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Review on the effects of ALAN in insects with a special focus on the Macaronesia Region

Funchal, 2023

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In the **LIFE Natura@night** project, the main objective is to reduce and mitigate the impact of light pollution in Natura 2000 areas in Macaronesia.

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Review on the effects of ALAN in insects with a special focus on the Macaronesia Region

Portuguese Society for the Study of Birds, 2022

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I. Species, distribution and abundance of nocturnal Lepidoptera in Macaronesia

1. Biogeographical Region of Macaronesia

Macaronesia is the term used to designate the various groups of archipelagos located in the Atlantic Ocean, which are proximate to the European and African continents. These archipelagos share many factors in common that will be exposed below, explaining the reasons why this area corresponds to a biogeographical region.

Furthermore, this ecological zone is shared by three countries and is composed of the next four archipelagos: Azores and Madeira (Portugal), Canary Islands (Spain), and Cape Verde (Republic of Cabo Verde). The first three belong to the European continent and the last one to the African continent. The European archipelagos of Macaronesia; Azores, Madeira, and the Canary Islands, are included in the LIFE Natura@night project and present Europe's highest degree of endemism. Due to its geographical location, singular ecological conditions, and the isolation of its constituent areas, the Macaronesia region brings together a high diversity of species and plant communities that are unique on the planet, being considered one of the most important centres of biodiversity at a global level.

Although oceanic islands frequently harbour fewer species per unit area, the proportion of endemic taxa is generally higher in comparison with the mainland, being considered global hotspots of biodiversity (Kier *et al.* 2009).

The archipelagos included in the Macaronesia region share common characteristics as they are remote islands, all of them present volcanic origin (most of them aligned on the same tectonic plate), share similar fauna and flora, are exposed to the same maritime currents and winds, and are established first-level tourist destinations. For the exposed reasons, Macaronesia encloses over 500,000 hectares of Natura 2000 protected areas, 154,794 of them involved in this project.

These islands have endemic and unique flora and fauna, including a great diversity of insects. The fauna and flora that inhabit Macaronesia originated in recent geological times, are predominantly of European origin, and descend from ancient lineages that used these islands as refuges and progressively have been diversified into a set of endemism of Macaronesia. This area is included in the largest biogeographic region on the planet, the Palaearctic biological kingdom, due to its climate and presenting some similar characteristics in fossils, fauna, and flora. To add, this ecological kingdom is included in the Holarctic Kingdom (which includes the Palaearctic and Nearctic biological kingdoms). Macaronesia consists of a geographical area composed of many oceanic islands of high scientific interest for understanding island systems with unique biodiversity under threat. This biodiversity resulting from different diversification processes is largely threatened by the presence of introduced species, which can easily invade and/or alter island ecosystems. Introduced species together with changes in land use constitute two major threats to this fauna and flora diversity (Florencio *et al.,* 2021).

The distance between islands and the mainland might constitute a dispersal barrier for the arrival of different organisms (in some occasions more than 1,500 km) this results in a common characteristic feature of oceanic islands called *taxonomic disharmony* which explains the absence of species belonging to some taxonomic groups that are well represented in the nearest mainland and due to obstacles (as the absence of suitable habitats) faced by these individuals during the colonization and establishment on islands upon their arrival, there are no representatives of some group of animals and/or plants (Borges *et al.,* 2015).

Additionally, this region is essential for migratory animals, as these islands are considered important resting areas for long-distance migrations.

The diversity of the flora and fauna of these islands make them a unique and valuable place from a biological and conservationist point of view. Information on these archipelagos' ecology, evolution, and conservation is so far patchy and scattered in the literature that synthesis is urgently needed. It is of utmost importance that the efforts made so far to obtain biodiversity data continue intensively in the short and long term to gain a thorough understanding of island ecosystems and their unique species (Bladon *et al.,* 2022).

2. Phylum Arthropoda

The phylum **Arthropoda** contains a wide diversity of animals that share hard exoskeletons and jointed appendages. Arthropods play a key role in all terrestrial ecosystems and are considered the most successful animals on Earth, where global estimations are between the number of seven and 8.7 million species of terrestrial arthropods representing over 85% of all known animal species belonging to this phylum (Borges *et al.,* 2022). This group is the most numerous and live in the widest range of habitats thus presenting a varied diet. Within this phylum, we can find various known and common classes of animals such as spiders, crustaceans, centipedes, and insects. Although they have great importance in environmental studies, arthropods are the least represented taxa in extinction risk assessments, conservation projects, and as interest for global biodiversity datasets (Cardoso *et al.* 2011).

2.1 Arthropoda in Macaronesia

50,000 species of arthropods are known to exist in the Iberian Peninsula, mostly from the Western part of Europe. Only in Macaronesia, there are approximately 258 arthropod species unique to the Azores, 428 for Cape Verde, 921 endemic species to the Madeira and Selvagens archipelagos and 2,768 for the Canary Islands (Arechavaleta *et al.* 2005). These numbers imply that Macaronesia contributes with an important set of 4,375 endemic species of arthropods providing great species richness in Portugal and Spain. A possible explanation for these numbers is that this may be due to the highly diverse flora (i.e. from the total number of vascular plants existing in these archipelagos, 840 are endemic (Borges *et al.* 2022; Borges *et al.* 2008).

The current data on the number of arthropods present in Macaronesia varies according to each archipelago, where each archipelago has its own distribution and number of endemic species due to the different physical characteristics of each archipelago.

According to Borges *et al*. (2008) which was one of the main studies consulted for the diversity in Macaronesia and to avoid any further possible confusion, the Madeira archipelago is divided into Madeira and Selvagens archipelago, in addition, when the term *taxa* is mentioned, it gathers species and subspecies.

Comparing these archipelagos in European Macaronesia, in relation to arthropod diversity, Madeira and Selvagens archipelagos host around 3,900 arthropod taxa. In terms of endemic species, the Azores has the least with around 500 endemic taxa, Madeira and Selvagens archipelagos host around 1,000, and the Canary Islands present the highest number of endemic taxa corresponding to around 1,500. This fact can be explained as this archipelago is nearer to the mainland and its geological history is older. Comparing Madeira island with any island from the Azores, its complex topography and habitat diversity is comparatively higher in the first (Borges *et al.,* 2022; Borges *et al.* 2008; Borges *et al.* 2010b; Arechavaleta *et al.* 2010).

In addition, there is a variation between islands from the same archipelago. The climatic, geological, and ecological differences between the older islands with erosive processes and increased aridity in each case, result in a lower diversity of habitats compared to the younger islands with a richer ecosystem of habitats. Also indicate that the size of the island, sampling effort, and frequency of study are also factors to be taken into account.

All the particularities that are shared between these archipelagos and which commonly occur in oceanic islands, contribute to the single island endemism (SIE), which reflects the endemism that are only present on a specific island. The great majority of the endemic species are SIE; In the Azores archipelago, São Miguel and Santa Maria islands host the larger proportion in relation to the total endemics per island, which is explained by their older geological ages, within the Canary archipelago the island of Tenerife stands out. In Madeira archipelago, the island of Madeira predominates.

Next, more information in detail about the arthropods found in the various archipelagos of Macaronesia is as follows:

2.1.1 Azores archipelago

The Azores archipelago is located at the triple junction of the Eurasian, African and American plates roughly between the coordinates 37º to 40º N latitude and 25º to 31 W longitude. Despite being an isolated archipelago with ample variation in terms of geological history and a wide range of elevations, it presents less ecological variation and a more uniform habitat composition between islands than the other Macaronesia archipelagos.

In terms of arthropod diversity and percentage of endemism, the Azores archipelago has the lowest and presents a high proportion of exotic introduced species, a critical problem in the

Azores. According to the colonisation status, a great proportion of the terrestrial arthropods are introduced (42%) and present 12% of endemic taxa (Borges *et al.,* 2015).

These figures are a consequence of the combination of several factors such as the recent and mismatched geological age, which is dated at seven million years (and even for those islands with old terrain a large proportion of the island areas is less than one million years), the small archipelago area, a very homogeneous landscape with low habitat diversity, and greater geographical isolation giving a large distance to colonization sources (Triantis *et al.* 2012; Borges *et al.,* 2015). Therefore, on this basis, in the recent IUCN red listing of Azorean arthropods, a large fraction of the endemic taxa seems to be under high threat (Borges *et al.,* 2022).

According to Borges *et al.,* (2022), the number of terrestrial arthropod taxa (species and subspecies) listed in the Azores is estimated at 2,397 species of arthropods.

The most diverse orders of Azorean arthropods belong to the Insecta and Arachnida classes. In the next chapter we will discuss in more detail the orders of insects but only to name that Araneae has a total of 132 taxa and in terms of endemic species and subspecies the order Sarcoptiformes has 27 taxa and Araneae has 25 taxa (Borges *et al.,* 2015).

Factors that may explain the low diversification in the Azores are human disturbance, mediated by natural habitat destruction, and the introduction of exotic and invasive species.

Native forests which have a high conservation value, are the most important habitats for endemic arthropods of the Azores, being dominated by *Erica azorica, Morella faya, Picconia azorica, Laurus azorica, Ilex azorica* and *Juniperus brevifolia* (Borges *et al.,* 2022). Currently, only five % of the total area of the archipelago is covered with native forest, so pastures are the predominant land use, accounting for 42% of each island area on average (Borges *et al.,* 2015).

2.1.2 Canary archipelago

The geographical location of the Canary Islands provides unique characteristics, being the closest to the African continent. Also, the existence of prevailing winds and ocean currents has allowed the arrival of numerous species to the islands, reflecting the presence of a large number of taxa.

It is stated that among the present fauna in the archipelago of the Canary Islands (which includes 14,254 species), the phylum Arthropoda stands out. This archipelago is the one with the highest number of arthropod species, as well as endemic species from the Macaronesia archipelago (Figure 1) (Arechavaleta *et al.,* 2010).

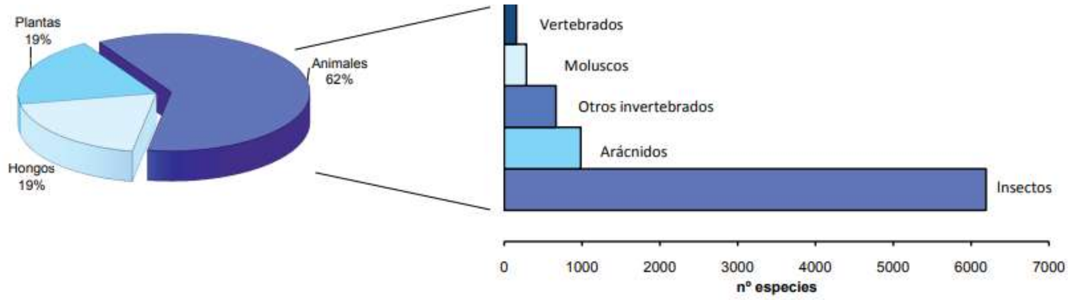

Figure 1 | Fauna proportion in the Canary Islands. Extracted from Arechavaleta *et al.,* (2010).

According to the most recent data collected from the Canary Islands Biodiversity Data Bank (Gobierno de Canarias, 2022), there are a total of 8,162 species of arthropods in this archipelago, of which 3,225 are endemic.

The number of recorded arthropods on the different islands according to Arechavaleta *et al.,* (2010) are the following; El Hierro presents 1,368 arthropods, of which 509 are endemic; La Palma has 2,741 species and 843 of them endemic; La Gomera with 2,321 species and 849 are endemic; Tenerife is the largest in terms of the number of wild species, endemic species, and island endemism with 4,988 species of which 1,630 are endemic species; Gran Canaria has 3,190 species, 1,026 of them endemic; Fuerteventura presents 1,695 arthropod species of which 434 are endemic and finally, Lanzarote with 1,391 arthropods and 396 of them endemic.

This data can be also explained as the geological age of this archipelago varies between the seven islands, the oldest is Fuerteventura (20.5 million years) and the youngest is El Hierro (0.8 million years).

2.1.3 Madeira archipelago

The oceanic archipelagos of Madeira and Selvagens are located in the eastern Atlantic, between 30-33ºN and 15-17ºW. This archipelago is composed of the islands of Madeira, Porto Santo, and Desertas, all these islands originated from a single volcanic building; *the Madeira - Porto Santo Complex* and is situated in the Atlantic Ocean, about 600 kilometres from the coast of Africa and 900 kilometres from the Portuguese mainland. The archipelago of Selvagens is 175km north of the Canary Islands and represents the oldest of Macaronesia (27My) displaying the last stages of the island life cycle (Serrano *et al.,* 2015).

The uniqueness of the Madeira archipelago's natural legacy includes excellent animal models that are suitable for the study of ecological and evolutionary patterns and processes that structure the diversity of life.

The biodiversity of terrestrial arthropods in the Madeira and Selvagens archipelagos presents as a whole a remarkable diversity in species and endemic life forms. Madeira has the largest area of Laurisilva (~15000 ha), encompassing a fifth of the island area, and presents a large number of pristine fragments, reasons that led to its classification as a World Heritage Site by UNESCO (Serrano *et al.,* 2015). Due to the above-mentioned factors and by being in an isolated position and the age of these islands, these islands present a significant number of unique species and are among the most biologically diverse regions of Portugal in endemic arthropods, and present a high proportion of native taxa (68%). However, this feature may be at risk due to the increasing number of introduced species as a result of globalization which is expected to keep rising (Bella & Aguiar, 2020). Additionally, other factors threaten the conservation of terrestrial arthropods in these areas such are habitat destruction and fragmentation, and climate change (Serrano *et al.,* 2015).

Madeira island stands out both in species richness and in the number of endemic taxa as it is the largest island with a complex orography and the highest number of habitat types. In the archipelagos of Madeira and Selvagens, there are listed a number of 3,859 arthropod species (3,891 taxa) consisting of 462 families and 2,118 genera. In specific, the archipelago of Madeira is composed of 3,801 taxa, while in the archipelago of Selvagens, only (202 species) of 201 taxa were recorded. The cumulative number of arthropod taxa on all islands is 3,542 in Madeira island, 7,660 in Porto Santo, 298 in Desertas, and 202 in Selvagens islands. Nevertheless, it should also be taken into consideration that Madeira's biodiversity has been studied in more detail since this island has been a target for several natural history expeditions and many visits from worldwide taxonomic experts (Serrano *et al.,* 2015).

As commented before, Madeira, is the richest in several recorded taxa with 3,542 species and 121 subspecies of arthropods, totalling 3,549 individual taxa constituting 90% of all the species and subspecies known from the archipelagos of Madeira and Selvagens (Borges *et al.*, 2008).

The most diverse of all arthropod groups are insects (i.e. 87 % of all arthropods) with 3,394 taxa. Altogether, the five orders of insects present in Macaronesia make up 79% of all known Madeira and Selvagens terrestrial arthropods. In addition, two other arthropod groups also present high species richness, namely Araneae (183 taxa) and Acari (130 taxa) (Borges *et al.*, 2008).

Madeira and Selvagens are a hotspot of endemic terrestrial arthropods, with about 979 endemic taxa (921 species and 77 subspecies) around the archipelagos. These are the numbers for the endemic arthropods in the specific islands; 795 in Madeira island, 140 in Porto Santo, 92 in Desertas, and 39 in Selvagens islands. The mentioned endemic species and subspecies of arthropods belong to 481 genera of which 337 are monospecific. The genera present in these two archipelagos have six or more endemic species and subspecies. Roughly nine of those genera are hyper-diverse, with 18 or more taxa endemic to the Madeira and Selvagens archipelagos. Interestingly, many of these genera are also represented by a high number of endemic taxa in both the Azores and the Canary Islands (i.e. Acalles, Laparocerus, Tarphius, Trechus).

The current situation on species recorded in Macaronesia

The number of species recorded in Macaronesia has increased exponentially over the last 15 years, despite taking into account that there is a high probability that many of the species may have been driven to extinction or were misidentified at the time as there are no new records for many of the species from the last century. The destruction of native

Laurissilva forests and the uncontrolled increase of invasive species highly endanger Macaronesia's wildlife (Borges *et al.,* 2008). Those which are the most sensitive to disturbance, with locally restricted distributions or habitat destruction are most vulnerable to extinction.
The great importance of biological knowledge can be observed throughout the biogeographical region of Macaronesia, the study of new species principally due to increased sampling effort (and a special focus on microhabitats) and broadening knowledge of those species that have been already discovered has been increasing. This information will be crucial for the development and implementation of successful conservation/management strategies for the protection of the highly diverse and unique terrestrial arthropod fauna of these archipelagos (Borges *et al.*, 2008).

