long life time and increased energy efficiency (Poiani *et al.*, 2014). Whilst they do emit light across a wider spectrum than other lamps, and hence may be attractive to more insects, they emit no UV radiation. A range of colours and types are available which allows for more control over spectral output (Barghini & Souza de Medeiros, 2013).

Studies investigating the effects of these different lamp types can be hard to compare, usually because of the different types (make and model) of lights used, meaning that spectral compositions differ even between lights of the same type (LEDs in particular).

UV light is known to be very attractive to insects (Bruce-White & Shardlow, 2011). The conversion from high pressure mercury lamps to high pressure sodium lamps reduced catches of all insects by 55% and moths by 75%. This was owing to the high pressure mercury lamps having a higher UV component than the HPS lamps (Eisenbeis & Hassal, 2000). Barghini & Souza de Medeiros (2013) concluded that while UV light triggers flight-to-light behaviour in insects, the mechanism is disproportionate and independent of the amount of UV radiation emitted. Therefore even small amounts of UV light can be harmful and lamps with a UV component such as HPS lamps should not be used or should be fitted with a filter to block the UV light.

In 2010 the International Dark-Sky Association released a report outlining some of the damaging effects that white LEDs, which emit energy below 500 nm, have on humans and animals, including insects. The shorter wavelengths of light in the blue to UV end of the spectrum are more visible, and therefore more attractive to a greater number of insects. They therefore recommend the use of yellow lights such as LPS (International Dark-Sky Association, 2010). Frank (2006) also recommends the use of LPS lamps for the protection of moths due to light being emitted at just two wavelengths, (averaging 589.3 nm) and thus fewer insect species might be sensitive to light at that wavelength. LEDs however, when tested against HPS lamps in a German insect trapping study, attracted fewer insects, outperforming HPS lamps by 40-60% (Eisenbeis & Eick, 2010).

Lamp types commonly used in UK street lights have both advantages and disadvantages in terms of their impact on biodiversity. Field studies directly comparing low pressure sodium and light-emitting diodes and their effect on insects are lacking, as are studies which are directly concerned with glow-worms. Therefore recommendations involving lighting designs and spectral composition that are specific to the conservation of *L. noctiluca* are not available. It is likely however, that lamps with a UV component, shorter wavelengths and broader spectral compositions may be more attractive and hence detrimental to male glow-worms.

2.4. Aims and Objectives

In collaboration with Conwy County Borough Council, the aim of this project was to investigate the impact of artificial night lighting on a population of common European glow-worms (*Lampyrus noctiluca*) in the town of Llandudno, North Wales. The population is one of the most accessible and largest remaining populations in Conwy. A local volunteer had observed males gathering under the Low Pressure Sodium street lights along Marine Drive each night of the 2013 mating season (J. Cox, 2013, pers. comm. 22 July). Understanding this phototactic behaviour may help inform the lighting decisions of other councils, lighting professionals and members of the public regarding the conservation of *L. noctiluca*.

The key research questions were:

1. How do low pressure sodium, high pressure sodium and light-emitting diode lamps compare in terms of their relative attractiveness to male *L. noctiluca*?
2. What is the best lighting solution for the conservation of *L. noctiluca* on the Great Orme?

3. METHODOLOGY

3.1. Study Site: Great Orme Country Park

The study took place between 1st June and 31st July 2014 at the Great Orme Country Park and Local Nature Reserve. The Great Orme is a limestone headland located at the North-Western tip of the Creuddyn peninsula in Llandudno, North Wales (Figure 5). The peninsula is a regional hotspot for animal and plant diversity because of its low elevation, range of habitats and limestone geology (Cowley *et al.*, 2000).

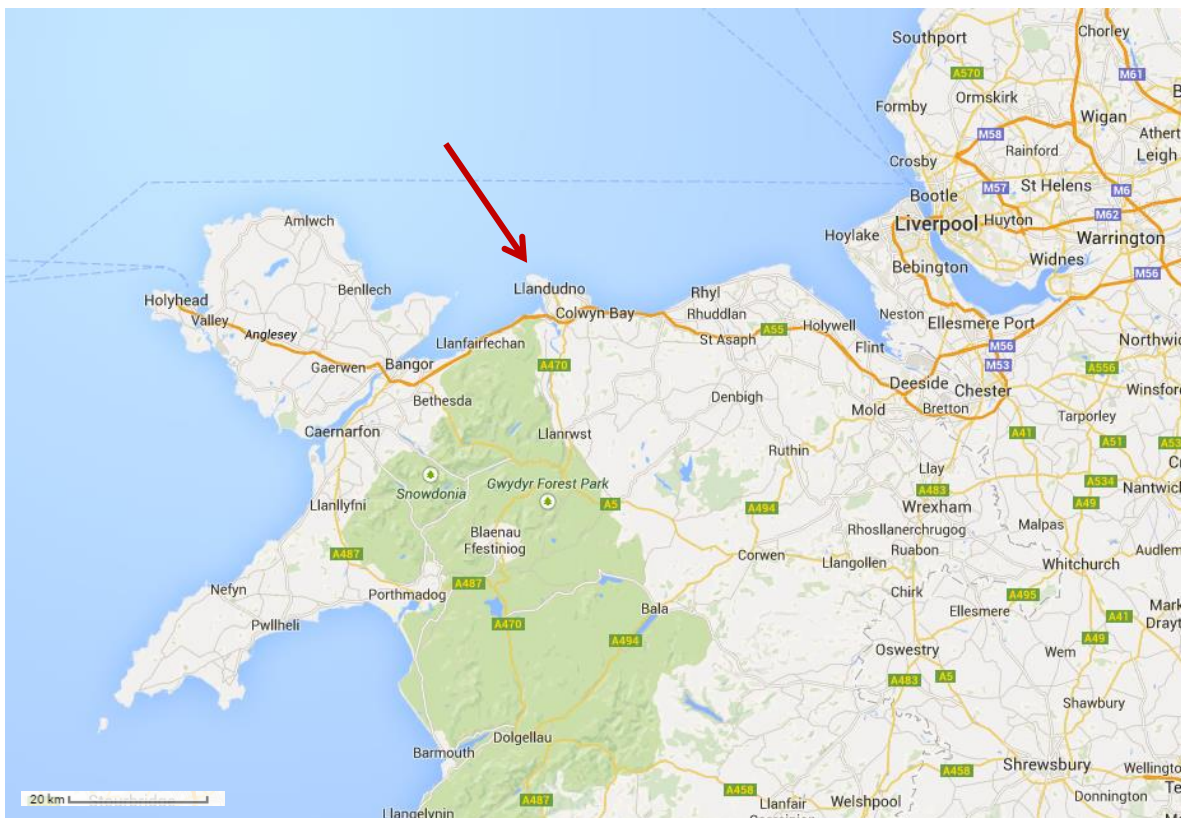


Figure 5. Location (red arrow) of the town of Llandudno on the Creuddyn peninsula on the north coast of Wales, UK. Google maps 2015.

