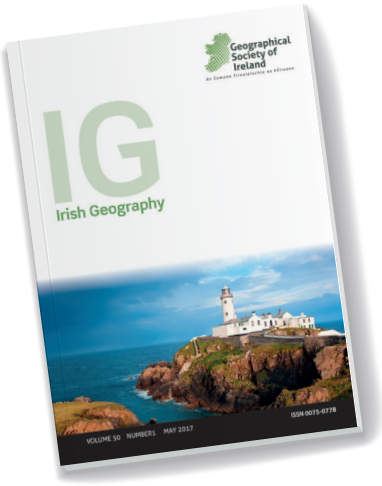

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Light pollution: spatial analysis and potential ecological effects in rural Ireland

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Abstract: Increasing use of artificial light at night has led to many areas across the globe being exposed to light conditions above the natural background level. Research is only now uncovering the impacts of 'ecological light pollution' on the environment. Artificial light at night can disrupt circadian rhythms, cause interference with orientation and migration, alter predator/prey interactions and affect other behaviour and physiological features. Intercalibration of Defense Meteorological Satellite Program's Operational Linescan System images shows that night light emissions in Ireland have increased significantly from 1995 to 2010. In this period, artificial light has spread into previously dark rural areas, including County Mayo where 28% of land surface is designated for habitat and species conservation purposes. To investigate light pollution in rural areas, examination into the conservation area of Owenduff/Nephin Beg Complex was undertaken. Spatial analysis of light measurements taken from Sky Quality Meters surrounding the site were overlaid with species distribution records to determine the proximity of protected species to sources of artificial light at night. Light measurements from the area show pristine night skies according to International Dark Sky Association standards, with one site indicating the presence of localised light pollution. Further work is required to determine if any potential adverse ecological impacts on protected species in the locality are occurring from artificial light at night. The findings of this study provide a foundation for ecological light pollution effects assessment in Ireland. Further work is required to establish the temporal and spatial scales of artificial light in Irish rural areas and determine the specific effects on species present there.

Keywords: *light pollution, ecological effects, protected habitats and species, spatial analysis, Ireland*.

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Introduction

The use of artificial light at night from humans has introduced light into environments where it does not naturally occur. During the 20th century, nightscapes have changed drastically across the world in terms of light intensity and spectrum (Cinzano *et al*., 2001; Longcore and Rich, 2004). Artificial light at night has given benefits to humans, including easier navigation and more work opportunities, but the costs of high usage are starting to appear and may soon outweigh the benefits (Kuechly *et al*., 2012). Humans orientate their lives around artificial light unlike many wild species that are entirely dependent and respondent to changes in the natural day length (Navara and Nelson, 2007). Night light emissions are now considered as one of the main elements in environmental pollution (Chalkias *et al*., 2006). They can disrupt biological rhythms in plants and animals, including humans, causing physiological and reproductive (e.g. hormone levels) as well as behavioural (e.g. migration and predator/prey relationships) disruptions (Rich and Longcore, 2006). Investigation into 'ecological light pollution' on various species of flora and fauna is gaining momentum worldwide (Navara and Nelson, 2007). Various research strands have developed with the aim of determining the range of adverse consequences of anthropogenic night light sources on biodiversity and of devising mitigation measures to address identified issues.

The ecological effects of artificial light have only gained attention recently, being identified as a serious threat to biodiversity and ecosystem functions (Hölker *et al*., 2010; Perkin *et al*., 2011). Nevertheless, due to the complexity of light pollution, research studies have varying results, with effects on organisms showing neutral, beneficial or detrimental impacts (Kyba *et al*., 2011; Davies *et al*., 2012; Mathews *et al*., 2015). While many studies have demonstrated direct behavioural or physiological impacts of illumination at night, it is unknown to what extent artificial light affects ecosystem level processes (Bennie *et al*., 2015). Further studies are required in order to fully understand the complex interactions between artificial light and the environment, and its effects on biodiversity. Examining these issues and identifying areas where light pollution is a major problem can facilitate measures for minimising the environmental impacts caused by artificial light. Different management solutions have been put in place to reduce night sky brightness, including the creation of naturally unlit areas in Dark Sky reserves for maintaining observation of celestial objects. While these reserves have received a lot of attention, protected biological conservation areas around the globe still suffer from light pollution (Gaston *et al*., 2012).

In the Republic of Ireland (Ireland from here on), over 60% of the population lives in urban environments, and hence is exposed to light conditions above the natural background level (Redmond *et al*., 2012). Urban expansion in the last decade has seen the spread of light into rural areas, and the most recent estimates indicate that 40% of the land area, and 84% of the population, are under skies which are 150% of the natural value, with 18% of the population using daytime vision at night (Falchi *et al*., 2016a; 2016b). Rural areas are considered to be under light pollution threat as increases in light in these areas are disproportionately larger than those in urban areas. Moreover,

species' sensitivity to light is more likely to be higher in rural environments due to the presence of natural dark areas. Preliminary measurements taken from Dublin city centre southwards into the Wicklow Mountains found that light from the city reaches into parts of the Wicklow National Park as well as heritage sites such as Glendalough (Espey and McCauley, 2014). The impacts and inefficiency of lighting in Ireland, while acknowledged by the local authorities as an issue, is still largely unexplored. Quantitative measurements of light pollution in Ireland are only emerging and little is known about its ecological effects on Irish habitats and species.