All of the above is shared across Macaronesia, although not at the same level. In the Azores, the number of endemic taxa is low, and the discovery of new species started relatively later (in 1859) as the Azorean archipelago was less targeted by entomological scientists' when compared to Madeira or the Canary Islands (Borges *et al.*, 2015). The interest in the Azores increased after the publication of Darwin's Origin of the Species as it was believed that these islands could contain transition forms of flora and/or fauna between the Nearctic and Palearctic regions.

Due to their lower number in arthropod diversity and their great efforts in biological and ecological studies in the last decade, two checklists of terrestrial arthropods of the Azores archipelago were published (Borges *et al.,* 2008; 2022) and currently consist of the archipelago that has the most up-to-date information and peer-reviewed by specialists, therefore, it has the most recently reviewed checklist (Borges *et al.,* 2022). Some of the biodiversity study bodies that have provided the most information include the University of the Azores and the Azores Biodiversity Group, which was founded in 2006.

In contrast with the naturalistic studies in the Azores, the beginnings of naturalist study in Madeira started in 1687. The description of new endemic terrestrial arthropods from Madeira and Selvagens has been relatively high since 1980, although it may seem less impressive if compared with the outstanding work of Thomas Wollaston during the 1850s. Some important data on the knowledge of insects in Madeira are the following: the first endemic species was sighted in 1770, later on, Thomas Wollaston published *Insecta Maderensia* (1854) and the publication of the checklist of fauna and flora from Madeira and Selvagens archipelagos (Borges *et al.*, 2008). This checklist was followed by two important studies where conservation properties were identified within the context of Macaronesia aiming to simultaneously protect native species and control invasive species.

In spite of the high number of species reported to the Madeira and Selvagens archipelagos and Canary Islands, the current knowledge on the taxonomic biodiversity of these islands is far from complete.

The cumulative discovery curve in endemic arthropod species and subspecies was generated of both Portuguese archipelagos; Azores (Borges *et al.,* 2022) and Madeira (Borges *et al.,* 2008) (Figure 2). On the graphics, it can be seen the efforts of arthropod study by the accumulation rate of identification of new species over time, which differs between both of them, despite taking into account the year of both publications.

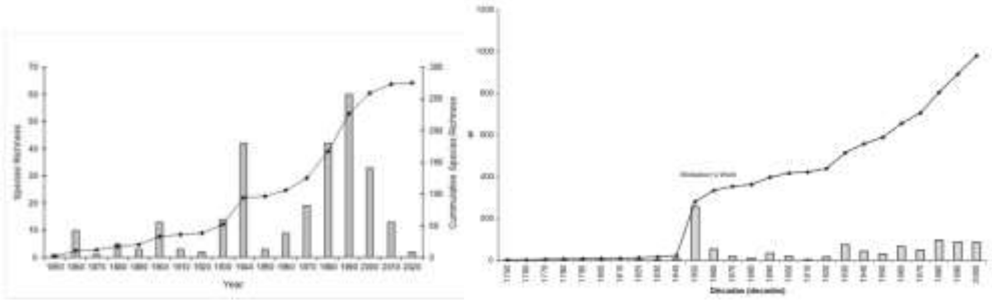

Figure 2 | Cumulative discovery curve in endemic arthropod species and subspecies of both Azores (Borges *et al.,* 2022) and Madeira (Borges *et al.* 2008) archipelagos.

As discussed above and extrapolated by this figure, the slope from the cumulative new taxa discovery curve by Borges *et al.,* (2022) in the Azores, is suggested, since the slope is starting to slow down, reaching the asymptote, that at least initially for most studied taxa, the inventory of Azorean endemic arthropods appears to be close to completion. As mentioned before, the publications on the inventorying and monitoring of Azorean terrestrial arthropods have increased although there is still poorly studied groups like Acari, Diptera, Micro-Lepidoptera, and Hymenoptera that need further taxonomic and sampling effort. For example, more studies are needed in microhabitats (such as volcanic caves) so although the graphic suggests that the inventory of endemic species is close to being finished, in reality, is closer to being complete (Borges *et al.,* 2022).

However, Madeira presents its cumulative discovery curve (Borges *et al.,* 2008) with a steep slope, indicating it is far from a complete inventory of endemic species. Canary Archipelago and Madeira have a greater number of existing species, the current number of known endemic species and subspecies is certainly a poor estimate of its real number in terrestrial arthropods, therefore this strongly suggests that the number of known endemic species and subspecies is far from been complete (Borges *et al.*, 2008). Major efforts should be endorsed to survey less explored habitats and regions and to focus on still understudied hyper-diverse arthropod groups like Acari, Araneae, Diptera and Hymenoptera.

3. Class Insecta

Insects are the most diverse class of animals on Earth and are the largest and most widely distributed group of arthropods on the planet. This class presents a high number of species with approximately 5.5 million species, representing more than 70% of all described species (Borges *et al.,* 2022). There are about 30 formal orders of insects, depending on the classification system adopted. This class is taxonomically synonymous with Ectognatha. This class is composed of invertebrates with a chitinous exoskeleton, their body is divided into three *tagma* (head, thorax, and abdomen), they have three pairs of jointed legs and present compound eyes (that are sensitive to a broad range of wavelengths) and two antennae.

Insects establish innumerable interrelationships that can be distinguished into two important types, herbivory and mutualism. In the category of herbivory, we can consider the predation of insects on plants (feeding) playing an essential role in the trophic chains contributing to the control of infesting plants, but also causing agricultural damage. In the category of mutualism, there are several insects that contribute to plant reproduction through pollination (Picanço & Borges 2017).

The main ecosystem services provided by insects are habitat maintenance and pollination (Borges *et al.,* 2018).

- Insects contribute to habitat maintenance by decomposing dead matter, soil fertility, nutrient cycling, and natural pest control in agroecosystems, and constitute important hosts for parasitoids among others (Grubisic *et al.,* 2018b).

- Globally, pollinating insects are responsible for maintaining a vital ecosystem service for the sustainability of the planet and food security is in decline. This makes it more urgent to identify the ecology and distribution of insects and to assess their contribution to pollination (Picanço & Borges 2017). Pollinating insects are vital components of many ecological communities, where they contribute towards pollination of a diverse array of ecologically and economically important crops and wild plants.

Widespread concerns about declines of wild pollinating insects have attracted considerable research interest, largely directed towards identifying key nectar sources and assessing the contribution of pollinators towards ecosystem services. However, previous work has almost exclusively focussed on bees and other diurnal taxa. Note that apart from the most recognised pollinators which belong to the Hymenoptera and Lepidoptera order, Coleoptera and Diptera also contribute (Picanço & Borges, 2017). In general, Lepidoptera order spends longer than Diptera at flowers, both of which have substantially longer handling times compared to Hymenoptera (Anderson, Rotheray & Mathews, 2023).

Nocturnal insects are of eminent significance as pollinators and as the primary food source of many vertebrates (Altermatt & Ebert, 2016). However, little is known about the extent of the contribution of nocturnal pollinators, with almost all pollination research having been conducted on diurnal-active insects (Anderson, Rotheray & Mathews, 2023).

There is a clear possibility for the pollination rates of flowers that are adapted to nocturnal pollination to be affected by emitted light pollution. Some insects like those with superposition eyes are sensitive to even very low light levels (Bruce-White & Shardlow, 2011).

Focusing on those orders that are most common and diverse, currently, there are records of approximately 6,000 species of Odonata (dragonflies), 24,000 of Orthoptera (grasshoppers and crickets), 158,000 Lepidoptera (butterflies and moths), 156,000 Diptera (flies and mosquitoes), 104,000 Hemiptera (bedbugs, cicadas, and aphids), 387,000 Coleoptera (beetles) and 117,000 Hymenoptera (bees, wasps and ants).

Insects in Macaronesia

In the following figure, it can be observed comparatively the distribution of endemic species richness in the main orders of arthropods according to a global level and to each European archipelago of Macaronesia (Azores, Canaries, Madeira) (Figure 3).

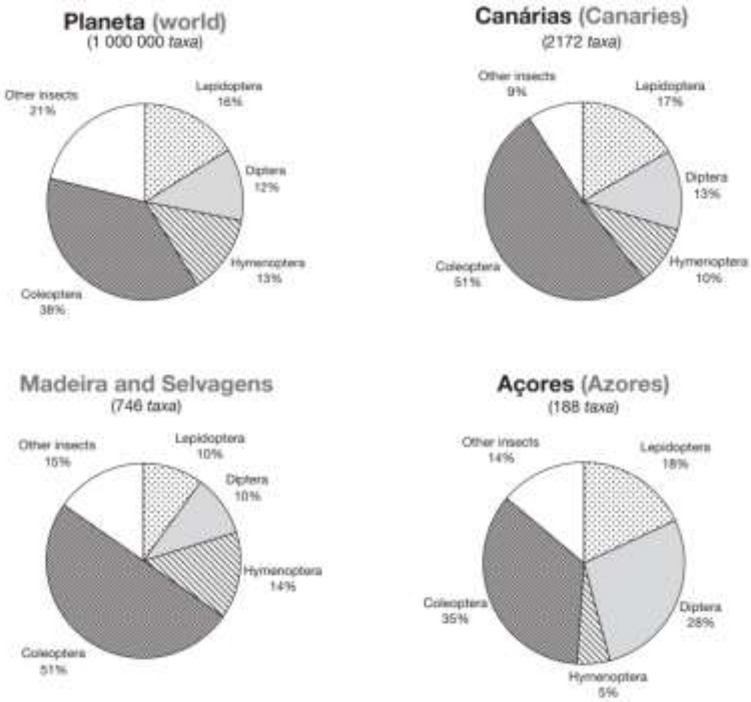

Figure 3 | Proportional endemic species richness of the main insect orders in the planet, Canary Islands, Madeira, and Azores. Extracted from Borges *et al.* (2008).

As seen in Figure 3, the worldwide hyper-diverse orders are also the most diverse in the European Macaronesia archipelagos with slight differences

- Azores archipelago presents 1,942 species of insects, 840 of them endemic (Borges *et al.,* 2022).

The richest terrestrial insect groups (=orders) in taxa are Coleoptera (585 taxa), Diptera (422 taxa), Hemiptera (338 taxa), Hymenoptera (162 taxa), Lepidoptera (159 taxa). This is in general accordance with worldwide diversity (Figure 3), the exception is the Hymenoptera order which is a globally diverse order that is not reflected in the Azores. This could also be because this order has been less studied. The most species-rich islands are São Miguel and Terceira, while the islands that are the least diverse are Corvo, Graciosa, and São Jorge. Remarkably, Santa Maria and Faial are relatively biodiverse islands in relation to their sizes.

In terms of endemic species and subspecies of insects, the same results are extrapolated as in Figure 3, Coleoptera (80 taxa constituting a 27%), Diptera (48 taxa constituting a 19%), Lepidoptera (40 taxa constituting a 14%), Hemiptera (with a 4%) (Borges *et al.,* 2022; 2015).

São Miguel, Terceira, and Pico are the islands with a higher number of endemic species and subspecies (Borges *et al.,* 2022; Borges and Brown 2008, Triantis *et al.* 2012).

Further, when the diversification that occurred in these islands is considered, it is also very low as only 18 genera have three or more endemic taxa, representing 30% of the overall endemism, while genera with a single endemic species account for 49% with 134 species (Borges *et al.,* 2015).

- In Madeira archipelago includes highly diverse insects, with 3,394 taxa present (constituting 87 % of all arthropods) and in terms of endemism's, there are 746. Going into detail on the islands, Madeira island specifically has 3,012 species (644 of them endemic), Porto Santo has 674 (120 endemics), Desertas has 272 (80 endemics) and Selvagens has 150 (30 endemics) (Borges *et al.*, 2008).

As seen in Figure 3 the main orders of insects are also the most diverse in Madeira and Selvagens archipelagos: Coleoptera (1,040 taxa), Hymenoptera (610 taxa), Diptera (555 taxa), and Lepidoptera (331 taxa). Singularly, Hemiptera is also highly diverse (522 taxa). The worldwide hyper-diverse orders are also the most speciose; Coleoptera (416 taxa continuing 40% of endemism), Hymenoptera (107 taxa constituting 18% of endemism), Diptera (80 taxa constituting 14% of endemism), Lepidoptera (81 taxa, 25% endemism) (Borges *et al.*, 2008). Together these hyper-diverse insect groups represent nearly 77% of the terrestrial arthropod endemic taxa diversity (Serrano *et al.,* 2015).

Comparing archipelagos in Macaronesia, the proportion of Coleoptera species richness on the Madeira and Selvagens archipelagos is similar to that found in the Canary Islands. However, the same does not apply to the orders Lepidoptera and Diptera, which are underrepresented in the first (Borges *et al*. 2008).

- In the Canary Islands there is a total of 6,361 species of insects of which, 2,540 are endemic. The most diverse orders are Coleoptera and Diptera, with 2,185 and 1,117 species respectively. Both orders are also the most endemic, with 1,275 (58.3%) and 301 (26.7%) endemic species (Suárez *et al.,* 2018; Gobierno de Canarias, 2017).

3.1. Insect declines

At present there is an ongoing global and progressive decrease in insects, the total decline of insects in the past decade corresponds to 41% (Sánchez-Bayo & Wyckhuys, 2021). This fact can be related to our daily routines, where there is a clear reduction of insects all around the world. This not only occurs in cities but also in less modified and further remote areas. In a German study where data was recorded between 1989 and 2016, it has been stated a decline of flying insects in protected areas in the order of 80% (Desouhant *et al.,* 2019).

The extinction or disappearance of insects is responsible for the vanishing of many other species of living beings such as birds, reptiles, amphibians, and bats who can no longer be able to feed around the environment and affect nature in a greater extent. Apart from the cascading effect on the upper levels of the food pyramid, extinction has also an economic impact. This situation is consecutively aggravating and problems associated with this issue will be soon evidenced as rising food prices, droughts, forest fires, and persistent agricultural pests. To recall the mentioned statements, insects have great importance in pollination, as about 85% of plants rely on pollinators which are mostly composed of insects (Haarman, 2022).

Data from the 10 major insect taxonomic orders indicate that an average of 37% of species are declining in numbers due to several drivers, while mainly populations of agricultural herbivores and pest species are increasing by 18% (Sánchez-Bayo & Wyckhuys, 2021).

3.2. The major drivers of insect decline

Declining insects correspond to 37% and as acknowledged, the key drivers behind these insect declines are modification/loss of habitat, climate change, invasive species, and the use of agrochemicals/ pesticides.

1) Modification/loss of habitat

The destruction of habitat consists on the loss of habitat by degradation, where fragmentation of habitat is the most important reason affecting the viability of insects. Initially, it is assumed that habitat must be composed of very vast areas but when it is related to insects, very small areas can correspond to the specific habitat of insects, and so, small changes in the environment can deal with great changes and shrink populations of insect species. Some well-known examples of area modification are urbanization, agricultural and/or woodland management.

2) Chemical pollution

Chemical pollution is a key constituent of intense agricultural practices. Agricultural intensification through increasing input of chemical products and cropland expansion has caused rapid loss of semi-natural habitats and the subsequent loss of natural enemies of agricultural pests. As to what happens with *light pollution,* according to specific literature, there is no clear evidence that it is a driver of insect declines, on the other hand, a great number of scientific literature indicate that this is one of the most dangerous reasons for insect decrease.

The indiscriminate and massive use of fertilizers and the use of fossil fuels generate as a result of nitrification, a great deal of nitrogen input which triggers a complex change in plant communities. Those insects that are associated with nitrogen-limited or nutrient-poor habitats (such as bogs, oligotrophic grasslands, barrens, sandplains, and dunes habitats) are expected to be disproportionately impacted (Wagner *et al.,* 2021).

3) Climate change

Climate change describes global warming, the ongoing increase in global average temperature, and its effects on Earth's climate system. The current rise in temperature is more rapid than previous changes and is primarily caused by humans burning fossil fuels. Due to climate change, deserts are expanding, while heat waves and wildfires are becoming more common, increased warming in the Arctic has contributed to melting permafrost, glacial retreat, and sea ice loss, higher temperatures are also causing more intense storms, droughts, and other weather extremes, rapid environmental change in mountains, coral reefs, and the Arctic is forcing many species to relocate or become extinct.

Relating these effects on to how it affects insects, factors such as increasing drought and aridity, atmospheric and water temperatures, and soil moisture (depending on temperature and precipitation is crucial for larval survival and development) are the most endangering to insects.

4) Non-native/ invasive species

The dominance of exotic invasive species on native communities is affecting them to an important extent, their dominance can lead to changes in the structure of insect communities, by competing and displacing native species. In the USA, studies found that non-native woody plants supported significantly less abundance and species richness of moth and butterfly larvae than native trees and shrubs, even if the alien plants were the same genus as the native hostplants (Fox, 2013).