The Great Orme Country Park and Local Nature Reserve, comprising 291 hectares of land that rises from sea level to 207m, is a Site of Special Scientific Interest (SSSI) designated in 1957 and given Special Area of Conservation (SAC) status in 2004. The Great Orme's coastline is a Heritage Coast and the Irish Sea surrounding it, a Marine Special Area of Conservation (MSAC) (Conwy County Borough Council, 2011). The Great Orme is a reserve of regional, national and international importance, due to its rare and threatened habitats and species including its European dry heaths, semi-natural dry calcareous grasslands and vegetated sea cliffs.

The Great Orme's population of glow-worms is found on the cliffs of limestone grassland on the south-western side of the headland. It is a habitat suited to all life stages of *L. noctiluca*. The study area (Figure 6) concentrated on 12 street lights along Marine Drive - a one-way road that runs around the headland and requires lighting where the road narrows and becomes two-way to accommodate access to residential housing. It is here where male *L. noctiluca* were found to be attracted to and gathered under the low pressure sodium street lights by local wildlife volunteer J. Cox during the 2013 mating season of June and July (J. Cox, 2013, pers. comm. 22 July).

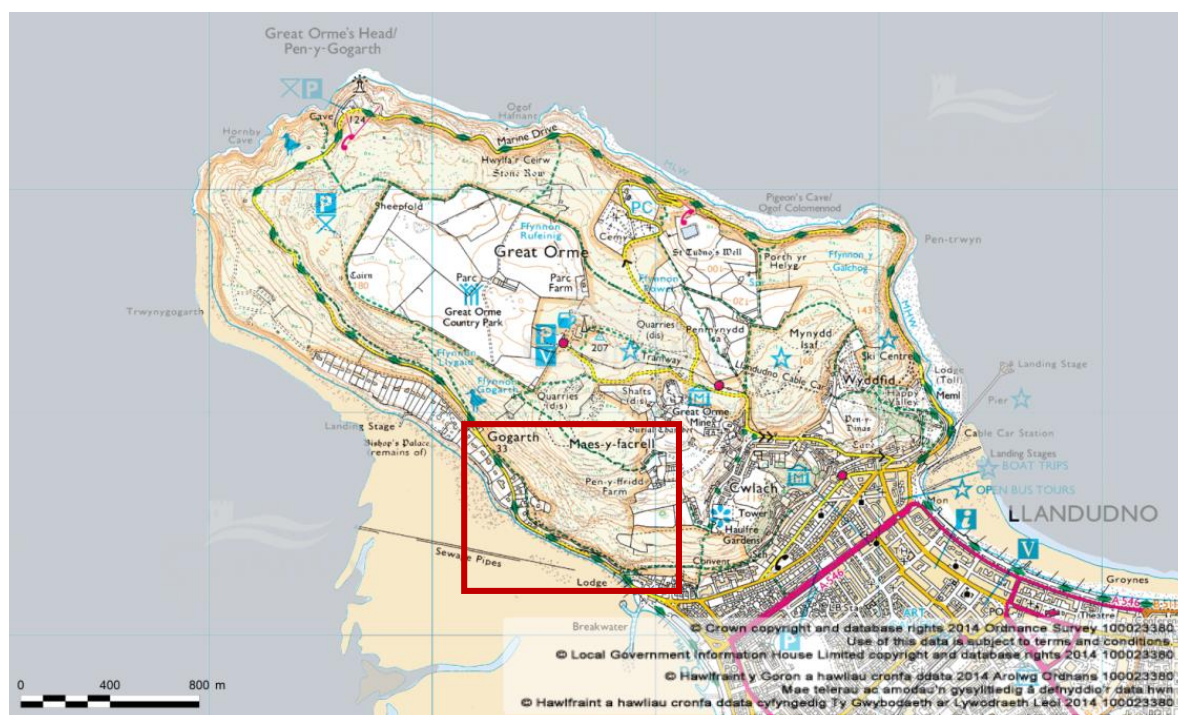


Figure 6. The Great Orme Country Park and Local Nature Reserve, located on the limestone headland above Llandudno. The red box highlights the section of Marine Drive (yellow road) with the 12 street lights that constitutes the study area. Ordnance Survey 2014.

3.2. Study Organism: The Common European Glow-worm

Field studies and experiments on glow-worms commonly use transects in order to determine population density and distribution. Most transect walks are designed to survey glowing females and recommendations include avoiding wet and windy nights, as this reduces counts, and to start within an hour of sunset (Gardiner, 2011). However, males are often neglected because they are difficult to spot unless they are mating with a female, and so instead a light lure can be used.

Light lures with different lamps can be used to assess the impact of artificial night lighting on males as this enables a catch ratio to be calculated with which to assess the level of attraction for each type of lamp (Eisenbeis, 2006). Another method is to place LED light traps (to simulate

females) beneath and between sources of artificial light pollution, such as in Ineichen & Rüttimann's 2012 study. Here all male glow-worms (*L. noctiluca*) were trapped only in the dark areas (between the HPS lamps used) indicating that the street lamps were interfering with the ability of the males to locate females.

An insect trap placed under a light can also be used to assess the attractiveness of each street lamp. In Eisenbeis and Hassel's study (2000), traps were suspended below the lamp and insects were trapped in a funnel that led to a receptacle containing chloroform. This enabled a catch-ratio to be calculated which was used to compare each type of street light.

Therefore there are several ways that the impact of artificial night lighting on glow-worms can be investigated. This study however was limited by a number of practical and time constraints and instead the direct source of light pollution – the street lights – were used to examine the impact on male glow-worms.

3.3. Methods

Between June and July 2014, the lamp type of 12 street lights along Marine Drive, Llandudno was varied in order to monitor the phototactic response of male *L. noctiluca* to the changes.

3.3.1. Lighting Types

The three lamp types investigated in this study were low pressure sodium (LPS), high pressure sodium (HPS) and light-emitting diode (LED) lamps. Prior to the study, 10 of the 12 lamps being investigated were LPS and two were HPS. With the help of the street lighting department of Conwy County Borough Council, the lamp type of each street light was changed at the beginning and middle of the study (Table 1). This enabled the effect of these changes on *L. noctiluca* males throughout the season to be monitored and analysed. Due to technological and time constraints, it was not possible to change the lamps on a regular or daily basis and once a lamp had been changed to LED, it could not be changed back to an LPS or HPS lamp. During the study only one lamp was HPS and therefore the main comparison investigated was between LPS and LED lights. All lamps differed considerably in terms of their physical characteristics (Table 2) and therefore each may elicit different responses from male *L. noctiluca*.