Night-time brightness measurements across Europe show a general increase in light levels across Ireland but such change has not been examined in detail (Bennie *et al*., 2014). Further work is needed to map Ireland's light changes to see if there has been a significant increase in levels, particularly in the context of recent urban expansion (Espey and McCauley, 2014). A focus on rural areas using site-specific measurements can help to identify any such changes and associated effects, and allow for the appropriate research and management techniques to be put in place to prevent further ecological impacts from light pollution. Using the conservation area of Owenduff/Nephin Beg Complex as a case study, this paper examines the potential for ecological effects arising from artificial night light in an Irish rural context to gain insight into light sources, intensity and habitats and species exposed to them.

Study Area

The Owenduff/Nephin Beg Complex is located in North-West Mayo, close to the Atlantic Ocean (Figure 1). The site was chosen due to its protection status on an international and national level (e.g. Birds Directive and Habitats Directives or the Wildlife (Amendment) Act 2000). It is a protected area situated within the Nephin Beg Mountain range and incorporates the catchment of the Owenduff River, as well as the Owenmore River and various tributaries of both rivers. Within Nephin Beg, a designated wilderness area known as Wild Nephin exists. As of September 2016, Ballycroy National Park and Wild Nephin have been granted gold tier International Dark Sky status and will be jointly known as the Mayo International Dark Sky Park. Under this, efforts are being made in the area to ensure that the existing dark sky quality is preserved and to promote the reduction of light pollution.

The Owenduff/Nephin Beg Complex Special Protection Area (SPA) was designated for four bird species listed in Annex I of the Birds Directive (EC, 1979); Greenland white-fronted goose (*Anser albifrons flavirostris*), golden plover (*Pluvialis apricaria*), peregrine falcon (*Falco peregrinus*) and merlin (*Falco columbarius*) (NPWS, 2006). The Owenduff/Nephin Beg Complex is also designated as a Special Area of Conservation (SAC) due to the presence of nine Annex I habitats and four species listed in the EU Habitats Directive (EC, 1992). The four species include the otter (*Lutra lutra*), Atlantic salmon (*Salmo salar*), marsh saxifrage (*Saxifraga hirculus*) and shining sickle moss (*Drepanocladus vernicosus*) (NPWS, 2006). One of Ireland's six national parks, Ballycroy National Park,

was established in November 1998 and is managed under the National Parks and Wildlife Service (NPWS). It is included in the Owenduff/Nephin Beg Complex SAC and SPA under the EU Habitats and Birds Directives (Kiely, 2006; Williams and Gormally, 2010).

The study site is bounded by a national road on its North, West and South limits with conifer plantations and semi-improved agricultural lands (NPWS, 2006; Murray *et al.*, 2013). Altitudes in the Nephin Beg Mountain range between 400-720m (Kiely, 2010; Murray *et al.*, 2013). The site is characterised by large expanses of lowland and upland blanket bog which are of great importance in a national and international context (Williams and Gormally, 2010). Primary land cover surrounding the study site includes peat bogs, transitional woodland, agriculture and coniferous forest. The transitional woodland on the Eastern boundary of the study site is a result of reclaiming old commercial forestry lands to form Wild Nephin, a wilderness area. It supports a variety of habitats and species, including active blanket bog which is important on international and national scales (Williams and Gormally, 2010). The study site is relatively isolated, with few inhabitants and limited access throughout the site by car.

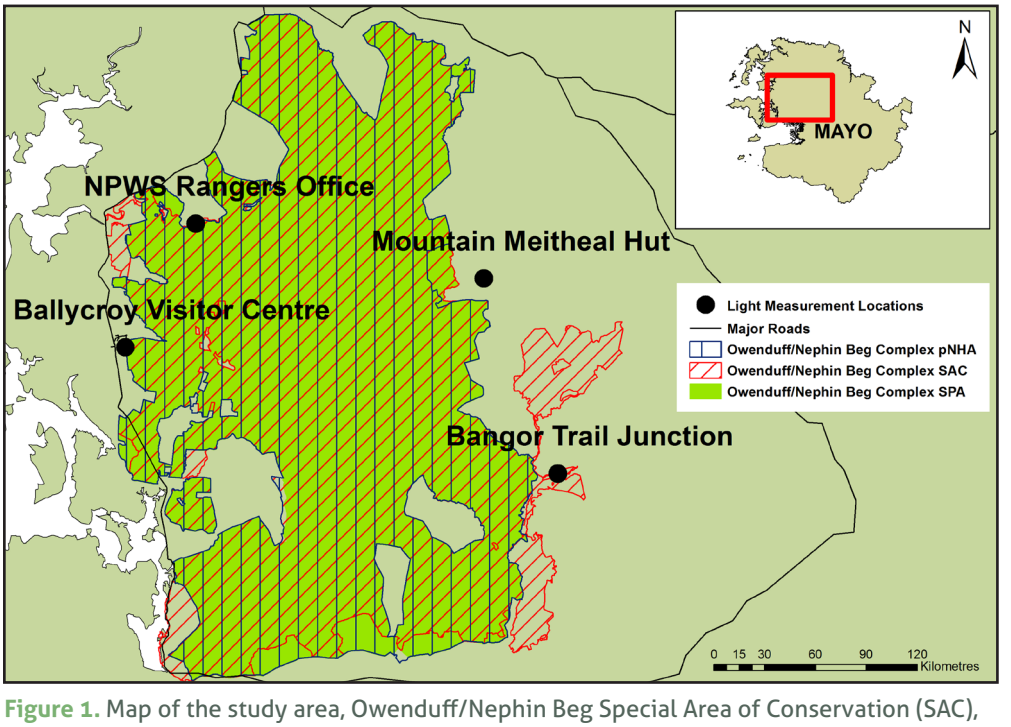

Figure 1. Map of the study area, Owenduff/Nephin Beg Special Area of Conservation (SAC), Special Protection Area (SPA) and proposed Natural Heritage Area (pNHA). Four stationary Sky Quality Meter's (SQM's) surround the site and record light measurements from dusk to dawn.

