The Ecological Effects of Light Pollution:

A three site (Bull Island, Trinity College Dublin & Killiney Hill) comparative study.

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DECLARATION

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ABSTRACT

The increasing trend of artificial light in the night sky is of global concern. The ecological impacts of light pollution in Ireland has not yet been established. Previous studies have been carried out in rural Ireland in County Mayo, however studies have not been carried out in urban Ireland. Increases in artificial light in the night sky can have both ecological and human impacts. Artificial light levels can alter a number of behaviours in humans, flora and fauna. Disruptions can occur to the circadian rhythm, migration patterns, orientation ability and predator-prey relationships of species. Light level trends in Ireland were determined through the use of satellite imagery of the night sky provided by the Defence Meteorological Satellite Program's Operational Linescan System (DMSP/OLS). Imagery for the year 1992 which was the first year of the programme was compared to 2013 imagery showing the most recent night sky satellite imagery. A significant increase in light levels was recorded across Ireland over the two decades. Further analysis of the phases of the "Celtic Tiger" (2001-pre "Celtic Tiger", 2007- "Celtic Tiger" and 2013- post "Celtic Tiger") showed a great increase in light levels leading up to the year 2007 when construction in Ireland was carried out intensively. Examination of the light levels in Ireland was carried out with the use of Sky Quality Meters (SQM) at three locations to determine the levels of light in the night sky of Dublin. A number of selected species were chosen for this study to identify any possible ecological impact to these species as a results of artificial light pollution. High levels of light in the night sky was recorded at all three light meter locations. The levels of light recorded were well out of the range provided by the International Dark-Sky Association (IDA) for the designation of these areas as dark sky reserves/parks. These high levels are a risk to all the protected species selected in this study. These risks include disruption to migration patterns, reproduction alterations and some species listed may be impacted indirectly. To further develop knowledge of the ecological impacts of light further studies like this are required in Ireland to develop a national light pollution database that will assist in tackling both the increasing level and concerns regarding light pollution. Without establishing a knowledge of the ecological impacts of light pollution appropriate conservation measures cannot be put in place.

KEYWORDS

Light Pollution, Light sensitivity, Behavioural changes, Ecological impacts, Spatial analysis, Ireland.

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1. INTRODUCTION

1.1. Light pollution.

1.1.1. What is Light Pollution?

The night sky has been greatly altered by humans through the introduction of artificial lighting during hours of darkness. The night sky's characteristics have been greatly modified over the last one hundred years (Longcore *et al*. 2007). It is estimated that the night skies of a large number of cities across the world are one hundred times brighter than the natural light levels which normally occur at night (IDA- International Dark Sky Association). The increase in artificial brightness in the night sky results in the stars and natural light emitters becoming harder to view with the naked eye. This excess artificial light is known as light pollution. Light pollution is believed to have widespread consequences for humans, wildlife species both animals and plants and to the global climate. Approximately 30% of all vertebrates and 60% of invertebrates are nocturnal, an alteration in the light regime will therefore have a vast and wide impact on biodiversity (Holker *et al.* 2010, Thomas *et al*. 2016). The International Dark-Sky Association (IDA) defines light pollution as "the inappropriate or excessive use of artificial light" (http://darksky.org/light-pollution/). Other organisations such as the National Lighting Product Information Programme (NLPIP) further explains light pollution as "an unwanted consequence of outdoor lighting and includes such effects as sky glow, light trespass, and glare" (National Lighting Product Information Programme (NLPIP) (2003) Lighting Answers. Rensselaer Polytechnic Institute. Vol 7, Iss 2. pp 2). It is essentially light which is wasted and has no function. Light pollution occurs as a result of the increased use of artificial light sources utilised by civilisation globally. The increased use of artificial light in both interior and exterior lighting of households, commercial units, street lighting, the lighting of venues and stadiums, factories and offices has led to increases in artificial light pollution. Concerns over light pollution in terms of the changes in the characteristics of the night sky were first voiced by astronomers (Riegel 1973). Recently, the impacts of light pollution on animal and plant species has been the focus of many studies (Longcore *et al*. 2007, Davies *et al.* 2013, Rodríguez *et al.* 2015, Bliss-Ketchum *et al.* 2016). The United Nations (UN) announced 2015 as the International "Year of the Light", while its scope was on light science and its uses, light pollution was also discussed (Bruning *et al.* 2016).

Light pollution consists of a number of components. These components include:

- Glare,
- Sky glow,
- Light trespass,
- Clutter.

These components of light pollution greatly differ from each other, Mc Colgan 2003 describes in detail the characteristics of all these components.

Glare: Artificial lighting may cause glare, this is as a result of the incorrect use and installation of artificial lighting. Glare can reduce visibility or cause discomfort to view an area. This can affect both humans and animals. The development of equipment which produces less light may reduce glare (Mc Colgan 2003).

Sky Glow: The occurrence of sky glow is present naturally and as a result of artificial light. Sky glow is present through natural sources such as the reflection of sunlight from the moon and earth's surfaces, as well as the reflection of sunlight off interplanetary dust, the light glow in the upper atmosphere, the scattering of light from starlight through the atmosphere and natural lighting from distant and faint stars and nebulae. Sky glow is also as a result of human introduction of artificial lighting. As a result of this artificial lighting the level of brightness in the night sky has increased. This light enters the night sky by the direct emitting of light to the sky or by the reflection of downward light off the ground into the atmosphere through the scattering by particles in the atmosphere such as gas and dust (Mc Colgan 2003). Sky glow increases during periods of bad weather when there are more particles present in the atmosphere causing the sky glow to be more evident and obvious (Kyba *et al.,* 2011). It is visible as an orange glow over an urban area and can be visible from up to 200km away (Duffek 2009).

Light Trespass: Light trespassing is as a result of artificial light where the installation of lighting devices are reaching unwanted targets. An example of this is the installation of lighting to illuminate a pathway through a wood, the surrounding woodlands will receive artificial light as a result of this installation. This can have great impacts on the species which utilise this woodland habitat. The correct installation of lighting devices by focusing the light on the intended target will greatly reduce light trespassing. Light trespass also impacts humans as street lighting will enter the windows of households which may lead to effects on sleep patterns (Mc Colgan 2003).

Clutter: The excessive grouping of lighting equipment leads to the clutter of artificial lighting. Cluttering of lighting results in high concentrations of artificial lighting to an area. This can cause confusion to many species and can result is disorientation in these species. Clutter lighting is common in urban areas (Mc Colgan 2003).

1.1.2. The Current Trends in Light Pollution

The changes in light pollution are made evident when comparing satellite images captured since the 1970s (Bennie *et al*. 2014). It has been reported that on a global scale light pollution is growing at a rate of 6% annually (Khorram *et al.* 2014). This is identified as a high threat to flora and fauna, light pollution being ranked in the top ten emerging issues in biodiversity (Holker *et al.* 2010, Stone *et al.* 2012, Newman *et al.* 2015). At the current rate of use, the generation of artificial light requires 19% of the global electricity, which generates approximately 1900 Mt. of carbon dioxide annually. With the increase of global population, this figure may increase considerably as a result of the increase in supply and demand (Raap *et al.* 2015). In 2001, it was found that 19% of the world's surface area is receiving artificial light intensities above the recommended pollution level threshold (Bennie *et al.* 2014). When countries and continents are examined separately, these figures further increase. For example, it is believed that 23% of the land surface of the USA receives a level of artificial light intensity over the threshold, while 37% of Europe receives artificial light over the set threshold (Cinzano *et al.* 2001, Gaston *et al.* 2013). An estimated two thirds of the world's human population are living in areas with a polluted sky as a result of artificial light (Rodríguez *et al.* 2015).

1.2. The impacts of Light Pollution

1.2.1. Impacts on Fauna

The changes in the number of hours of brightness impacts a vast number of species including humans. The extent of these impacts vary from species to species. From previous studies it has been found that artificial lighting affects species in a number of different ways, including alterations to their foraging behaviours, reproduction, communication, orientation and prey/predator relationships (Longcore *et al.* 2004, Kempenaers *et al.* 2010, Rotics *et al.* 2011). All these impacts can lead to stress on a species and may result in population declines in an area of high light pollution. A number of studies have focused on the impacts of light pollution on the circadian rhythm of species including humans. Throughout many species, the photoperiod plays a huge role in their daily behaviours. The length of the day and night influences the period in which species are active or resting (Royal Commission on Environmental Pollution 2009). Light pollution alterations to this rhythm may results in impacts like those discussed above (Rich *et al.* 2006, Royal Commission 2009). Studies have found that light which is blue-rich has great impacts on the circadian rhythms of many mammal species (Berson *et al.* 2002). A vast range of animals are impacted by light pollution with various different effects being reported as further discussed below. The impacts found are not exclusive to one habitat, with impacts being recorded in both marine and terrestrial habitats.

1.2.2. Effects on Circadian Rhythms of Species

Studies have found that the presence of light pollution in a habitat interferes with the roosting and foraging behaviour of bats. As a result of such pollution, species do not forage during dusk when their food preference is at its highest supply (Jones *et al.* 1994, Downs *et al.* 2003). These changes in behaviour may result in weak and nutrient-deficient bats, causing problems in the success and the recruitment of the population. Artificial light sources may indirectly affect a species; for example insects, may be attracted to these light sources. As insects are the main component of the diet of many species they will be influenced to follow the insects to the area were the light source is located (Eisenbeis 2006). A study by Bruning *et al*. (2015) discussed the impacts of artificial light on the production of melatonin in fish species. Melatonin is essential in controlling the day and night sleep patterns of a species. Melatonin production is greatly reduced during hours of brightness while optimal production occurs during darkness. Extra hours of brightness in the night reduces melatonin production levels and greatly impacts the fish species. This paper also discusses the importance of light in the timing of reproduction of fish, reproduction readiness and the production of the sex steroid which is triggered by the gonadotropins, luteinising hormone and stimulation of the follicle hormone. The changes of the melatonin levels in a fish species can hinder and prevent gonadotropin production. It has also been found that sexual maturity can be delayed or prevented due to the suppression of gonadotropin (Khan *et al.* 1996, Amano *et al.* 2000, Chattoraj *et al.* 2005, Bhattacharya *et al.* 2007, Sebert *et al.* 2008, Carnevali *et al.* 2011). This will greatly affect the spawning success and recruitment of fish species, and spawning outside of the regular season may also occur.

1.2.3. Effects on Migration and Orientation

Artificial light can be up one million times brighter compared to natural light sources, this light intensity may result in very obvious behavioural changes by a species as a response to cope with this light intensity (Perry *et al.* 2008, Newman *et al.* 2015). These large scale behavioural changes have been identified in a study carried out on Atlantic salmon; changes in the various stages of their life cycle have been recorded (Newman *et al.* 2015). A number of conclusions were found in a study by Newman *et al.* This study found that dispersal at the fry life stage was delayed as a result of artificial light, as well as this hours of darkness are required during the migration of young salmon aged two known as smolts however, with increased hours of brightness this migration period is greatly reduced (Riley *et al.* 2000, Riley *et al.* 2012a, Riley *et al.* 2012b). The orientation of sea turtles has been greatly affected as a result of natural lighting on coastal areas. Sea turtles spend a minimal amount of time on land, during periods when they are laid as eggs on the beach, when they emerge as hatchlings and when as adults the females return to the nesting beaches to lay eggs. All these practises of returning to land depend heavily on reflected light from the moon. Emerging hatchlings depend on the moon to orientate themselves to the ocean. After laying her clutch of eggs on the beach the female will also find the ocean by the illumination from the moon (Weishampel *et al.* 2015). However, the increase of developments on coastal areas has increased the levels of artificial light on these nesting beaches

(UNEP2008). This causes disorientation of hatchling and female turtles and has been identified to have led to thousands of deaths of hatchlings in Florida as they follow the artificial light away from the ocean (Salmon 2003). Disorientation can cause stress to the female turtles and can lead to exhaustion due to unnecessary excessive travelling along the beach.

1.2.4. The effects on predator-prey relationships

The changes in the hours of brightness may affect the lifestyle traits of many species. The success of many habitats is aided by the division of diurnal, nocturnal and crepuscular species. This prevents over competition for shelter, space and food. The increased brightness may disrupt these patterns and may cause ecosystem disturbance (Kronfeld-Schor *et al.* 2003, Gutman *et al.* 2005). During active hours, these species will prey on certain other species, however if the hours of activity are altered this relationship may change and predators may prey on species which they would normally not consume. This may result in ecosystem imbalance as a result of the over consumption of one species. During hours of brightness preyed upon species are most susceptible to predation, as a response to this they may reduce the hours in which they are active during the day causing a reduction in prey availability (Gaston *et al.* 2013). These behavioural changes are believed to be costly in terms of energy output (Smit *et al.* 2011). It has been reported that prey species will forage in close proximity to light sources as their food source species are attracted to the light and congregate around it. This is evident in orb-web spiders *Larinioides sclopelarius* which build their webs close to light sources as high numbers of insects are found in these areas. This behaviour is natural, however with artificial light sources increasing the effect is exaggerated, spiders are encouraged to these areas to build webs and to forage (Heiling 1999).

1.2.5. Effects on Birds

Increased mortality in petrel (Order Procellariiformes) populations as a result of light pollution has been found, particularly in young fledgling populations. It has been identified that young fledglings embarking on their first flight become disorientated by artificial lighting and will mistakenly fly out to the ocean, although this has been identified it is not fully understood (Imber 1975). Fledgings have been recorded as injured or killed as a result of flying into artificial lighting equipment. Grounding of birds as a result of artificial light occurs as the birds are unable to fly due to these light sources. This is of particular concern as petrels are a group of birds which are identified as being an order of species which is one of the most endangered seabird species (Croxall *et al.* 2012). Studies have found that over 40 burrow-nesting petrels are currently affected by artificial light (Rodriguez *et al.* 2015). Zebra finches *Taeniopgyia guttata* have also been found to face negative impacts as a result of light pollution. Increased daylight hours lead to sleep deprivation in these birds. This results in the disruption of their activities resulting in increased mortality (Snyder *et al.* 2013). The excessive use of artificial light has great impacts on a number of song birds. Song is normally heard during hours of brightness, sun rise and sunset, however when artificial light extends the hours of brightness the birds continue to sing. This can result in sleep loss for the birds (Kempenaers *et al.* 2010, Dominoni *et al.* 2013a, Dominoni *et al.* 2013b, Schlict *et al.* 2014, Da Silva *et al.* 2014). From previous studies carried out examining the interaction between bird species migration and light pollution, it has been found that management is required in terms of the spectral composition of light (Poot *et al.* 2008). The migration direction of the European robin *Erithacus rubecula* is known to be determined by the use of blue and green photoreceptors. The altering of the natural light in the atmosphere may hinder the migration path of this species (Wiltschko *et al.* 2007). In contrast, the migration of silvereyes *Zosterops l. lateralis* is greatly disrupted by red light (Wiltschko *et al.* 1993).

1.2.6. Effects on Flora

The exploration of the impact of light pollution on plant species has yet to be carried out to the same extent as those studies carried out on vertebrates and invertebrates. Photosynthesis is affected by the length of brightness in the day. Photosynthesis is at its peak during hours of brightness and is reduced during hours of darkness. Although this affect is believed to be relatively low, a study by Raven *et al.* (2006) found that photosynthesis during hours of brightness was increased in the presence of sky glow and moonlight. The reduction of hours of brightness has been hypothesised to affect the recovery and repair time which is essential for many species. The reduction of hours of brightness can be used to explain the ozone injury in plants found in areas of high altitudes (Vollsnes *et al.* 2009). This is supported by the relationship between artificial light and ozone pollution (Cinzano *et al.* 2001). As with animals, the extension of the photoperiod will reduce the limitation on growth and on the reproductive processes of plant and tree species. This was the case in the study carried out by Bennie *et al.* (2015) where it was found that artificial lighting influenced the growth and the reproductive cycle of plants. Further study, was carried out to find that this impact indirectly affected the herbivores in the area. As a result of this study it can be determined that there is a ‘bottom up’ effect of light pollution resulting from artificial light sources from human settlements. The photoperiod is also responsible for the development of leaves and buds. The photoperiod can determine the structure of the leaf such as it’s shape the pubescence and the pigmentation. The timing during the year in which the buds will become active is also determined by the photoperiod. If a bud comes out of dormancy too early during the winter months, it’s survival chances will be greatly reduced. Trees which are exposed to continuous lighting may display foliage which is larger in size compared to trees which receive natural lighting. The foliage may be prone to air pollution and stress as a result of the stomatal pores being open for long periods of time (Chaney 2002). Trees with reduced health were reported in the 1960s with the introduction and installation of high pressure sodium (HPS) lamps. These lamps emit both red and infrared spectral light of a high intensity.

1.3. Light Pollution in Ireland

1.3.1. Current Status of Light Pollution in Ireland

From Figure 1 below, the distribution of light pollution in Ireland is evident. The capital of Ireland, Dublin shows the highest level of light pollution in the country. The spread of the light pollution on the image extends past the Dublin City border to semi-rural areas. Smaller cities such as Galway, Limerick, Cork and Belfast also show high levels of light pollution. An increase in the levels of artificial light pollution was as a results of the "Celtic Tiger" years due to the sudden increase of the building in the housing sector (Espey *et al.* 2014). During this period, one eighth of the land surface of Ireland recorded increases in light pollution as high as 20%. However, darker areas are also visible in counties Cork and Mayo showing lower levels of light pollution. The light pollution free areas of Ireland seen in Figure 1 are supported by a study by Espey *et al.* (2014), who found pristine sky conditions. An estimated 60% of the Irish population are living under polluted skies. According to the Sustainable Energy Authority Ireland (2011), there are approximately 420,000 public lights spread across Ireland. The combined usage of these street lights alone consumes an estimated 205 GWh of energy, with annual emissions of 110,000 tonnes of carbon dioxide as a result. The total cost of the running and maintenance of these street lights is approximately €50 million annually. The majority of these public lights are owned by Local Authorities. One major issue in the running of 98% of these public light is the fact that they are un-metered (SEAI 2011). The National Energy Efficiency Action Plan 2009-2020 has set a target to reduce the cost of public lighting by 33% by the year 2020, this will lead to improved energy saving measures and more efficient lighting (NEEAP 2014). With better management of these lighting devices a reduction in the impacts to humans, wildlife and the climate is sought by the action plan.

Figure 1. Imagery from the International Space Station displaying the hotspots of Light Pollution in Ireland. High light levels can be seen in the capital city of Dublin when compared to rural regions of Ireland (Source: www.globeatnight.org).