Table 1. The lamp type of the 12 street lights before the study and under the first and second conditions, which both lasted a month. Refer to Figure 7 for the ID number and location of the lamps.

Lamp ID Number	Lamp type prior to study	Lamp type 1st June – 30th June 2014	Lamp type 1st July – 31st July 2014
41	HPS	HPS	LED
1	LPS	LPS	OFF
2	LPS	OFF	LPS
3	LPS	LPS	OFF
4	LPS	LED	OFF
5	LPS	LPS	LED
6	HPS	LED	OFF
7	LPS	LPS	LED
8	LPS	OFF	LPS
9	LPS	LPS	LED
10	LPS	LPS	LED
11	LPS	LPS	OFF

Table 2. Characteristics of each lamp type used in the study (D. Gerrard, 2015, pers. comm. 12 February).

Lux: Luminous flux per unit area, a measure of light intensity as perceived by the human eye.

Wattage: Energy consumption as a rate of Joules per second.

Wavelength: Average peak wavelength of light within the colour spectrum.

Colour Rendering Index (CRI): A measure of the ability of a light source to reveal the colours of objects faithfully in comparison with a natural light source. A value of 0 gives no colour rendering and 100 gives perfect colour rendering.

Colour temperature: The relative colour appearance of a white light source, a warm light is under 3000K, while temperatures above 5000 K are called cool colours.

Lighting regime: Standard regimes involve lights that turn on from dusk until dawn. Lights that are trimmed turn on slightly later and turn off slightly earlier. Lights can also be dimmed and LED lights were dimmed to 75% between 00:00h and 06:00h.

Characteristic	Low Pressure Sodium	High Pressure Sodium	Light-Emitting Diode
Make and Model	Thorn: Beta 5	CU Phosco: P567a	Urbis Schröder: Urbis Axia LED
Lux (lx)	16	21	18
Wattage	35	50	22
Wavelength (nm)	580	650	300-350
UV Component (%)	0	0.3	0
Colour Rendering Index	0	25	>60
Efficiency (Lumens per Watt)	80-200	90-130	60-80
Colour Temperature (Kelvin)	1750	1950	5000
Mounting Height (metres)	6	6	5
Degree of light spill above the horizontal (°)	5	5	0
Colour of light	Orange/yellow	Pink/white	White
Lighting Regime	Dusk until dawn	Dusk until dawn	Trimmed and dimmed
Control Gear	Low loss ignitor and high frequency control	Electronic	Electronic

3.3.2. The Transect

A 1 km transect was walked 18 times during the study period along Marine Drive, which passed under the 12 street lights along the sea wall and outside residential housing (Figure 7).

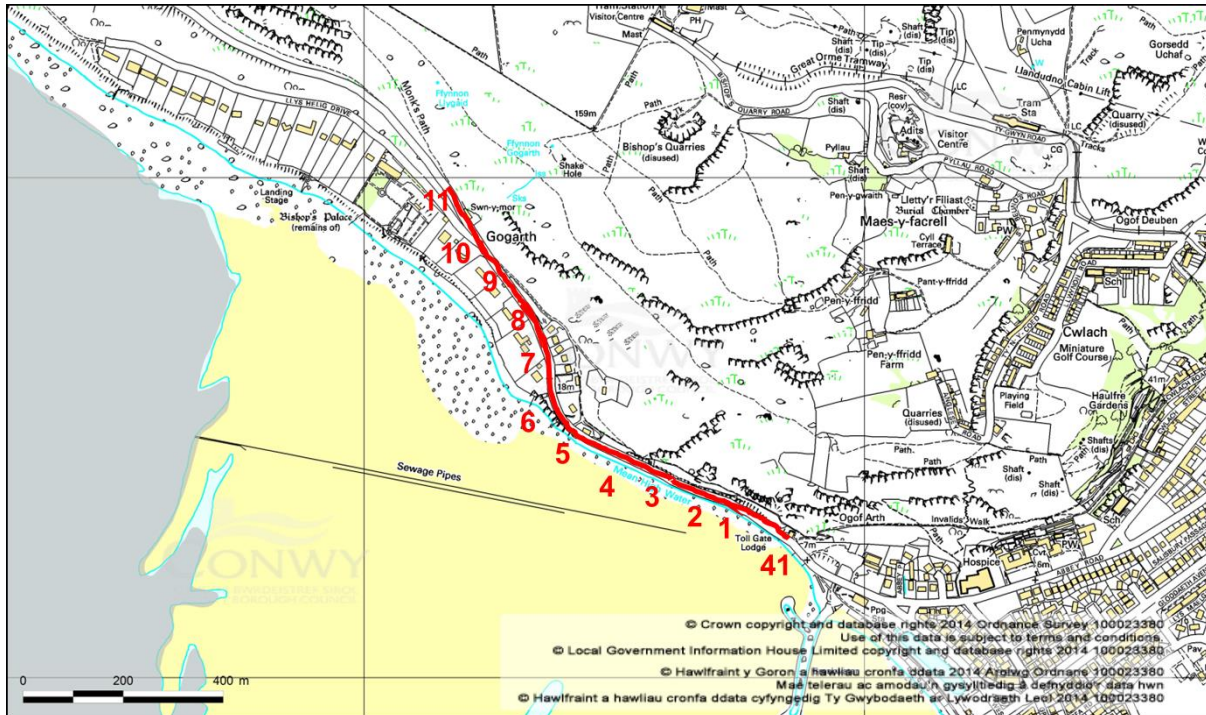


Figure 7. Location of the transect (red line) along Marine Drive, Llandudno. The red numbers indicate the approximate position and ID number of the street lights (refer back to Table 1 for the lamp type of each).

The transect started approximately 120 minutes after sunset (which ranged between 21:33h at the beginning of June, 21:47h at the end of June and 21:12h at the end of July (BST)), as this coincided with peak male *L. noctiluca* activity (J. Cox, 2013, pers. comm. 22 July). The start of the transect was altered each time to help avoid bias and, due to health and safety issues with the work being carried out late at night, it was walked once each night.

Male response to the different lamp types was assessed by recording the number of males attracted to each light along the transect. In order to standardise search effort, recording was restricted to the area of road and pavement illuminated by each street light. Recording was limited to one minute and males were not counted if they flew away or flew into the lighted zone during that time. These specifications ensured consistency within and between transect walks, that males were conspicuous and easy to record, and that the search area was large enough to provide a representative sample but small enough to avoid double-counting the males.