Methods

Satellite measurements of night-time light

The US Defense Meteorological Satellite Program's Operational Linescan System (DMSP/OLS) was developed for monitoring world weather, but due to its night-time sensitivity it has also been used to monitor night-time light around the globe (Elvidge *et al.,* 2013). Although there are difficulties with the data due to the satellite system not being originally intended for monitoring light pollution, the long life of the satellite series means that data are available to follow historical trends in light output since the first data were digitally archived in 1992.

To overcome the limitations of the satellite hardware (e.g. non-solidstate sensors, and the lack of on-board calibration) various efforts have been made. Calibrated data provided by Bennie *et al*., (2014) have been used to produce a series of annual averages of georeferenced cloud-free images covering the years 1995 to 2010. The value of each pixel is represented by a digital number (DN) in the range of 0 to 63 with 0 representing darkness and 63 representing brightly lit areas. Although this calibration is not referenced to an absolute system of units, the data are intercalibrated, so that measurements of year-on-year effects and relative measurements within each image are reliable (Bennie *et al*., 2014).

To examine change in brightness over time periods across the study area, the difference in mean values of calibrated DN between 1995-2000 and 2005-2010 was calculated for the area of County Mayo where the case study site is located. Bennie *et al*., (2014) determined that pixels that increased or decreased more than three intercalibrated DN's would minimise the inclusion of pixels whose change in brightness could not be attributed to known changes in light. The difference image was then colour coded accordingly and the resulting maps were compared visually to aerial imagery to attribute high levels of light at night to features on the ground.

Ground-based measurements

To complement the satellite data, ground-based zenithal light luminance measurements were obtained from February to March 2015 from four instruments near the periphery of the Owenduff/Nephin Beg area (Figure 1). At each location, these data were taken using a data-logging Sky Quality Meter (SQM), an instrument commonly used for environmental monitoring of light pollution. Meters were placed off the ground and away from local sources of light and any obstructions, and data were collected for each day from dusk twilight to dawn twilight. During night hours, the SQMs were set to measure the intensity of light every 5 minutes.

The native readings of the SQM are in astronomical units of magnitudes per square arcsecond (mag/arcsec^2), defined such that larger numbers represent fainter skies, but can also be converted to more convenient values such as relative to a natural sky level through the conversion: Sky brightness (natural units) $= 10^{-0.4*[(\text{mag/arcsec}^2) - 21.60]}$. The reference level for natural sky of 21.60 mag/arcsec^2 is (roughly) equivalent to 0.25 mcd/m^2 (Falchi *et al*.,

2016a; 2016b). The meters were cross-calibrated (with residual relative errors of 5-10%) so the results from individual meters are on a correct relative scale.

Data were differentiated according to location, and manually checked to ensure there were no instrumental problems. Based on the availability of contemporaneous data for all locations, two time periods for further study were chosen, namely the 15th-28th of February and the 1st-7th of March. This division also splits the data according to the phases of the Moon as the New Moon occurred on the 18th of February, and the Full Moon occurred on the 5th of March. While the Moon is roughly one million times fainter than the Sun, levels of light resulting from the presence of the full moon contribute to increased night sky brightness and represent the peak of the natural night-time environmental light level. As only four monitoring points were measured, there is insufficient information for a comprehensive spatial data coverage and mapping of light pollution in the area (Bruehlmann, 2014), although the collected measurements provide ground-truth for the satellite light source data. Bar charts of light intensity were overlaid onto species distribution maps and light meter habitat maps to examine if light frequencies differed between the light meter sites and to determine any potential effects on the protected species present in the study site.

Field and species survey

A list of species records found in the Owenduff/Nephin Beg Complex was downloaded from the National Biodiversity Data Centre (NBDC). While a variety of species occur in the Owenduff/Nephin Beg Complex, species distributions to be examined were chosen based on three criteria: (1) occurrence of SAC/SPA designation due to their presence; (2) their protection under national or international legislation; and (3) significance of effects of light pollution on the taxonomic group being examined in published literature. Only species records available on a $1km^2$ and $4km^2$ scale were chosen for the assessment. This small-scale mapping approach was undertaken to give indicative rather than exact locations, thus protecting these species and preventing any potential threat from visualising their distribution. Distribution data of certain species occurring in the study site were unavailable and thus were omitted from the study (e.g. shining sickle moss (*Drepanocladus vernicosus*) is found in only one location within the Owenduff/Nephin Beg Complex and marsh saxifrage (*Saxifraga hirculus*) has only three locations within the study site).

Field survey work was carried out from the 25th - 28th of June 2015. Three out of the four light meter sites were visited (i.e. Ballycroy National Park Visitor Centre, the Brogan Carroll Bothy and the Ranger's office grounds). Due to its remote location and limited accessibility, the meter at the Mountain Meitheal hut was not surveyed. Desk-based habitat mapping was undertaken prior to the field survey using the Fossitt classification system, a standard habitat classification scheme, covering all of the habitats likely to be encountered in Ireland (Smith *et al.*, 2011). These provisionally classified habitats were verified during fieldwork, as well as additional habitats identified, which enabled updating of the relevant maps. If habitat mosaics occurred, all habitat types present were

noted. Any major light sources in the vicinity of the light meters were also mapped and examined, including distance from the light meters and the type of light.