1.3.2. Measures to Eradicate Light Pollution

A number of measures and procedures have been suggested to reduce and possibly eradicate light pollution from the night sky. Unlike other forms of pollution, such as chemical and oil pollution, light pollution is easy to remove from the atmosphere. This is evident during periods of electrical blackouts when the night sky becomes almost instantly clearer with a greater number of stars becoming visible.

One suggestion to reduce light pollution levels is to design and utilise efficient luminaires which will illuminate the intended target with a reduction in trespass light. Gaston *et al.* (2012) discusses a number of resolutions to include in a management plan to reduce artificial light pollution. These measures include the prevention of installing lighting equipment in certain areas, such as areas of conservation to prevent sensitive and protected species from being impacted. Another measure is to reduce the number of hours the equipment is emitting light for, this will allow for periods of darkness during the night. By reducing the intensity of the light, glare will be prevented which will, in turn, reduce disorientation of animals. Finally it has been suggested to modify the spectral composition of the emitted light, it is believed that by modifying the composition of the emitted light the impacts of the light will be reduced. It has been identified that blue light is more damaging and has the potential to cause greater impacts (Gaston *et al.* 2012).

1.4. Dublin Study Sites (Bull Island, Trinity College Dublin and Killiney Hill)

1.4.1. Study Site Locations and Background

This study is focused on highly populated urban areas of Dublin. The land use and land types at the study sites (i.e.- Bull Island, Trinity College Dublin and Killiney Hill) vary greatly from each other. These three sites were selected for a number of reasons. Due to the high population density of Dublin there are a number of City and County Council Divisions in the County of Dublin Figure 2.

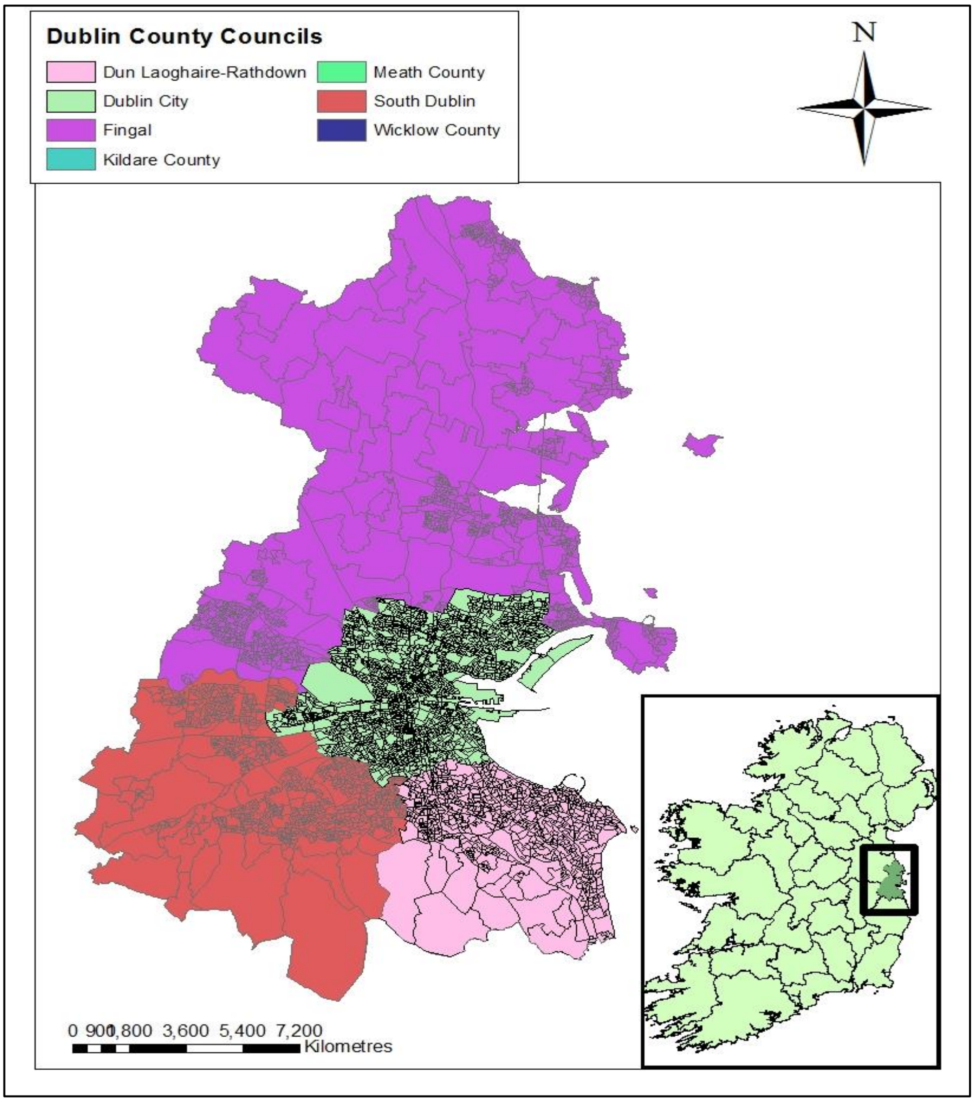

Figure 2. Due to the high population density of the County of Dublin this area is divided into a number of City and County Councils, each with the responsibility of enforcing various environmental policies within these County Council divisions.

1.4.2. Bull Island

Bull Island is situated in the northwest section of Dublin Bay on the East coast of Ireland. Dublin Bay is located in the heart of urban Dublin and receives a lot of shipping traffic. The Island was formed as a result of deposition of sand along the Bull Wall, this formation occurred within a 200 year period. Bull Island has been a designated Nature Reserve for a number of years, in the 1930's it was first designated as a Bird Sanctuary. The Island was then recognised as a UNESCO Biosphere Reserve in 1981 and was then further upgraded as a Nature Reserve in 1988. Bull Island is widely used by tourists accessing Dollymount Beach and its golf courses and as a popular walking site. It is managed and categorised as a public park by Dublin City Council. A number of rare and sensitive habitats are found on the island making it an important area were conservation is required. Much of the biodiversity of the island is protected under Annexes I and II of the EU Habitats Directive (Council Directive 92/43/EEC of 21 May 1992 on the conservation of natural habitats and of wild fauna and flora). Bull Island was selected as a study site as it is located on the outskirts of the city centre and provides information on light pollution in suburban Dublin (Figure 3).

1.4.3. Killiney Hill

Killiney is located on the South coast of Dublin Bay, approximately 15 km from the city centre. Killiney is on the central east coast of Ireland (Clerc *et al.* 2012). Killiney Hill Park located in the area, was opened in 1887 and is composed of Killiney Hill, Dalkey Hill and Roches Hill. The park has been proposed to be designated as a National Heritage Area (NHA). Sites designated as NHAs are protected and therefore protect habitats which may be vital for a number of species found in the area some of which may be sensitive. The area is a popular site among hill walkers and offers views extending from Dublin Bay and the city centre as far as the Dublin and Wicklow Mountains. The area is surrounded by native woodlands with walkways through the various habitats, these habitats include grassland, wildflower meadows, deciduous woodlands, stonewall habitats and coniferous woodlands (Irish Wildlife Trust 2009). These habitats are vital for the many protected species found in the area (Dún Laoghaire-Rathdown County Council 2009). The site is surrounded by marine and coastal habitats. The site also provides accessible cliffs for climbing enthusiasts. Killiney Hill was chosen as a study site as it is located a further distance from Dublin City in comparison to the Bull Island location, this therefore provides information on light pollution in more a secluded part of Dublin (Figure 3).

1.4.4. Trinity College Dublin

Trinity College Dublin is located in the heart of Dublin city centre, it is located on the south side of the City. The University was first opened in the 1500s and since has expanded greatly in size and in student population. The University provides many functions primarily education and research with approximately 16,000 students carrying out their studies on the campus. Trinity College is a very popular tourist attraction with high levels of tourists visiting the Book of Kells annually. The expansion of many of the faculty buildings has reduced the greenery within the University grounds. The growth of the student population in the University has led to the development of off-site buildings to facilitate the demand. However, green areas can still be seen throughout the college grounds used for recreation, research and landscaping. The areas surrounding Trinity College Dublin receive high volumes of both vehicular and pedestrian traffic. Tall buildings surround the grounds of the University, these building functioning as offices, retail establishments and accommodation. Historical buildings and public parks are also found in close proximity to Trinity College Dublin. Including Trinity College Dublin as a study site in this research will provide information on intense urban light pollution as this site is located in the city centre.

The location of the three of the light meters of Bull Island, Trinity College Dublin and Killiney Hill can be seen in Figure 3. These three study sites will be compared to one another in this research study.

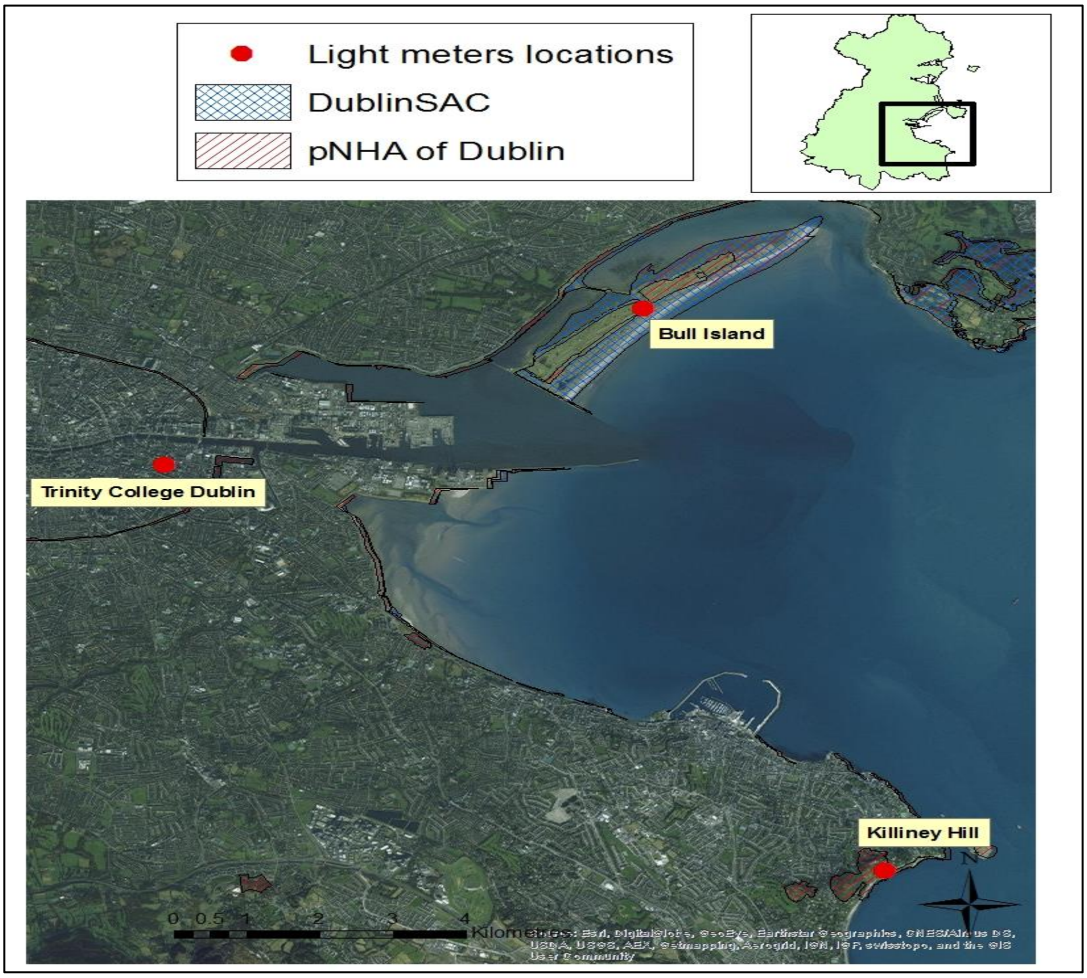

Figure 3. The locations of the three study sites- Bull Island, Trinity College Dublin and Killiney Hill.

1.4.5. Previous Studies

Previous studies have focused on the impact of light pollution on human health (e.g. Griefahm *et al.* 2006, Kantermann *et al.* 2009) and on the impact of light pollution on terrestrial animal species (e.g. Davies *et al.* 2012, Kempenaers *et al.* 2010, Lewanzik *et al.* 2014). In recent years, an increased number of studies have examined the impacts of light pollution on aquatic species with a focus on species used in aquaculture (Yeh *et al.* 2014, Boeuf *et al.* 1999) Artificial light in aquaculture was examined in terms of improving the growth of the species in question, the control of reproductive periods and reducing stress on fish. Raap *et al.* (2015) reports that while in depth laboratory studies of the impacts on organisms due to artificial lighting have been carried out there are only a few field studies on free-living animals which examine the experimental manipulations of light conditions in the wild.

It is known and established that artificial light impacts a range of species, however further studies are required to identify the light sensitivity of various other species which have not been the focus of many studies. This research should be carried out to further current knowledge. Studies on the composition of light should be examined, as species will be impacted by different spectra and characteristics of light. For example, as previously discussed, sea turtle orientation is greatly dependant on the natural light of the moon. Therefore, the introduction of white artificial light into the environment causes disorientation. Nevertheless it has been found that sea turtles are not sensitive to red light (Salmon *et al.* 1995). This knowledge is very useful in preventing harm and protecting sea turtles. Species impacts vary depending on the spectrum of light they are sensitive to, studying species to determine what spectrum is most harmful to them will be of great benefit for the development of management plans.

A study was previously undertaken to look at the ecological impacts of light pollution in rural Ireland, the study site of the Owenduff/Nephin Beg Complex SAC, SPA and pNHA was selected. This site is found on the west coast of Ireland in County Mayo. A number of protected species are found at this study site. This study found pristine night skies at three of the study sites, while the fourth study site of Ballycroy had localised light pollution. This localised light pollution has the potential to impact the sensitive species of the area. This study provides evidence that light pollution is not only a concern in relation to cities but also to rural Ireland. Further studies, like this study detailed, are required in Ireland to identify light pollution hotspots and the species which are being impacted by this form of pollution. It is possible that a number of species which are being effected by light pollution are protected under Irish legislation, therefore the problem of light pollution must be eradicated or reduced.

1.5. Project Aims and Research Questions

This research work will focus on answering the research question: what are the ecological impacts of light pollution in highly populated areas of Ireland such as Dublin city. The objectives and tasks to achieve the overall goal above are as follows:

Objective 1:

- Gain a knowledge and identify the effects of light pollution on a number of species, including those considered to be light-sensitive.
    - The habitat types of the study sites will be determined through field site visits and data provided by National Parks and Wildlife Services (NPWS) and the National Biodiversity Data Centre (NBDC). A profile of the three sites where the light meters

- were located will be developed identifying sites which may be vulnerable and sensitive to light pollution.
- The distribution of sensitive species at the study sites will be identified and mapped through Geographic Information System (GIS) software with data from the National Biodiversity Data Centre (NBDC).
- Light data provided by Dr Brian Espey of the Department of Physics Trinity College Dublin will be analysed to determine the light levels at the three monitoring sites. When the light levels are determined the impacts on the sensitive species found in the areas of the study site can be determined by reviewing previous literature on these species.

Objective 2:

- To study the changes of light pollution in Ireland and to examine the growing trends in light pollution.
    - The changes in light levels in Ireland, with a focus on Dublin, over the last two decades will be examined to identify the full extent of the increase of light levels. Light maps were acquired from the National Centres for Environmental Information (NCEI) and the National Oceanic and Atmospheric Administration (NOAA), with data provided by the Defence Meteorological Satellite Program's Operational Linescan System (DMSP/OLS). These data are freely available at http://maps.ngdc.noaa.gov/viewers/dmsp_gcv4/and http://ngdc.noaa.gov/eog/dmsp/downloadV4composites.html
    - The light level data will be used to identify areas which are at high risk of excessive light by comparing the increases of levels over a number of selected years. The areas of the three study sites of Dublin will be compared to determine the extent of light level changes.

Objective 3:

- The findings of this study will be compared to a previous study carried out in rural Ireland last year. This will assist in the development of a country-wide database on the effects of light pollution on sensitive species.
    - The results of this research study will be compared to a previous study carried out in 2015 by a master's student of Trinity College Dublin. This previous study focused on light levels in County Mayo concentrating on the Owenduff/Nephin Beg Complex SAC/SPA/pNHA.

2. RESEARCH METHODS

2.1. Habitat Profile

2.1.1. Pre-habitat Surveys

Literature on each of the study sites was gathered and reviewed to develop an insight and knowledge of these sites. Data on the species present at the study site areas were retrieved from NPWS and the NBDC. Previous studies carried out at the sites were gathered to further understand the importance of the locations as well as identifying previous issues which have affected the area. Using the World Imagery layer available in AcrGIS 10.3.1 the locations of the light metres were located and the surrounding features and habitats were displayed and examined to allow for digitisation. ArcGIS 10.3.1 was selected for this study as this software assisted in spatial analysis and has a range of tools to aid in the representation of the data of this study. Contact was also made with a number of organisations, such as Dublin City Council, NPWS, NBDC and Dún Laoghaire-Rathdown County Council, to obtain an insight into the survey sites and for details on the species present, however this was mainly unsuccessful. Obtaining data from these organisations was unsuccessful for a number of reasons such as the organisations being unable to release sensitive data, a lack of staff to reply to emails and data request forms or the organisations did not have the data required.

With the data provided by the NPWS and the NBDC a profile of the study sites was developed, this included existing habitats and species, land uses and the soil and bedrock types. Site visits were undertaken to further gather a knowledge of these habitats and to determine where the light meters are located to allow for habitat verification. These site visits allowed for any issues encountered during the pre-survey practises to be overcome and for intense light sources to be identified.