3.3.3. Weather Variables

Weather data was sourced from the United Kingdom Meteorological Office's Integrated Data Archive System (MIDAS), Land and Marine Surface Stations Database (accessed online 22nd October 2014), and included daily rainfall and mean temperature. Daily rainfall in millimetres was recorded at the Llandudno Maesdu station (MIDAS source ID 18966), 3 km from the study site. However, as no temperature readings were available at this station, mean temperature (at 21:00h) in degrees Celsius was obtained from the Rhyl recording station (MIDAS source ID 1137), approximately 26 km away. These variables were added to the data set as possible covariates to explain the change in numbers of males recorded under the street lights.

3.4. Statistical Analysis

Initial testing indicated that the data deviated significantly from a normal distribution and, due to its nominal format, no transformations could normalise the data. Therefore non-parametric testing ensued. A Kruskal-Wallis test with post-hoc testing was carried out in SPSS (IBM Corp, 2014; version 22.0) in order to determine differences between the numbers of males counted under street lights of each type. The majority of values for the number of males found under the street lights was zero (164 of the 216 data points, 76%), indicating a zero-inflated distribution. Therefore a Zero-inflated Poisson regression model (ZIP) was fitted to the data using the *zeroinfl* function (Zeileis *et al.*, 2008) from the library *pscl* (Jackman, 2014) in the R statistical program (R Core Team, 2014; version 3.1.2). The ZIP model modelled the excess zeros independently using a logit model, while the count values were modelled on a Poisson model (Zuur *et al.*, 2012). This allowed the effect of lamp type, lamp number, date, mean temperature and daily rainfall on the number of males recorded to be investigated.

Firstly, the use of the ZIP model was confirmed by using the intercept value in the logistic function (-0.350) to calculate the probability of the data having false zeros, of which the probability was significant ($0.413 < 1$), allowing the use of the model to continue. The Pearson residuals were then extracted to check for overdispersion, but there was no evidence of such. Finally a chi-square test on the difference of log likelihoods between the ZIP model and the null model indicated that the data fitted the ZIP model significantly better than the null (log lik. $1.4756e-28$, $df=8$), further confirming the use of the model (Zuur *et al.*, 2009; Gardener, 2012).

4. RESULTS

In total, 564 males were counted during the 2014 survey, with the highest number recorded on a single night being 116 on the 23rd June. The number of males recorded fluctuated over the season, with two peaks in June and no males seen during July. The mean temperature also fluctuated but remained above 12°C. Daily rainfall was sporadic across the study period with a day of extremely heavy rainfall on the 28th June (Figure 8).

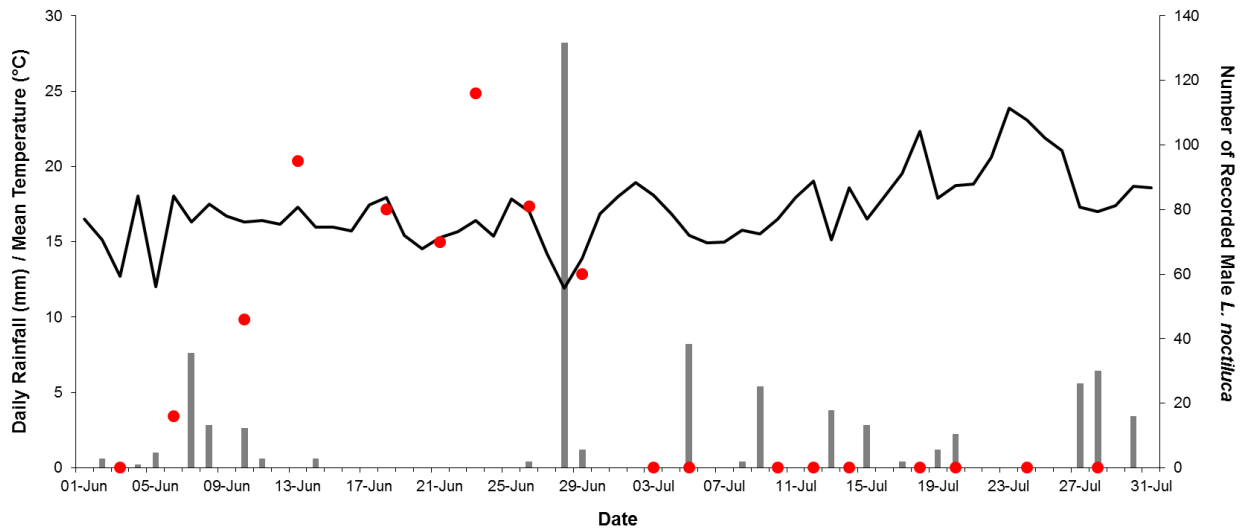


Figure 8. Total recorded male *L. noctiluca* for each transect count (red dots), daily rainfall in millimetres (grey bars) and mean temperature in degrees Celsius (black line) throughout the study period. All male activity occurred in June and peaked on 23rd June. No males were recorded in July.

The number of males found under the street lights differed significantly with lamp type (Kruskal-Wallis $\chi^2 = 97.796$, $df = 3$, $asympt. sig. = 0.000$). Low pressure sodium lamps attracted the highest number of males (556 out of the total 564), followed by high pressure sodium lamps (which attracted 8). No males were found under lamps that were LED or those which were switched off (Figure 9).

The only lamp type that differed significantly in the number of males found under it was LPS (Mean Rank, $MR = 148.48$, Standard Deviation, $s = 8.38$) and it only differed significantly to LED ($MR = 82.50$, $s = 0$) and OFF ($MR = 82.50$, $s = 0$) conditions (all $p < 0.01$). The number of males found under the one HPS lamp did not differ significantly from any other lamp type ($MR = 112.72$, $s = 1.81$, $p > 0.05$). The number of males found under LED and OFF conditions also did not differ significantly ($p > 0.05$) (Figure 10).