Invasions involving arthropods are perhaps the most pervasive and underappreciated component of grand challenges to global development and prosperity, particularly to; human health, nutritious food, clean water, resilient environments, and sustainable economies. Direct effects on food or the environment can be readily appreciated.

5) Light pollution

Furthermore, the impact of light pollution presents conflicting ideas regarding stating if it has a negative effect, or whether light pollution would be considered as certainly a driver of insect decline *per se*. So far, from the consulted literature related to insect declines, all of them agree with the statement "*light pollution is a driver of insect decline*" except for four which state that more studies are needed urgently for further conclusions on the topic (more data to make robust conclusions about the scope and nature global insect declines and also little evidence of light pollution in non-native species) (Wagner *et al.*, 2021; Grubisic & van Grunsven, 2021; Fox, 2013; Sánchez-Bayo & Wyckhuys, 2021). In addition, other scientific articles suggest that it may be due to light pollution, although without certainty of this (Macgregor *et al.,* 2015; Boyes *et al.,* 2021).

In this case, light pollution is going to be considered a crucial driver for the decline of insects, concurring with the large majority of bibliographic articles consulted (Owens *et al.*, 2020; Meyer, 1995; Bolliger *et al.,* 2020a; Grubisic *et al.,* 2018a; Eisenbeis *et al.,* 2009; Desouhant *et al.*, 2019; Macgregor *et al.*, 2017).

Considering light pollution as a recent driver of insect declines, this factor affects the manner that the insects are attracted by lights, and with a compromised sense of orientation, they become more susceptible to predators, flying incessantly around the light source. More information is in detail in Chapter II.

In addition, light pollution contributes to habitat fragmentation, it is easier to notice with those insects that present reduced mobility, however, those insects that have flying abilities are more difficult to understand. For example, excessive public lights and road lights at night become major attraction islands and lead to mass fatalities. These types of insect hotspots become sheltered micro-climates in relatively exposed landscapes.

In general, these five above-mentioned components constitute the main drivers of insect declines. As there are multiple drivers implicated, they may interact synergistically, additively, or antagonistically and operate at different time periods (Wagner *et al.,* 2021; Fox, 2013). They are also mutually reinforcing, impacting each other to a greater degree. Although direct evidence to explain the trends is indeed very limited, there is a clear potential for negative impacts. It's complicated to study without a good number of yearly compiled data, so a long time series of data is needed to know population cycles as insects have very varied population dynamics (Fox, 2013).

4. Lepidoptera order

Lepidoptera is a megadiverse order of insects whose main anatomical characteristic is to have two pairs of membranous wings covered by scales, which include butterflies and moths. This order constitutes the second largest, after Coleoptera, in terms of diversity and is distributed mostly worldwide composing between 160 and 175 thousand species.

The life cycle of Lepidoptera consists of four stages; egg, larva, pupa, and adult. They undergo a complete metamorphose, when the individual is in a larval stage, it presents a chewing-type oral apparatus (eats leaves, flowers, fruits, stems, and roots of plants), and when it becomes an adult it transforms into a spiritromp (feeds on nectar, rotten fruit, and other plant and animal exudates).

Nocturnal and diurnal Lepidoptera

In Portugal, there is currently a total of 2,600 inventoried species of Lepidoptera of which 135 species represent diurnal butterflies (Pedro Pires, 2022). The majority of Lepidoptera on the planet are considered nocturnal butterflies, also called moths. Despite moths comprising 88-91% of all described Lepidoptera, they are subject to a disproportionately low level of research compared with butterflies (Anderson, Rotheray & Mathews, 2023).

The diurnal butterflies are included in the superfamilies Hesperioidea and Papilionoidea, which constitute the informal group "Rhopalocera". This name was adopted as diurnal butterflies have at the end of each antenna a thickened mace-shaped (*rhopalo*) while nocturnal butterflies belong to the "Heterocera" group, meaning that they present their antennae with different shapes (*hetero*).

Nocturnal and diurnal butterflies can be distinguished by three main differences:

- Antenna: this anatomical structure is very important for their sense of smell, with which they can identify the scent of flowers, and also helps some species to orient themselves during migration trips. Diurnal butterflies always present the same type as mentioned above, which are filiform (linear) and end in a small ball (clavate). Nocturnal butterfly antennas can be very diverse; filiform or pectinate, and are not clavated, devoiced of round end at the end.

- Wings: the diurnal species usually close their wings when they land, placing them vertically. This does not occur for many nocturnal species, as they normally leave their wings open, unfolded in resting position.

- In butterflies the frenulum, which joins the anterior and posterior wings can be observed.

Please note that the above-mentioned differences have their exceptions (as what normally occurs with other groups of fauna and flora) and should not be taken as a statement. It is also common to say that moths have less patterned designs with a high predominance of dark colours, are not as colourful, and fly only at night, although while the rule is confirmed for some species, these affirmations are not always correct.

Importance of Lepidoptera

Lepidoptera are essential for the food chain and environmental balance thus they constitute the food base for other animals and perform a key role in pollination.

Diurnal butterflies are well-known indicators of wildlife and environmental wealth. The use of butterfly's taxa is used as an indicator of wider insect biodiversity trends. Nocturnal Lepidoptera, are much more ecologically diversified and at least 15 times more taxonomically diverse than butterflies. Moths offer additional advantages over butterflies for assessing insect biodiversity change (Wagner *et al.,* 2021).

Moths play a key role in ecosystem services, they are well-known indicators of a healthy environment. They play an underestimated role of pollinators, complementing the work of diurnal pollinators, and helping to maintain diverse and abundant plant populations. As nocturnal pollinators, they pollinate many flowers at night. Moths present colour vision at a low light intensity as they require both visual and olfactory floral stimuli in order to locate and feed on flowers.

Lepidoptera decline

There is an accentuated decline in insects and there is no doubt that Lepidoptera diversity has also decreased. The State of the UK's Butterflies 2022 report has revealed the alarming news that 80% of butterflies in the UK have declined since the 1970s. To emphasize, those butterflies which are in the worst conditions are the specialists, particularly the ones related to affected habitats (Fox *et al.,* 2022).

In addition to facing many of the same pressures as their diurnal relatives, moths are also threatened by factors that are unique to nocturnal lifestyles such as ALAN (Anderson, Rotheray, & Mathews, 2023).

Regarding nocturnal Lepidoptera, Fox (2013) highlighted the need to understand the causes of moth declines as one of the 100 ecological questions of high policy relevance. Numerous studies provide evidence of moth declines on a large geographical scale (as biogeographic regions) but the details and consequences of those declines are best studied at smaller scales (Wagner *et al.,* 2021). The great moth diversity may facilitate an improved understanding of the drivers of change and the impacts that insect declines will have on other organisms, communities, and ecosystem functioning (Fox, 2013). Such losses are likely to have substantial impacts at higher and lower trophic levels, because of the importance of moths as herbivores, pollinators, and prey items and may affect the delivery of some ecosystem services (Fox, 2013). For example, faunal turnover associated with farmland abandonment and forest succession is an underappreciated factor affecting moth diversity (Wagner *et al.,* 2021). In short, there are still many studies to undertake specifically on moth declines.

4.1 Lepidoptera in Macaronesia

The Lepidoptera of this biogeographical region has been studied since the mid-19th century. As also generally occurs with insects, many of the endemic Lepidoptera are strictly linked to the different types of vegetation to such an extent that these species are important Macaronesia native forest pollinators and are far more sensitive to human influence (Meyer, 1995).

In Macaronesia, 177 species of nocturnal butterflies are known, which lack information on distribution and updated conservation status. Those Lepidoptera that coexist in these areas present mostly a predominant Palearctic affinity (Hölker *et al.,* 2010; Vieira & Constância, 2002). Although most of the endemic forms are also closely related to Palearctic species there are a few exceptions such as *Phlogophora interrupta* (Warren, 1905) in Azores, and *Phlogophora wallastoni* (Bethune-Baker, 1891) in Madeira, that are closely related to Nearctic species.
According to Meyer (1995), depending on the family there may be a higher or lower proportion of endemism. For example, Geometridae has a higher rate of endemism at an 88% rather than Noctuidae at a 17%. Families that contain species with high flight performances like Sphingidae as *Acherontia atropos* (Linnaeus, 1758) and *Agrius convolvuli* (Linnaeus, 1758), and Noctuidae as *Peridroma saucia* (Hübner, 1808), *Noctua pronuba* (Linnaeus, 1758), *Phlogophora meticulosa* (Linnaeus, 1758), *Autographa gamma* (Linnaeus, 1758) show a lower level of endemism and, reciprocally a higher proportion of non-differentiated continental elements (Meyer, 1995). For certain endemic species, the variation in wing patterns is very high compared to related continental species (Meyer, 1995).

4.1.1 Lepidoptera in the Azores Archipelago

There is a long-standing stability in the species inventory between islands throughout the Lepidoptera order, where butterflies of the Azores are considerably well studied (Borges *et al.,* 2015). Many publications on Lepidoptera from the Azores can be found in books, guides, scientific articles, and journals (Borges *et al.,*2022; Borges *et al.,* 2010a).

The diversity of Lepidoptera fauna of the Azores islands, shows a relatively poor evolutionary development in the number of endemic species, being the one with the least number of species in Macaronesia when compared with the archipelagos of Madeira and the Canaries. This fact might have resulted from various reasons; low altitude and isolated position of the archipelago, the recent geological age, the lower number of endemic species of plants, and the type of colonization (accidental transport and/or migration).

Primordial colonization was more complicated at first, though currently what arrives nowadays in the archipelago is more likely to have an invasive character. A flying insect survey took place in the Azores and noted an increase in alien species from 2013 to 2018. Because of the introduction of these alien species, those species that are rare, less generalist, and with fewer dispersal abilities are mostly affected by invasive species, observing a decline of 11 endemic and native species from the Lepidoptera fauna (Santa-Rita *et al.,* 2020; Borges *et al.,* 2022).

In the Azores, there is a total of 159 taxa of Lepidoptera, distributed in 29 different families present in this archipelago. Analysing into detail these records, five of these are endemic species to Macaronesia, 63 native species, and 47 introduced species (Borges *et al.,* 2022). A number of 40 species are endemic to the Azores, corresponding to a value of endemism in the order of 27% (Picanço & Borges 2017). Compared to the other archipelagos, there are fewer subspecies than in the rest of the other European archipelagos (Borges *et al.,* 2022; Borges *et al.,* 2018; Santa-Rita *et al*., 2020).

Five endemic species from the Azores are already included in the Red List extracted from the International Union for Conservation of Nature and Natural Resources (IUCN).
A total of 260 species were assessed during the last decade in the UICN Mid Atlantic Island Specialist Group (*see* http:// www.maiisg.com), in which all the Azorean rare endemic arthropods were evaluated.

In summary, the information recollected about the Conservation Status provided by the Red List Biodiversity Portal IUCN is available for a number of 34 Lepidoptera, all of which are endemic species and are the following;

Low Concern	12 species; *Cyclophora azorensis* (Prout, 1920), *Eudonia interlinealis* (Warren, 1905), *Eudonia luteusalis* (Hampson, 1907), *Hipparchia azorina* (Strecker, 1898), *Hipparchia miguelensis* (Le Cerf, 1935), *Mesapamea storai* (Rebel, 1940), *Noctua atlantica* (Warren, 1905), *Phlogophora interrupta* (Warren, 1905), *Scoparia aequipennalis* (Warren, 1905), *Scoparia*

	coecimaculalis (Warren, 1905), *Scoparia semiamplalis* (Warren, 1905), *Xanthorhoe inaequata* (Warren, 1905).
Near Threatened	4 species; *Argyresthia atlanticella* (Rebel, 1940), *Noctua carvalhoi* (Pinker 1983), *Phlogophora cabrali* (Pinker, 1971), *Udea azorensis* (Meyer, Nuss & Speidel, 1997).
Vulnerable	4 species; *Eudonia* melanographa (Hampson, 1907), *Neomariania oecophorella* (Rebel, 1940), *Phlogophora furnasi* (Pinker, 1971), and *Scoparia carvalhoi* (Nuss, Karsholt & Meyer, 1997).
Endangered	7 species; *Apamea ramonae* (Wagner, 2015), *Apamea sphagnicola* (Wagner, 2014), *Argyresthia minusculella* (Rebel, 1940), *Brachmia infuscatella* (Rebel, 1940), *Eudarcia atlantica* (Henderickx, 1995), *Micrurapteryx bistrigella* (Rebel, 1940), *Neomariania scriptella* (Rebel, 1940).
Critically Endangered,	There are 7 species found in the highest category awarded by the IUCN are the following; *Argyresthia poecilella* (Rebel, 1940), *Eupithecia ogilviata* (Warren, 1905), *Hadena azorica* (Meyer & Fibiger, 2002), *Homoeosoma miguelensis* (Meyer, Nuss & Speidel, 1997), *Homoeosoma picoensis* (Meyer, Nuss & Speidel, 1997), *Neomariania incertella* (Rebel, 1940), *Phlogophora kruegeri* (Saldaitis & Ivinskis, 2006).

Of the total count of all the above species, the vast majority are nocturnal except for two diurnal species; *Hipparchia azorina* (Strecker, 1898), and *Hipparchia miguelensis* (Le Cerf, 1935). Also, the last species is found under the list of the "*100 priority species*" by UICN, which is an endemic species to São Miguel.

Out of the existing number of Lepidoptera present in the Azores (159), there is a total of 149 species of nocturnal Lepidoptera, 36 of these species of moths were described as endemic to the Azores archipelago, and are included in the following families; two representatives of family Argyresthiidae, eight in Crambidae, one in Gelechiidae, five in Geometridae, one in Gracillariidae, 12 in Noctuidae, one in Pterophoridae, two Pyralidae, three Stathmopodidae, and one in Tineidae (Borges *et al.,* 2022).

In addition, two diverse families; Noctuidae (presents 11 endemic species) and Crambidae (presents 8 endemic species). Both families have a large distribution around the archipelago with 58% of them occurring in at least four out of the nine islands and many of them are widely distributed within each island (Borges *et al.,* 2018). Others have a very restricted distribution, nine out of these 36 endemic species only occupy a particular island three in Flores, three in São Miguel, one in Faial, one in Pico and one in São Jorge).

Despite the fact that Lepidoptera is one of the most well-studied insect groups in the Azores and the inventory of Azorean endemic arthropods is almost complete (Borges *et al.*, 2022), there recently were discovered and described four new endemic species. These species were classified in the Noctuidae family suggesting that still more recollecting, taxonomic and genetic studies must be undertaken to assess identifications.

Extracting from historical data, at present there are five species in the Azores that are susceptible to being extinct due to the lack of information, as only one individual representative of one of both sexes is recognized, leaving basic information unknown. For example, *Eupithecia ogilviata* (Warren, 1905) is most probably extinct as there are no recent records.

Also, initiating in the subject from this bibliographical review on how nocturnal Lepidoptera is affected by ALAN, it is known that the most abundant Lepidoptera in the Azores which is attracted to artificial lights belongs to genus Argyresthia (Santa-Rita *et al.,* 2020).

4.1.2 Lepidoptera in the Canary Islands

In terms of Lepidoptera within Macaronesia, the Canary Archipelago is the most important in terms of the number of species richness and endemism. Specifically, there is a number of 599 different species of Lepidoptera (Figure 4) distributed in 42 different families present in this archipelago of which there is a total of 285 endemic species (Suárez *et al.,* 2018; Gobierno de Canarias, 2022; Arechavaleta *et al.,* 2010).

Familia	N.º de especies en Canarias	Hábitos generales
Alucitidae	1	Crepusculares y diurnas
Geometridae	83	Nocturnas, crepusculares y diurnos
Noctuidae	148	Nocturnas y diurnas
Sphingidae	6	Nocturnas y crepusculares
Psychidae	7	Diurnas y crepusculares
Pyralidae	104	Nocturnas
Coleophoridae	30	Crepusculares
Nepticulidae	13	Nocturnas
Erebidae	40	Nocturnas
Pterophoridae	26	Nocturnas y crepusculares
Cosmopterigidae	18	Nocturnas y crepusculares
Gelechiidae	63	Nocturnas
Tineidae	48	Nocturnas y crepusculares
Plutellidae	4	Nocturnas y crepusculares
Yponomeutidae	8	Nocturnas y crepusculares
TOTAL	**599**	

Figure 4 | Species of nocturnal Lepidoptera described in the Canary Islands. Extracted in October 2022 from BIOTA https://www.biodiversidadcanarias.es/biota.