2.1.2. Study Site Visits

Site visits were carried out over a number of days. Site visits to Bull Island and Trinity College Dublin were carried out on the 6th of July 2016, while a site visit to Killiney Hill was carried out on the 9th of July 2016 with a follow up visit carried out on the 11th of July 2016. The study site at Killiney had a number of light metre locations, it was decided to focus on one site in terms of mapping and interpretation. One site at Killiney Hill was selected as a site representing the area to prevent excessive mapping of the area and to keep to the title of this research study project of a three site comparative study. This selected study site was at Killiney Hill, this location was selected to represent Killiney for this study as there are a high number of species present in this area and it is a popular attraction. The sites of Bull Island, Trinity College Dublin and Killiney Hill are all open to the public therefore permission was not required to visit these sites. All the sites were accessed in a safe manner and no risk was involved in reaching the sites. The purpose of the site visits was to verify the habitat classification determined during the pre-survey tasks and to identify any features or issues in the areas which were not obvious or visible when mapping dominant habitats. During the site visits to all the selected study sites (i.e. Bull Island, Killiney Hill and Trinity College Dublin) the areas surrounding the location of the light meters were surveyed on foot to identify any features and habitats that were missed or were not visible on the satellite imagery. The dominant habitats of the area were recorded and small patched habitats were noted. Any light sources surrounding the location of the light meters were also identified and recorded. Site visits assisted in the development of profiles of the location of the light meters as well as identifying any disturbances to any of the three sites. After the site visits a number of corrections were made to the habitat maps.

2.2. Collection and Analysis

2.2.1. Light Levels Analysis

Two aspects of light levels were analysed. The first involved the changes of light levels in Ireland over a 20 year period. The data provided by the Defence Meteorological Satellite Program (DMSP) were used during this analysis. Data from 1992 was first examined as it is the earliest light level records provided by DMSP. Further data from 2001, 2007 and 2013 were examined. 2001 displays data showing light levels previous to the “Celtic Tiger” era when construction was at a low level. Light levels from 2007 were selected as these data were collected during the boom years of the “Celtic Tiger” when Ireland, especially Dublin, became very developed and populated. The most recent data provided by the DMSP is for the year 2013, therefore these data were included in this study, and this provides information on the most recent update status of light pollution in Ireland.

Data on the light measurements of the three light meter locations of Bull Island, Trinity College Dublin and Killiney Hill were provided by Dr Brian Espey of the Physics Department of Trinity College Dublin. Two separate aspects of analysis were carried out; the analysis was separated into two as data for Killiney Hill did not contain as much information in comparison to the light level datasets for Bull Island and Trinity College Dublin. Analysis of light levels in Bull Island, Trinity College Dublin and Killiney Hill for the 26th of March 2016 were examined and the results for each study site were compared to each other (Figure 4). Data for the 26th of March were selected as it was the only date in which data was collected simultaneously at all the three study sites. Further analysis was then carried out on the larger datasets of Bull Island and Trinity College Dublin. Data collected over the new moon phase from the

$8^{th}$to the 15^{th} of February 2016 were analysed for both these sites to show the changes in light levels over this seven day period between the study sites. The new moon phase was selected in this study as during the new moon light reflected by the moon is at its lowest level, therefore the levels of artificial light are evident in the readings from the light meter on site. Further analysis was carried out on data collected during the full moon phase from the 22^{nd} to the 29^{th} of February 2016 for both Bull Island and Trinity College Dublin, to again examine the changes in light levels and to compare the two sites to each other. Data collected during the full moon phase provides information on the levels of artificial light pollution at night combined with the high levels of light reflected by the moon.

2.2.2. Study Site Characteristics and Habitats Data/information Collection

Further spatial analysis allowed for the over-lay of a number of datasets to develop study site profiles. Datasets such as predetermined sensitive species present in the areas, the habitat types of the sites, the bedrock of Dublin, the soil types of the study sites and the waterbodies of the area. Habitat profiles for each of the selected sites were developed based on a compilation of data and information. Habitat datasets were freely downloaded from the (NPWS) website. Further information was gathered from an officer of NPWS, greatest detail was provided on the study site of Bull Island. Information on Killiney Hill habitats was obtained from the information provided in the "Killiney Hill: Biodiversity Education Programme: An action of Dún Laoghaire-Rathdown Biodiversity Plan 2009-2013" (Irish Wildlife Trust 2009). Data relating to designation classifications were also gathered from the National Parks and Wildlife Services, these classification include Special Areas of Conservation (SAC), Special Areas of Protection (SPA), National Heritage Areas (NHA) and proposed National Heritage Areas (pNHA). Land cover, lakes and river, soil types and the bedrock of Dublin datasets were all downloaded from the Geological Survey of Ireland (GIS) and the Environmental Protection Agency (EPA). The County Council divisions of Dublin were provided by Geofabrick. As a result of the high population density of Dublin the county has a number of City and County Council divisions. The Councils of the study site and the surrounding areas include Fingal, Dún Laoghaire-Rathdown, Dublin City and South Dublin County Councils. A species list was developed based on information from the literature on species sensitive to light pollution and information provided by the NPWS officer on the sensitive species present at the three research sites. All the species selected for the study are all protected under legislation both on a National or International level. Further data on the location of the sensitive species were downloaded from the NBDC. Data from the NBDC were provided at various resolutions these include $10km^2$, $2km^2$, $1km^2$ and $100m^2$ scales. Species data to a scale of $1km^2$ were selected for all the chosen species as it represented the species distribution at the study sites and the surrounding areas appropriately. Data to a scale of $1km^2$ were available for all the species selected in this study. Species represented at a resolution of $100m^2$ was not included in this study as the species selected for this study are both sensitive and protected, data at this resolution was not available for all the selected species therefore it was omitted. Species represented at a scale of $2km^2$ were omitted from this study as the $1km^2$ represented the species appropriately to a finer scale.

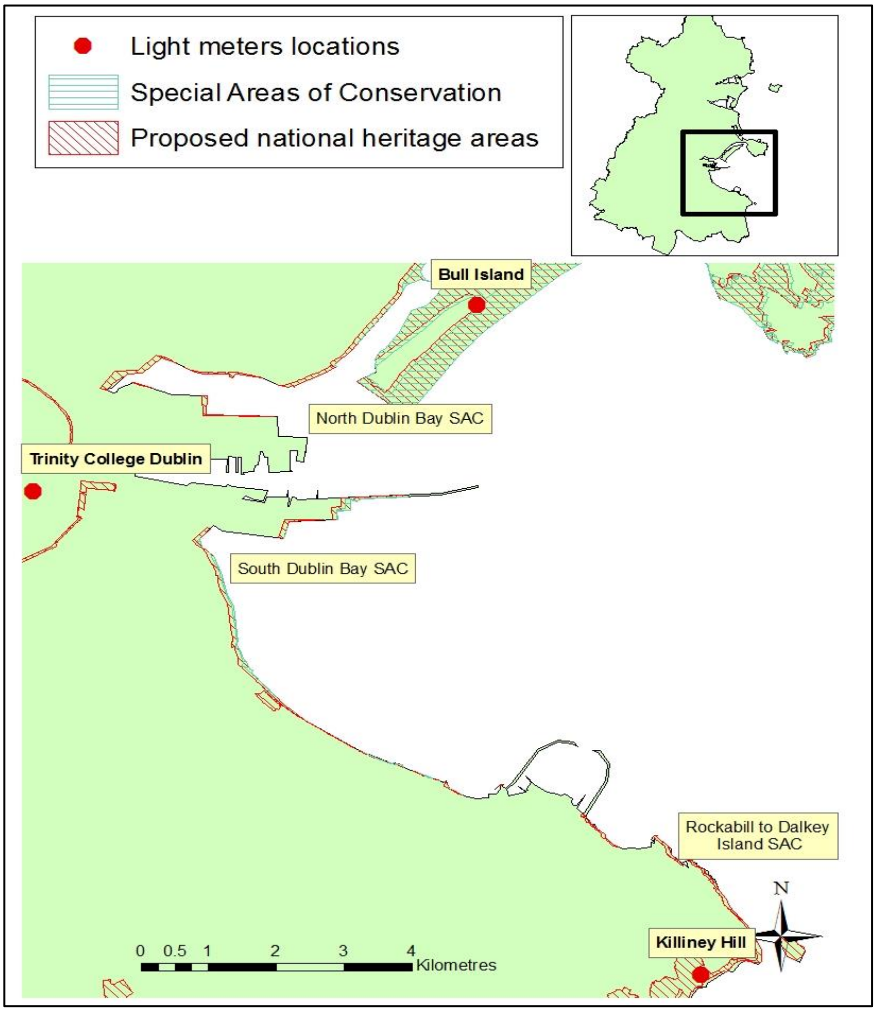

Figure 4. The three comparative study sites displaying the location of the light meters at these sites. The Special Areas of Conservation (SAC) and the proposed National Heritage Areas (pNHA) are also displayed.

2.3. GIS Analysis

2.3.1. Light Level Mapping

The various datasets gathered for this study were represented visually through the use of mapping in ArcGIS 10.3.1 provided by the IT services of Trinity College Dublin. ArcGIS 10.3.1 facilitated in the spatial analysis of the study sites of Dublin. All files were imported to the Irish National Grid Coordinate System, to facilitate for consistent analysis. The imported images were georeferenced to a shape file of Ireland to show the county boundaries. The pixels of this image represent the light intensity levels of the area of focus with digital numbers (DN) on a scale of 0 (low light levels) to 63 (high light levels). All images of the different light levels in Ireland for the selected study years of 1992, 2001, 2007 and 2013 were set under the exact same range to allow a comparison between the images to identify an increase or decrease in the light levels over the selected years of this study. Determining the changes in light levels over the study periods was carried by taking the DN counts for each year away from each successive year to identify the increases or decreases in the light levels between the periods. Comparison of the light levels was carried out between 2001 and 2007, between 2007 and 2013, and between 1992 (the earliest light record by the DMSP) and 2013 (the most recent light level records provided by the DMSP). The comparison of these images will show the changes of light levels in Dublin over three equal time periods (2001, 2007 and 2013) as well as showing the changes of light levels in Dublin from the first record (1992) up to the most recent recording (2013). These light level maps were then further referenced to aerial imagery of Dublin to identify the features and buildings which emit high levels of light.

2.3.2. Study site characteristics and habitat mapping

The characteristics of the study sites were developed through mapping the various datasets as previously discussed during data collection. Shapefiles detailing the underlying bedrock and soil types of Dublin were provided by the GSI and the National Soils Database were provided by the EPA. Unlike many counties of Ireland Dublin has a number of City and County Councils dedicated to the county due to the high population density. Datasets for the County Councils boundaries were downloaded from Geofabrick and were mapped to identify the County Council designated to each study site. Each designated Council has various biodiversity plans allocated to the relevant district and therefore the efforts made for the protection of biodiversity may vary between these Councils. Data displaying the land uses of Dublin (i.e. CORINE (Co-Ordinated Information on the Environment) Landcover 2012) were downloaded from the EPA, CORINE. Land use data from CORINE Landcover 2006 was also mapped to identify any changes of the land uses in Dublin and in doing so explore if these changes may relate to variation in the light levels of Dublin. The area of the various different land use types were calculated and compared between 2006 and 2012 to identify the scale of the increase or decrease of the land use type. The locations of the study sites were displayed in each of these characteristic maps to show and develop the profile of the three sites.

2.3.3. Habitat and Species Maps for the Light Meter Locations

To develop habitat indicative maps of the study sites the data sets which were gathered from NPWS were imported and displayed in ArcGIS. The further information and shapefiles provided by the officer of the NPWS was added to the indicative map to develop more information on the sites and habitats.

The maps on Killiney Hill habitats from the information sourced (Irish Wildlife Trust 2009) were digitised to ArcGIS by creating new feature classes and manually digitising habitat type polygons to fill in the missing habitat information. Indicative habitats were also mapped by examining aerial photographs and as previously discussed manually digitising these habitats by creating feature classes. These indicative habitats were then verified through site visits. Much of the land area of Dublin has been urbanised and this fact was detailed in the habitat maps, this is especially the case at the study site of Trinity College Dublin. The selected species for this study were mapped from the data provided by the NBDC, this was done effectively through the use of the ArcGIS plugin GeoWizard which produced grid squares at a predetermined square size, which allowed for the species occurrence data to be digitised in the same location as that on the same location on the maps provided by the NBDC. All species were mapped to a 1km^2 scale. The location of the light meters were represented on these species maps to show the locations of the species in relation to the light meters. Variations between the species present at the different light meter locations were displayed visually.

2.4. Light Meter Data Analysis

2.4.1. Data Analysis

Light meter data for the three study sites (i.e. - Bull Island, Trinity College Dublin and Killiney Hill) recorded the Sky Quality Meter (SQMs) level at each site. The SQM value provides information on the light intensity at the study sites, it is the measure of light intensity at the study sites recorded in square arcseconds (Kyba *et al.* 2011). A vast amount of data were collected from the light meters of Trinity College Dublin and Bull Island, while light data for Killiney Hill were considerably less. Data were only collected on one day, 26th of March in Killiney Hill. Unlike the sites of Bull Island and Trinity College Dublin, the site at Killiney Hill was not monitored by an automated light meter. Therefore light levels were recorded using a manual light meter over the course of one day. An automated light metre would allow for monitoring over a longer duration. Data were selected for the same time for the other sites of Trinity College Dublin and Bull Island to allow comparison between the research sites. Boxplots and scatterplots (Figure 15 and 16) were produced for the light levels of these locations to display the difference in the SQM at the three study sites. Further in-depth analysis was carried out between Bull Island and Trinity College Dublin. Data collected during the new moon (darkest moon phase) for the 8th to the 15th of February 2016 and data for the full moon (brightest moon phase) from the 22nd to the 29th of February 2016 (leap year) were analysed and compared between the two sites. These phases of the moon were recorded to determine the light levels when high levels of light are reflected by the moon during the full moon. The light levels during the new moon phase when a greatly reduced level of light is reflected by the moon is used to determine the level of artificial light is in the night sky.

These two phases of the moon were graphed with the use of R 3.3.1, scatter plots were produced with the use of this software. This software allows for a wide range of statistical analysis and outputs high quality graphs. These scatterplots allow for trends to be identified when the moon is fully present and when the brightness of the moon is reduced.

3. RESULTS

3.1. Light Pollution Trends

3.1.1 Artificial Light Result

The light levels recorded for 1992, the first years of recording by Operational Linescan System (DMSP/OLS) and 2013, the most recent year of lighting recordings by DMSP/OLS are shown in Figure 5. Maps showing the levels of light in Ireland for 2001 (Pre-"Celtic Tiger" period), 2007 ("Celtic Tiger") and 2013 (post "Celtic Tiger"/recession) are also detailed (Figure 6). All the light maps display the light levels on a scale of 0 to 63 DN, this range is represented on a green (low) increasing to a red (high) scale based on the digital number. Rural areas of little light pollution are represented as a green colour while areas of high light pollution such as urban areas are represented by a red colour, red is commonly surrounded by a yellow/orange colour representing the surrounding suburbs of these urban areas. Light maps from 1992 show light levels on a low to moderate level, levels of high light can be seen in the cities of Cork, Dublin and Belfast. The spread of light to the suburbs is on a much lower scale when compared to the map detailing the 2013 light levels where much of the high levels of light extends from Dublin to counties such as Meath and Kildare. An increase in levels of readings of 63 DN can also be seen in the 2013 light map, therefore there is an increase in red levels on Figure 6. While there is a reduction in green areas on the map.

The light level maps which represent the various phases of the "Celtic Tiger": pre- "Celtic Tiger" (2001), "Celtic Tiger" (2007) and post "Celtic Tiger"/recession (2013) show an increase in the levels of high intensity light as well as increased levels of moderate light pollution. Light mapping for the three phases of the "Celtic Tiger" shows the East and North East coasts of Ireland to have the highest levels of light pollution in the county. The light levels of these areas have greatly increased with a large selection of the recordings being at the saturated 63 DN level. Small cities such as Cork and Galway are also seen to have increased levels of light. The spread of light pollution in Ireland has been found in areas where in previous years light pollution was not recorded, this can be seen in parts of the West coast of Ireland such as Mayo and Galway. When these maps are all compared to each other in chronological order it is obvious that light pollution has increased throughout Ireland with the greatest increase found in Dublin.

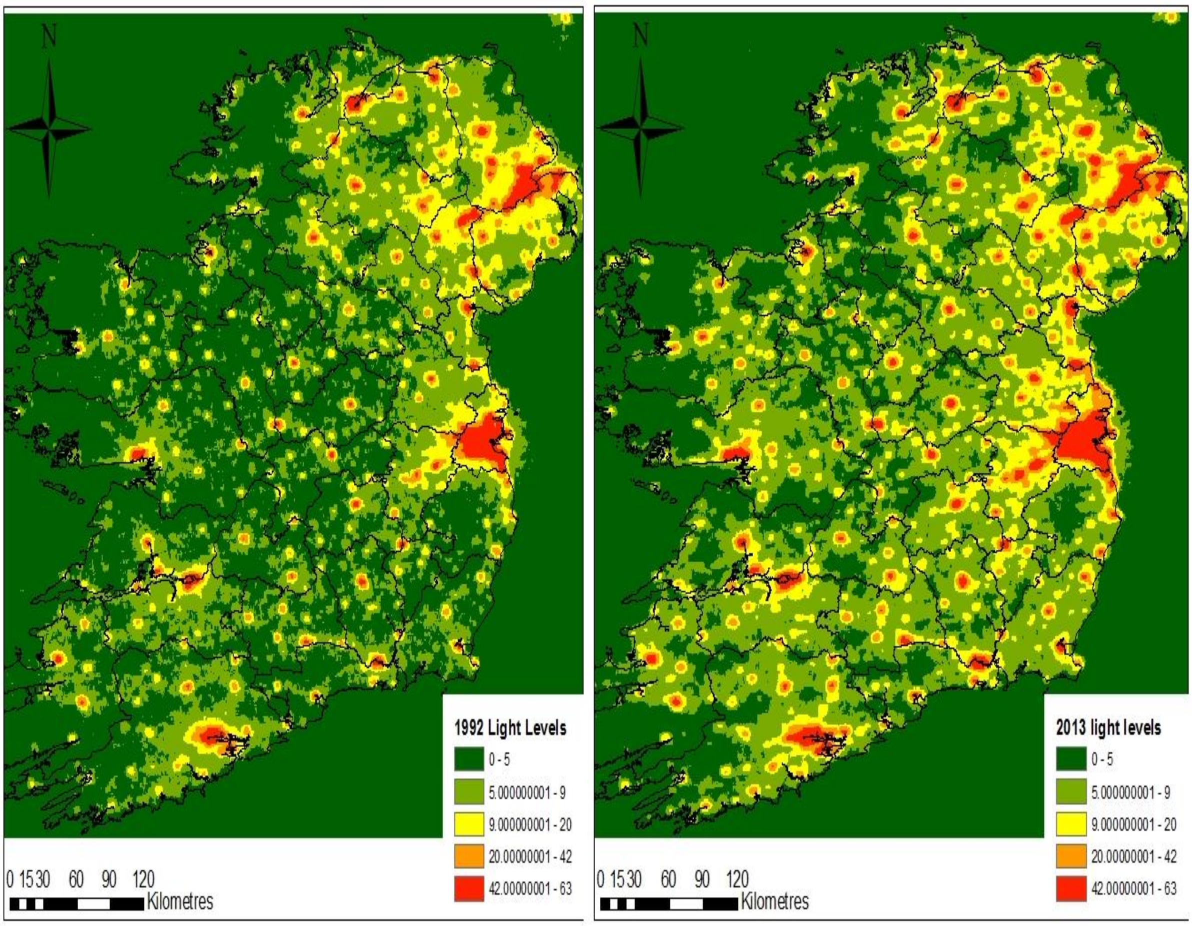

Figure 5. The changes in light trends between 1992 (left) and 2013 (right) can be seen. Changes in the saturation of light is evident in 2013, where the spread and the saturation of light has increased.