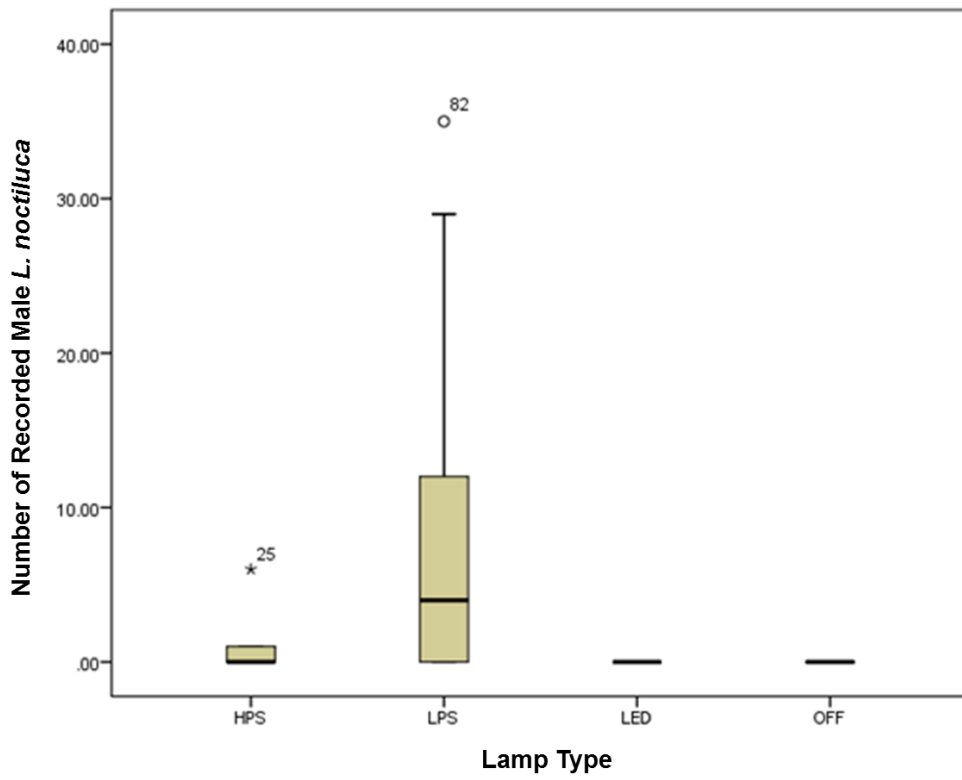


Figure 9. Box-and-whisker plot of the number of males recorded under street lights of each type. The brown box represents the upper and lower quartile, and the bold black line is the median number of males recorded. The whiskers show the 95th percentiles and the open circle and star are the outliers.

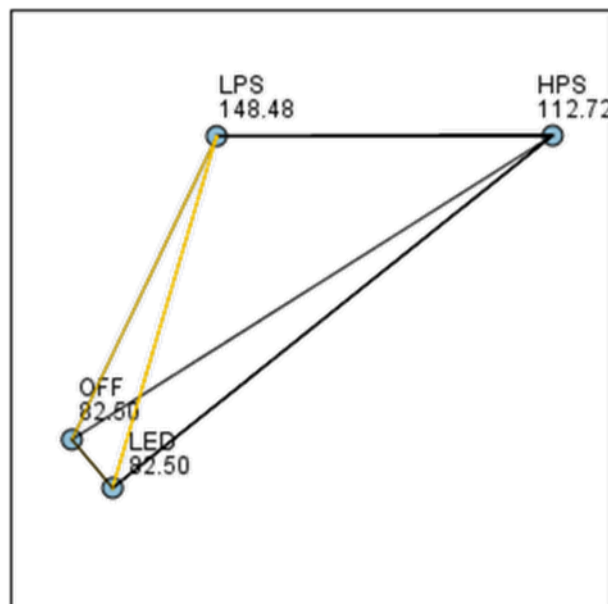


Figure 10. Pairwise comparisons of lamp type on the number of males found under each type. Each node represents the sample mean rank of lamp type. Yellow lines indicate significant comparisons.

Results of the zero-inflated Poisson regression model (ZIP) indicated that low pressure sodium lamps attracted a significant number of male *L. noctiluca* ($p < 0.01$) and lamp number was also a significant predictor in the model ($p < 0.05$). Daily rainfall was found to have a significant influence on the number of males recorded ($p < 0.05$).

When explored further, it was found that lamp numbers 3 ($p < 0.05$), 5 ($p < 0.0001$), 7 ($p < 0.0001$) and 11 ($p < 0.0001$) attracted a significant number of male glow-worms (Figure 11).