According to the number of species in Arechavaleta *et al.,* (2010) and Gobierno de Canarias (2022), whether nocturnal or diurnal Lepidoptera, they are grouped into 44 families. The number of endemic individuals belonging to each specific family, if any, is marked in parentheses in the following table;

Acrolepiinae (for some authors considered a subfamily of Glyphipterigidae)	Alucitidae (1 endemic)	Arctiinae (a subfamily of Erebidae; 3 endemic taxa)
Autostichidae (8 endemic)	Bedellidae (1 endemic)	Blastobasidae (7 endemic)
Bucculatricidae (2 endemic)	Carposinidae (3 endemic),	Choreutidae
Chrysopeleiinae (a subfamily of Cosmopterigidae)	Coleophoridae (11 endemic)	Cosmopterigidae (2 endemic)
Cossidae	Elachistidae, (2 endemic)	Epermeniidae

Epipyropidae	Ethmiinae (a subfamily of Gelechiidae)	Gelechiidae (14 endemic taxa)
Geometridae (42 endemic taxa)	Glyphipterigidae (1 endemic)	Gracillariidae (8 endemic)
Hesperidae (1 endemic)	Lecithoceridae,	Lycaenidae (1 endemic),
Meesiidae (two endemic species; *Infurcitinea canaricola* (Gaedike, 2020) and *Infurcitinea toechophila* (Walsingham, 1908)	Momphidae (3 endemic)	Nepticulidae (9 endemic)
Noctuidae (74 endemic taxa)	Notodontidae (1 endemic subspecies)	Nymphalidae (6 endemic)
Oecophoridae (3 endemic taxa)	Pieridae (9 endemic taxa)	Plutellidae (1 endemic species)
Psychidae (4 endemic species)	Pterophoridae (3 endemic species)	Pyralidae (19 endemic taxa)
Scythrididae (9 endemic species)	Sesiidae (1 endemic species)	Sphingidae (1 endemic species)
Stathmopodidae. (1 endemic species; *Tortilia flavescens* (Falck & Karsholt, 2019)	Tineidae (9 endemic taxa)	Tischeriidae (2 endemic species)
Tortricidae (22 endemic species)	Yponomeutidae (2 endemic species)	

In addition, from the different orders of Lepidoptera present in this archipelago, there are 7 existing endemic genera which are:

Ambloma	*2 species; Ambloma brachyptera* (Walsingham, 1908) and *Ambloma klimeschi* (Gozmány, 1975).
Archigalleria	*1 species; Archigalleria proavitella (*Rebel, 1892).
Chersogenes	*1 species; Chersogenes victimella* (Walsingham, 1908).
Mniotype	*4 species; Mniotype fratellum* (Pinker, 1965), *Mniotype schumacheri* (Rebel, 1917), *Mniotype usurpatrix* (Rebel, 1914).
Paranataelia	*2 species; Paranataelia tenerifica* (Hampson, 1906), *Paranataelia whitei* (Rebel, 1906).
Pragmatodes	*1 species; Pragmatodes fruticosella* (Walsingham, 1908).
Stathmopolitis	*1 species Stathmopolitis tragocoprella* (Walsingham, 1908).

Also, the information recollected about the Conservation Status provided by the Biodiversity Portal IUCN Red List profiles from Canary Lepidoptera fauna in comparison with the Azores, gave fewer results (12) and mainly all diurnal Lepidoptera;

Least concern	8 species; *Cyclyrius webbianus* (Brullé, 1839), *Euchloe hesperidum* (Rothschild, 1913), *Euchloe grancanariensis* (Acosta, 2008), *Euchloe eversi* (Stamm, 1963), *Hipparchia gomera* (Higgins, 1967), *Hipparchia tamadabae* (Owen & Smith, 1992), *Hipparchia wyssii* (Christ, 1889), *Pararge xiphioides* (Staudinger, 1871).

Vulnerable	3 especies; *Gonepteryx cleobule* (Hübner, 1825), *Hipparchia bacchus* (Higgins, 1967), *Hipparchia tilosi* (Manil, 1984).
Endangered	1 species; *Pieris cheiranthi* (Hübner, 1808).

In the Canary Islands, there is a large number of recorded species but there are also many that are still undescribed. As attested by Falck *et al.,* (2022), where it has been published the description of six new species belonging to the Pyralidae family. This situation is due to many factors; mainly identification is particularly complex and sometimes based on morphological and genetic work, and to a lesser extent; to insufficient collecting efforts and the demand for funds to compare between species or study recent records.

4.1.3 Lepidoptera in Madeira archipelago

According to the information available on the study of Lepidoptera in Madeira, and as is generally the case in this order of insects, there is a wealth of information from articles and journals, especially from diurnal butterflies and macrolepidoptera, which are well studied.

Due to the isolated position and age of these islands (Aguiar & Karsholt, 2008), the Lepidoptera present in the Madeira archipelago consists of a total of 331 taxa. Now, the cumulative number of Lepidoptera taxa on all islands is divided as follows; in the Madeira archipelago there are 331 present taxa, of which 81 are endemic; in Madeira island, there are 315 (of which 80 are endemic), in Porto Santo, there are 137 (of which 18 are endemic), in Desertas there are 26 different taxa (and 6 endemic taxa) and finally there are 24 present taxa and none endemic species nor subspecies in Selvagens islands.

According to the number of species in Borges *et al.,* (2008), whether nocturnal or diurnal Lepidoptera, they are grouped into 36 families. The number of endemic individuals belonging to each specific family, if any, is marked in parentheses on the table below;

Acrolepiidae (2 endemic)	Arctiidae	Autostichidae 1 endemic to Macaronesia; *Apatema fasciata* (Stainton, 1859)
Bedellidae (1 endemic)	Blastobasidae (22 endemic, 2 of them MAC)	Carposinidae (2 endemic)
Choreutidae (1 endemic)	Coleophoridae (1 endemic to MAC)	Cosmopterigidae
Crambidae (7 endemic, 1 of them MAC)	Depressariidae (1 endemic to MAC)	Elachistidae (2 endemic, one of them to MAC)
Epermeniidae	Ethmiidae	Gelechiidae (4 endemic, 1 to MAC)
Geometridae (14 endemic, 3 of them to MAC)	Glyphipterigidae (Both 2 endemic to MAC endemic)	Gracillariidae (7 endemic, 5 of them to MAC)
Lycaenidae (1 endemic)	Lyonetiidae	Nepticulidae (1 endemic to MAC)
Noctuidae (18 endemic, 4 of them to MAC)	Nolidae	Nymphalidae (3 endemic, one of them to MAC)
Oecophoridae (1 endemic to MAC)	Pieridae (2 endemic)	Plutellidae
Psychidae	Pterophoridae (3 endemic, 2 of them to MAC)	Pyralidae (2 endemic, 1 to MAC)

Schistonoeidae	Sesiidae	Sphingidae
Tineidae (2 endemic)	Tortricidae (10 endemic, 3 of them to MAC)	Yponomeutidae (3 endemic, 2 of them to MAC)

- In Madeira, the most hyper-diverse genus, which presents a large number of species, and also endemic species is namely the moth genus Blastobasis.

- There are no representatives of hesperiid butterflies nor notodondid moths on these islands (Serrano *et al.,* 2015).

Although in recent times and in line with the current situation, only a few and mostly invasive species have been added, among micro Lepidoptera fauna, discoveries still occur regularly, and a number of taxonomic problems still await resolution (Rota *et al.*, 2014).

II. Effects of ALAN (Artificial Light at Night) on nocturnal insects

1. ALAN: Artificial Light at Night

As an introduction to this section, it's important to differentiate between the terms ALAN, which stands for "*Artificial Light at Night*" and "*light pollution"*. These terms are used often indistinctly and can be easily confused. In short, the negative effects of ALAN are referred to as light pollution.

Without a doubt, one of the great achievements of humanity is the generation of artificial light and the possibility to use it at any time (preferably when needed). Before mentioning the negative issues related to ALAN, it cannot be forgotten how essential it has been for human development. Some examples of advantages and benefits achieved by anthropogenically created light are mainly related to the great importance of the economy's expansion and the welfare of human society by enhancing human safety and providing longer periods of work and recreation.

Culturally, light is a symbol of enrichment, modernity, urbanity, and security so it is adequate to mention that light production has a co-evolutionary factor with the development of human beings, having a great impact on the population (Hölker *et al.*, 2010). ALAN is a widespread phenomenon of continuous expansion due to urbanization increases.

As mentioned, the development of street lighting can be mainly considered as a by-product of increasing development (Altermatt & Ebert, 2016), it is also estimated that the amount of artificial light seen on Earth at night increases by an average of 2% each year.

This type of lighting is between 100 and 200 years old and its generation has evolved from different types of gases to the current electricity. Artificial light was once produced by burning substances, these combustion-based forms of lighting emit a broad spectrum of light but are inefficient. The introduction of the electric filament lamp in the mid-19th century caused a revolution in lighting, allowing much brighter, more efficient light to be produced (Bruce-White & Shardlow, 2011).

As stated above, artificial lighting in the night-time environment has brought many benefits to humankind but also costs, ALAN is now considered a major concern for biodiversity and human health (Gaston *et al.,* 2015; Desouhant *et al.*, 2019; Pérez Vega *et al.,* 2022). The growing urbanization and increased human population near coastal areas have threatened its ecosystems. For example, ALAN is one of the most important environmental stressors associated with the urbanization of sandy beaches.

The brightness of the night sky is what results from the reflection of radiation scattered by the components of the atmosphere (gas molecules, aerosols, and particulate matter). This brightness results from two separate components; *natural sky brightness* and *artificial sky brightness*. The first, natural sky brightness is much more quantifiable and is globally much lower than artificial sky brightness, however, the second is the brightness attributed to artificial radiation sources, especially those emitted to the sky and also those reflected from the earth's surface. This phenomenon is highly variable and depends on four aspects;

1) Amount of light directed to the sky
2) Amount of gas and dust in the atmosphere
3) Immediate weather conditions
4) Direction in which it is seen

- Some locations have decreased their brightness in the light sky, due to incentives to reduce ALAN and other pollutants, which include technological innovations driven by ecological and economic incentives.

Currently, artificial lighting consumes 19% of total global electricity (Hölker *et al.,* 2010). To generate greater economic and energy savings, there has been a general tendency worldwide to transition from energy-inefficient light sources to energy-efficient LED, changing old bulbs which wasted more energy, to LED light bulbs. This proposal for change, even being common and widely shared, is not as beneficial as it was thought initially. So even if a reduction in energy consumption is achieved, the use of LEDs has a rebound effect. In a recent report from the Dark Sky Association (IDA, 2020) it is stated that the luminous flux currently installed on LED lamps is thousands of times greater than before using LEDs. The spectral shift between LPS to LED lamps becomes an ecological experiment that has potentially devastating ecological results, so a better understanding of the impact of different light sources is needed (van Grunsven *et al.,* 2019; Owens & Lewis, 2018).

Recent global studies on the brightness of the night sky concluded that lighting technology has precipitated exponential increases in night sky brightness worldwide (Figure 1) raising scientist's concerns to the point of, an 88% of Europe experiences light pollution in the form of an increase in night sky brightness (Owens & Lewis, 2018).

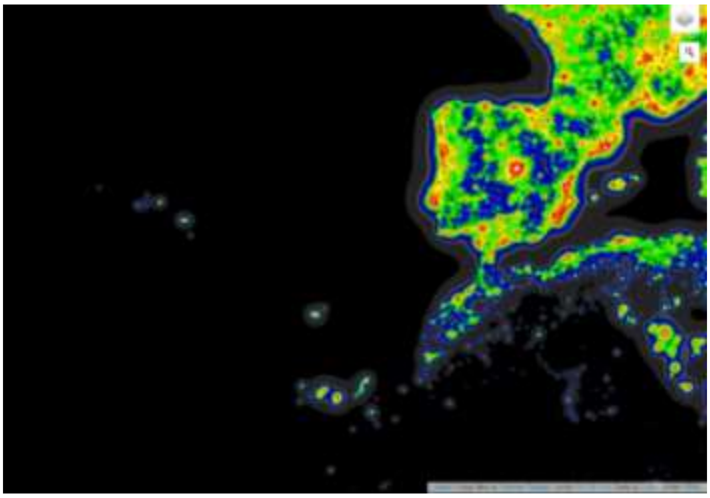

Figure 1 | Map of light pollution as a result of the brightness of the night sky, focusing on Macaronesia. Extracted from: *https://darksitefinder.com/maps/world.html#5/36.503/-24.899* on the 5th of December 2022.

As can be seen on the map from Figure 1, the quality of the night sky is at risk. Never before has outdoor artificial light been so abundant at night, with an extraordinary increase in the last decades. The question of artificial light outdoors is generally approached from the energy point of view, neglecting its polluting factor which affects health and ecology.

ALAN is an irrevocable growing factor occurring on a global scale, the locations with the highest levels of ALAN tend to be more economically developed places, where the service and industry sectors predominate. In addition, the coastal areas are highly affected as a result of tourism. An estimated 22% of the global coastline is exposed to artificial light, and many offshore coral reefs are chronically exposed to artificial lighting from cities, fishing boats, and hydrocarbon extraction (Swaddle *et al.,* 2015).

Due to the increase in development, involvement of lighting systems, higher population numbers, and in some cases the indiscriminately imposed lighting, a significant increase in ALAN is expected. At present, 21% of the population is living around light pollution night-time services as a result of developmental activities (Kumar *et al.,* 2019).

Interestingly, on the same map (Figure 1), we can see how the northern hemisphere is mostly impacted by light pollution, while in the southern hemisphere, it is noticeable that it does not reach those levels, except for some strategic locations which are more developed. This does not mean that places in the southern hemisphere should be banned from expansion, but it is important to understand that development also means lighting with respect for nature. Being aware of the mistakes that have been performed in the past and still at present together with using mitigation measures that will be seen in **Chapter III** will be helpful to avoid the disadvantages of ALAN.

1.1 Light Pollution - Negative Effects of ALAN

Light is recognized as a polluting agent by the United Nations and the European Union. Light pollution is one of the most disregarded forms of contamination that impact human activity. Astronomers first identified light pollution as a threat to night observations in 1930, since the brightening of the sky was produced by artificial light. Currently, 33% of the world's population can no longer see the Milky Way from their homes due to the concomitant increase in light pollution (Kumar *et al.,* 2019).

According to Kyba *et al.,* (2017), Portugal does not display positive results about excess light. It is stated as the worst country in Europe regarding light pollution, consisting in the European country that most increased its illuminated area between 2012 and 2016 and is also the country that generates the highest light pollution per inhabitant and per GDP. For a better term of comparison, mainland Portugal emits to the atmosphere a per capita flux of four times higher than Germany.

In order to emphasize the importance of protecting the night as a natural resource, it is going to be listed some negative effects that must be protected not only for nature protection and controlling carbon dioxide emissions but for the population to be able to see the night sky, which consists of a worldwide right.

Apart from the mentioned benefits of ALAN, there is mounting evidence of how light pollution affects a large number of organisms and populations, ecosystems, wildlife, and biodiversity. The loss of natural night hampers not only flora, fauna, and micro-organisms but also human life. From an anthropocentric point of view, the effects on human welfare can be economic, health, and cultural actions such as nocturnal activities. Each year 6% more of the earth's surface is contaminated, and currently, 80% of the human world's population lives under light-polluted skies (Desouhant *et al.,* 2019).

Giving an example in the economic area, a large part of the energy produced for outdoor lighting is dissipated as a result of poorly designed lighting. The energy lost due to light pollution represents 50% of the energy produced for public lighting and costs the European Union around 5.2 billion euros per year. This is the equivalent of 30 euros per person living in Macaronesia and the total financial burden of light pollution on the islands would be 36 million euros. So there are significant financial expenses with light pollution and this cost could easily be avoided by, for example, well-designed quality lighting installation, which reduces energy use by 60-70%, saving millions of euros annually. We will see other examples of mitigation actions in Chapter III.

In addition to urban and economically developed areas where light pollution is a fact, rural and protected areas have also been affected (Gaston *et al.*, 2015). Since 1992, levels of light pollution have doubled in high biodiversity areas and are likely to continue to rise. By 2014, over 23% of the land surface of the planet experienced artificially elevated levels of night sky brightness (Owens *et al.*, 2020). The consequences of ALAN can be detected at places located tens or even hundreds of kilometres away from the source (sky-glow effect) and light pollution in urban areas must be controlled to reduce its effects on protected areas

(PA). These PA are intended to buffer biodiversity from anthropogenic stressors, but many are not sheltered from ALAN or the impacts of sky glow. Up to 42% of the protected territory in several regions of Europe, Asia, and South, and Central America have experienced recent significant increases in nocturnal lighting (Gaston *et al.*, 2015), PA are often embedded in agricultural landscapes where insect populations are pressured by multiple stressors. Therefore, declines observed in protected areas may be a reflection of population declines acting at a larger landscape scale (Grubisic *et al.,* 2018a).