3.1.2. Changes in Dublin Light Pollution Trends

Dublin light levels have always presented high levels of 63 DN, however throughout the years the occurrence and the spread of readings of 63 DN has increased significantly. The central region of Dublin stretching from East Dublin to West Dublin has consistent readings of 63 DN, this includes highly populated areas such as Blanchardstown, Swords, Clontarf, Rathmines and Dublin city centre. The North of Dublin has the lowest light levels for the County. The spread of the data in County Dublin are continuous with no patches like those seen in rural areas such as the West and South of Ireland (Figure 6). Changes in brightness were compared between 1992 and 2013. Increases in light levels >5.1 DN were found in the suburban areas surrounding Dublin city centre, while the city centre increased by levels of 3 DN. As much of the Dublin city centre and the surrounding areas had readings of 63 DN saturation in 1992 the readings remained constant and did not decrease.

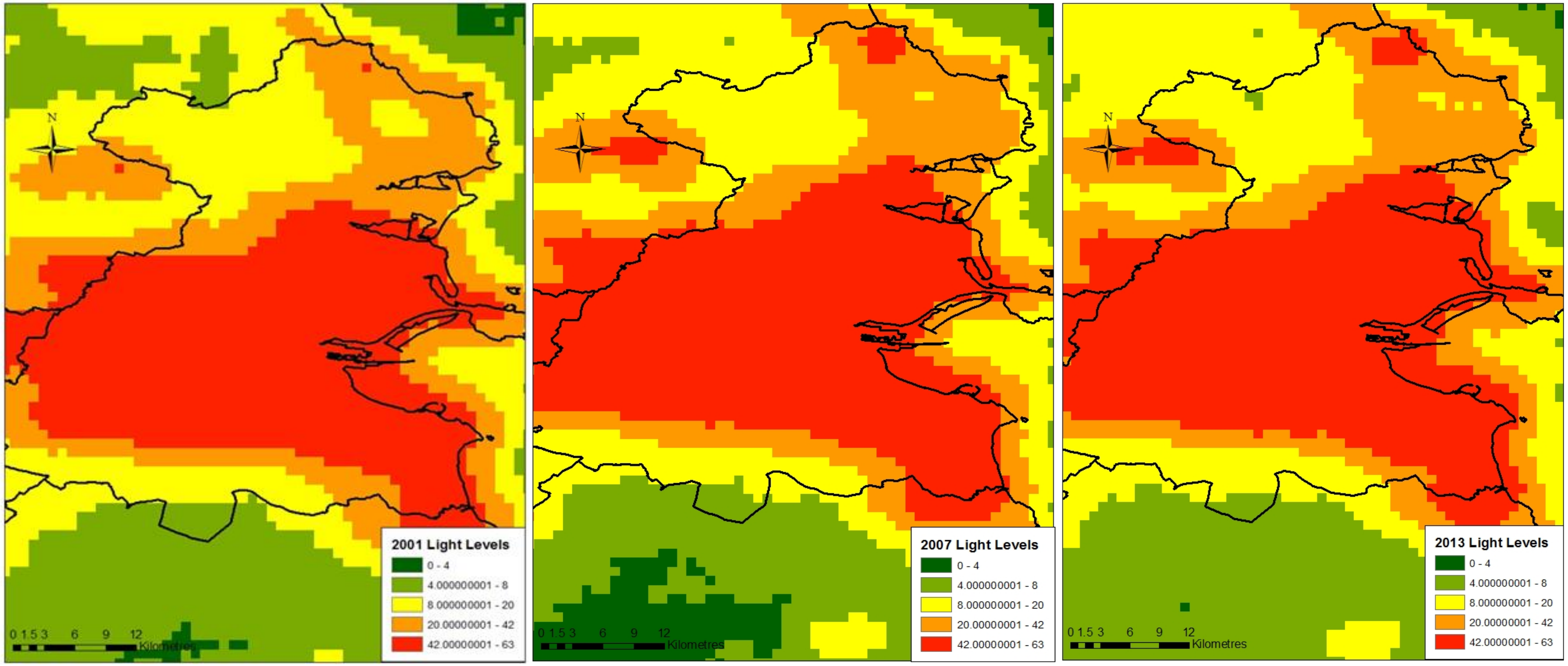

Figure 6. The changes in light trends in 2001 (left), 2007 (centre) and 2013 (right). This shows the various phases of light changes over the various phases of the Celtic Tiger. Increases in the saturation of light is evident across Ireland this is very significant in the County of Dublin.

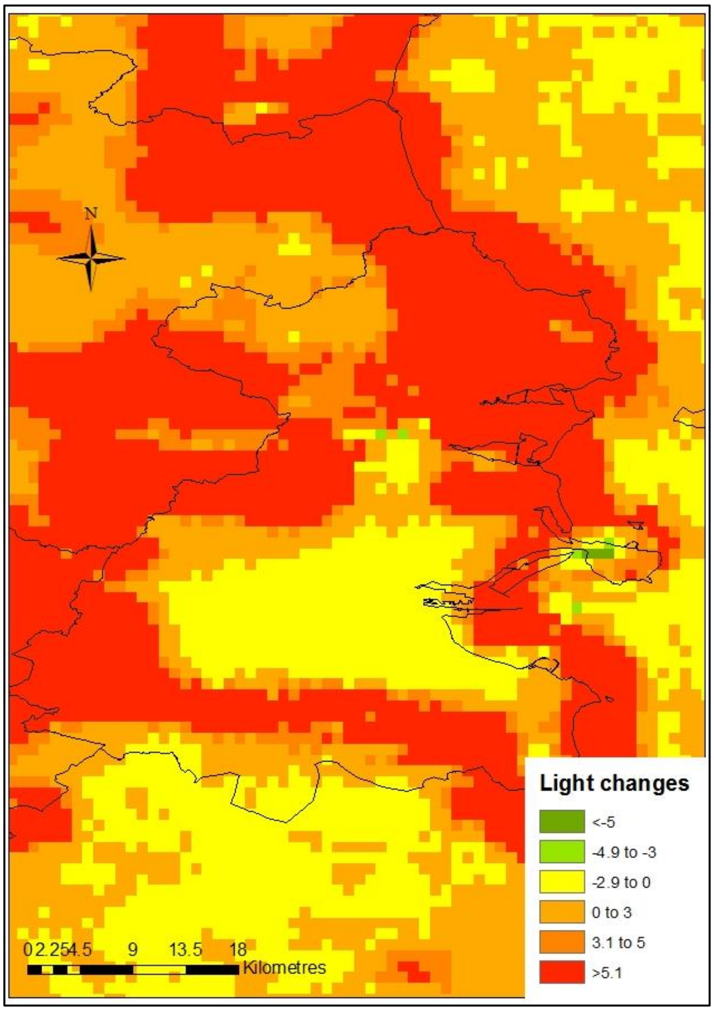

Figure 7. The changes in brightness between 1992 (the first year of recording) and 2013 (the most recent year of recording) in Dublin County. The means of the two periods were compared to show the increase or decrease of light levels between the two periods.

The increases in light levels in Dublin are attributed to the increase in the development and expansion of the city centre and the nearby towns. The changes in brightness over the phases of the "Celtic Tiger" were compared. The pre "Celtic Tiger" (2001) was compared to the "Celtic Tiger" (2007) phase, while the "Celtic Tiger" phase (2007) was compared to the post "Celtic Tiger" phase (2013). During 2001-2007 light levels in the North of Dublin increased in levels >5.1 DN, this is indicative of development and growth leading up to the "Celtic Tiger". While many areas of Dublin showed increases of light levels a number of areas decreased, this is evident in coastal areas. This provides information on the focus areas of the development of Dublin during 2001-2007 (Figure 8). The changes in brightness between 2007- 2013 show increases in brightness in coastal areas of Dublin, while the mid North of Dublin decreased.

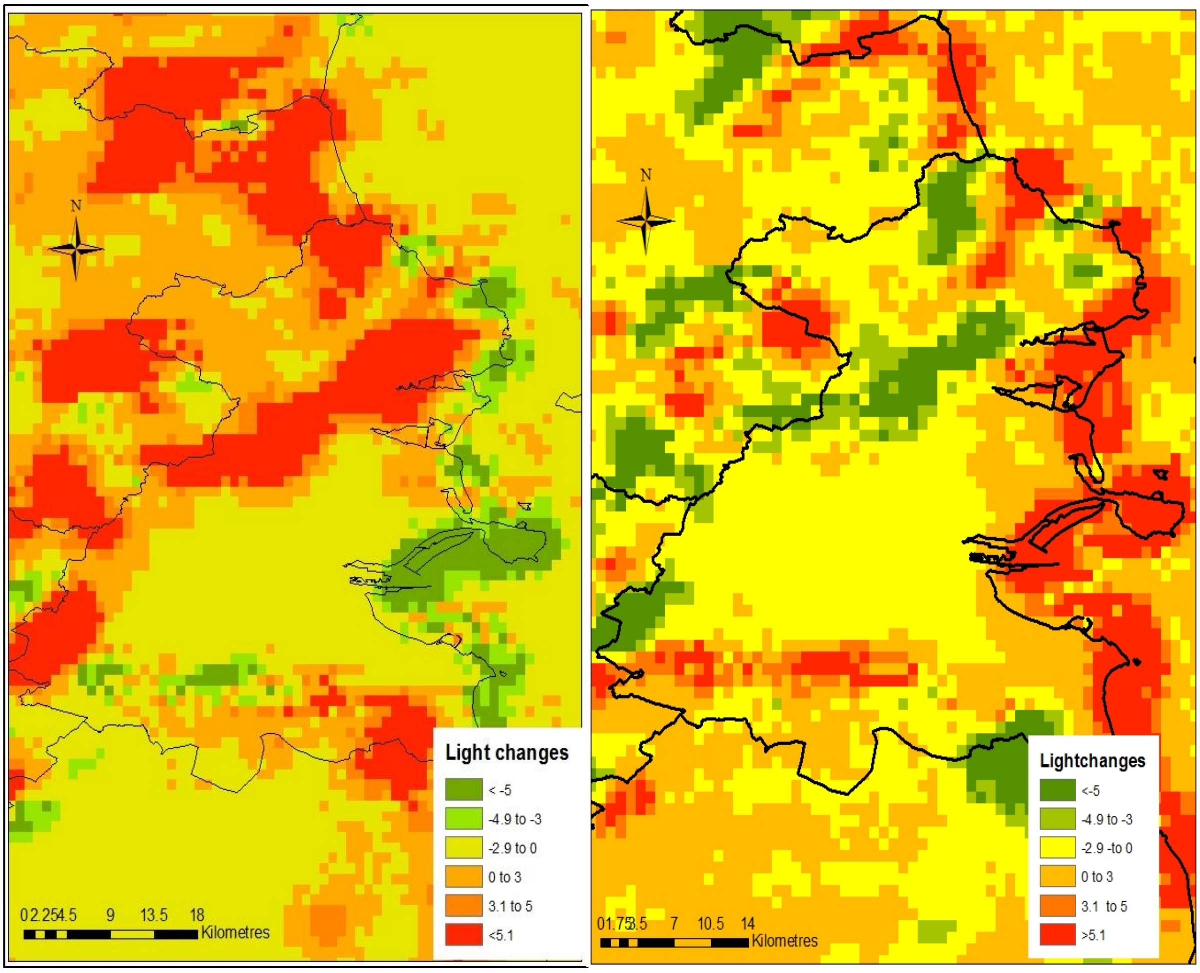

Figure 8. The changes in brightness in Dublin between 2001-2007 (left) and 2007-2013 (right). The means of the two periods were compared to show the increase or decrease of light levels between the two periods.

3.2. Study Site Characteristics and Habitat Mapping Results

3.2.1. Bedrock and Soils of Dublin

The bedrock of Dublin and the study sites is mainly composed of granite, various types of limestone and shale (Figure 9). Dark limestone and shale dominate the Northern section of County Dublin, while granite widely composes the southern section of Dublin. The bedrock to the West of the study site is composed of dark grey to black limestone and shale. The bedrock of the three sites all vary from each other, the study site of Bull Island is composed of dark limestone and shale, Trinity College Dublin study site lies on a bedrock of dark grey to black limestone and shale while the study site of Killiney Hill has a bedrock of granite with microcline phenocrysts with selections of embedded lime mudstone.

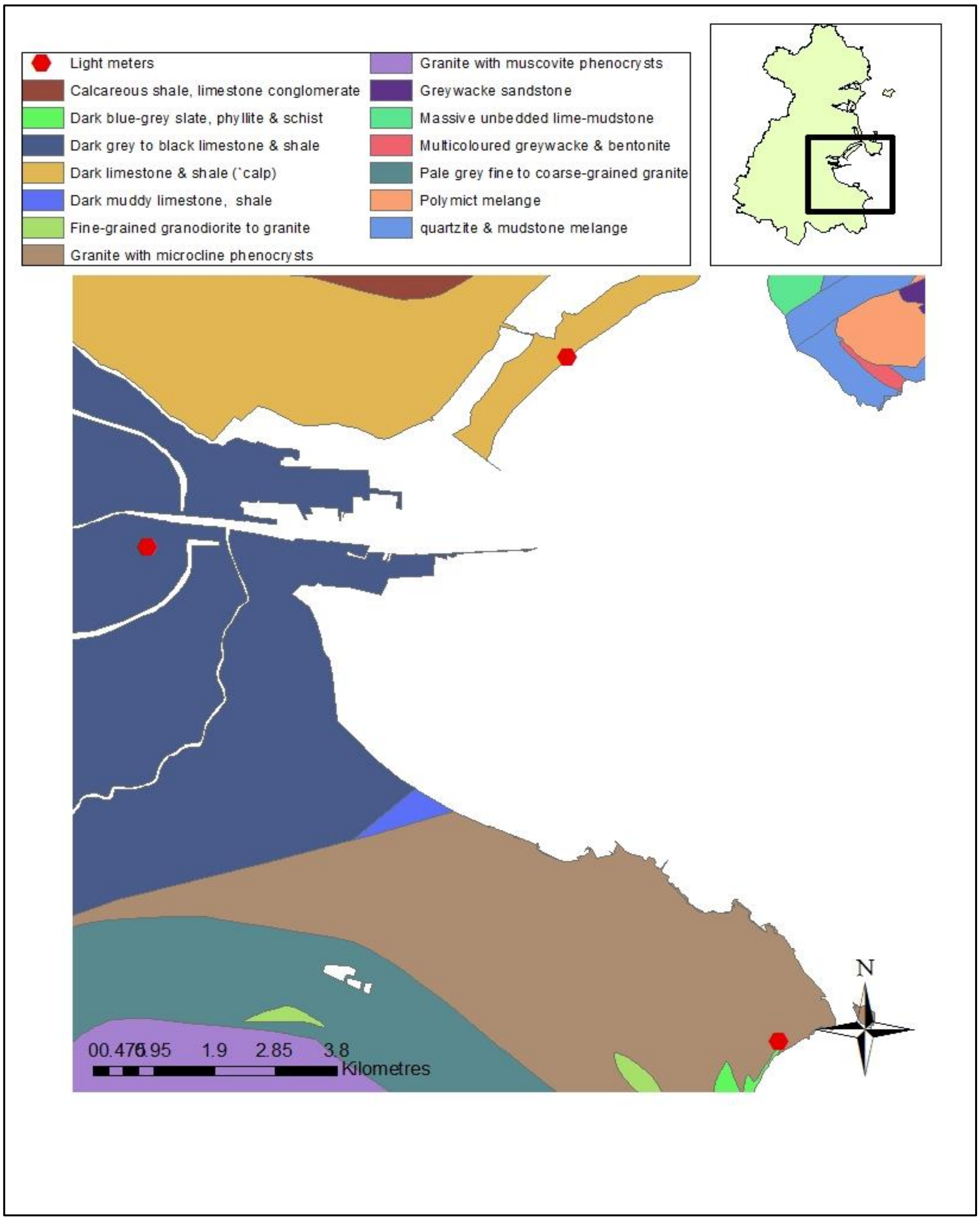

Figure 9. The bedrock of the study sites in Dublin. The location of the three light meter are detailed. The bedrock of Dublin and the study areas is mainly composed of granite, various types of limestone and shale.

The area of Dublin is found on land classified by the NPWS as made/built land. There is a reduced amount of exposed soil in Dublin due to the high level of development of this land, this is evident in Figure 10. The study site of Trinity College Dublin is located in the city centre on land which is classified as made/built land. The two study sites of Bull Island and Killiney Hill are located in the outskirts and on land which is less urbanised. Bull Island is classified with aeolian undifferentiated soils while Killiney

Hill has lithosols and regosols soils, described as a shallow well drained mineral soil derived from mainly non-calcareous parent materials.