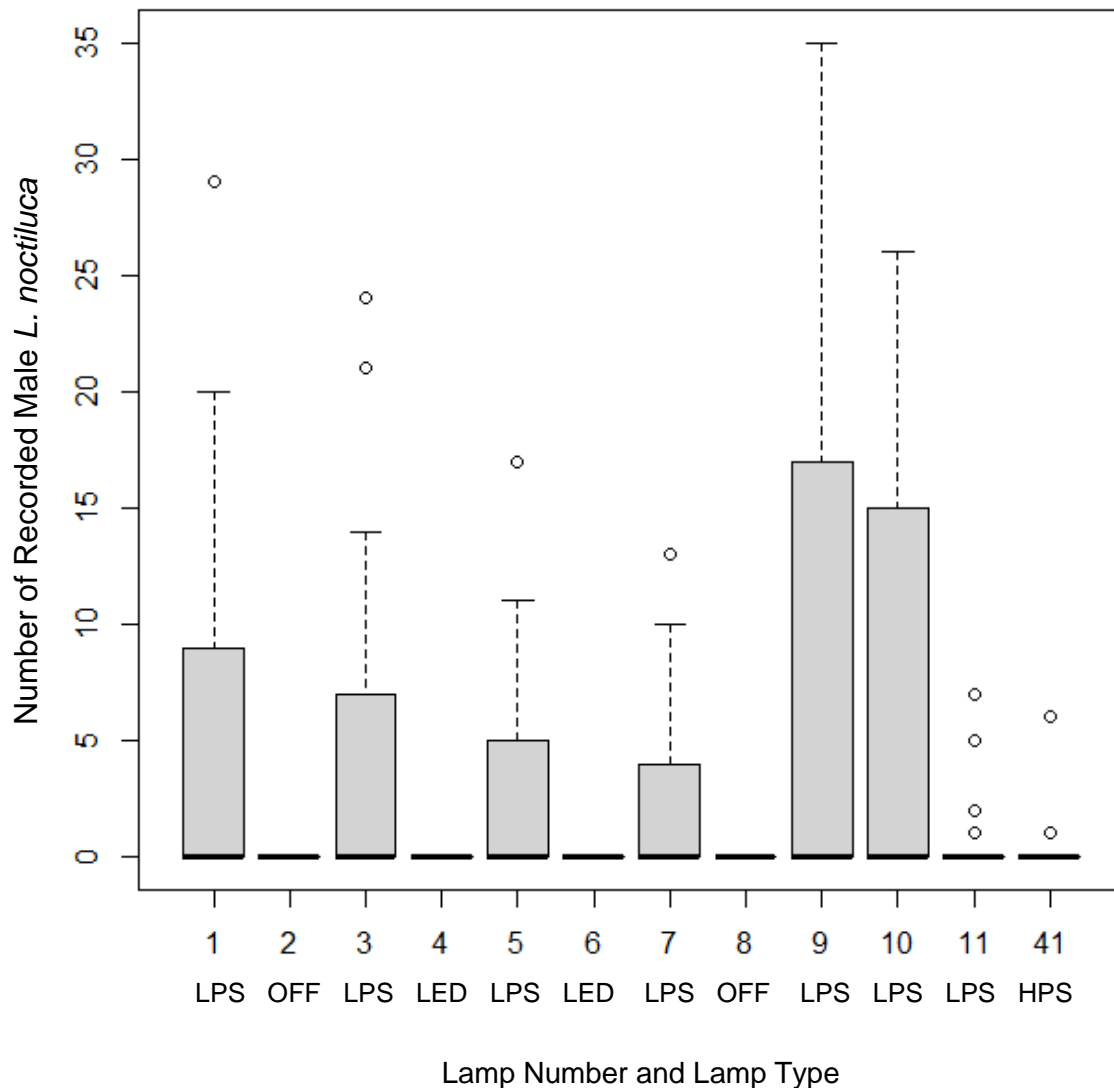


Figure 11. Box and whisker plot of the number of males recorded under each lamp number (and type) between 1st June and 30th June (first lamp condition). The grey box indicates the upper and lower quartiles, the bold black line is the median number of males recorded and the whiskers are the 95th percentiles. The open circles indicate outliers. Lamp numbers 3, 5, 7 and 11 attracted a significant number of males.

High pressure sodium lamps, LED lights and lamps that were off, were non-significant factors, as were mean temperature and date (all, $p > 0.05$).

5. DISCUSSION

Low pressure sodium lamps attracted the most male glow-worms (98.5% of the total recorded). No males were counted under street lamps that were LED. Daily rainfall and lamp number were found to be significant predictors of male counts, while mean temperature and date were not.

5.1. Effects of Lamp Type

From what is known about insect vision, the more visible a lamp is, in terms of its intensity and spectral composition, the greater the attraction will be (van Langeveld *et al.*, 2011). The peak visual spectral sensitivity of glow-worms corresponds with peak bioluminescent emissions (Lall & Worthy, 2000), and Booth *et al.* (2004) found evidence for green and blue chromatic sensitivity in *L. noctiluca*. It follows therefore that males would be most attracted to green (the colour of the female's bioluminescence) and blue wavelengths of light. However, fireflies of the *Photinus* genus, which share the same photic niche of *L. noctiluca*, are insensitive to short wavelengths of light under 500 nm, which includes blue light (Buck, 1937; Schwalb, 1961; Lall & Worthy, 2000).

The LPS lamps used in this study, which had a peak wavelength output of 650 nm (yellow/orange), were the most attractive to male glow-worms and must have stimulated the visual range. The LED lights, despite emitting light over a wider range of wavelengths, were not attractive to male *L. noctiluca*. The average LED wavelength was between 300 and 350 nm and so was outside of the range of visual sensitivity. HPS lamps were not significantly different (in the number of males they attracted) to any other lamp type or condition. However, as there was only one HPS lamp used during the study, no strong conclusions can be drawn about the effect of high pressure sodium lighting on *L. noctiluca*.

The result that LPS lamps are more attractive than LED lamps contrasts to most literature which advocates the use of low pressure sodium lamps for the protection of insects (Frank, 2006), due to light being emitted at just a narrow range on the spectrum. While LED lamps have been seen to outperform HPS lamps by reducing catch ratios by 40-60% (Eisenbeis & Eick, 2010), this is most likely due to high pressure sodium lighting containing a UV element. Reviews of blue-rich LED lighting (below 500 nm) detail the damaging effects on humans, (which include chronodisruption and glare) and on biodiversity, highlighting impacts of both positive and negative phototaxis (International Dark Sky Association, 2010). Despite this, research on the effect of LPS and LED street lighting on male *L. noctiluca* is lacking. Therefore, conclusions should not be coloured by research which is not always directly comparable.

During the study, the different lamp types were all in competition with each other. Studies with moths have suggested that they only exhibit a phototactic preference to certain lighting types under conditions of light competition – where they have a ‘choice’ of light to be attracted to (Scheibe, 2000). Therefore in this study, it is uncertain whether the response of *L. noctiluca* males to the different lamp types would have been different had all the lights been of the same type (i.e. males might have been attracted to LEDs in the absence of LPS lamps). This design was unavoidable due to practical constraints which included the inability to change the lamp type back to LPS once it had been changed to LED, and the fact that it was not feasible for the street lighting engineers to change the lights on a daily basis. However, more recent studies (Longcore & Eisenbeis, 2006; Somers-Yates *et al.*, 2013) contradict Scheibe (2000), finding that insect catch ratios for a particular lighting type in competitive (choice) and non-competitive (no choice) experimental designs were similar. Therefore the number of males recorded under each lamp in light competitive conditions should be representative of the relative attractiveness of each lamp type.

5.2. Effects of Covariates

Lamp number (which indicates position) was found to significantly affect the number of males found under the streetlamps of each type. This suggests that the position of the street light along the transect might affect the results due to differences between the locations such as distance to glowing females and exposure to wind and rain. Further investigation revealed that the lamp numbers which attracted a significant number of males were all LPS lamps in the first month. As nearly all males were found under LPS lamps, this could indicate that lamp type, and not lamp location, is the determining factor. The lamps which attracted a significant number of males (3, 5, 7 and 11), were spread out evenly along the transect and covered sections of the route that were along the sea wall and which were opposite residential housing. Therefore it is difficult to relate the position of the lamp to changes in biotic or abiotic factors which may have altered male response.

No males were counted during July, which was when the lights were under the second condition. Having two conditions would account for the lamp number (position) and reveal whether males were detecting a change in lighting type, but the absence of males in July (the reason for which is not understood) made this difficult. Therefore again the significance of the effect of lamp number on the number of males recorded is slightly ambiguous.

Daily rainfall influenced the number of males recorded under the street lights by suppressing activity. Rain was recorded on five of the 18 study nights and it rained more frequently in July than June. Gardiner (2011) found rainfall to significantly reduce the chance of finding female

glow-worms and Tyler (2002) details the detrimental effects of rain and wind on the flight performance of males.