Results

Changes in Irish light pollution as seen from space

Comparison of the two mean images in Figure 2 shows that between 1995 and 2010 an increase of brightness at night has occurred across Ireland. Areas shown in red are primarily urban areas and key towns or cities within the counties. Note that due to the limited dynamic range of the Operational Linescan System (OLS) on the DMSP satellites, the detectors saturate in the centre of urban areas, so no useful information is obtained there. However, there has been an expansion of high to moderate levels of light in the regions immediately surrounding population centres, together with an increase in light across rural areas, coinciding with a period when the construction of housing developments was at its highest. Areas in the West and North-West, which previously had low light levels during the period 1995-2000, have begun to experience the encroachment of artificial light at night, and this reduces the number of areas in Ireland previously considered to be close to natural levels of sky brightness.

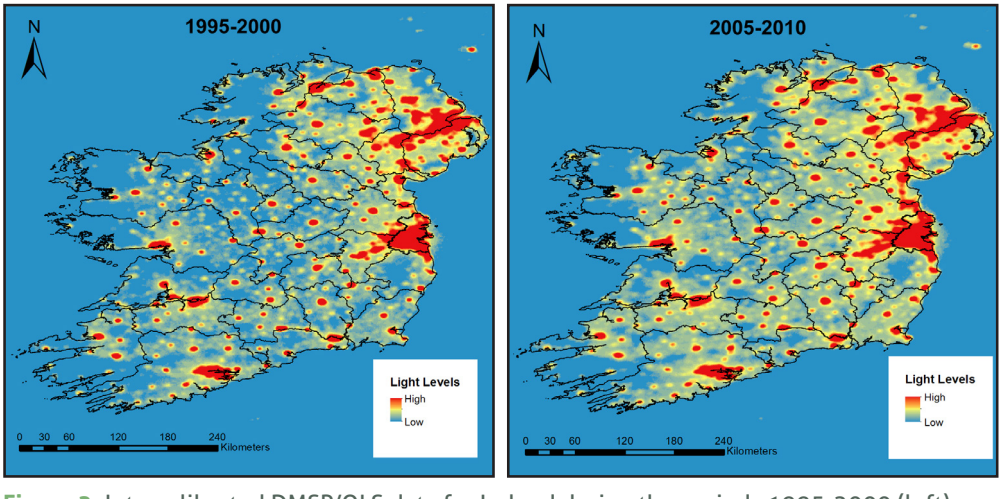

Figure 2. Intercalibrated DMSP/OLS data for Ireland during the periods 1995-2000 (left) and 2005-2010 (right). Saturated light levels of 63 DN (in red) are primarily found in urban areas. Light previously limited to urban areas has spread into surrounding rural areas.

While light levels in County Mayo are saturated at 63 DN in some areas, the North-West of the county has relatively low light levels as can be seen from Figure 3. Much of the area has not experienced significant change in light levels although there has been a considerable increase in brightness (> +3DN) in the East of the county at population centres and along major road routes. This increase can be attributed largely to urban expansion and development in the last decade, and its spread into the surrounding

countryside along the road network. It should be noted that the DMSP linescan system is subject to saturation effects, so regions close to brightly-lit population centres showing apparent decreases in intensity are less trustworthy, and the low-level increases in the countryside are, therefore, more indicative of the general condition over the county. No increase in DN appears to have occurred in the study site Owenduff/Nephin Beg Complex as expected for the low level of habitation in that area.

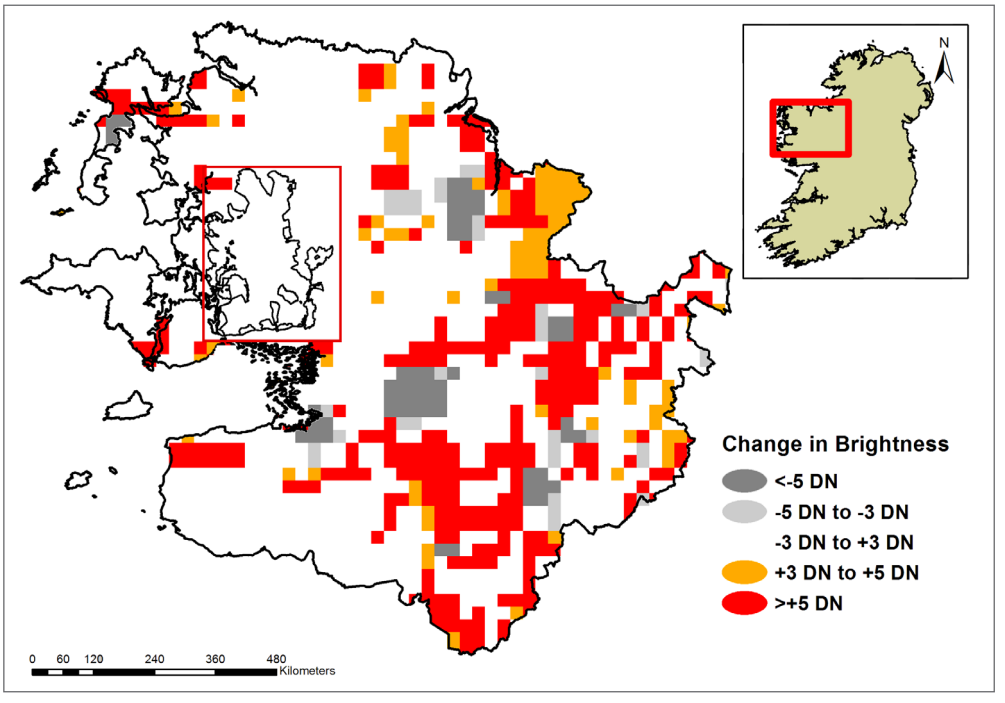

Figure 3. Change in brightness (calibrated DN) in Co. Mayo calculated as the difference in mean values for the periods 2005–2010 and 1995–2000.