It is also expected that the effects of ALAN on the barrier islands and coastal areas will translate into effects in the intertidal habitats. Coastal PA regularly experience foggy and high-aerosol conditions, which scatter light and amplify the local effects of light. On nearby islets, light propagates unimpeded across open water and its reach is extended by the reflection of high clouds.

ALAN and acoustic pollution

Artificial lighting has been identified as a growing environmental stressor and also co-occurs with other anthropogenic pressures such as noise pollution. The correlation between light and noise pollution has been pointed out in several scientific articles (Swaddle *et al.,* 2015; Desouhant *et al.,* 2019; Pérez Vega *et al.,* 2022; Grubisic *et al.*, 2018a). Anthropogenic noise and artificial light are sensory pollutants that have increased over recent decades, and they pose a global environmental challenge to terrestrial and aquatic environments (Swaddle *et al.*, 2015).
Mounting evidence suggests that noise and light at night have strong human life effects and ecological consequences, especially when they co-occur (generating effects on density, activity and taxonomic richness, community structure, and foraging activity behavioural changes) but it is scarcely known how these stimuli can drive evolutionary responses and these anthropogenic changes should be studied in combination to see whether they act additively or synergistically.

1.2. Types of Light Pollution

Light pollution is a generic term that refers to the total of all the adverse effects of artificial light. Inadequate street lighting is a major contributor to light pollution and represents the artificial outdoor light that is excessive, poorly directed, or intrusive, and it can manifest (Figure 2) in the following various ways:

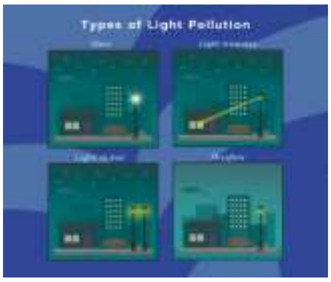

Figure 2 | Types of Light Pollution. Extracted from Natura@night official webpage. https://naturaatnight.spea.pt/?fbclid=IwAR0rxlBI9ehe45RaLB5jG3MLGX64A7rBO2zVRggLpB5Jt79Ch3yXJ0bORO8.

- Glare: Visual constraints that cause discomfort resulting from inadequately oriented or unshielded luminaires. Direct exposure to light reduces the ability to evaluate the light intensity and makes navigation difficult. Animals and humans are often dazzled and disorientated and may collide with infrastructures (also traffic, ships...etc.).
- Light trespass: Inadequately directed light to objects or areas where illumination is not required, such as inside dwellings or sensitive areas. Any light that penetrates private property should be unacceptable. They can impact the quality of life and circadian rhythm by making it difficult for people to sleep.
- Light clutter: Oversized light due to too many luminaires and/or too much luminosity in relation to the real needs. There are European standards that stipulate the amount and type of lighting required for specific areas.
- Sky glow: Results from diffused light from luminaires being emitted directly into the sky or light reflected by structures and roads. Diffuse or sky-glow not only reduces our ability to see the night sky but also interferes with natural processes such as photosynthesis and animal migration.

Direct light is relatively limited to small areas around light sources, indirect light or sky glow affects dark nights by scattering light in the atmosphere, spreading into much larger areas kilometres from its source. Light pollution is not uniform across the sky, for example, it will always be brightest in the direction of the nearest city. Sky glow prevents the visibility of stars, 23% of the world's non-polar land surface experiences light pollution today cause of sky glow (Grubisic *et al.*, 2018b).

2. Effects of ALAN on wildlife

ALAN is increasingly being recognized as a major driver of global change in the 21st century and is still an underestimated challenge for the environment, the importance of ecosystems at night has been long undervalued. In biological systems, darkness is used for essential processes concerning survival as resting and cellular repair among others that will be explained next.

ALAN is a serious environmental stressor that reshapes entire ecosystems. While some species appear to benefit from the direct effects of ALAN at first, the vast majority present negative aspects. There are currently many studies on how ALAN affects wildlife, but there is an urgent need to undertake many more studies on this matter in order to understand and counteract what is possible (Bolliger *et al.,* 2020a; Owens *et al.,* 2020).

Artificial light can have a large effect on intra and interspecific interactions resulting in a cascade of effects on biodiversity and ecosystem services (van Langevelde *et al.,* 2011). It weakens the resilience of individuals and ecosystems to other factors that are responsible for declines like climate change, habitat use or chemical pollutants, and exponentiation of this damage. Due to the fact, that it is a relatively recent impact, the rapid rise of these novel stimuli could decrease the likelihood that organisms possess the genetic variance to adapt to the altered environmental conditions, so evolutionary change is not yet reached to carry out responses to persist without being affected (Swaddle *et al.,* 2015).

In Desouhant *et al.,* (2019) it is highlighted that ALAN impacts all levels of biological organization, from organisms to communities and ecosystem functioning, and thus, confirms its detrimental impact as promotes consequences in human well-being.

Before introducing how it affects nature in general, some of the negative effects of ALAN on humans (impacts on human health, visual disturbance, economic and energy waste) have already been discussed above, although it is going to be explained an aspect shared by other organisms that have great influence, the modification of an endogenous process in the organism and synchronized to the environment through light, the circadian rhythm (Figure 3).

Figure 3 | Circadian cycle. Extracted from EELABS.

Both light and darkness are to be seen as important resources for organisms. ALAN disrupts the timing of various biological events due to a mismatch between the internal clock and natural cycles of light and darkness, this masking of lunar cycles may disturb these vital circamensual rhythms which may desynchronize ecological interactions (Desouhant *et al.*, 2019; Owens & Lewis, 2018 Altermatt & Ebert, 2016; Gaston *et al.,* 2013).

Following on from what has been discussed, varied organism groups experience a wide range of alterations under ALAN (Figure 4) and wavelength-dependent responses of affected behaviours and physiological processes vary among species, it even favours the spread of various vector-borne diseases (Desouhant *et al.,* 2019; Pérez Vega *et al.*, 2022).

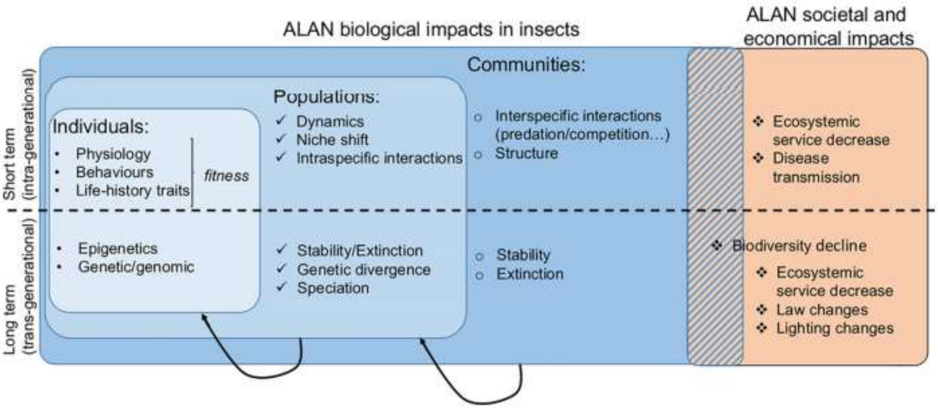

Figure 4 | Summary of ALAN effects at various levels of biological organization. Extracted from Desouhant *et al.,* (2019).

The effects of ALAN occur in all existing habitats invading biodiversity hotspots (Owens & Lewis, 2018). Basically, the same impacts occur, from one to different habitats, affecting distinct groups of flora and fauna. Also, some habitats are especially sensitive to ALAN, for example, freshwater habitats seem to be more affected than marine ecosystems. This may be because some habitats and their effects with ALAN have been more extensively studied than others. Here are some examples:

- In aquatic wildlife, other artificial lighting applications such as illuminated river bridges may over-illuminate the rear waterbody and potentially shift its optical composition at night (Pérez Vega *et al.*, 2022).

- In cave ecosystems which are normally dark locations, are affected by stage lighting Cave ecology has been mismatched by adding lights, enabling generalist species to invade the cave and out-compete the specialist species (Bruce-White & Shardlow, 2011). Some algae now can photosynthesize when it was never needed before which affects the cave environment (Gaston *et al.,* 2013).

- In marine ecosystems, reef-building organisms like mussels and polychaetes choose the site of settlement due to light levels, so due to the light penetrating deeper levels of water, resulting in that these organisms might settle in lower levels than supposed (Haarman, 2022).

Moreover, changes in light regime can be characterized as changes in spatial distribution, timing, and spectral composition or artificial light sources producing changes in behaviour, space use, migration, physiology, development, and reproduction in almost all organism groups, including microorganisms and plants. The ecological effects of ALAN depend on both its intensity and its spectral composition, while the severity of the impact depends on the degree of overlap between spectral sensitivity, spectral emission, and intensity of the particular ALAN source (Gaston *et al.,* 2013; Gaston *et al.*, 2015; Owens & Lewis, 2018).

Plants are also affected by artificial light, the following are some of the effects produced; ALAN stimulates and alters natural processes such as photosynthesis, budburst initiation, and flowering process, it impacts interactions between plants and herbivores, disrupts pollen transport, changes the rhythm of the foliage, the toughness of leaves, stems, density and colour. The increase in biomass produced by increased photosynthesis can seem positive at first, although, can also provide disadvantages such as damaging the photosynthesis apparatus, reducing starch production, and eventually causing premature leaf death, resulting in a vulnerable plant life (i.e. susceptible to frost damage).

2.1. ALAN effects on animals

Focusing on the animal kingdom, these organisms are mainly able to react in a wider range of possible responses to ALAN. In general, it is easier to observe those responses to direct light (phototaxis) in which these individuals *move to* or *move from* the light source. Despite sky glow responses also occur, the effects are not so clearly visible. Worldwide, more than 30% of vertebrates and 60% of invertebrates have evolved to cover nocturnal activities, which are generally denominated as nocturnal animals, meaning they have visual systems adapted to low natural night-time light such as the moon and stars (Grubisic *et al.,* 2018b; Hölker *et al.,* 2010; Owens & Lewis, 2018).

ALAN produces problems not only in nocturnal and crepuscular biodiversity. A key feature to understanding how to level the effects of ALAN is to know whether the individual's activity behaviour is strictly nocturnal (or diurnal) or facultative nocturnal (or diurnal). Light pollution can result in diurnally active species becoming more active at night (Bruce-White & Shardlow, 2011).

It is important to emphasize that in general, the positive and negative responses when exposed to ALAN, are the following; the animals suffer intra- and inter-specific effects, resulting in altered behavioural responses, predator-prey interactions, competition effects that benefit some and disadvantages others (in occasions camouflage is not useful anymore) (Grubisic & van Grunsven, 2021).

Although this project especially focuses on the interaction between ALAN and seabirds (A3), bats (A4) and nocturnal insects, more specifically on Lepidoptera (A5), many other animals are affected by light pollution such as fish, reptiles, and amphibians among others.

Next, some examples of different responses in different animal groups when ALAN interferes; Diurnal and crepuscular predators may become facultative nocturnal predators under suitable light conditions;

In avifauna studies;

- Birds sing during the day and rest at night but when ALAN interferes, it changes bird physiology and reproduction success.
- Nocturnal raptors. Despite being nocturnal, some show avoidance behaviour to strong darkness and also strong illuminance.

- Migratory birds on a normal basis rest and feed during the day and fly at night, when ALAN acts, it attracts these birds causing them to strike and also changing their behaviour. Using artificial light has been shown to interfere with the orientation direction during migration. In addition, it highlights the importance of this effect on a more local scale too, interfering with local dispersal and metapopulational connections (Bruce-White & Shardlow, 2011).

Also, spiders, even if they are typically nocturnal, have a preference to create their webs in illuminated areas in order to hunt their prey; snakes thrive in the dark, so they stop hunting when illuminated as a result of being seen. As an example in amphibians, a highly vulnerable taxon, ALAN might not constitute a population threat, although it can reduce resilience and increase the vulnerability against other anthropogenic stressors, such as changing preference for shelter and altered vocalization calls. Also, ALAN affects other diurnal species that become facultative nocturnal in order to forage more, mismatching their physiology.

Understanding the damaging effects of light pollution on nocturnal animals is a long-standing problem in conservation. ALAN is an underestimated threat to species and ecosystems and may exacerbate already precarious conditions for endangered species. There is clear evidence that ALAN is a potential stressor and can alter the hormonal balance, behaviour, physiology, orientation, or survival of selected organism groups by influencing organism fitness, food web interactions, biotope connectivity, community composition and population dynamics (Hölker *et al.,* 2010; Pérez Vega *et al.*, 2022). For example, the altered stress perception (which is indicated by low cortisol rates in different animal groups), induces a physiological and behavioural change in animals, as well as mass mortality episodes for certain species.

ALAN can disturb and draw individuals from long distances, whilst repelling others, affecting many activities (orientation, navigation, finding resources, courtship, the interaction between species, predator avoidance, foraging, reproductive behaviour and daily, monthly or annual movements, impacting on hibernation cycles) and influencing biodiversity and migratory flows in some cases.

In general, changed habitat use due to light produces common effects which are predation, competition, avoidance and disorientation, diminishing the ability of nocturnal animals to navigate. In Owens & Lewis (2018) it is recommended to classify the different effects of ALAN in nocturnal animals by five different categories of impacts (temporal and spatial disorientation, attraction, desensitization and recognition) which can be useful to better understand these effects.

2.2. ALAN effects on arthropods

Exposure to ALAN was shown to affect the abundance, community structure, and density and disrupt the reproductive behaviour of arthropods by affecting fertility, ovipositional and survival rate of the species during the larval stage (decreased hatch rate and prolonged egg period) resulting in the decreasing the reproductive success and survival of species.

Light even at very low intensities is considered an essential cue for arthropods (Fox, 2013). Although the vast majority of studies report positive phototaxis when arthropods are exposed to ALAN (Pérez Vega *et al.*, 2022), there is also negative phototaxis (avoidance). It is stated that there is an existing bias in the study of effects and that there is undeniably a gap that must have to be filled with scientific knowledge. Most studies do not describe the source of light or whether it is direct or indirect ALAN. Also, it has been acknowledged that there is a large majority of studies that have their main research on the different effects of LEDs, however, less research has been undertaken regarding the effects related to different types of light.

In short, there is still much to be studied and as will be seen in this literature review, the investigation mustn't cease. This is the first of its kind relating the effects of light pollution in insects focusing on the Macaronesia region so presenting knowledge gaps and research directions in the field should continue to be considered.

2.3. Visual systems

Vision plays a vital role in wildlife, helping them navigate, find food, avoid predators, and communicate. How do visual systems function? Light itself is invisible, it behaves both as a particle (photon) and as a wave. Wavelengths are measured in nanometres (nm) and can be perceived in two different ways:

- First, through the light source which shows the power of attraction to light. Most animals are attracted by light, meaning they are phototropic to such an extent that they cannot control their demand for light. Many internal systems are regulated by light and are observed externally by visible behaviours. These correspond to typically evolutionary changes.

- Secondly, light can be perceived through specific organs of sight, with several photoreceptors. These photoreceptors are photosensitive cells that enable vision and thus, are sensitive to specific wavelengths of light (each representing a specific colour). The spectral sensitivity of a photoreceptor is defined as the fraction of incident light that is absorbed by the photoreceptor's visual pigment and subsequently causes an electrical signal.

Animals can detect light in diverse ways depending on how their photoreceptors are built (eyes, cell spots or others). Each animal is affected differently by lights with different intensities and wavelengths. The photoreceptor cells of the vertebrate visual system are different from the visual systems of other invertebrate animals such as insects or molluscs. This is because vision has taxonomic features, each species perceives differently as they have different groups of photoreceptors, which are sensitive to specific wavelengths. Depending on the specific animal group, those animals that are from the same family or genus, will have fewer differences in the photoreceptor output while those from a different family will have unequal numbers and types which may provide different responses to light.

The ability of an animal to use the spectral composition of light independent of intensity is called colour vision and is widespread among animals. Colour vision is based on neuronal interactions that compare the outputs of, at least two spectral types of photoreceptors. Colour vision depends on the spectral sensitivities and interactions of the participating photoreceptors. The interaction between the intensity and spectral composition of artificial light and the adaptation of an organism's eyes will affect whether visual perception is enhanced, disrupted or unaffected by light pollution, and hence the potential downstream behavioural and ecological effects (Gaston *et al.,* 2013).

So in order to discuss how diverse is the vision capacity in different groups of animals, the example of humans will be used for obvious reasons.