In contrast, investigations on the effect of weather on insect trapping counts have often indicated that precipitation has no significant influence on catch ratios (Muirhead-Thomson, 1991; Puskás *et al.*, 2007; Nowinszky *et al.*, 2014). However, in these studies temperature was found to be the limiting factor and therefore this might explain the relatively insignificant effect of rainfall. In this research, temperature did not affect the number of male *L. noctiluca* and therefore rainfall was the main suppressor of activity. The fall in male numbers after the peak on 23rd June may have been exacerbated by the extremely heavy rainfall on 28th June and the more frequent rainfall in July. The drop in male numbers around 18th - 21st June however, does not seem to correlate with any major changes in rainfall.

Temperature did not appear to affect the number of males recorded under the street lights. Insect flight muscles must reach a critical temperature in order to function (Grimaldi & Engel, 2005) and it is known that male *L. noctiluca* are more regularly seen on warm nights (Gardiner, 2011). Bird & Parker (2014) noted severely reduced *L. noctiluca* activity when temperatures fell below 9°C. Therefore the mean temperature at 21:00h, which ranged from 12°C - 23°C throughout the study period, was high enough not to significantly affect male flying ability. It is important to recognise however that the mean temperature readings were taken from the Rhyl recording station which is approximately 26 km away from the study site. Therefore, when coupled with variability in local microclimate, these recorded temperatures are unlikely to accurately represent conditions experienced by *L. noctiluca* males along the transect.

5.3. Improvements and Extensions

Despite the study revealing significant information about the attractiveness of different street lighting types to male *L. noctiluca*, there are a number of design limitations which should be addressed in further studies at the site.

In this research, the transect was not walked every night and the transect nights were not evenly spaced throughout the season. Although statistically, the date was found not to influence the data, more frequent and regular transect data may have led to a different conclusion. Statistical analysis on mean temperature and daily rainfall could only be carried out on days where transect counts also took place. Therefore changes in weather variables between study nights would be reflected in the counts of glow-worms, but not in the statistical analysis of such, which again emphasises the benefits of nightly transects.

Data on the weather variables were gathered after the study. Daily rainfall readings were taken from a recording station 3 km away, while mean temperature was recorded 26 km away. This data is unlikely to accurately represent the conditions at the study site and therefore any further investigations should take readings *in situ* in order to account for local variations in microclimate.

This study focussed on the male glow-worm *L. noctiluca*, however further studies might wish to investigate the impact of street lighting on other insects. A potential method to do so is to hang light traps beneath each street light, which would catch insects in a funnel (Eisenbeis & Hassel, 2000). This would allow catch ratios of each lamp type to be calculated and indicate how different groups of insects respond to different types of lamp. A light lure could also be used, such as those commonly used to attract moths. By altering the type of lamp used, the relative attractiveness for different insects could also be studied.

Exploration of different lighting installations would also be a beneficial study extension. Low-level pedestrian lighting mounted along the sea wall could replace the street lights and the relative attractiveness of these lights compared to the street lighting opposite the residential housing. This might help reduce overall light levels however issues may arise over standards of safety where Marine Drive changes from a one-way to a two-way system.

5.4. Practical Applications

Low pressure sodium lamps are more attractive to male *L. noctiluca* than LED lamps. This suggests that when trying to conserve habitats for *L. noctiluca*, if artificial lighting cannot be minimised, LED lights are preferred over the use of LPS lamps. However, this statement of recommendation requires discussion of the conservation priorities on the Great Orme. Glow-worms are not the only organisms on the reserve that could be negatively impacted by artificial night lighting. Both the Great Orme Management plan and the Conwy Local Biodiversity Action Plan (LBAP) advocate the protection and conservation of bats, in particular the lesser horseshoe bat *Rhinolophus hipposideros*. The plans also recognise the presence of several rare species of moth, beetle, spider and other invertebrates (Conwy County Borough Council, 2011). As this review detailed, nocturnal organisms are negatively influenced by increasing levels of artificial light pollution and differ in their responses to the spectral quality and intensity of light. Therefore, a conservation strategy which benefits one species, might be detrimental to another. The consensus in the literature is that broad-spectrum lighting such as LEDs, have the potential to negatively impact more species than narrow-spectrum lighting such as LPS lamps (Gaston *et al.*, 2012). Therefore justifying the use of LEDs for the conservation of *L. noctiluca* in an ecologically sensitive area is difficult. Davies *et al.* (2013)

calculated the percentage of the visual spectrum stimulated by four types of street light for five classes of animals, including 216 species of insect (Figure 12).

Low pressure sodium lamps stimulated the lowest proportion of the visual field, while LED and HPS lamps stimulated at least 50% of the visual range of all animal classes. Therefore LEDs are likely to be more damaging, potentially disrupting visually-guided behaviours, fragmenting habitats and altering photoperiods. While this study generalises broad taxonomic groups and cannot be used to predict an individual species' response to each lamp type, it acts as a guide that indicates that LEDs have the potential to affect more organisms than LPS lamps.

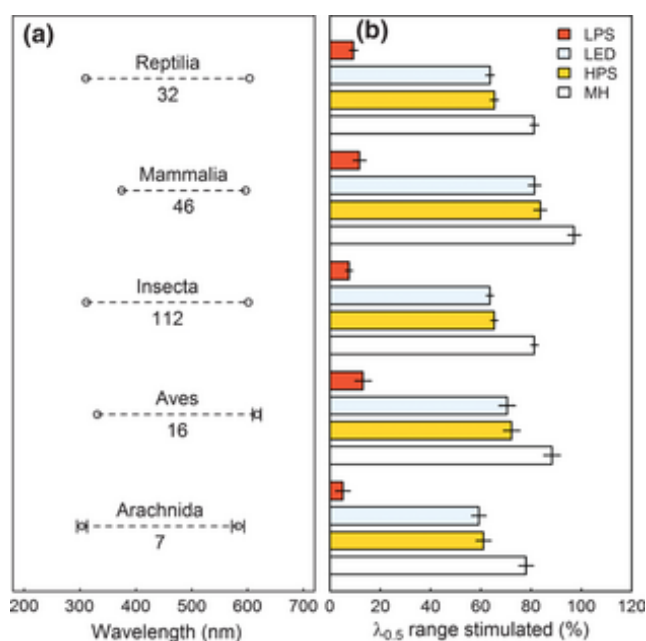


Figure 12. The percentage of the visual field stimulated in five animal classes by low pressure sodium (LPS), high pressure sodium (HPS), light-emitting diode (LED), and metal halide (MH) street lamps. a) The estimated minimum and maximum $\lambda_{0.5}$ range (at which the visual pigments are half maximally sensitive) in five animal classes, with 95% credibility error bars. The numbers underneath each line represents the number of species examined. b) The mean percentage of the visual field stimulated in five animal classes by each street lamp, with 95% credibility error bars. From: Davies *et al.*, 2013.