Local night sky brightness during dark-of-Moon

To supplement the satellite observations, light at the zenith was measured at a number of ground locations. As noted above, there is a natural variation in the brightness of the night-time sky due to differing strength and location of astronomical sources (i.e. airglow, Sun, Moon, stars, planets, and Milky Way) as well as weather conditions. To make data comparable, the median brightness for each of the four sites under clear and overcast conditions were determined (Table 1). As natural sky brightness varies during the night due to skyglow effects, etc., we include only clear sky data taken within one hour of local midnight. For the overcast nights, however, we have provided the brightest/darkest reading observed over the entire night. The results reflect the native measurements of the recording instruments (astronomical magnitudes, indicated as mag/arcsec^2), and that of the natural dark sky radiance, assuming a mag/arcsec^2 base value of 21.60 (Falchi *et al.*, 2016a; 2016b).

Location	Dates	New Moon (clear sky) mag/arcsec²	New Moon (clear sky) natural dark sky radiance	New Moon (overcast sky) mag/arcsec²	New Moon (overcast sky) natural dark sky radiance
Ballycroy Visitor Centre	17 – 20 Feb 2015	21.5	1.1	19.6	6.3
NPWS Ranger's Office	17 – 20 Feb 2015	21.6	1.0	23.0	0.3
Altnabrocky	17 – 20 Feb 2015	21.7	0.9	24.1	0.1
Bangor Trail	18 – 21 Mar 2015	21.6	1.0	23.8	0.1

Table 1: Median brightness values from the four light meter sites under clear and overcast conditions. Values are given in both mag/arcsec² and natural dark sky radiance.

Data analysis revealed that the clear-sky zenithal brightness is approximately that expected of a pristine natural sky, and conditions at the meter in Ballycroy show an *increase* in sky brightness when conditions are overcast, whereas the other locations show a *decrease* below the natural sky level at such times. The former result regarding night sky near-natural sky conditions has resulted in the awarding of Gold Tier International Dark Sky Park status to the Ballycroy National Park and Wild Nephin Wilderness by the International Dark-Sky Association (IDA). The latter result reflects the reduction in light from the sky in naturally dark areas when astronomical sources and airglow are occulted by clouds, and the increase in sky brightness when local sources of light are reflected back from the cloud base for brighter locations. This behaviour is important, as for the generally cloudy weather of the Mayo region it means that light pollution drives the environmental conditions in the opposite direction from natural behaviour, making them approximately 60 times above what they would be in a dark-sky area. This discrepancy between clear and cloudy conditions also provides a way to study the cloudiness over the meters as with data taken every five minutes the passage of individual clouds can be readily distinguished.

The effect of moonlight

The SQM instruments are not designed to handle point sources, and have non-uniform response with distance from the centre of the measurement field, but data from different locations were compared to provide an indication of the relative sky behaviour with Moon phase (Figure 4). Using data from the Visitor Centre, Altnabrocky (Meitheal hut), and Letterkeen (Brogan Carroll Bothy) around the time of Full Moon in March, it can be observed that the detected brightness when the Moon is on the meridian (i.e. highest in the sky, or 38 degrees) is typically 20 to 30 times that of the natural sky (Figure 5). There is some difference in both intensity and timing of maximum, potentially reflecting differences in the direction of the meter positions. The presence of cloud tends to increase

the detected sky brightness due to the reflection of moonlight into the detector. The effect of these increases on ecology depends on the sensitivity to point or diffuse illumination (e.g. for navigation or predation).

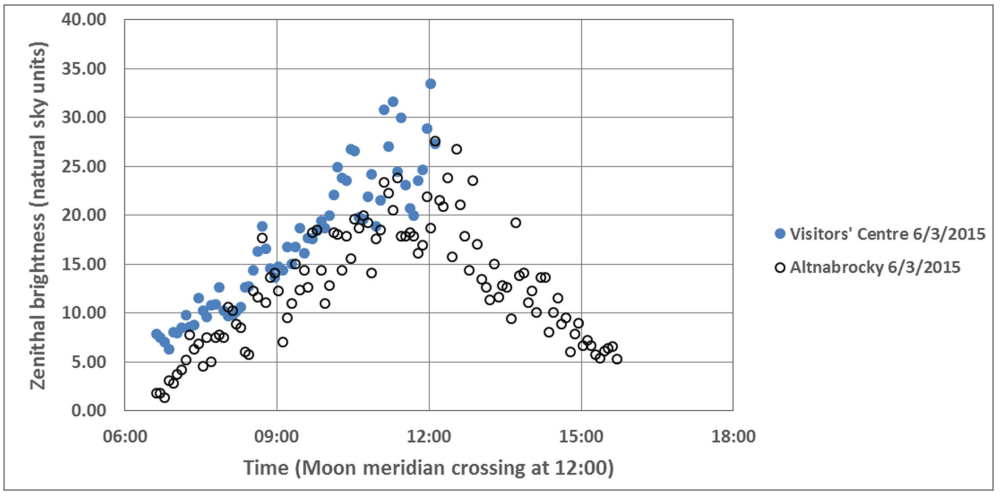

Figure 4. Data between astronomical twilight limits from the listed sites for the night 6th-7th March are overplotted to give an indication of the behaviour of sky brightness during Full Moon. Note that the presence of clouds in the instrument field-of-view leads to fluctuating readings and the lower sky brightness at the darker Altnabrocky site. The Visitor Centre meter was removed for relocation partway through the night.