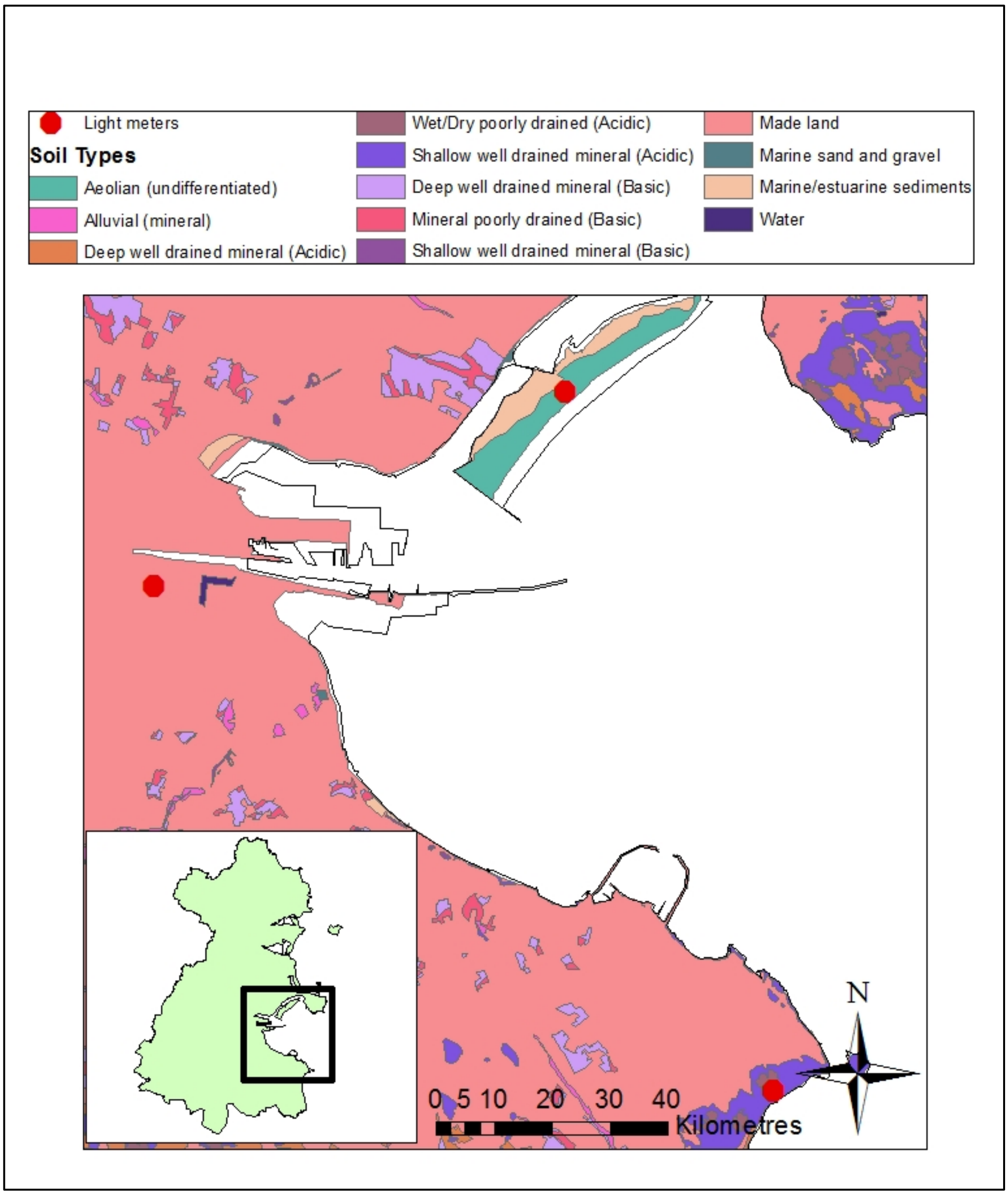

Figure 10. The soil types of the study sites in Dublin. The location of the three light meters are detailed. The area of Dublin is found on land classified by the National Parks and Wildlife Services as made/ built land.

3.2.2. Land Uses of Dublin and the Three Study Sites

A high proportion of the land in the study area (i.e. the land inclusive of the three study sites and the area in-between these sites) is defined as discontinuous urban fabric. Discontinuous is defined by CORINE as "residential areas around the edge of urban district centres, and certain urban districts in rural areas" (CORINE. Part Two- Nomenclature: illustrations CORINE land cover. pp 102). While a significant area of the land is classified as continuous urban fabric which is described by CORINE as land where by "most of the land is covered by structures and the transport network. Buildings, roads and artificially surfaced areas cover more than 80% of the total surface." (CORINE. Part Two-Nomenclature: illustrations CORINE land cover. pp 101). The land uses between the three study sites vary from each other, Bull Island is widely used for sports and leisure as it incorporates Dollymount beach, Trinity College Dublin is classified with a land use of continuous urban fabric while Killiney Hill is categorised as discontinuous urban fabric. Comparison between the CORINE 2006 and the 2012 shows increases in both continuous and discontinuous urban fabric, this shows an increase in development over these years.

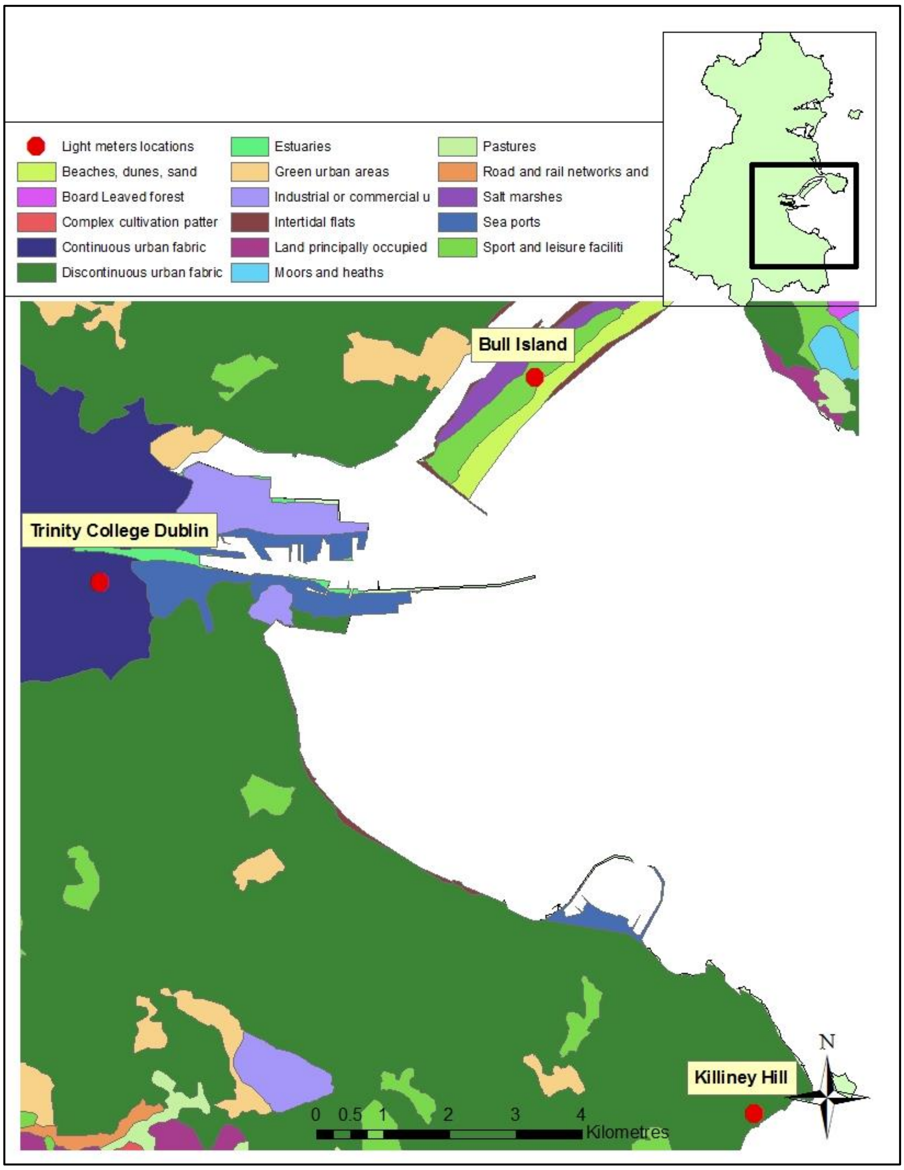

Figure 11. The land uses of the three study sites and the surrounding areas in Dublin. The location of the three light meters are detailed. The majority of the land in the study is classified as discontinuous urban fabric.

3.3. Light Meter Location Habitats

3.3.1. Habitat Mapping of Light Meter Locations- Bull Island, Trinity College Dublin and Killiney Hill

Figure 12 provides information on the surrounding habitats adjacent to the light meter located on Bull Island. The area is classified with fixed coastal sand dunes and non-saltmarsh habitats. The light meter is positioned on the grounds of the Bull Island Interpretive Centre. A golf course is located in close proximity to the location of the light meter. This golf course is illuminated by artificial lighting during periods of darkness. The location of the light meter is located close to the Causeway Road which connects Bull Island to the suburb of Clontarf and provides access to Dollymount Beach. Areas close to the light meter location are proposed National Heritage Areas (pNHA).

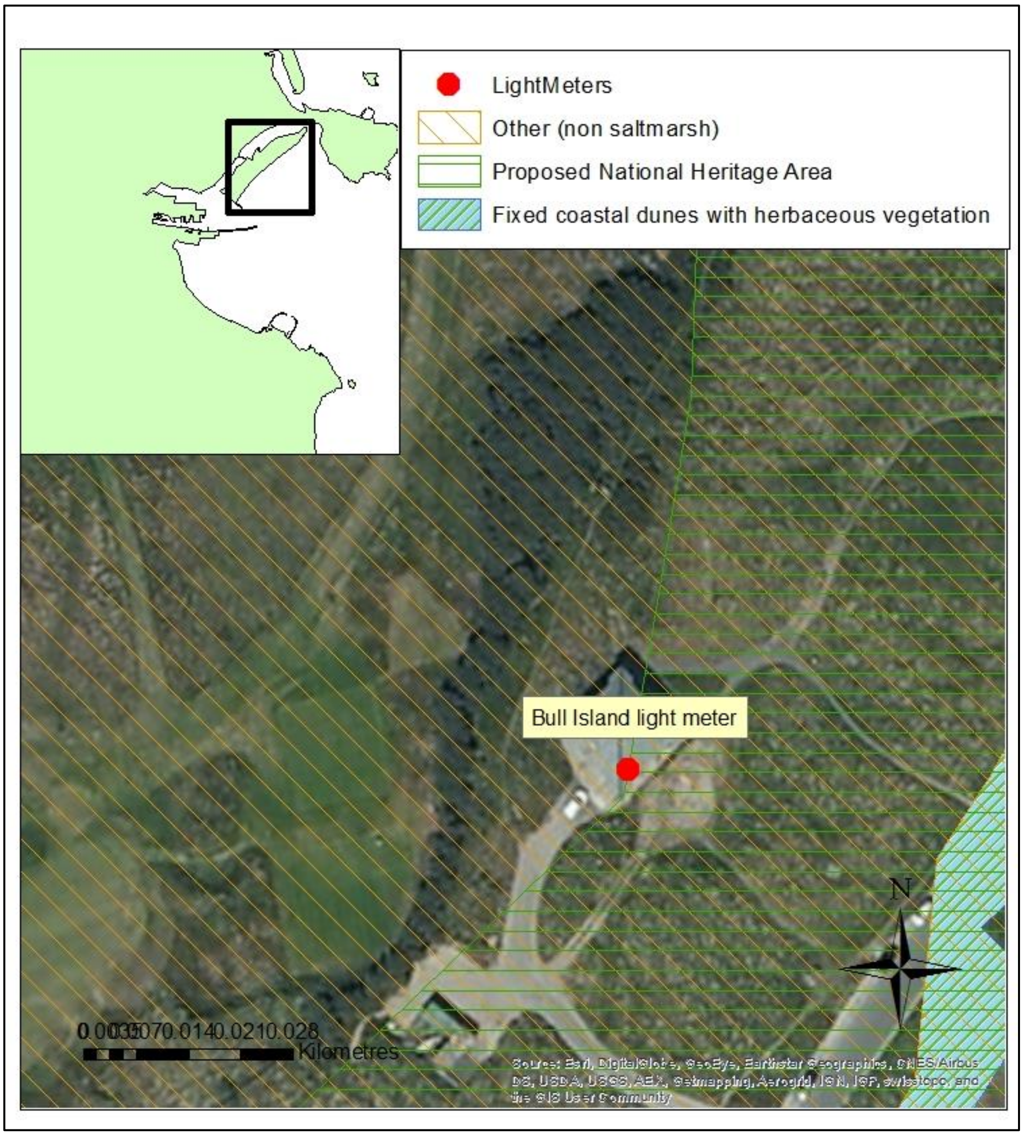

Figure 12. The surrounding habitats of the light meter location on Bull Island. The area is classified with fixed coastal sand dunes and non-saltmarsh habitats. Areas close to the light meter location are proposed National Heritage Areas (pNHA).

The habitats of Trinity College Dublin are detailed in Figure 13. This light meter is located on the grounds of Trinity College Dublin in the centre of Dublin city. Much of this land is classified as continuous urban fabric. This land is highly developed with buildings and extensive road and public transport networks surrounding the precinct of Trinity College Dublin. Heavy artificial light is found in the area from building light, street lighting and car lights. The grounds of Trinity College Dublin have a number of patches of urban green. These patches have various functions such as landscaping, recreation and research. These were classified by the site visits and then were digitised manually. The grounds of Trinity College Dublin are lit with street lighting and by lighting exiting from the various College buildings. The light meter for this site was located on the top of the Fitzgerald's Building in Trinity College Dublin.

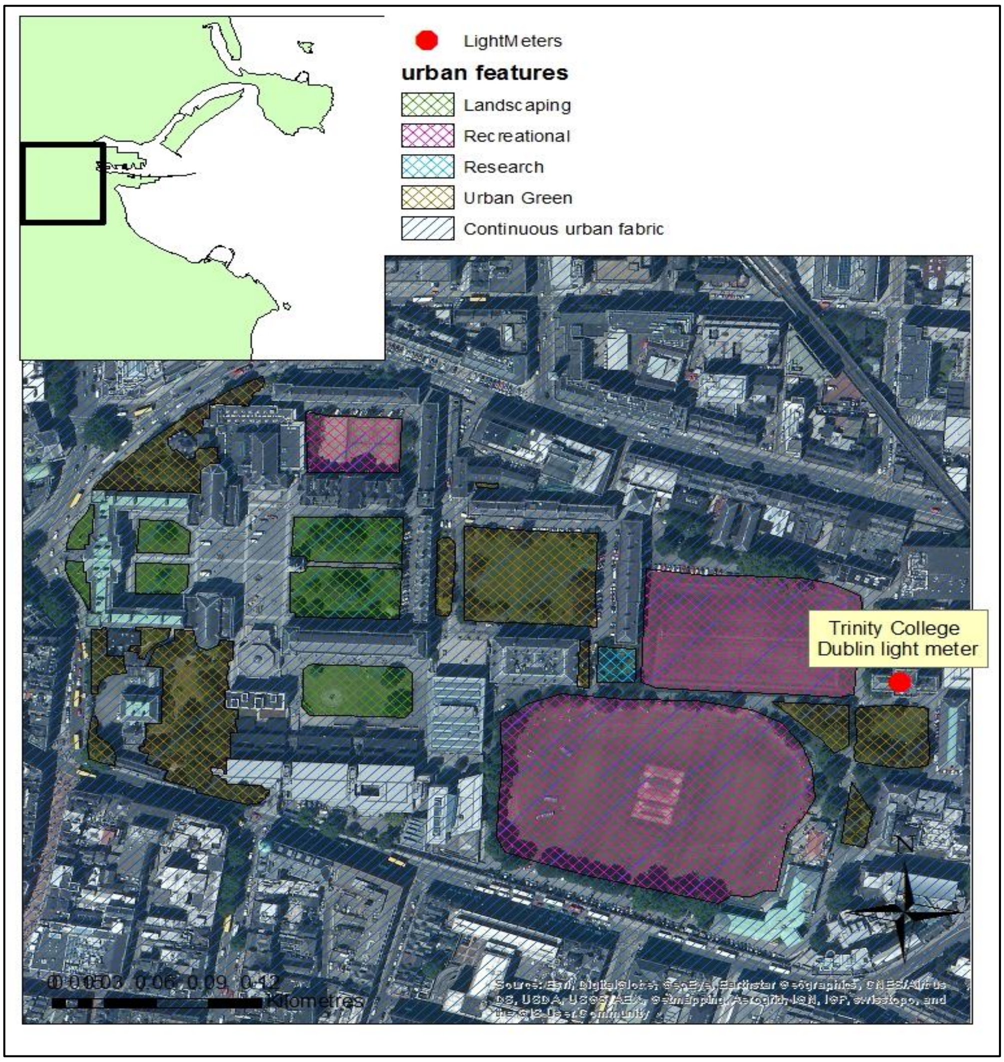

Figure 13. The surrounding habitats of the light meter location in Trinity College Dublin. The area is classified as continuous urban fabric and grasslands categorised by landscaping, recreation, research and urban green areas.

Light data were collected at a number of locations at Killiney Hill. However, for this study one location was discussed in terms of habitat classification. The chosen site is located on Killiney Hill at the Obelisk monument at the summit of the hill (Figure 14). The land around Killiney is classified as discontinuous urban fabric. The habitats of the area surrounding the light meter are classified as scrub habitats, deciduous woodlands and European dry heaths. These habitat types were determine through site visits and information on Killiney Hill gathered from the Irish Wildlife Trust (Irish Wildlife Trust 2009). A number of walking trails are located in close proximity to the location of the light meter. The Obelisk monument is illuminated by artificial lighting during hours of darkness.