Currently, the white LEDs used in street lighting use a yellow phosphor coating to convert light from a monochromatic blue to broad-spectrum lighting. There is potential for LED lights to create white light by mixing coloured light from three or more monochromatic LED sources (Schubert & Kim, 2005), unfortunately technological challenges limit the current use of these lights in street lighting. If overcome, this would give more control over the wavelength emitted and has the potential to minimise ecological impacts (Gaston *et al.*, 2012). However, when comparing catch ratios of insects under LED lights of different colour temperatures, Pawson & Bader (2014) found no significant difference, indicating that LEDs lights are still detrimental, regardless of spectral quality.

Minnaar *et al.* (2014) therefore argue that the development of light spectra with little ecological impact is unlikely and instead advocate mitigation strategies focussing on reducing outdoor lighting spatially and temporally.

Good lighting design can greatly reduce light spill contributing to skyglow, intrusion and glare. Full cutoff lamps prevent light spill above the horizontal and target light to where it is needed most (Figure 13). The LED lights used in the study are full cutoff, while LPS spill light 5° above the horizontal. Furthermore, the mounting height for LED is five metres and six metres for LPS (refer back to Table 2 for details). This means that the light spillage for LED lamps is less than that for LPS lamps.

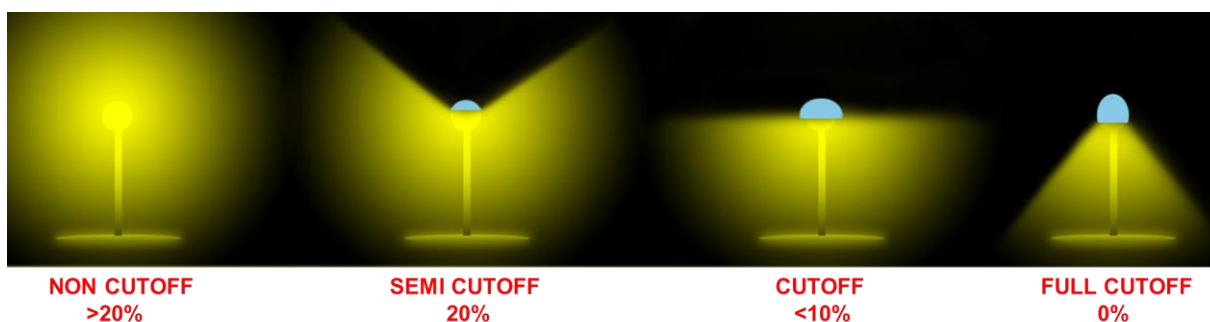


Figure 13. The stylised lighting design of four types of cutoff lamp. The numbers in red indicate the percentage of light spill above the horizontal. Adapted from: Bermudez, 2014.

LED lamps also allow for a more controlled lighting regime. LPS lamps turn on at dusk and off at dawn. Comparatively, the newer LED lamps can be trimmed to turn on slightly later than dusk and turn off slightly before dawn. LED light intensity can also be dimmed to 75% between 00:00h and 06:00h.

Recent advancements in street lighting technology include the integration of motion sensors. LED lamps can be dimmed to 10-20% unless activated by movement from a pedestrian, cyclist or vehicle (Kyba *et al.*, 2014). This would result in energy savings and substantially reduce light pollution.

Therefore both LED and LPS lamps differ considerably in terms of their spectral output, intensity, design and control measures, which affects their suitability for use along Marine Drive. Ultimately a balance must be struck between human and ecological needs. When comparing the two lamp types, LPS lighting may be the least environmentally detrimental, but it gives poor colour rendering and greatest light spill. LEDs on the other hand, are more efficient, can be dimmed and trimmed, give good colour rendering and are not attractive to glow-worms, but are likely to have worse ecological impacts.

The literature review provided by this study presents conflicting views on the practical applications of this research. While glow-worms are not a keystone species, they are relatively charismatic (a rarity among insects) and therefore have the potential to be a flagship species for invertebrate conservation. The population of *L. noctiluca* on the Great Orme is one of the largest known in Conwy (J. Cox, 2014, pers. comm. 10 June) and therefore could be considered 'worthy' of protection. Furthermore due to their sensitivity to environmental change, as well as their conspicuousness, glow-worms are ideal bioindicators for the impacts of artificial light pollution (Hagen *et al.*, 2015). However, the Great Orme is a SSSI which supports many other important species and the decision to make *L. noctiluca* a priority is a difficult one, especially when conservation strategies conflict. If developments allow for the use of LEDs with motion-sensing technologies to be mounted at low-levels along the sea wall, this might be the ideal for lighting along Marine Drive, Llandudno.

Any mitigation strategies implemented will need to be monitored in order to assess the effect of the changes on biodiversity. Insect traps can reveal how nocturnal insects are affected and, in subsequent breeding seasons, transect walks can be used to assess the response of male *L. noctiluca*. This monitoring is essential in assessing the long-term success of the mitigation and to the application of this research elsewhere. Conwy County Borough Council is the first local authority in Wales to modify street lighting to reduce the impact of light pollution on invertebrates (A. Butler, 2014, pers. comm. 21 November) and conclusions can advise other councils, lighting professionals and the public about reducing light pollution to protect populations of *L. noctiluca*.

6. CONCLUSIONS

For the conservation of the population of glow-worms (*Lampyris noctiluca*) on the Great Orme, Llandudno, it is recommended that the use of artificial night lighting is minimised. For the street lights along Marine Drive, any that are deemed 'non-essential' (by CCBC's street lighting department) should be switched off. For those which need to remain on, full cutoff luminaires should be used, which avoid light spill above the horizontal. This would not only reduce skyglow but also the amount of light to be attracted to, thus benefitting glow-worms and other light-sensitive species. Between a choice of low pressure sodium street lamps and LED street lights, LED lights are preferred as they are less attractive to male glow-worms. However, the Great Orme is a SSSI and an ecologically sensitive area and other protected organisms such as moths and bats must also be taken into account as these different species may be affected differently. Since LED lights emit light over a wide colour spectrum, they are likely to be attractive to more insects and have wider ecological impacts. Technological advancements however may mean that the use of LEDs will give more opportunities to limit the temporal and spatial spread of light pollution. The use of motion sensor technology in combination with low-level wall-mounted lamps might be the best solution for lighting along Marine Drive, Llandudno. Any mitigation measure implemented will need to be monitored in order to assess the success of the change long-term. This research is one of the first studies to directly assess the impact of street lighting on glow-worms in Wales and the results set a precedent which will help inform the lighting decisions of local authorities, lighting professionals and members of the public regarding the conservation of *L. noctiluca*.

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