Human organs of sight, correspond to the eyes and they present trichromatic photoreceptors which are sensitive to blue, red and green (Owens & Lewis, 2018). Light vision in the human visible spectrum is between 400 and 700 nm thus it is impossible to perceive other colours that have higher or lower wavelengths than the above (Figure 5).

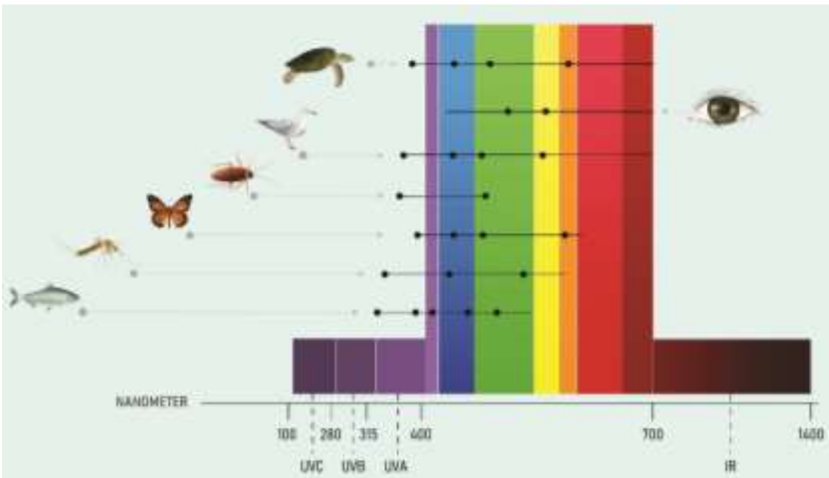

Figure 5 | Visual systems in different organisms (Commonwealth of Australia, 2020).

Colour vision is found in both diurnal and nocturnal insects, although most complex systems have been found in day-active groups. Different species' adaptations to their niches led to changes in the variability of spectral sensitivity whereby diurnal insects. Butterflies and dragonflies, present more visual **opsins** (macromolecules that are photosensitive to different wavelengths of light waves) that improve colour discrimination. Those nocturnal insects and those insects present in subterranean habitats, lost their opsins, reducing their ability to discriminate between colours and reducing their colour vision capacity (Van Der Kooi *et al.,* 2021; Owens & Lewis, 2018).

Each species has a different set of photoreceptors and is therefore sensitive to different wavelengths. Extrapolating this information to the ALAN theme, there is no artificial light without ecological impact, so each light has an impact on each animal group or specific species. In addition, polarization vision and motion vision generally use monochromatic information. The orientation of linearly polarized light represents an important visual stimulus for many insects, the detection of polarized skylights by many navigating insect species is especially known to improve their orientation skills.

Understanding the sensitivity of wildlife to different light wavelengths is essential for assessing the potential impact of artificial light on animal behavior and physiology.

2.4. ALAN effects on insects

Considering that light pollution is a recent driver of insect declines, this factor affects the manner which the insects are attracted by the lights. It is important to integrate all the information about the effects of ALAN about how it affects insects on a general basis before entering into the taxon-specific response to ALAN (specifically Lepidoptera).

Insects can be regarded as a relevant biological model group to demonstrate the negative effects of artificial lighting on nature (Eisenbeis *et al.,* 2009). Some of the reasons for this are listed below:

1) Insect class contains the largest number of species in the Animalia kingdom and it has colonized all terrestrial ecosystems (Borges *et al.,* 2022).

2) They present a short generation time that allows to conduct transgenerational experiments to simulate biological evolution and thus study evolutionary changes (Desouhant *et al.,* 2019).

3) Their varied visual system makes them sensitive to a wide spectrum of wavelengths. ALAN can have different effects depending on the overlap of its spectrum with the sensitivity of insect visual systems (Grubisic *et al*., 2018a; Desouhant *et al.,* 2019).

4) Due to their important role in ecosystems, the decline of their populations also causes cascading negative effects on birds, bats and other pollinators, these effects are transferred to the entire ecosystems. The most important ecosystem services provided by insects in Macaronesia are habitat maintenance and pollination (Borges *et al.,* 2018). For example, both nocturnal and diurnal pollinator communities play an essential and complementary role in plant reproduction.

Pollination is considered to be an ecosystem service that may be disrupted by increasing ecological light pollution (Macgregor *et al.,* 2015). Nocturnal illumination can disrupt visual cues for pollinators by changing the nocturnal light spectrum or reducing the release of floral scent, rendering flowers less attractive (Grubisic & van Grunsven, 2021). The nocturnal insects that postpone foraging until their habitat is sufficiently dark are most likely to be negatively affected by a reduction in temporal niche cascade of problems such as night-time pollination (Owens *et al.,* 2020).

5) Many insects are currently in critical conservation situations. Action is needed with urgency, namely the implementation of area-based management plans thus they are disappearing at a high rate. The damage to fauna groups with higher endemicity rates in

Macaronesia, such as bats and nocturnal Lepidoptera, are unknown but potentially high and changes in ALAN will contribute to their negative status.

The diffuse sky glows and local sources of artificial light can impact the behaviour, physiology and fitness of insects. Light pollution can impact insects by reducing their total biomass and by changing the relative composition of populations. Damage caused by light pollution to fauna groups with higher endemicity rates, such as insects in Macaronesia, is unknown but is considered potentially high thus changes in artificial light at night will contribute to their conservation.

Next, the main effects on insects:

- **Alteration of behaviour**: Light pollution can alter the behaviour of insects, such as their feeding, mating, and migration activities. For example, artificial lights can interfere with the ability of insects to navigate in the dark, which can affect how they search for food or mate.
- **Alteration of life cycles:** Exposure to artificial light can also alter the life cycles of insects, such as their growth and development. This can have cascading effects on ecosystems, as insects are an important food source for other animals.
- **Changes in physiology:** Exposure to artificial light can have effects on the body functioning of insects. For example, it can affect the production of hormones that control growth and reproduction.
- **Reduction of habitat quality:** Light pollution can reduce the quality of habitat for insects by altering the availability of natural resources such as light, darkness, food, and shelter.
- **Changes in geographic distribution**: Light pollution can also alter the geographic distribution of insects, as artificial lights can create physical and psychological barriers that hinder their movement and migration.
- **Reduction of species diversity**: Light pollution can change the structure of ecosystems by affecting the diversity of insect species. Artificial lights can attract certain species of insects, while others may avoid them. This can change the composition of the insect community and reduce species diversity.
- **Decreased survival**: Exposure to artificial light can also increase the mortality rate of insects. In some cases, artificial lights can attract insects and make them exhausted, which makes them more vulnerable to predators and reduces their survival.
- **Impact on pollination**: Insects play an important role in pollinating plants, and as mentioned, light pollution can interfere with this process. Artificial lights can attract pollinators away from plants, which can reduce pollination and affect food production.

To recap, ALAN affects the movement, reproduction and development of many insect species and can alter predation rates. Also, changes in reproductive behaviour, can disrupt natural rhythms, lead to ecological mismatches, and delay foraging times, reducing the fitness of individual insects as of the entire local population. Additionally, may further disrupt ecological interactions by shifting species into temporal niches in which they experience greater competition and/or lower fitness (Owens & Lewis, 2018).

Unsurprisingly, those insects most affected by excessive light are those with nocturnal habits; ALAN highly affects bioluminescent insects: For glow-worm and firefly populations ALAN has been suggested to be the second most important threat worldwide. They are highly sensitive to ambient light cues which indicate the time of day, affecting predatory lure and reproductive success by sexual communication and courtship signals (Haarman, 2022; Owens *et al.,* 2020).

Even at beyond lit areas, those flying insects attracted by lights and with their sense of orientation compromised become more susceptible to predators, flying incessantly around light fixtures. Nevertheless, the effects of ALAN are not limited to nocturnal or crepuscular insects but also to diurnal insect communities (Grubisic & van Grunsven, 2021; Grubisic *et al.,* 2018a).

The insect community in urban areas is not composed equally as those in natural areas and might be selected to be progressively less sensitive to ALAN. Nocturnal insects from pristine habitats might be more sensitive to light than those species living in urban areas, as the natural light levels experienced are normally higher (Grubisic & van Grunsven, 2021; Altermatt & Ebert, 2016). For example, insect communities from open habitats like grasslands are more exposed to the effects of ALAN.

The most affected insects are those that are not able to adapt to the altered environment and which do not have sufficient genetic plasticity to deal with these changes. The disappearance of certain insects whose entire biology is not known can trigger a cascade of effects on the functioning of ecosystems (Swaddle *et al.,* 2015).

In the following, a summary of the behaviours of various insects that are guided by colour will be discussed (Van Der Kooi *et al.*, 2021);

- **Body colouration/camouflage:** Colour change resulting from changing pigment and/or structure occurs in many insects. Excess light decreases the main purpose of camouflage, so predators benefit as they can be able to distinguish the individuals.
- **Skylight compass:** The colour of light is used as part of a sky compass by locusts, bees, and dung beetles.
- **Detection of shelters and landmarks:** Even though insects likely use achromatic intensity cues for flight control, the use of colour for landmark navigation is also being studied.
- **Detection of food sources:** Insect pollinators detect and discriminate flowers by colours, many species learn flower colours after one or a few rewarded visits. Both Lepidoptera and bees use colour to recognise, guide and land into flowers.
- **Detection of the oviposition substrate:** Many herbivorous insects express a colour preference that helps them find the optimal oviposition substrate. Many of them are

attracted by yellow, which seems to be a supernormal stimulus for dichromatic sight systems, comparing signals from green receptors and blue and/or UV receptors.

- **Selection of oviposition sites**: Female butterflies and moths also use colour cues to find oviposition sites, preferably they choose young and soft leaves for oviposition. Some butterfly species with multiple red-sensitive photoreceptors may be able to detect the narrow chlorophyll-dominated reflectance spectrum of young leaves and thus avoid older leaves as oviposition substrate, increasing offspring fitness.

- **Mate choice:** Conspicuous body colouration can evolve as a signal to predators; however, the complexity of and inter- and intraspecific variance between colour vision systems found in many butterfly taxa is presumably related to mate choice. Perching butterfly males often react to contrasting objects that move, whereas patrolling males pay attention to the colours of stationary females; furthermore, though pheromones are often relevant during courtship flights, colour also plays an important role. In some butterflies and fireflies, body colouration is considered to have coevolved with visual systems.
- **Reduction of mating time**: As the duration in which the optimum darkness is diminished, insects have a smaller window of time to meet at night.
- **Habitat fragmentation:** As mentioned in Chapter I, excessive light contributes to habitat fragmentation. This situation can be either produced by light attraction or avoidance and could generate a population bottleneck, decreasing genetic variance. A continuous line of luminaires can affect insect connectivity by triggering habitat fragmentation, through blocking and/or reducing movement and dispersal from the light source.

Insects often occupy discrete microhabitats within larger light environments which suffer several disadvantages, among which are highlighted; the reduction of flower visitation and less availability of food for predators leading to less resilient insect populations (Grubisic *et al.,* 2018b; Swaddle *et al.,* 2015).

- **Flight-to-light behaviour / Phototaxis:** This is the most studied effect of ALAN, also known as positive phototaxis. It consists of the contribution of ALAN to insect declines in diversity and abundance, although the basic mechanism of ALAN attraction is still unclear and varies according to species, populations and individuals (Fox, 2013). Nocturnal species with positive phototaxis suffer the highest decline and insects such as moths and aquatic insects are the most studied (Desouhant *et al.,* 2019).

Light produces the *light sink* effect to some insects, resulting in insects flying directly into the bright light or spiralling inwards, to orientate. The insects eventually are blinded and trapped, many do not survive and those who persist, remain in the so-called *light sink* where they are unable to engage in vital behaviours for fitness (Owens *et al.,* 2020). One of the main consequences is the reduction of foraging behaviour and increasing the starvation risk of nocturnal prey insects. The insects are also affected in terms of reproductive behaviours and higher energy expenses on their natural habitat, using up valuable energy and time, thus complicating the achievement of their ecological function.

Insects, which have short life spans are disadvantaged as they are attracted to light sources. Insect mortality increases substantially reducing total biomass, affecting entire communities by changing the relative composition of populations. About 30-40% of insects that approach street lamps die soon thereafter as a result of overheating and exhaustion, collision, electrocution, dehydration or predation (Owens & Lewis, 2018). These attracted night-flying insects regularly die before sunrise, while those attracted to vehicle headlights are more likely to die immediately (Owens *et al.,* 2020). The relative position of insects to light sources impacts their biodiversity. For example, down-welling light might affect species on the ground more than those with wings, while up-welling is more likely to affect flying insects (Owens & Lewis, 2018).

Historically, light traps have been adopted as a common method of pest control, the most frequent insect orders attracted and captured are Diptera, Coleoptera and Lepidoptera (Owens & Lewis, 2018). Around the year 1950, light traps also became popular among scientists to survey community composition, monitor beneficial insects and survey insect biodiversity (Owens *et al.,* 2020). To add, female Lepidoptera are unfrequently found in light traps because biologically they are not so attracted. Those found in traps are usually because they are transporting the eggs for oviposition, and may be compelled to oviposit in the immediate area regardless of habitat suitability (Owens *et al.,* 2020; Desouhant *et al.,* 2019).

Explaining in more detail how spatial disorientation occurs; ALAN can affect insects due to direct light or sky glow, by permanently or temporarily blinding or dazzling them so their spatial orientation is compromised. The complete or partial recovery to gain their original visual sensibility may take hours. This situation leads them to enter into unsuitable habitats, disrupting their temporal activity patterns, reducing their visual sensibility, altering foraging activity and species interactions and thus originates temporal mismatches between bats, spiders and insects acting as a forage attraction (Haarman, 2022; Owens & Lewis, 2018).

On the contrary, the avoidance of light or negative phototaxis also contributes to environmental problems such as temporal mismatches and disrupts natural processes. Also, the acclimatisation of those insects that are in highly illuminated places changes their activities and more progressively their physiology through generational changes. In particular, those with short generation times and in areas with a longer illumination history (van Grunsven *et al.,* 2019).

In summary, light pollution has many negative effects on insects, from altering behaviour to decreasing survival and reducing species diversity. It is important to address this problem to protect biodiversity and ecosystem balance. The adverse effects of light on insects emphasize the importance of addressing light pollution to protect their populations and ecological balance.

2.5. Visual system in insects

Colour vision, the ability to discriminate between colours independent of intensity is widespread among insects. However, it varies within species because many anatomical alternatives progressively acclimatise to every niche in each habitat, generating evolutionary changes (Van Der Kooi *et al.,* 2021). Generally, most insects have a colour vision system that is based on a variable number of types of colour receptor cells.

Insects are commonly trichromats, strongly attracted to UV light, corresponding with UV-, blue-, and green-sensitive photoreceptors and normally are least attracted to red light (Bruce-White & Shardlow, 2011). Also, there are some tetrachromat insects which have an additional red-sensitive receptor.
Insect visual pigments are called *r-opsins* and arthropods in general present 5 visual r-opsin families. At first, ancestral insects possessed 3 types of photoreceptors called opsins, of which one was sensitive to ultraviolet (UV300-400nm), another to short wavelengths blue, (400-480nm) and another to long wavelength green to amber (480-600 nm). Among insect orders whose opsin evolution has been studied in detail, multiple cases of gene duplications and losses have occurred (Owens & Lewis, 2018).

In insects, three types of eyes occur:

- Stemmata: Simple eyes, with a small number of receptors. Present in larvae of holometabolous groups.
- Ocelli: Simple eyes, which have an extended retina but low spatial resolution.
- Compound eyes: Consist on the main visual organ of insects, it presents between tens and thousands of ommatidia (insect photoreceptors). Found in the imagoes of holo- and hemimetabolous insects.

Colour vision serves various vital functions; insects use colour information in different behavioural contexts. Colour preferences are used to evaluate ambient light, which does not require high spatial resolution and is often served well by a dichromatic system, which is present in many insect ocelli (phototaxis or navigation), or used to detect and recognize objects and mate and predator detection. This use is more complex, involving both spontaneous choices and learned behaviours and has likely led to the high variation in colour vision systems in groups such as the butterflies. There is a co-evolution between the colour of flowers and pollinators' visual systems.

Insects have great properties for very sensitive visual systems. They saturate at moderate light levels varying according to species although depending on the different order of insects. They present different photoreceptors, so they have different spectral sensitivities (van Grunsven *et al.,* 2019).

Generally, those insects by having UV-sensitive receptors for blue and green are disproportionately attracted to short wavelengths, between 300 and 440 nm. Therefore, reducing/suppressing harmful short wavelengths is a promising approach to reducing the attractiveness of light to insects. Attractiveness can also be taxon-specific as LEDs attract more flies, moths and butterflies than HPS (high-pressure sodium) lamps, although, fewer beetles. Additionally, it can vary with developmental stages for given species, as the visual system undergoes profound changes during development (Grubisic *et al.,* 2018a).