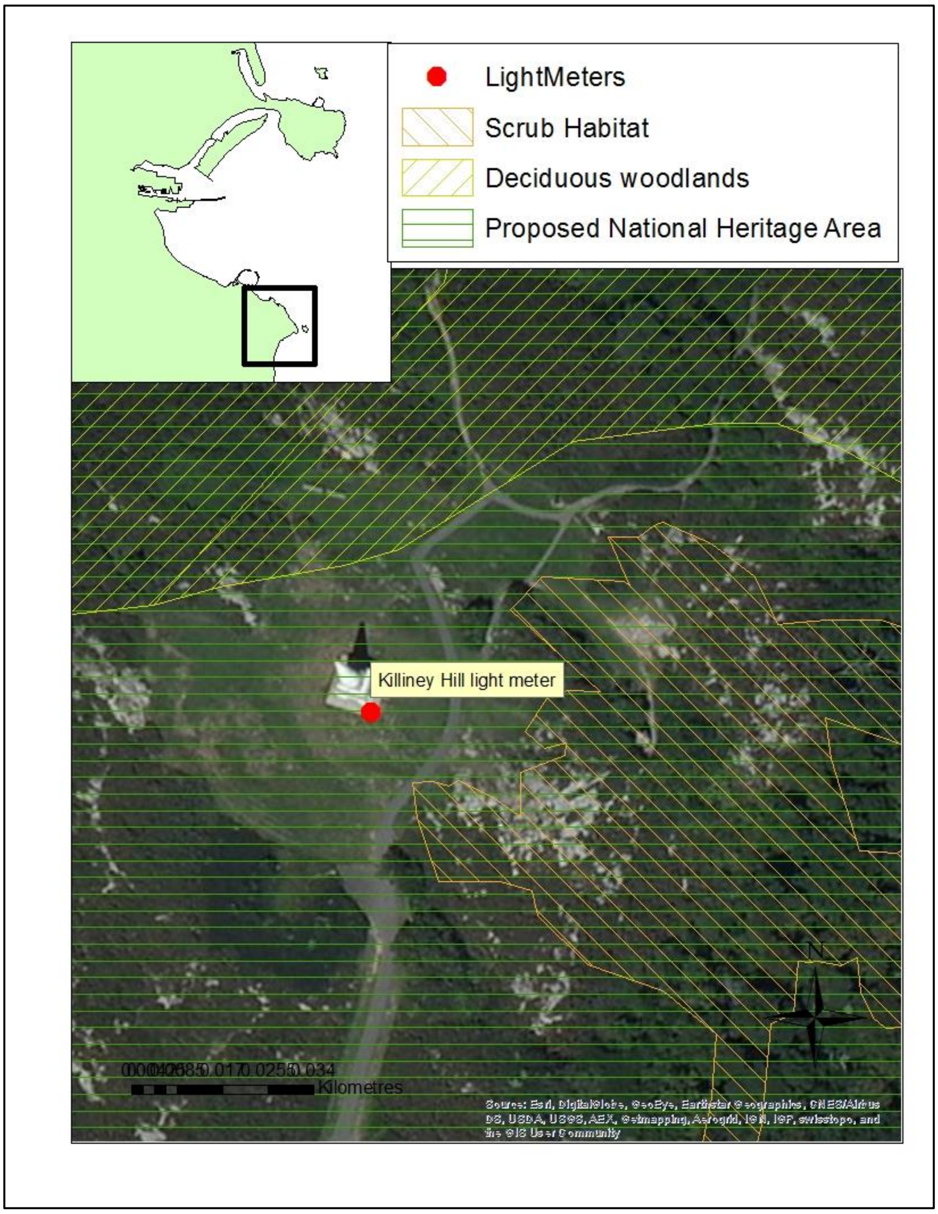

Figure 14. The surrounding habitats of the light meter location on Killiney Hill. The area is classified as a number of habitats these include scrub habitat, deciduous woodlands, European dry health and discontinuous urban fabric.

3.4. Species at Risk

3.4.1. Protected Species of the Study Site

Due to the variations in the habitats and land uses of the three research sites (i.e. - Bull Island, Trinity College Dublin and Killiney Hill), various species can be found in the sites and the surrounding areas. A species list of 19 species was developed based on information from the literature on species sensitive to light pollution, from information provided by the NPWS officer and NBDC data on the sensitive species present at the three study sites. All the species selected are protected under various National and International legislation (Table 1).

SPECIES- COMMON NAME	SCIENTIFIC NAME	CONSERVATION ISSUES	LEGISLATIVE PROTECTION	MAXIMUM LIGHT LEVELS EXPOSED TO AT STUDY AREA	IMPACTS BASE ON LITERATURE
OTTER	*Lutra lutra*	Populations are stable in Ireland, however many European pollutions are threatened, declining, rare, or extinct.	EU Habitats Directive Annex 92/43 II & IV, Wildlife Act 1976/2000, Bern Convention Appendix III.	17.85 mag/arcsec^2	Undetermined.
COMMON FROG	*Rana temporaria*	Widespread throughout Ireland but vulnerable in Europe.	EU Habitats Directive Annex V, Wildlife Act.	17.85 mag/arcsec^2	Possible disruption to circadian rhythm.
RED SQUIRREL	*Sciurus vulgaris*	Under pressure due the growth of the grey squirrel population.	Wildlife Act 1976/2000, Bern Convention Appendix III.	19.42 mag/arcsec^2	Possible indirect impacts.
BROWN LONG EARED BAT	*Plecotus auritus*	In decline due to habitat loss, poisoning and a reduction in food supply.	EU Habitats Directive Annex 92/43 IV, Wildlife Act 1976/2000, Bern Convention Appendix II.	19.42 mag/arcsec^2	Discourage species from area.
WHISKERED BAT	*Myotis mystacinus*	In decline due to habitat lose, small litter's leads to longer population recovery and food reduction.	EU Habitats Directive Annex 92/43 IV, Wildlife Act 1976/2000, Bern Convention Appendix II.	17.85 mag/arcsec^2	Discourage species from area.
NATTERERS BAT	*Myotis nattereri*	One of the rarest bats in Ireland. Vulnerable as a result of habitat loss, reduction of food and poisoning.	EU Habitats Directive Annex 92/43 IV, Wildlife Act 1976/2000, Bern Convention Appendix II.	19.42 mag/arcsec^2	Discourage species from area.
GREY SEAL	*Halichoerus grypus*	Populations previously declined due to hunting. Now under pressure due to disease, disturbance to habitat, illegal shooting and decreasing water quality.	EU Habitats Directive Annex 92/43 V, Wildlife Act 1976/2000, Bern Convention Appendix III.	19.42 mag/arcsec^2	Possible indirect impacts.
PINE MARTEN	*Martes martes*	Main threat is accidently poisoning. Impacted by habitat loss.	EU Habitats Directive Annex 92/43 II & V, Wildlife Act 1976/2000, Bern Convention Appendix III.	19.42 mag/arcsec^2	Undetermined.
RAZORBILL	*Alca torda*	Amber-listed species. Breeding by the majority of the Irish population occurs at less than ten sites.	Wildlife Acts 1976/2000, Birds of Conservation Concern- Amber List.	19.42 mag/arcsec^2	Undetermined.

KINGFISHER	*Alcedo atthis*	Amber-listed species. European population accessed to be depleted.	Wildlife Acts, EU Birds Directive Annex I, Birds of Conservation Concern- Amber List.	18.61 mag/arcsec^2	Changes to circadian rhythm.
BADGER	*Meles meles*	Killed by human through badger baiting and accidental road kills.	Wildlife Act 1976/2000, Bern Convention Appendix III.	19.42 mag/arcsec^2	Possible impacts to reproduction.
SAND TERN	*Sterna sandvicensis*	Amber-listed species. Breeding is localised. European population accessed to be depleted.	Wildlife Acts 1976/2000, EU Birds Directive Annex I, Birds of Conservation Concern- Amber List.	17.85 mag/arcsec^2	Undetermined.
SHORT EARED OWL	*Asio flammeus*	Amber-listed species. Breeding is localised. European population accessed to be depleted.	Wildlife Acts 1976/2000, EU Birds Directive Annex I, Birds of Conservation Concern- Amber List.	18.61 mag/arcsec^2	Changes in predator/prey relationship
RED KITE	*Milvus milvus*	Previously extinct in Ireland due to poisoning and habitat loss. Reintroduced to Ireland in 2007.	Wildlife Acts 1976/2000, Birds of Conservation Concern- Amber List.	19.42 mag/arcsec^2	Undetermined.
PEREGRINE FALCON	*Falco peregrinus*	No longer in decline, previously threatened due to chemicals reducing reproduction.	Wildlife Acts 1976/2000, EU Birds Directive 2009/147 EC Annex I.	19.42 mag/arcsec^2	Early reproduction.
WIGEON	*Anas penelope*	Amber-listed species. Wintering by the majority of the Irish population occurs at less than ten sites.	Wildlife Acts 1976/2000, EU Birds Directive Annex II & III, Birds of Conservation Concern- Amber List.	18.61 mag/arcsec^2	Changes to circadian rhythm.
KESTREL	*Falco tinnunculus*	Amber-listed species. European population is in decline.	Wildlife Acts 1976/2000, Birds of Conservation Concern- Amber List.	18.61 mag/arcsec^2	Undetermined.
MUTE SWAM	*Cygnus olor*	Amber-listed species. Wintering of 20% of the European population occurs in Ireland.	Wildlife Acts 1976/2000, Birds of Conservation Concern- Amber List.	19.42 mag/arcsec^2	Undetermined.
KEMPS LOGGERHEAD TURTLE	*Lepidochelys kempii*	Migrant species. Listed as endangered by IUCN (International Union for Conservation of Nature) red list.	EU Habitats Directive 92/43 Annex IV, Wildlife Act 1976/2000.	18.61 mag/arcsec^2	Impacts to migration and orientation.

Table 1. Details the selected species with information provided on the conservation issues of these species, the legislation which protects each species and the average light levels these species receive at the study site. The impacts of light pollution based on the literature is also detailed.

3.4.2. Light Meter Results

The light data collected by the light meters for the three study sites is displayed in Figures 15 and 16. As data at the light meter at Killiney Hill was only recorded on one day, the corresponding comparison data for the three sites for the 26th of March 2016 was analysed. The spread of the data shows that the light meter readings for both Killiney Hill and Bull Island have an equal spread of data with equal numbers above and below the median values showing a gradual increase of night sky darkness in the night. This displays decrease of light levels from daylight hours to night time hours. In contrast, the majority of data for Trinity College Dublin show the values of the light meter to fall below the median showing that the night's sky does not become as dark in comparison to the other two study sites (Figure 15). This shows a greater intensity of artificial light at night at the light meter location of Trinity College in comparison to Killiney Hill and Bull Island. Light levels of brightness are constant at Trinity College Dublin as a result. This indicates that a high number of artificial lighting sources are installed at this site.

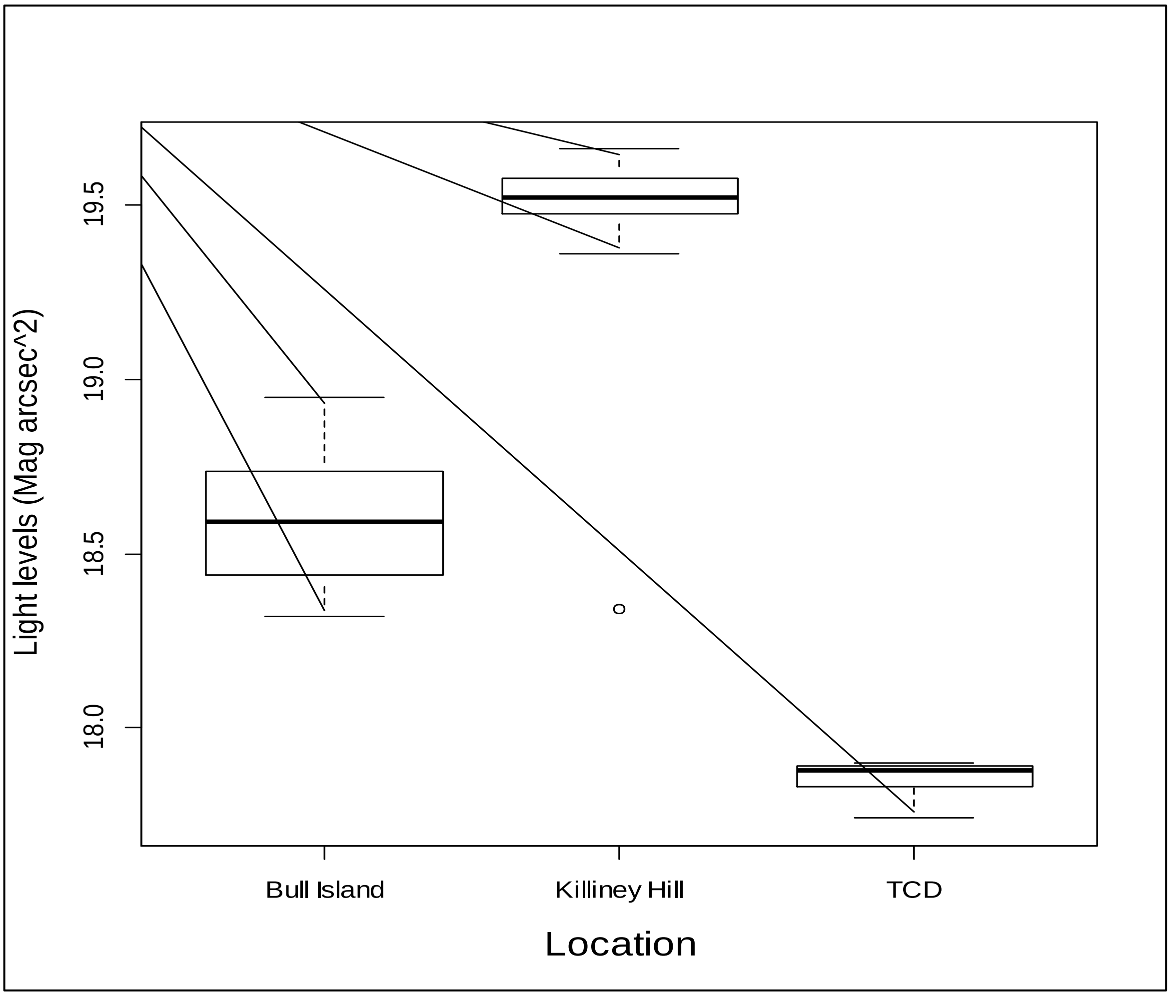

Figure 15. Boxplot of the night sky measurements for the 26th of March 2016 for all three study sites- Bull Island, Trinity College Dublin and Killiney Hill.

The light meters provide evidence that the study site of Killiney Hill has the darkest night skies of all the three study sites with an average reading of 19.42 mag/arcsec^2. The study site of Bull Island was in the midrange with an average of 18.61 mag/arcsec^2 in comparison to the other two sites. While Trinity College Dublin had the brightest sky at night with an average reading of 17.85 mag/arcsec^2 showing the highest levels of light pollution out of all three sites. The International Dark-Sky Association (IDA) has developed a three category system for consideration when designating dark sky reserves. These categories indicate the quality of the skies of the reserve based on the mag/arcsec^2. These categories are as follows: Gold (>21.75 mag/arcsec^2), Silver (21.74-21.00 mag/arcsec^2) and finally Bronze (20.99- 20.00 mag/arcsec^2). A dark sky reserve categorised as Gold would be a dark night sky with little light pollution. When the values of these three dark sky reserve categories are compared to the values collected at the three study sites it is evident that all three sites are not suitable to be considered as a dark sky reserve as they receive an excessive amount of artificial light preventing dark skies classification. The light level values of all three research sites significantly fall below these IDA categories this shows the pure quality of the skies and the high levels of artificial light in the night sky.

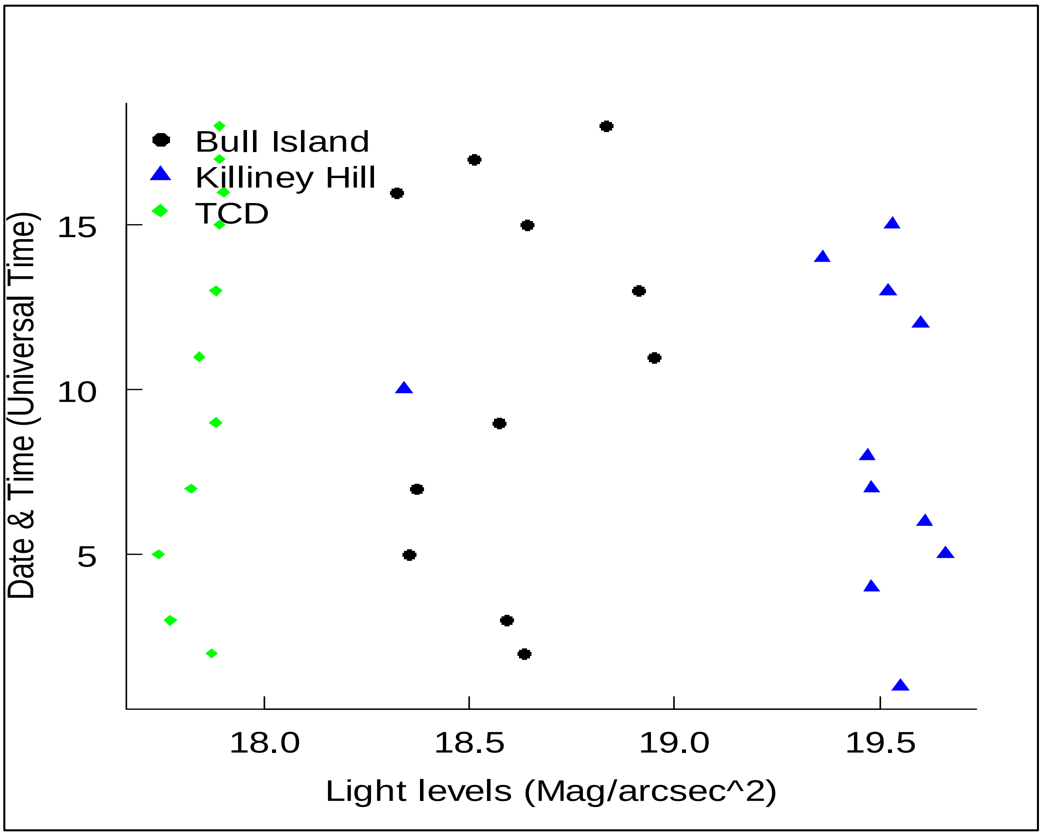

Figure 16. Scatterplot of the night sky measurements for the 26th of March 2016 for all three study sites- Bull Island, Trinity College Dublin and Killiney Hill. Killiney Hill shows areas of dark night skies, while Trinity College Dublin had the brightest sky at night.

Light meter data were collected for Bull Island and Trinity College Dublin over a long period of time when compared to the dataset collected from Killiney Hill where light levels were only recorded on the 26th of March. Further analysis was carried out on these larger datasets. Relevant data were selected from the datasets for both Bull Island and Trinity College Dublin. Data from February 8th until the 15th February 2016 during a period of a new moon were selected as these were recorded during a phase when illumination reflected from the moon was at its lowest, providing information on the darkest skies these areas receive. Readings from Trinity College Dublin showed higher levels of light pollution in comparison to Bull Island during a new moon (Figure 17 and 18). The average reading for Trinity College Dublin was 15.36 mag/arcsec^2 while the average reading for Bull Island was found to be 17.03 mag/arcsec^2. These values as above do not fit the categories for designation of these selected sites as dark sky reserves, therefore the quality of the skies for all three sites are of poor quality and record high levels of artificial light. Figures 19 and 20 details the analysis carried out on the data collected during the period of a full moon at both of the study sites. The full moon phase is the brightest stage of the lunar cycle. This is evident in the average light reading at each of the study locations, the average reading for Trinity College Dublin was found to be 15.35 mag/arcsec^2 and the average light reading for Bull Island decreased to 16.46 mag/arcsec^2. Both these values show a slight decrease in dark sky this is due to the increase of light reflected by the full moon in comparison to the lower levels of light reflected by the new moon. By analysing data collected during the new moon phase the extent of light pollution can be established when it is compared to the full moon data. This comparison shows that the reflected light from the moon is not the only light source in the night sky.