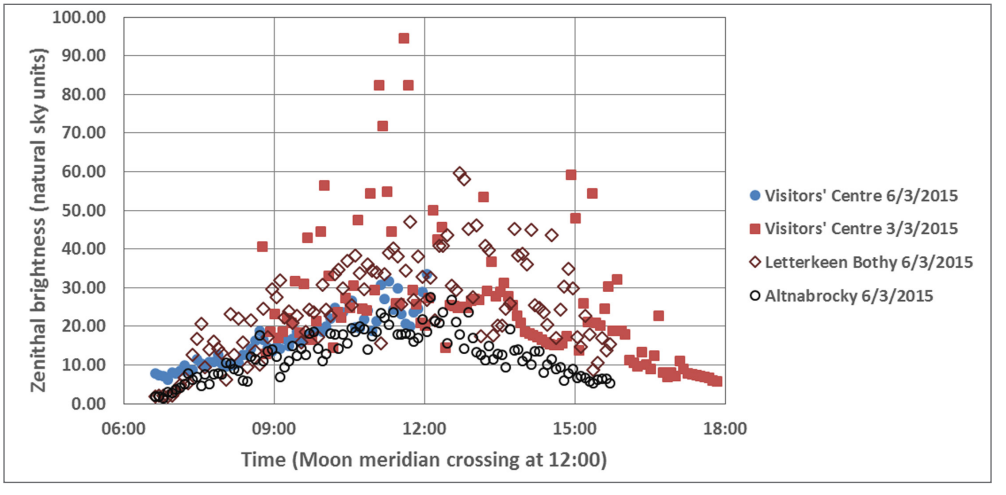

Figure 5. Data for astronomical night from the listed sites for the Full Moon of 6th-7th March are overplotted to give an indication of the behaviour of sky brightness during Full Moon. Note that the presence of clouds in the instrument field-of-view leads to fluctuating readings peaking at 95 times natural values, although as these measurements are taken over a small patch of sky, the averaged illuminance (i.e. light on the ground) will vary by much less. Aside from the bright excursions, there is a general similarity of sky brightness between the sites, peaking at ~25 times the natural sky level when the Moon is highest in the sky.

The surrounding area around the Meitheal hut was not ground-surveyed, but its examination through aerial imagery showed that it is located along the isolated Bangor trail in an area dominated by forest and upland blanket bog. No light sources appear to be present in this area due to its isolation. Light measurements from this site are the most pristine with 51.6% of its measurements from February and March falling into the three IDSA categories (Table 2). An examination of these data for the period 1st-7th of March shows slightly brighter values than those obtained in February. This is likely due to it being closer to the presence of the full moon on the 5th of March. Lower values than 20 mag/arcsec^2 could also be attributed to the presence of clouds which could potentially amplify any sources of light present at night. Light data from the Brogan Carroll Bothy follows a similar pattern with 50.1% of its total measurements falling into the three IDSA categories. The Bothy is located in Wild Nephin, a designated wilderness area located in Nephin Beg. Dwellings around this area are widely dispersed and are primarily agriculture based, and present the primary light sources as no street lights are present.

Site	<15 mag/arcsec^2	<20-15 mag/arcsec^2	20-20.99 mag/arcsec^2 (Bronze)	21-21.74 mag/arcsec^2 (Silver)	>21.75 mag/arcsec^2 (Gold)
Mountain Meitheal Hut	14.6	34.0	6.8	13.5	31.2
Brogan Carroll Bothy	14.0	35.9	6.5	14.0	29.6
NPWS Ranger's Office**	13.7	19.7	7.5	26.1	33.1
Ballycroy Visitor Centre	14.4	41.6	11.8	28.2	4.0

Table 2: Light frequency data from the four light meter sites in percentages. ** represents data only present from the 15th-28th of February 2015.

While measurements were only available for February from the NPWS Ranger's station, data from this meter indicate pristine skies with 66.6% of the February data falling into the three IDSA categories. A number of dwellings occur near the Ranger's office, of which most appeared to be summer dwellings. Land cover around the office is primarily agricultural lands and conifer plantations. There are very few light sources in the area, mainly from dwellings with no street lights present. The darkest value from all sites was taken on the 18th of February, coinciding with the new moon. Data from the Ballycroy Visitor Centre displays a different trend in comparison to the data obtained from the other three meters. Only 44% of its total data falls into the three IDSA categories. While frequencies appear to follow the pattern of the lunar cycle, division of light measurements between the three IDSA categories differs drastically in comparison to the other three light meter sites. Only 4% of all light measurements fall under the Gold IDSA category compared to the other light meter sites (Meitheal hut (31.2%), NPWS Ranger's office (33.1%) and Brogan Carroll Bothy (29.6%)). Light measurements taken from Ballycroy Visitor Centre fall predominantly into the Silver IDSA category with a higher frequency of values falling into the 15 to <20 mag/arcsec^2 category. The

area surrounding the Ballycroy Visitor Centre is more modified in terms of development. Houses are more clustered together with amenity use evident due to the presence of a sports pitch, a community centre and pubs. Street lamps are present around the village with the sports pitch containing floodlights for playing at night. Lights exist in the car park of the Visitor Centre and around the vicinity. From the light measurement values at this site, it is obvious that the light sources and their closeness have an impact on the night sky in this area.

Distribution of protected species in Owenduff/Nephin Beg Complex

Records for 18 protected species were gathered to determine their distribution across the study site (Table 3). This included species present in the study site protected under national legislation (Wildlife (Amendment) Act 2000) and European legislation (Annex I of the EU Birds Directive and Annex II and Annex IV of the Habitats Directive). Many of the protected bird species are distributed across the site with the whooper swan found in one locality in the South-East (Figure 6). Protected birds use this site for breeding (golden plover, peregrine falcon and merlin) or along their migratory path (Greenland white-fronted goose and whooper swan) with merlin found in the direct vicinity of the village of Ballycroy. The hen harrier currently utilises the site for hunting with no breeding records noted.