Insect flight behaviour is different when different types of lights are close (Eisenbeis *et al.,* 2009) leaving at risk the recognition of objects or individuals, due to the loss of sensitisation generated by the light wavelength from the ALAN source in question. For example, lamps with high UV and blue light emissions such as MV (mercury vapour bulbs) or LEDs are highly attractive for up to distances of 130 m. As seen, changes in lighting are necessary, the change from MV to LEDs reduced the attraction of nocturnal insects substantially and differed between groups of insects (van Grunsven *et al.,* 2019). Although according to Boyes *et al.,* (2021), the impacts were more pronounced for white LEDs than for HPS lamps.

In addition, the polarization of light by shiny surfaces is a significant problem as it attracts aquatic insects, particularly egg-laying females, away from water, and reflected light has the potential to attract pollinators and impact their populations, predators and pollination rates.

- Low-level ALAN is known to accelerate development in a range of insect taxa with varying effects on their fitness (Owens & Lewis, 2018).

3. ALAN effects in Lepidoptera

Focusing on the specific problems associated with the effects of over-lighting among Lepidoptera, the best studied and most affected by light pollution which is also the order with more species-rich insect groups and with significant population declines in Europe (Boyes *et al.,* 2021). Light pollution is one of the major threats to moth population dynamics, correlative studies established direct links between ALAN and population declines in moths (van Langevelde *et al*., 2011; Grubisic *et al.,* 2018a).

In Macaronesia, there are about 170 species and at least 49 endemic species of nocturnal butterflies known that lack information on distribution and updated conservation status, so it is utmost important to protect from these negative effects as light pollution.

3.1 Lepidoptera vision

Lepidoptera order presents well-developed organs of vision and is the most varied of any single insect order, suggesting that vision plays an important role. Their eyes are typically ellipsoid and have more than one receptor type with long-wavelength sensitivity. Normally they present many facets which are compound by three *ommatidial types*, with two blue receptors, two UV receptors, or one blue and one UV receptor. They also present long *rhabdomeres* (structures containing the visual pigments) that collect light from multiple facets. The normalized sensitivity spectrum is slightly widened concerning the visual pigment absorption spectrum due to this self-screening. In addition, they present a structure called *mushroom bodies* where they combine information on light intensity and olfactory cues (Warrant *et al.,* 2003).

The main visual organs in adult Lepidoptera are the compound eyes, which generally take up a large proportion of the head surface. Males tend to have larger eyes than conspecific females. Larger eyes generally have higher visual performance, so larger eyes are mainly present in bigger-sized Lepidoptera. Compound eyes can differ into two types according to their behaviour; most diurnal butterflies (which need more definition to differentiate between colours) present afocal apposition while superposition is found in most moths. Also, the largest eyes occur in actively foraging crepuscular/nocturnal taxa such as sphingids and noctuids (Warrant *et al.,* 2003).

This order has undergone great anatomical changes to live in different habitats and thus to occupy different spatial and temporary niches. Therefore, it can be concluded that there are clear differences in the nocturnal and diurnal Lepidoptera visual systems (Figures 6 and 7).

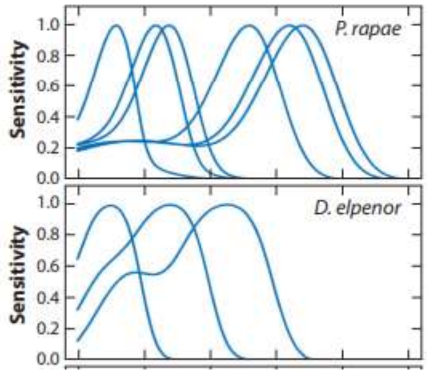

Figure 6 | Schematic representation of photoreceptor anatomy for diurnal Lepidoptera *Pieris rapae* and nocturnal Lepidoptera *Deilephila elpenor* giving clear differences in their sensitivity (Van Der Kooi *et al.,* 2021).

Day-active species rely on spectral cues so vision is essential for; orientation, mate and food detection, and selection of oviposition sites. While for nocturnal species, its relevant to a lesser extent as for orientation during flight and locating food. In some groups of butterflies, particularly those with complex and sexually dimorphic visual systems, wing colouration and vision likely coevolved. Nymphalidae is the most studied family in the field of the visual system of Lepidoptera. Many nymphalid species have more than three photoreceptors (Figure 7) and thus a broad visible wavelength range. There is a higher number of photoreceptors in diurnal Lepidoptera than in nocturnal Lepidoptera.

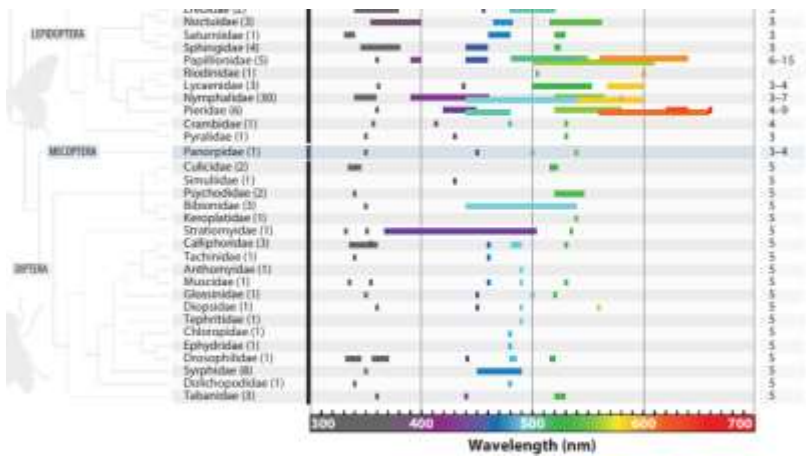

Figure 7 | Photoreceptor spectral sensitivity maxima for different insect orders, focusing on Lepidoptera. The number of photoreceptor types is shown on the right (Van Der Kooi *et al.,* 2021).

Lepidoptera have long been known to rely much more on vision for all tasks associated with mate recognition (nocturnal moths to a lesser degree). Also, the spectral richness of these insects may be partly linked to body colouration, where wing patterns are very important visual cues for mate recognition. Among nocturnal moths, the detection and interception of mates are usually mediated by pheromones, with visual input being used to overcome obstacles while following the pheromone plume. Additionally, another feature of importance for detecting mates is the size of the eye.
Thus, whereas vision is arguably the dominant sense in butterflies, it is only one of many well-developed senses in nocturnal Lepidoptera. Moths, sacrifice resolution to gain up to 1000x more sensitivity. This reason is why they are so sensitive to light and end up disoriented easily. The difficulties associated with seeing reliably at night have led to enhanced olfactory characteristics, especially for mate location and flower detection. Moths rely more strongly on pheromones for mate detection and on odours for finding nectar sources. Also, many moths have the capacity to recognize the sonar calls of predatory bats (Warrant *et al.,* 2003).

3.2 ALAN Effects on Moths

Moths have been known for typically be attracted to artificial lights at night. All the mentioned effects triggered by ALAN in insects also apply to this specific order, although the following are highlighted in nocturnal moths according to Owens & Lewis (2018); disruption of their nocturnal activity, suppressing nocturnal behaviours (such as phototaxis, mating, recognition, altering feeding behaviour and cascading effects on the population of plants and herbivores) (Owens & Lewis, 2018; van Langevelde *et al.,* 2017). In addition, constant light can inhibit female sex pheromone release, reduce male attraction, induce male sterility, and disrupt female ovipositional (temporal disorientation). These principles are being successfully used in pest control against moths in crops (Owens & Lewis, 2018).

Moths are the major nocturnal pollinators of flowers, which have been long under-appreciated. Moths are pollen vectors for a diverse range of plant taxa in ecosystems across the globe (Macgregor *et al.,* 2017). Some examples to highlight are nectarivorous species from the families Sphingidae, Noctuidae, Geometridae and Erebidae (Macgregor *et al.,* 2015). As great pollinators, they use a combination of olfactory and visual cues to locate flowers. Nocturnal moths are often attracted by bright flowers at night. In contrast, newly eclosed nymphalids, nocturnal hawkmoths and noctuids are only motivated to search for visual flower cues when flower odours, or highly concentrated plant odours, are present.

Studies by Macgregor *et al.,* (2015; 2017) indicated that moths are negatively impacted by ALAN, with cascading effects on species with which they interact, notably diurnal pollinators (Desouhant *et al.*, 2019). A decline in such specialist pollinators due to light pollution might lead therefore to a reduction in plant density in many species (van Langevelde *et al.,* 2011; Macgregor *et al.,* 2015).

- In four species of moths from the families Noctuidae, Geometridae and Erebidae, the feeding probability was higher when individuals were exposed to darkness than when exposed to ALAN of different spectral compositions, reducing the feeding time by 58-82% (Desouhant *et al.,* 2019; van Langevelde *et al.,* 2017).

- In some moths, attraction to light was demonstrated to be size biased. Long-term records confirm that positive phototaxis macromoths in lit habitats have undergone disproportionate declines in abundance over the past 50 years (Owens & Lewis, 2018). Relatively larger moth species and higher abundances of these moth species are caught in traps dominated by small wavelengths. This will consequently result in higher mortality for larger species with potential consequences for population dynamics (van Langevelde *et al.*, 2011; Grubisic *et al.,* 2018a).

- Studies indicate the possibility of a male-biased flight to light behaviour in moths. The vast majority of males are more disproportionately mobile than females so they are more often attracted to light due to their biological activities and physiology (Owens & Lewis, 2018; Altermatt & Ebert, 2016).

Most studies comparing the attractiveness of insects to lamp types differing in spectral outputs have been undertaken principally in studies about moths (van Grunsven *et al.*, 2019). Lamp types that are dominated by smaller wavelengths, attract higher species richness and abundance of moths. Whereas those LEDs without UV emissions attracted fewer insects (van Langevelde *et al.,* 2011). Artificial light attracts many moths, especially light containing high ultraviolet (UV). Nocturnal Lepidoptera are particularly sensitive to this light spectrum (300 - 400nm). Moths are affected by the artificial lights from high-pressure sodium street lights while LPS lights rarely attract moths (Macgregor *et al.,* 2017).

- Certain families of moths are more attracted to short wavelengths than others. This is explained by the variability in spectral sensitivity among taxa. For example, Noctuids are more attracted to short-wavelength lights, whereas Geometrids are equally attracted to short or long-wavelength lights (Desouhant *et al.,* 2019).

In addition, and in accordance with Virgilio Vieira (2022), there is a great number of nocturnal families, although the vast majority of moths belong to Geometridae and Noctuidae families which present distinct behaviour to light:

-Geometridae generally approach the light source, flying slowly, making a few circles around it, and landing in its vicinity. Morphologically, they present more triangular wings. They usually leave their wings folded in repose like diurnal butterflies.

-Noctuidae have a more frenetic behaviour to light, their flight is powerful and erratic around the light source, striking numerous times before landing. When they do land, they move quickly and directly to protected surfaces, which serve as hiding places during the day.

- Moths in the vicinity of street lights are attracted upwards to light, away from field margins. They fly at higher levels around the light although it is not known whether this is a local or temporary change (Macgthe regor *et al.,* 2017).

- Brighter and higher-intensity lights are likely to be more attractive or to disrupt individuals over a wider area as the light reaches further into the darkness. Reducing the intensity of lights used at night would help to minimize the impact on moths while maintaining lighting for the population in key areas (Gaston *et al.,* 2012).

- The distance in which the insects are attracted to light varies greatly according to other environmental factors and the specific species. Moths are known to fly to light from distances varying from three to 130m, but greater distances up to 500m have also been observed (Bruce-White & Shardlow, 2011).

- Artificial light can affect growth rate and natural predator-prey balance, which could at first seem to benefit a few species while possibly negatively impacting many more. It has been found that mercury vapour streetlights increase bat predation on moths because the lights interfere with the ability of moths to detect the ultrasonic sound-burts used by bats to locate their prey. Mercury vapour lamps interfere with the bat defence of tympanate moths (Bruce-White & Shardlow, 2011).

- Experiments have shown that extending the day length using artificial light prevents some moth larvae from entering diapause. In such circumstances, non-diapausing would not survive the extreme conditions of winter (Bruce-White & Shardlow, 2011).

According to Altermatt & Ebert (2016), the insect community in urban areas is not the same as in natural areas and thus, might be biologically selected to be progressively less sensitive to ALAN. This issue should be considered carefully because the idea of these animals "getting used to light" might get misunderstood as a decrease in diversity due to this factor in natural dark places as a preserved location, they are largely threatened.

Therefore, an observed difference in the impact of different light sources in semi-natural habitats might not be representative of an urban context (Altermatt & Ebert, 2016). Assessing whether the setting area affects the ways that the two different light sources attract insects, in terms of the number of insects attracted as well as the composition of the catches (van Langevelde *et al.,* 2011).

- Few studies have investigated the effect of artificial light on wild moth communities and none have utilised existing light sources to do so (Macgregor *et al.,* 2017).

It is crucial to study further the effects of different types of light in insect communities. Additionally, scientific consensus should be reached on a research methodology to conduct environmental research relating to the impact of light pollution. Most experimental studies on ALAN have focused on individual organisms and provide a mechanistic understanding of the effects of artificial lightning in nature. ALAN has numerous lethal and sub-lethal effects which have been demonstrated at the organism level and could contribute to population declines.

Indeed, the effect of light pollution on the biodiversity web must be taken into account in future research studies.

III. Best practices to mitigate ALAN effects on insects

As outlined in the previous chapters, the basic information on insect abundance, focusing on Lepidoptera, in Macaronesia (Chapter I) and their effects on ALAN (Chapter II) have already been discussed confirming that, diminishing the effects of light pollution (Chapter III) and undergo actions to reduce artificial light impacts are necessary and justified, as it is a major challenge. In the following chapter, there will be a collection of information on mitigation measures for the aforementioned effects of excessive artificial light.

Mitigation measures are essential to minimize the risk of a decrease and eventual loss in biodiversity along with other negative impacts produced by light pollution. However, it can only be achieved if financial and security concerns in accordance with community needs are unified to achieve this welfare. Since the population suffers continuously from this topic and although is not a familiar issue to the community at the moment, in order to limit its negative effects, more awareness along with the adoption of rules and procedures are essential.

In the scope of years of research and literature on light pollution and its consequential effects, it is imperative to implement transformative changes and measures. Such changes imply a collaborative interdisciplinary approach, involving researchers, policymakers, non-governmental organizations (NGOs), and a diverse array of stakeholders. Technological innovations, policy interventions and public engagement efforts can be the pillars that drive mitigation and reduction of light pollution.

Many actions can be accomplished at different levels; personal, local, within organisations, companies and, regional and country-level authorities. For this reason, it is important to adopt new beneficial habits. The willingness to change small routines or preconceived ideas that may be mistaken or damaging without knowing the real impacts of the community's choices generates a substantial impact.

Benefits of reducing light pollution

Changing street lighting to adequate light needs has several benefits such as in the environment, energy cost savings, quality of life, safety and tourism.

- **Environment** → Artificial lighting has major negative impacts on biodiversity, its reduction will protect nocturnal biodiversity.

- **Energy costs** → Changing lighting to more energy-efficient fixtures and switching off and/or dimming the lighting at night will have up to 60% of energy benefits.
- **Quality of life** → The quality of life for those living in excessively lighted areas will improve when intrusive light is reduced.
- **Safety** → Lighting is often known as synonymous with safety. However, contrary to what is supposed, many lights end up giving less safety as they provide important sources of glare.
- **Tourism** → Night sky observation is becoming increasingly popular and is one of many attractions in the archipelagos of Macaronesia. The astrotourism industry continues to grow as more people seek to experience and learn about dark skies. Reducing/changing the lighting at night will increase the number and quality of tourists in these regions.

Throughout this chapter, there will be reviewed and identified a number of mitigation measures and initiatives that can help reduce the impacts of light pollution (LP). Before entering into detail, according to Hölker *et al.*, (2010), some improvement methods could consist of; 1) setting priorities for human health and environmental protection, 2) validation of indicators and guidelines, 3) identifying technical and economic possibilities to improve energy-saving and environmentally friendly lighting, and 4) developing sustainable lighting concepts and techniques for future nightscapes.

To organise the mitigation measures exposed, the recommended actions are divided into four important components which are: raising awareness, habitat protection, light pollution policies, beneficial changes in ALAN and additionally "other mitigation measures". In every subcategory, we can find a series of simple actions in which the community can be easily involved.