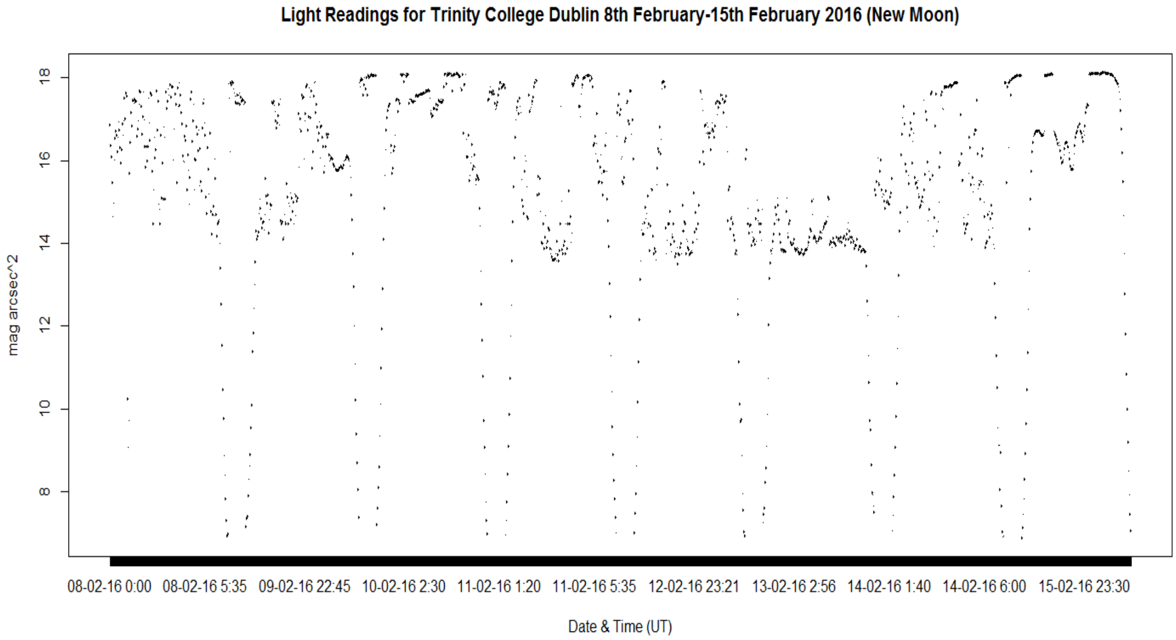

Figure 17. Light readings at Trinity College Dublin. These readings were recorded from February 8th until the 15th 2016 during a period of a new moon when illumination reflected from the moon was at its lowest, these provide information on the darkest skies this area receives.

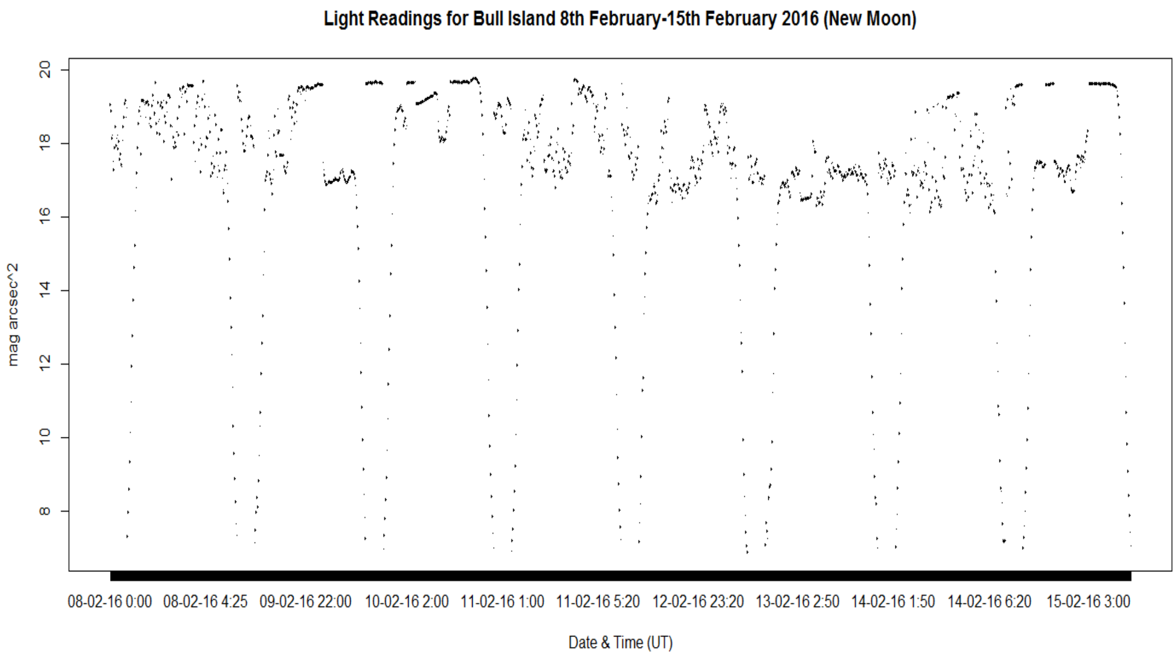

Figure 18. Light readings at Bull Island. These readings were recorded from February 8th until the 15th 2016 during a period of a new moon when illumination reflected from the moon was at its lowest, these provide information on the darkest skies this area receives.

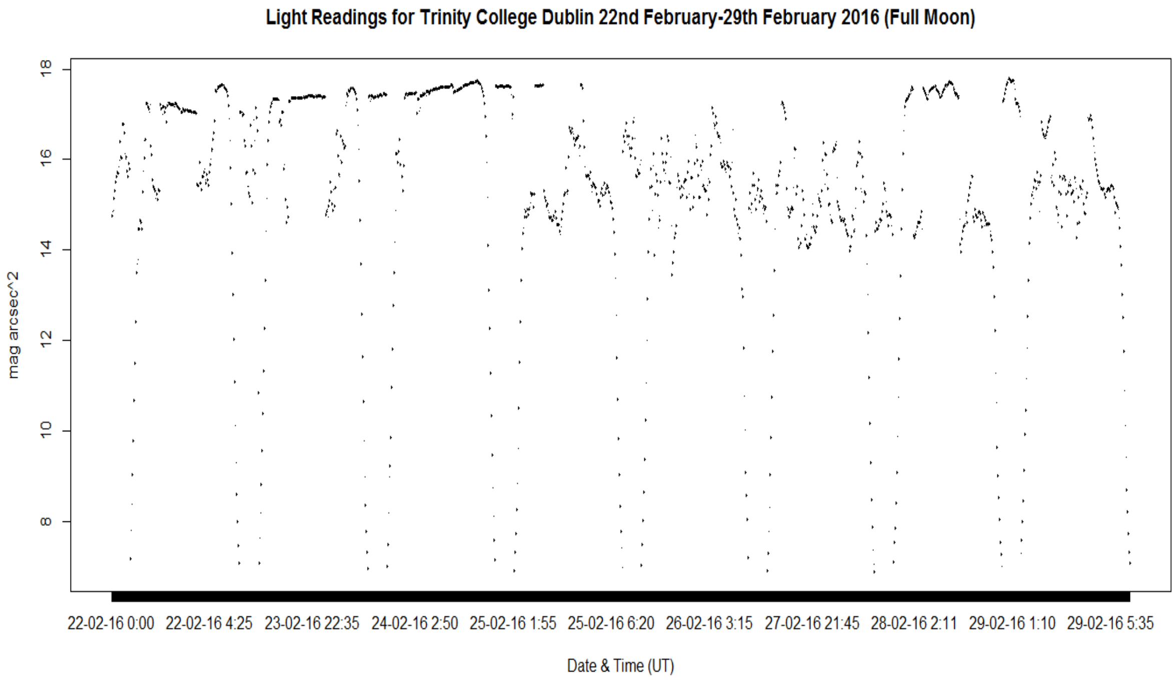

Figure 19. Light readings at Trinity College Dublin. These readings were recorded from February 22nd until the 29h 2016 during a period of a full moon when illumination reflected from the moon was at its highest, these provide information on the brightest skies this area receives.

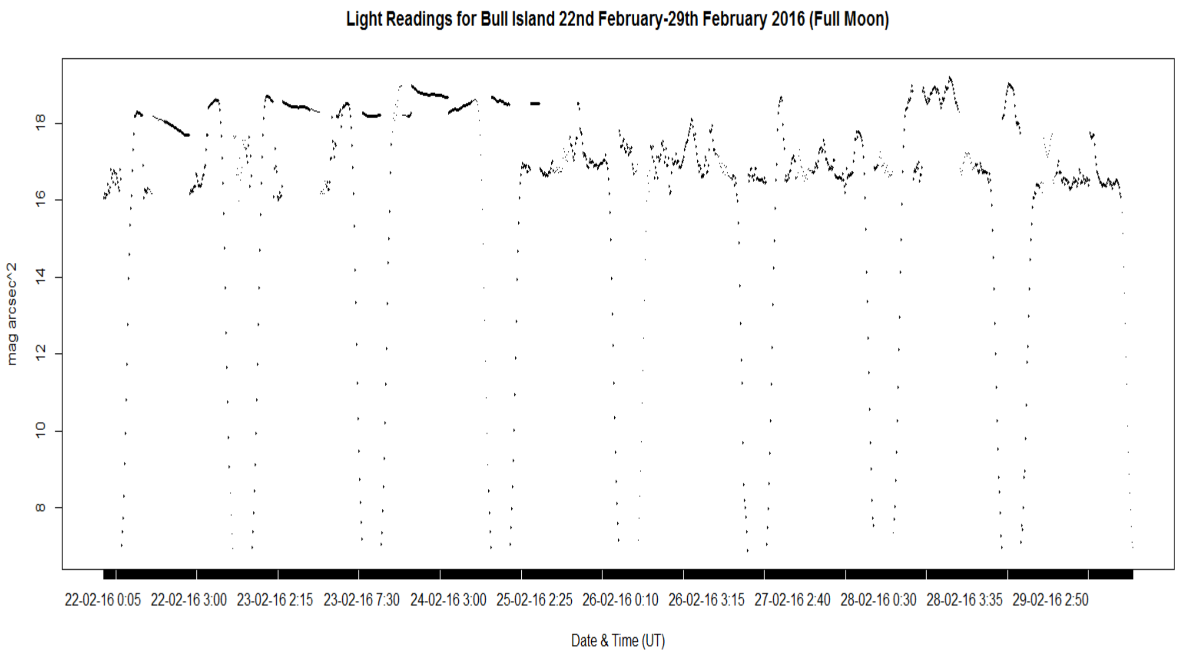

Figure 20. Light readings at Bull Island. These readings were recorded from February 22nd until the 29th 2016 during a period of a full moon when illumination reflected from the moon was at its highest, these provide information on the brightest skies this area receives.

3.4.3 Protected Species and Light Pollution

Figure 21 provides information on the distribution of the protected species selected for this study based on data accessed on the NBDC website and the information provided by NPWS. Mammals, birds, reptiles and amphibians are all represented. As discussed in section 1.2.1- 1.2.6 light pollution can affect these selected species in a number of ways. In this study, the distribution of three bat species (i.e. - Brown long eared bat *Plecotus auritus*, Natterer's bat *Myotis nattereri* and Whiskered bat *Myotis mystacinus*) was displayed. These nocturnal species were recorded mainly to the North of the study area in close proximity to Killiney Hill. The Brown Long Eared bat was found to be the most abundant species in the study site.

Other nocturnal species examined in this research include the pine marten, badger and otter. Badgers *Meles meles* are mainly found in the South of the study area, however distributions have also been recorded close to the study site of Bull Island. While the distribution of pine marten *Martes martes* in the study area is much rarer and mainly to the West. Otters *Lutra lutra* are wide spread throughout the study site and have a high concentration at the water bodies of the areas surrounding Trinity College Dublin. The red squirrel *Sciurus vulgaris* was included in this studies to examine the impacts of a diurnal species. The direct impacts may be less when compared to the impacts on nocturnal species, however they may be impacted indirectly. The highest abundances of red squirrels was found in both the north and south of the study areas. Grey seals *Halichoerus grypus* were one of two marine mammals examined in this study, this species was mainly reported in the south of the of the species distribution map.

The increased level artificial light at night may impact species which are uncommon to Ireland. Kemp's Ridley *Lepidochelys kempii* were used to examine the impacts of species which may not be common to Ireland. Kemp's Ridley sea turtles have been recorded on the Southern side of Howth, close to the study site of Bull Island. The only amphibian species included in this study was the common frog *Rana temporaria* which was found to be wide spread throughout all the three study sites and the surrounding areas.

Many protected birds are found at the three selected sites. The wigeon *Anas penelope* is a migrating species which is found in Ireland during the winter months. This species highest occurrence was recorded close to the study site of Bull Island. The peregrine falcon *Falco peregrinus* is found near all three study sites all of which are located close to the coast. Other coastal species of this study included the razorbill *Alca torda* which was found to the south of the study map extending out to sea. While the sand tern *Sterna sandvicensis* was recorded to the northern coast and sea of the study area. Finally the only owl species included in this study was the short eared owl *Asio flammeus* which was only recorded at Bull Island. The razorbill, sand tern and short eared owl all practise localised breeding in Ireland. The only swan species discussed in this study was the mute swan *Cygnus olor* which winters in Ireland, this species was found to be primarily to the north west of the study area. Recordings for the red kite *Milvus milvus* were sparely distributed to the south close to Killiney Hill. Kestrels *Falco tinnunculus* distributions were recorded in both the north and south of the study area, with the highest number recorded close to the Bull Island study site. While kingfisher *Alcedo atthis* birds were abundant throughout the study area.

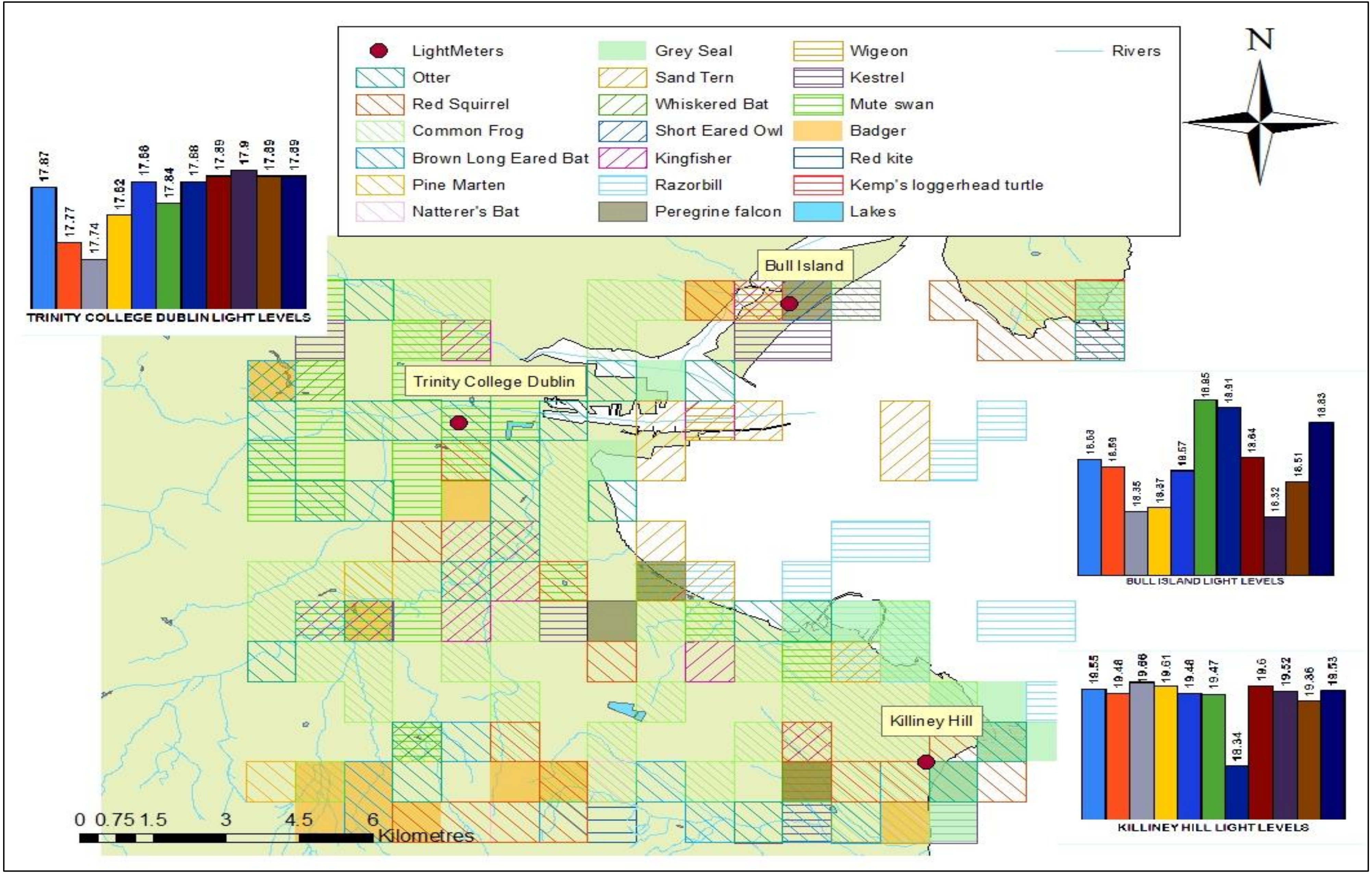

Figure 21. The distribution of the selected protected species found at the study sites and the surrounding areas. The locations of the light meters are detailed along with the light levels recorded on the 26th of March 2016.