Species	Protection	Scale	Species	Protection	Scale
Common frog *(Rana temporaria)**	Wildlife Act	1km²	Badger (*Meles meles*)	Wildlife Act	1km²
Smooth newt *(Lissotriton vulgaris)*	Wildlife Act	1km²	Greenland white-fronted goose (*Anser alibfrons flavirostris*)	SPA designation	4km²
Common lizard *(Lacerta vivipara)*	Wildlife Act	1km²	Golden plover (*Pluvialis apricaria*)	SPA designation	4km²
Soprano pipistrelle *(Pipistrellus pygmaeus)**	Wildlife Act, Annex IV Habitats Directive	1km²	Peregrine falcon (*Falco peregrinus*)	SPA designation	4km²
Common pipistrelle *(Pipistrellus pipistrellus)**	Wildlife Act, Annex IV Habitats Directive	1km²	Merlin (*Falco columbarius*)	SPA designation	4km²
Daubenton's bat *(Myotis daubentonii)**	Wildlife Act, Annex IV Habitats Directive	1km²	Hen harrier (*Circus cyaneus*)	Annex I Birds Directive	4km²
Lesser noctule *(Nyctalus leisleri)**	Wildlife Act, Annex IV Habitats Directive	1km²	Whooper swan (*Cygnus cygnus*)	Annex I Birds Directive	4km²
Red deer *(Cervus elaphus)*	Wildlife Act	1km²	Otter (*Lutra lutra*)	SAC designation	1km²
Pine marten *(Martes martes)*	Wildlife Act	1km²	Atlantic salmon* (*Salmo salar*)	SAC designation	1km²

Table 3: Summary of species records chosen for spatial analysis. * indicates species for which effects of light pollution have been examined in previous literature.

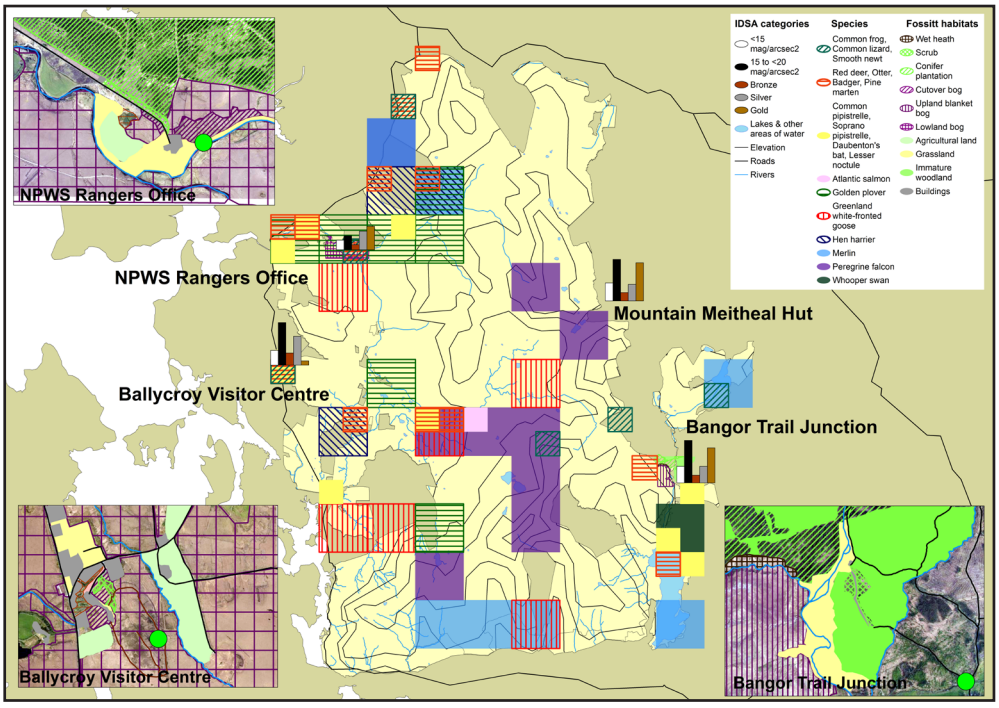

Figure 6. Species distribution map for the Owenduff/Nephin Beg Complex SAC/SPA. Light frequencies from the four measurement sites are shown according to IDSA categories. Habitat maps of light meter locations are also displayed.

Species records of protected mammals show that they are primarily distributed along the Western fringes of the site. Red deer, badgers and pine martens are primarily located around the NPWS Ranger's office. The lesser noctule, common pipistrelle and soprano pipistrelle have been recorded in the vicinity of Ballycroy. Similarly, distribution records show the presence of otters in the surrounding river systems of Ballycroy. Other species of interest include the common frog, common lizard and smooth newt. These appear to be found throughout the study site and close to water bodies. All three are found in the Ballycroy area. Atlantic salmon is found in the Owenduff River which stretches across the site, just North of Ballycroy village.

Discussion and conclusion

DMSP/OLS satellite imagery from 1995 to 2010 shows an increase in night-time light across Ireland. This can be attributed to widespread housing developments that have occurred as part of urban expansion during the Celtic Tiger, a period of rapid economic growth that occurred in Ireland during the 1990s and early 2000s. Most of County Mayo's lands have experienced an increase in night-time brightness of 3DN or more. Areas that have shown high night-time light levels have experienced, in some cases, decreases in brightness of 3DN or more. This is likely due to these areas having reached maximum

levels of night-time light with small decreases in brightness likely having no significant positive impact.