4. DISCUSSION

4.1. Light Pollution in Ireland Examined Through Satellite Imagery

As a result of an examination of the changes of brightness in Ireland, using the data gathered from the DMSP/OLS, the results show considerable increases in brightness between the years 1992 to 2013. The analysis of the first satellite imagery taken in 1992 shows saturated light levels in cities such as Dublin, Belfast and Cork. When this imagery is compared to that analysed for the year 2013 it is evident that the spread of saturated light levels have increased and light pollution is reaching areas of semi-rural Dublin. Areas with little or no light pollution in 1992 are found to have increased to moderate light pollution by 2013. The imagery of this research study shows that light pollution is spreading across the County of Ireland in various levels which is a change from the patchy light pollution seen in 1992. The increases in light pollution across Ireland found in this research study is supported by a ground-based study carried out by Espey et al. 2014. This study identified the lack of ground based light level data and developed an Irish light level database. The outcome of this study similarly found the highest light intensities in the capital of Dublin when satellite imagery was analysed. The results of this study, where urban and highly developed areas of a country are found to have the highest levels of light levels at night, has been supported by a study carried out in Greece (Chalkiasa et al. 2006). Athens, the capital of Greece was found to have high levels of light pollution which, like Dublin, has increased greatly in recent years.

The increase of light levels in Ireland is seen in greater detail in the imagery displaying the light levels over three phases of the “Celtic Tiger”. These phases show the increase in light pollution from the pre “Celtic Tiger” to the period of the “Celtic Tiger” and then from the “Celtic Tiger” period to the time when there was a down turn in the Irish economy. When focusing on light pollution in Dublin, there is an increase in levels of 63 DN in Dublin city centre with these high levels almost covering the whole of County Dublin. This shows that Dublin has reached the highest levels of light saturation. This finding is supported by the study carried out by Power M., 2015 where these saturated light levels in Dublin were found in this previous study. Dublin City Council has identified that Dublin receives a high proportion of its light pollution from the 22,000 low pressure sodium street lighting equipment installed throughout the city. Medium levels of light pollution cover counties Meath and Kildare. This increase can be explained by the increase of development and building within the capital of Dublin and its spread to the adjacent counties. During the years 2001 to 2007 many areas of Dublin increased by values greater than 5.1 DN, this shows great increases in brightness to these areas. The increase in the night time light levels may be directly linked to the economic boom in the East of Ireland. These increasing trends are of great concern as they provide evidence the light levels are not only increasing in intensity but it is also increasing in range. This is of concern to sensitive habitats and species which are accustomed to pristine night skies. The disturbance to these conditions can have detrimental impacts. Habitats and species found in the urban areas of this study will be put under increasing pressure and strain, many of which are already greatly impacted by other anthropogenic pressures such as reduction in water and air quality, habitat degradation and increased noise levels.

Care must be taken when discussing the imagery analysis, as over the course of surveying by DMSP a number of different satellites have been utilised. These satellites over the years have become more advanced and may record high levels of light which may not have been recorded by previous satellites (Han *et al.* 2014).

4.2. Light Pollution in Dublin and the Light Meter Locations- Bull Island, Trinity College Dublin and Killiney Hill

While previous studies have examined the light levels of the counties Ireland (Espey *et al.* 2014) little study has been carried out on the towns and cities of these counties. Therefore there is little information on the localised light pollution of Dublin. From the light meter readings of the three study sites of Bull Island, Trinity College Dublin and Killiney Hill it is evident that County Dublin has widely spread light pollution, however the intensity of this light varies across the county. The majority of this light pollution is at a saturation level based on the range of this study (0DN to 63DN). As a result of this high level of artificial light in the night sky a number of naturally occurring phenomena are not visible at the study sites, these include the reduction in the appearance of the Milky Way and the number of visible stars in the night sky. This study has found that lands closest to the city receive high levels of light pollution and decreases in light pollution level with distance from the city. A workshop was hosted in April of 2016 under the title of "Workshop on Light Pollution & Its Impact. Light@Night: Environment, Ecology and Health". During this workshop Dr Brian Espey provided preliminary results of a study identifying the levels of brightness of various areas of Dublin in relation to their distance from the city centre. These results indicated that Trinity College Dublin had the highest levels of sky brightness of all the study sites, while Bull Island had values lower than Trinity College Dublin. While sites to the south of Dublin recorded the lowest readings further supporting the results of this study (Espey 2016).

4.3. Mitigation Measures

With the introduction of mitigation measures the current levels of light pollution can be reduced (Marcantonio *et al.* 2015). To solve the problem of light pollution a number of measures can be put in place to mitigate the problem. Determining hotspots where there is light pollution will identify areas which are at high risk and will allow for appropriate measures to be put in place. Assessing the current lighting equipment in an area to identify any issues is essential. By reinstalling appropriate lighting equipment for the purpose for which it is intended, an example of this would be installing equipment such as shielding on the instrument which would then reduce light trespass. The introduction of motion sensing lights to an area would reduce the constant hours of light during the night and would only provide illumination to an area when needed. Removing or dimming lighting in areas which are not utilised at night will reduce the artificial light levels of this area. The replacement of older equipment with modern energy efficient light equipment may greatly reduce light pollution. Changing the type of light emitted may also reduce the impacts of light pollution, utilising light from a different spectral class to a wave length which will not disturb the species of the area will greatly reduce the ecological impacts of light pollution (Gaston *et al.* 2012). Replacement of the 22,000 low pressure sodium lights throughout the city would greatly reduce the current light pollution levels of Dublin.

The installation of energy efficient lighting as a result of the increase in the awareness of light pollution has been linked to the reduction in artificial light levels in a number of Europe countries such as Belgium (Bennie *et al.* 2014).

4.4. The Ecological Impacts of Light Pollution

From reviewing the literature on the 19 selected protected species of this research study, it is evident that these species are either directly or in directly affected by light pollution. Artificial light at night can have many impacts on these selected species, as previously discussed (section 1.2.1- 1.2.6) light pollution can effect animals in a number of ways such as altering the foraging behaviours, reproduction, communication, orientation and prey/predator relationships (Longcore *et al.* 2004, Kempenaers *et al.* 2010, Rotics *et al.* 2011). The impacts of light pollution on three bat species were discussed in this study, these bat species included the Brown Long Eared bat Plecotus auritus, Natterer's bat Myotis nattereri and finally Whiskered bat Myotis mystacinus. Bats are protected by legislation throughout Ireland (Table 1) therefore impacts to these species must be eradicated. It is widely agreed that studies focussing on the impacts of light pollution on bats are suitable for these artificial light impact studies as bats are nocturnal therefore they would be greatly impacted by an increase of artificial light at night (Stone *et al.* 2015). Bats are bio-indicators of the impacts of light pollution as well as being indicators of a healthy ecosystem (Jones *et al.* 2009, Stone *et al.* 2015). Bats play a very important role in maintaining the health of a habitat (Kalka *et al.* 2008). Bat species can be classified as light sensitive or light tolerant. The impacts of light on bat species depend on which group they are classified into. Light sensitive species will avoid artificial light while light tolerant bat species will be drawn to such light, they forage under artificial light as there is an increase in insects attracted to this type of light. The three bat species examined in this study are all light sensitive; therefore, it can be anticipated that artificial light sources in an area will alter the behaviour of these bats and can discourage them from the area. Protected reptiles and amphibians are also discussed in this study, this includes the Kemp's Ridley sea turtle *Lepidochelys kempii* which is a species of global concern as this species is listed as critically endangered by the International Union for Conservation of Nature (IUCN). The IDA widely discusses the impact of light pollution on sea turtles and identifies them as one of the highest risk species. Like bats the impacts of light pollution has been well studied in sea turtles. The hatchlings of sea turtle species such as Kemp's Ridley sea turtles heavily depend on the natural light of the horizon for orientation to make their way back to the ocean as discussed in section 1.2.3. Female sea turtles also depend on natural light to navigate to locations on the nesting beaches, artificial light on the beaches can draw the turtles further up the beach at a greater distance from the ocean. Increases of artificial lighting on the coast line of Ireland may draw these sea turtle closer to the coast line. In comparison to studies carried out on sea turtles, studies on amphibians are conducted on a much smaller scale therefore the full scale of impacts of light pollution has not yet been fully established. A paper by Wise 2007 discusses the possible impacts of light pollution on amphibians and its role in their global decline. Many amphibian species are nocturnal or have biological rhythms influenced by light therefore the introduction of artificial light can greatly disturb these rhythms and activity patterns therefore the common frog *Rana temporaria* may be at risk to the level of artificial light recorded in Dublin.

The IDA identifies that light pollution can have many "devastating" impacts on bird species. Species specific studies have not been carried out on all the protected bird species of this study however based on their behavioural and lifestyle traits the potential impacts can be hypothesized for these various species. These impacts are detailed in section 1.2.5. The wigeon *Anas penelope* is a winter visitor to Ireland therefore they are a migrating species, the impacts of light pollution on migrating animals is discussed in section 1.2.3. The wigeon is known for being a noisy species and disturbance to the sleeping cycle may cause this species to become active earlier in the morning hours and may result in an increase in noise levels earlier than in low light pollution areas. These impacts can be wide spread over a number of bird species these impacts are also found in Kingfisher *Alcedo atthis* (Parrish *et al.* 1984). This is of great concern as all the selected bird species in this study are protected under various acts of legislation and depend on many of the habitats of the study sites. The peregrine falcon *Falco peregrinus* is found within close proximity to coastal areas. As we know coastal areas are increasingly being developed and this is leading to an increase of artificial light to these areas. This increase of light pollution can lead to early reproduction in this species and can cause further issues in the successful recruitment of the species. Peregrine falcons feed on smaller birds and ducks therefore they can be indirectly impacted by light pollution due to the impacts caused to these species. These predator/prey relationships are also evident in short eared owls *Asio flammeus,* a study found during periods of strong illumination deermice *Peromyscus maniculatus* reduce their hours of activeness. As a result this food source was not available to the short eared owl (Clarke 1983). The impacts on a number of the remaining bird species have not yet been determined these include the razorbill *Alca torda*, sand tern *Sterna sandvicensis,* red kite *Milvus milvus,* kestrel *Falco tinnunculus and* mute swan *Cygnus olor.*

Other species of this study which may be indirectly affected by the impacts of light pollution is the red squirrel *Sciurus vulgaris* and the grey seal *Halichoerus grypus*. As discussed in section 3.4.3. a study by Sheehy *et al.* 2014 believes that the success of red squirrel populations in the mid lands of Ireland is dependent on the population of pine martens *Martes martes* in the areas. The theory is that pine martens will control the population of grey squirrel *Sciurus carolinensis* therefore reducing competition to the red squirrel. A study by Sheehy et al. 2014 found that populations of the invasive North American grey squirrel decrease in the midlands of Ireland where pine martens are found. This reduced the risk of population crashes of the native red squirrel by removing this competitor. Therefore, it could be argued that if the pine marten populations of the midlands decreased due to the impacts of light pollution this would cause the grey squirrel population to increase causing pressure on the red squirrel population. The IDA have identified that light pollution not only affects terrestrial mammals but impacts can also be seen in marine mammals and other marinespecies. Another example of the indirect impacts of light pollution can be discussed in term of grey seals. Grey seals are known to have excellent underwater eyesight but their eyesight is not essential for foraging. However the increase in coastal lighting can lead to the shoaling of fish therefore altering the feeding habitats of the grey seal.

There is a lack of literature and studies on a number of the selected species examined in this research study such as the pine marten *Martes martes*, badger Meles meles and otter *Lutra lutra*. Although the impacts of light pollution on these species have not been studied to the same extent as other species such as bats previously discussed it is believed that artificial light at night is impacting these mammals. Durham County Badger Group state that artificial light impacts reproduction in badgers causing a reduction in the population size, as well as causing problems in foraging (Natural England 2002). These impacts may be the same for those other species listed as they show similarities in their lifestyle traits. It is important to study the impacts of light pollution on these species as they are all protected under Irish legislation and may require conservation measures to prevent a decline of these species. This is of particular importance in Dublin as protected species experience other threats such as habitat loss and other forms of pollution

4.5. Comparison to Previous Studies in Ireland

When the results of this study are compared to a study carried out under the title "Species Sensitivity to Light Pollution: a case study at Owenduff/Nephin Beg Complex SAC/SPA/pNHA" by Power M., 2015 of Trinity College Dublin, it evident that there are greater levels of light population in the Dublin city in comparison to rural areas of Ireland where this previous study was focused on. This study focused on the Owenduff/Nephin Beg Complex SAC/SPA/pNHA located in Mayo and was found to have dark sky levels allowing for the designation of this area as a dark sky reserve unlike the sites studied in Dublin. The SQM metre readings for the Owenduff/Nephin Beg Complex SAC/SPA/pNHA provided evidence that artificial light pollution was lowest in the more remote and less illuminated areas of this study area, when compared to the readings from the meter located at Ballycroy visitor centre which was found to have local light sources. This shows that this area is affected by localised light pollution, therefore light pollution is not an issue only concerning developed areas like Dublin. Many of the same species are found at both the study sites of Dublin and Mayo. These species include the Otter *Lutra lutra*, Common frog *Rana temporaria*, Pine marten *Martes martes,* Badger *Meles meles* and Peregrine falcon *Falco peregrinus.* It would be of interest to carry out a comparative study to determine the variation in the impacts between these study sites.

4.6. Limitations of This Research and Future Studies

A number of limitations of this study which may have influenced or affected the results are identified. Distribution data for protected species were difficult to acquire as this is sensitive information and is often not available to the public. Data request forms for this information were submitted to the NBDC but were unsuccessful. Distribution data were digitised manually in ArcGIS 10.3.1. allowing for minor errors in the location range of these species to enter the map however these would not significantly affect the results of this study. The range of the species may be slightly offset by a small margin, but the digitised map will still provide information on their location. Data which represented the species distribution were found on the NBDC, this data is represented in an interactive map. This resource represents a number of species distributions in Ireland based on the combination of a number of datasets collected by various established organisations. Some of these distribution records are dated, and as a result of this, the species many no longer be present in the area therefore this must be taken into account when using and discussing this data. Data were only available on vertebrate species found in these areas therefore preventing the examination of the impacts of light pollution on plants and habitats. When acquiring habitat data and site characteristic data, it was found that information on the site of Bull Island was more detailed in comparison to the other sites. This meant there was a higher amount of verified data for one site in comparison to the other sites. Missing information was determined through site visits and by looking at satellite imagery of the study sites.

Light meter data for the three sites were collected over the course of one day the 26th of March 2016. This makes it difficult to determine the levels of artificial light in the night sky as only one day is provided for analysis. However, when the light meter readings for this period for the three study sites were compared it could then be determined which area had the higher levels of light pollution. Also the use of different light meters at the three sites may have led to slight variations in the meter readings and accuracy. Extensive data were only collected for two of the study sites (i.e. - Bull Island and Trinity College Dublin). This prevented an in-depth three site comparison to be carried out as Killiney Hill was excluded.

When reviewing the literature on the impacts of light pollution on the selected protected species of this study it was apparent that a number of species have been greatly studied in terms of their reaction to light pollution while other species which may face great impacts which have not yet been studied. Examples of species which have been widely studied are bats and birds. While species from families such as mustelidae have not yet been studied to the same extent as the bats and birds. Therefore information on these various impacts to the species was often difficult to find. Much of the literature on the impacts of light pollution on fauna was discussed on a higher order relating it to a taxa rather than species specific.

Further study is required on light pollution and its impacts in Ireland. Studies focused in Ireland will be essential in monitoring species and the extent of the impacts which may result. The surveys carried out during these studies could identify impacts which may have previously been overlooked or not considered. Studies in various locations of Ireland like that carried out by Power 2015 will allow for sites to be used in comparison to each other to determine areas which are hotspots for light pollution. The maximum light pollution threshold in terms of species tolerance can be determined from these studies allowing sites which are at the maximum threshold to become a priority in monitoring and eradicating light pollution. More studies are required on flora in relation to light pollution, plants are vital in many habitats and harm or deterioration to these would lead to ecosystem degradation.

5. Conclusion

Artificial light levels have greatly increased in Ireland over the last two decades. High levels of construction and the development of infrastructure as a result of the “Celtic Tiger” has contributed to this. This is evident in the capital city of Dublin where the saturation of light levels and the spread of light has greatly increased. Dublin city centre receives 63 DN saturated levels of light pollution being the highest range of this study, while the suburbs receive slightly reduced levels of light pollution between the ranges of 20-42 DN. None of the sites concerned in this study meet the criteria to be designated as a dark sky reserve/park. The full extent of the impacts of light pollution has not yet been fully established. Studies on light pollution should be expanded to focus on plants, inverebrates and habitats and not just focus on vertebrates, this would allow for a better knowledge and understanding of light pollution to be developed. Such studies would facilitate measures to be put in place to protect species at risk and to assist in putting protective measures in place to prevent further degradation. Light pollution is a global issue and is of concern to human health, animals, plants and habitats. Further studies like this are required in Ireland to develop a national light pollution database that will assist in tackling both the increasing level and concerns regarding light pollution.

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APPENDIX 1

Table 2. Datasets analysed in GIS and the organisation in which they were sourced.

DATASET	SOURCE
IRELAND-AND NORTHERN IRELAND COUNTY COUNCIL DIVISIONS	Geofabrik
PROPOSED NATIONAL HERITAGE AREAS (PNHA)	NPWS
SPECIAL PROTECTION AREAS (SPA)	NPWS
SPECIAL AREAS OF CONSERVATION	NPWS
ESTUARIES	NPWS
FIXED COASTAL DUNES WITH HERBACEOUS VEGETATION	NPWS
CORINE LAND COVER 2006 & 2012	EPA
BEDROCK GEOLOGY	GSI
OTTER SURVEY OF IRELAND 1982	NBDC
ATLAS OF MAMMALS IN IRELAND 2010-2015	NBDC
NATIONAL FROG DATABASE	NBDC
AMPHIBIANS AND REPTILES OF IRELAND	NBDC
IRISH SQUIRREL SURVEY 2012	NBDC
IRELAND'S BIOBLITZ	NBDC
NATIONAL BAT DATASET OF IRELAND	NBDC
NPWS SEAL DATABASE	NBDC
MARINE SPECIES DISTRIBUTIONS IN IRISH COASTAL WATERS	NBDC
THE SECOND ATLAS OF BREEDING BIRDS IN BRITAIN IN IRELAND: 1988-1991	NBDC
BIRDS OF IRELAND	NBDC
EUROPEAN SEABIRDS AT SEA (ESAS) BIRD SIGHTINGS FROM 1980 TO 2003	NBDC
IRISH WETLAND BIRDS SURVEY (I-WEBS) 1994-2001	NBDC
LOCAL BIOBLITZ CHALLENGE 2013	NBDC
ROAD KILL SURVEY	NBDC
BIRD ATLAS 2007-2011	NBDC
IRISH MARINE TURTLE DATABASE	NBDC