While evidence is lacking for widespread light pollution across the Owenduff/Nephin Beg Complex, light frequency differences at Ballycroy Visitor Centre indicate localised light pollution. Further work is required to clarify this and other factors need to be investigated, including climatic effects on light pollution. Night sky brightness is amplified as clouds reflect artificial light back down to Earth (Kyba *et al*., 2011). Light measurements were taken from four stationary SQM's on clear and cloudy nights. Examining the difference in measurements in each light meter site on clear and cloudy nights could provide further evidence of artificial light pollution occurring in Ballycroy. This is important to monitor to ensure that the IDSA Gold tier designation of the Dark Sky Park remains intact.

As part of the International Dark Sky Park application, mitigation measures were planned to reduce artificial night light levels in Ballycroy and surrounding areas. Lighting fixtures adversely adding to artificial night light levels were identified with plans to replace them with light-emitting diodes (LED's) that were shielded, making use of motion sensors and timers when possible. While LED's have proven to be more energy efficient, their ecological effects have been conflicting and many species remain unexamined for their potential ecological impacts (Stone *et al*., 2012). Following a survey of Ballycroy residents, it was agreed to trial part-time lighting between 12:30am and 5am in Ballycroy village. Artificial light currently present in the environment is likely to be already integrated with ecological factors, i.e. species present in the area are potentially adapted to current levels of artificial light. It is important to understand the ecological effects of the current lighting systems first, before applying any mitigation measures to ensure no more detrimental effects occur.

NDBC distribution records show most of the 18-protected species examined are found in the direct vicinity of Ballycroy (Figure 6). If artificial light pollution is present in Ballycroy, there is a potential likelihood that species in the surrounding area are at risk. The considerably low number of Gold IDSA category night skies and a higher frequency of 15 to <20 mag/arcsec^2 category nights at Ballycroy signal that artificial light present in the area is shortening the period in which pristine dark skies occur. Species found in the vicinity include three out of the four protected bat species (lesser noctule, common pipistrelle and soprano pipistrelle), Ireland's only native amphibian and reptile species (common frog, common lizard and smooth newt), the otter and merlin. It is important to start ecological monitoring on species found around Ballycroy to determine if positive, negative or neutral species-specific effects are occurring due to the above natural night sky levels found at this site.

For many species found in the study site, little or no work has been carried out on the effects of artificial light. Any work carried out on amphibians and reptiles is considerably out-dated with no conclusive data on the effects of artificial light (Rich and Longcore, 2006). No work on the effects of artificial light has been carried out on certain mammal species in the site (e.g. pine marten, badger, otter and red deer).

Recent work has shown that the distribution of the common pipistrelle is negatively associated with lighting on a landscape scale in open areas yet the lesser noctule in Ireland has higher activity in the presence of street lights (Mathews *et al.*, 2015). Potential risks to the bird species on site include disorientation during flight and disruption to reproductive cycles which have been recorded in other bird species (Kempenaers *et al.*, 2010; Rodríguez *et al.*, 2012; Dominoni *et al.*, 2013). Adverse effects to artificial light at night have been recorded in Atlantic salmon including disruption of spawning and migratory cycles (Riley *et al.*, 2013; 2015). Atlantic salmon have experienced population declines in Europe. In monitoring the population found within the study site, it is important to consider any potential effects of artificial light on population numbers. Future research on the potential ecological light pollution effects at the study site needs to consider species-specific responses.

This paper shows that expansion of artificial light at night into rural areas has occurred in Ireland over the past 15 years. Research on species has demonstrated that the increasing presence of artificial light during periods of darkness disrupts the natural cycles of light and dark that species have evolved to. However, the ecological effects from current and future forms of lighting are yet to be understood fully. Although the analysis into the Owenduff/Nephin Beg Complex represents a snapshot into the spatial and temporal patterns of artificial light in Ireland, it substantiates specific light pollution issues, particularly those associated to point sources (e.g. Ballycroy village). This first spatial examination into the potential effects of ecological light pollution in an Irish rural context provides a basis for future work on the effects of light pollution in protected areas throughout the country.

Future recommendations

While there are a variety of sources of light in Ballycroy, most, if not all, would be considered point sources and should be relatively easy to reduce. As part of a light management plan created in the International Dark Sky Park application, removal or replacement of these light sources is currently underway. Monitoring of the site (i.e. as part of SAC/SPA requirements) for research and conservation by the NPWS is ongoing continually and it is now also a requirement as part of the Dark Sky Park designation. Much work needs to be done to understand if the species present in the study site are affected by artificial light. Stronger ecological monitoring is required, particularly in the area of Ballycroy, to understand if behavioural patterns differ in species compared to individuals of the same species who are located throughout the site where pristine night skies occur. If species have already adapted to current artificial light levels present (i.e. increased sky brightness), current mitigation measures to reduce artificial light at night (i.e. turning off lights at certain time periods) could make no difference or even worsen current adverse effects. Research has shown that artificial light can have positive effects so it is vital to consider species-specific impacts. Personnel are to be appointed by the NPWS to take quarterly readings from at least four locations within the park with light measurements

that fall outside the IDSA categories during expected pristine night skies to be thoroughly investigated. While this will monitor the night sky in local vicinities, determining the spatial distribution of light at night would require multiple point measurements from across the study site. The Mayo International Dark Sky Park offers the potential of being a novel comparative between species found in pristine night-time environments and those affected by artificial light at night throughout their distribution.

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