1. Raising awareness of ALAN effects

It is important to become aware of the negative effects of ALAN and to be committed to making small changes in daily routines to reduce the negative impact of LP on ecosystems and thus lead a healthy lifestyle.

Raising public awareness of ALAN effects can be divided into different sectors:

- Workshops on the effects of light pollution, technical aspects of lighting and ways to mitigate their effects are essential. in order for the community to have a broader knowledge about ALAN. This training proposal obviously should be tailored according to the target audience. Whether for municipal workers (city council workers, engineers, architects, lighting specialists), children in schools or specialised communities (such as universities and marketing specialists).

- Create guidelines and informative material for good practice use of light at home and other public buildings. These documents should be available in both online and activity-based formats and in various languages (Figure 1).

Figure 1 | Possible changes in ALAN at home. Extracted from EELABS.

- Create awareness days such as "The biodiversity that lives at night", and "*The Restoration of Night*". These events would take place on specific days/weeks and would be focused on activities and workshops to explain in greater detail this issue, giving importance to nocturnal diversity. Some of the activities at night could also be nocturnal *bio-blitz,* organise blackouts at iconic locations to observe the night sky, and other activities in conjunction with an astronomy association.

- Place special emphasis on night-time preservation in those locations that do not require lights such as light-sensitive areas, especially the periphery of residential areas, forests, parks and shores of water bodies.

- Create and offer awards, and quality seals to those private entities - from individual citizens to hotels and organisations, that adopt light pollution mitigation measures. An example is Night with Life award, which certifies that an establishment takes measures to minimise light pollution, such as using sensors, timers and power reducers to avoid unnecessary lighting.

- Raising awareness in specialised and non-specialised shops (as in electrical, gardening, indoor and outdoor decoration, and building shops) within private entities, in order to reach different audiences to decrease of light spills in private residences.

- The lack of knowledge on basic information about terrestrial arthropod species is a serious impediment to their effective conservation. It is crucial to have as a priority the development of inventorying and monitoring programs targeting these animals (Serrano *et al.,* 2015). An example of this is action A9 from Natura@Night Project.

The various checklists of terrestrial arthropods in the Macaronesia archipelagos have been compiled and published. Also, online biodiversity databases have proved to be important tools both for research and education by easily and visually providing valuable information on species identification, ecology and distribution (Serrano *et al.,* 2015).

An important component in nature conservation is increasing the public and policymakers' awareness of this theme. Arthropod conservation suffers from several impediments that include a public and political dilemma. The general public is not aware of invertebrates and their ecological services, as policymakers and stakeholders are mostly unaware of their conservation problems (Borges *et al.,* 2015). The conservation strategy of terrestrial arthropods should pursue the involvement of the scientific community, stakeholders and the general public and develop several guidelines to protect this group (Serrano *et al.,* 2015).

All these initiatives contribute to raising public awareness for nature conservation and promote the understanding of the reason why arthropod biodiversity should be valued and protected (Borges *et al.,* 2015).

For terrestrial arthropods, the efforts made in the European Community towards conservation priorities were based on the knowledge of Northern and Central European arthropod biodiversity, where a lot more information is available, including historical data. As a result, some of the species protected under the Habitats Directive are species that, for example in Portugal are relatively common, while Portuguese endemic species with restricted distributions (such as islands) received no consideration (Borges *et al.,* 2015).

1.1. Training and comprehensive further studies

For instance, urban lighting workers require further training in ecology, environmental sciences and astronomy to address matters and reduce the effects related to LP. To reduce these impacts, it is essential to translate relevant knowledge on the adverse effects of LP to urban planners, outdoor designers and other workers involved in the design, planning and approval of public areas which will also benefit.

Conversely, scientists and conservation officers, among others, need technical training related to the technicalities of light, street lighting and urban light policies to understand more finely how light functions apart from keeping up to date with innovations and the latest studies so that the effects on each studied group and possible remedies are achieved. Furthermore, as intended in this project, it is planned to contribute to technical solutions for LP reduction directed towards the elaboration of municipal plans for public lighting (which will be discussed in more detail in the "Light pollution policies" subchapter).

Nevertheless, it is also very important to share the information that is available and unfortunately, it is generally only used between people from the same area of knowledge, it is important to be aware of the need to become multi-disciplinary.

It is necessary to receive more funding for research in science and conservation, in order to answer some of the questions that so far exist among the scientific community. Some of these issues will be explained below, although to see more examples of questions to be answered in detail, please search for *Action A5 Final Report* document.

In addition, for the future of these scientific publications, there is scattered information with different applicability and without being systematised. This is why it is necessary to reach a common established consensus on the studied parameters to be able to extrapolate the studies that have been achieved (Gaston *et al.,* 2015). For example, there are studies that test in laboratories and others in the field, so results should be considered in accordance with each environment.

Some of the questions that remain unanswered and are linked to the effects of LP:

Understanding how animals perceive light is crucial for implementing actions to reduce light pollution. Research gaps need to be filled in all the taxonomic study groups affected by LP to gain a sharper knowledge of the impacts of ALAN. For those corresponding to groups of insects that remain unexplored along with those that have allegedly been studied the most although still have important questions that need to be answered.

For the reasons set out above, here it is appealed to complete the information related to ALAN among the questions that remain unresolved. Some questions are simple enough to answer such as what phase of the moon the study is being conducted and other climacteric conditions. For instance, the following are other examples of information that should also be added; naming the basic technicalities from the source of light that is being studied, and designating if it constitutes direct or indirect ALAN.

In addition to reaching a scientific consensus on the research methodology to conduct environmental research related to the impact of light pollution, some recommendations that the studies need to question towards the future are;

- More studies using different types of light so that the varied effects can be noted in each studied species.

- The location, duration and wavelength composition of ALAN, are crucial components to knowing how ALAN can affect (Gaston *et al.,* 2015; Sánchez-Bayo & Wyckhuys, 2021; Pérez Vega *et al.,* 2022).

Specific questions related to insect study:

Common questions that scientists bring to the spotlight about studying different insect taxon groups. Studies on communities and higher levels of biological organizations are increasing but experimental studies on long-term effects on populations are still lacking (van Langevelde *et al.,* 2018; Grubisic *et al.,* 2018a).

Further studies on the effects of LP:

- Using different types of light.

- Different effects of LP in the sexes in each species.
- How LP affects host plants (they give rise to the matrix in which these insects will develop).
- How photoperiod affects the larval stages.
- Supplementary studies on the interaction between affected species.
- Specific wavelength affinities of insects.
- In what manner do the different wavelengths affect the species under study.
- Effects of the lunar component.

Although, studies are not directly comparable or of equal value. Factors such as the study and design size reported metrics and relevance of the study should be considered rather than simply counting the number of studies that support a particular interpretation (Bladon *et al.,* 2022).

Example of the applicability to the questions mentioned above: Monochromatic LEDs can be engineered to produce light at any desired spectral composition. Therefore, once specific wavelength affinities of insects are known, lights can be designed with minimal output in the wavelengths that most affect insect fitness (Owens *et al.,* 2020).

Hence, once an answer is achieved, it is easier to provide a mitigation measure and could be implemented in a guideline or best practice lighting design.

Among many other concerns forthcoming, other questions and studies are setting trends such as studying together the effects of artificial light and sound. Another is, that since the vast majority of studies have a continuous ALAN exposure, it would be interesting to investigate the impacts of flashing lights (flickering).

2. Habitat protection

Biodiversity is the scientific term for the variety of life on Earth. It does not only refer to species but also to ecosystems and the genetic differences between species. The main cause of biodiversity loss is the destruction and deterioration of habitats. The alteration of the environment can affect a great deal of life forms as the natural conditions have been modified, leading to eradicated or dimmed populations.

The cause of environmental and habitat loss can be classified as direct or indirect causes (derived from other actions that cause habitat fragmentation) that are frequently anthropological (their underlying causes are social, economic and political).

Habitats consist of both biotic and abiotic factors and should provide and support their organisms with food, water, shelter and space to survive. Several conditions have to be fulfilled so that particular species are able to live and reproduce under their specific needs, the space should be suitable and should meet the necessary requirements for species to develop.

Habitat loss occurs mainly due to land use change from pristine ecosystems to agricultural, livestock, industrial, tourism, oil or mining activities. The effect of habitat fragmentation by transforming habitat decreases the number of species, shrinking their populations and shrinking their resilience to changes.

For a long time, pollution was seen as a small spatial-scale problem, but nowadays it has become large-scale using a holistic point of view, where the production of pollutants affects the whole planet. The deterioration of the composition, structure or function of ecosystems impacts the species and ecological services which can be obtained from nature.

Relating this topic to insects, although the vast majority of insects are most active in spring and summer, many other species are active in autumn and winter. For both, it is recommended, during the winter months, not to do any excess garden work in public or private areas (preference in leaving fallen leaves and natural debris on the ground, keeping the hedges unpruned, and other branches and plant stems uncut). If not possible, do these works on a rotational basis (so that the insects that shelter there will make it through to spring), avoiding putting their viability at risk. This is one of the best alternatives to maintaining green zones without waiving a great generation of insects (Fox *et al.,* 2022).

Arranging a wild space area as an insect winter home is a great initiative to protect these animals, sheltering them from difficult environmental conditions such as wind, rain, cold temperatures and possible predators. Habitat loss is one of the major reasons Lepidoptera are in severe decline, so establishing this area would enable them to feed, breed and shelter, completing their lifecycles. These areas can be of any possible size and range and should be permanent and free from pesticides.

Light pollution produces habitat fragmentation: Some locations are particularly sensitive to light pollution, and lighting schemes in these areas should be carefully planned to avoid negatively affecting the environment The illumination of non-typically illuminated sites at night fragments the habitat by creating an invisible barrier produced by the light, which has indirect effects on insect-plant community dynamics. This generates small areas of resistance, which become progressively forced to diminish as increasing sources of unnecessary lights are added.

Many rare and threatened moths are now restricted to small, isolated patches of habitat and subject to multiple human impacts such as chemical and light pollution, climate change and radical shifts in farm and forestry management. Mitigating these effects to give moth populations the best chance of long-term survival often requires active intervention. There are some ways to alleviate these effects that we will indicate below:

A) Light pollution levels should be generally reduced everywhere. However, areas that currently have low lighting levels and areas that are important for wildlife must be left the most pristine possible. In sensitive locations like areas of conservation value is preferable to avoid lighting in these areas. **Areas with**

natural light or near natural lighting regimes should be officially conserved. In these areas, light pollution should be reduced and strict limits and constraints should be placed on any new lighting

- Conserve and create areas with natural light regimes (or near natural light regimes):

These areas should be likely to be carefully planned, reduced or totally moved to avoid negative effects. For example, identify areas which have all the requirements to make a partnership with the Dark-Sky Association, progressing to become and create Dark Sky Preserves.

- Sources of polarized light pollution should be identified and reduced.

- Avoid using electrocuting or stunning insect traps in rural places. Normally they are placed outdoors and forgotten all night, they should only be installed as a last resort to prevent a serious public health risk.

B) Plant endemic host species, to counteract and avoid the progress of this problem so insects can have an ecological niche where they can shelter, feed and reproduce.

- Create guidelines to encourage the local population to plant native flora in their public and private gardens.

- Give assistance and support to the authorities in charge to take care of natural forests and plant endemic species in public gardens, to protect insect diversity and habitat loss.

C) Create ecological corridors. An ecological corridor is a clearly defined geographical area that is governed and managed over time to maintain or restore effective ecological connectivity. It constitutes a key feature for conservation. Generating ecological corridors on a small scale and in polluted locations can alleviate the burden of insect habitat fragmentation. When created in protected areas along with other effective conservation mechanisms, these components are the fundamental core elements for conservation and any ecological network. Connected, protected and conserved areas are stronger against their limiting ecological obstacles. Corridors are a major component in successfully fighting fragmentation and fortifying biodiversity. These physical links are one of the most important ways to ensure that species are able to move between protected areas and maintain genetic strength (Hilty *et al.*, 2020).

- Creating "Dark areas" that offer refuge to organisms and in addition to dark corridors is important to interconnect nocturnal habitats, by carrying out blackouts at the most crucial places, days and times. In this manner, a safe '*green passageway*' is created.

To have a healthy environment, habitat protection is essential, it requires measures to be achieved to maintain or restore to a favourable state through the establishment of an ecological network and a legal regime for the protection of species.

3. Light pollution policies

Culturally, light is a symbol of enrichment, modernity, urbanity and security, reason why, policies against light pollution need to take into consideration the many advantages of artificial lightening for economic production, social lifestyles and safety while at the same time, addressing its negative effects (Hölker *et al.,* 2010).

Advocacy and engagement of local authorities, stakeholders and the population are crucial to adopt appropriate biodiversity-friendly solutions. As the primary beneficiaries and stakeholders of urban lighting, public engagement and awareness are essential in driving change and demanding responsible lighting solutions. There is an undeniable need to increase the notion of nature in laws and regulations towards beneficial changes.

Biodiversity policies promote the protection, conservation, and sustainable use of biologically diverse ecosystems and habitats conjointly, generate significant public benefits and contribute to social well-being. Although there are indeed, laws for the protection of nature, there is still much to be achieved to help protect wildlife. Additionally, it is necessary to monitor and comply with the norms and laws of the competent authorities by international national, regional and local laws to help achieve these objectives. Other countries have already produced and implemented specific legislation against light pollution, which are similar legal tools to those that exist for noise pollution.
In recent years, there has been some concerns about the impacts of artificial lighting as it was summarised in the 2009 Royal Commission on Environmental Pollution report on artificial Light in the environment. However, this is not common in all countries, and the European standards for public lighting are not supported by scientific knowledge. For that, establishing a multidisciplinary technical and scientific committee to evaluate and present proposals for light pollution, mitigation and control of outdoor artificial light could alleviate its effects.

As mentioned before, on some occasions, laws are created regardless of the current situation, and these laws should be reviewed and changed if appropriate. There are examples of laws that are well-intentioned but not so useful in practice.

- Management efficacy strategy is needed due to the lack of implementation of laws.

It is important to legislate outdoor artificial light, including lipid lighting and illuminated advertising, whether in residential areas, commercial areas or in the historic centre. Setting limits on light emission (intensity, colour, quality and quantity) according to best practice and scientific knowledge. Use as an example some well-recognized laws such as *Ley del Cielo*, always taking into consideration specialists and public opinion. For example, it is banned to use 3000K colour temperature bulbs, not using more than 2700K in the pedestrian area (Figure 2).

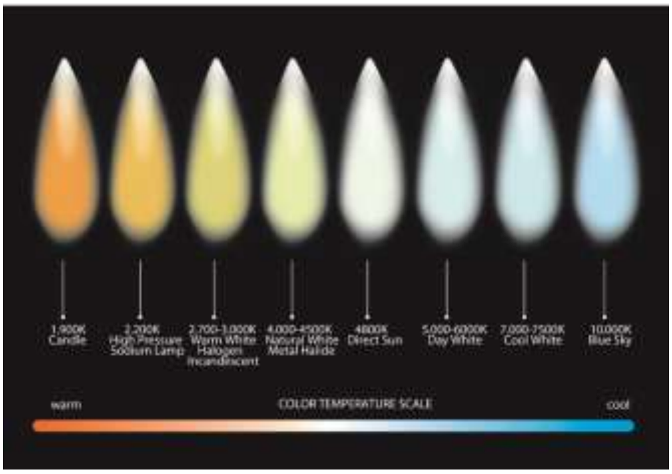

Figure 2 | Colour temperature scale. Extracted from Commonwealth of Australia (2020).

- Promote better land-use planning. Better links between research policy and practice connect the research that has been conducted in different disciplines (Gaston *et al.,* 2015).

- Add consideration of light and sound pollution stimuli in conservation plans and ecosystem restoration plans.

Environmental Impact Assessment

The potential impacts of light pollution should be a routine consideration in the environmental impact assessment process. Risks should be eliminated or minimised wherever possible. The potential for light pollution should be considered at the scoping level of the Environmental Impact assessment process. Light spills into wildlife habitats should be avoided altogether whenever possible, when this is not possible, the impact should be considered as being likely to be significant and should be fully assessed in the Environmental statement.

It is important to assess the need for lighting when planning a new development, or re-evaluating an old lighting scheme. The first aspect that should be considered is whether lighting is necessary, instead of assuming that light is mandatory *per se*. The promoter should consider if the development could function without artificial night lighting, evaluate cost/benefit issues, and alternatives to lighting, and develop better security methods instead of excess lighting, which has been seen to be less effective (Bruce-White & Shardlow, 2011).

- The environmental statement should include a survey of species with conservation significance that may be sensitive to light and an experienced entomological consultant would be able to provide advice on the scope of the survey.

Elaboration of municipal plans for public lighting

Local authorities and Government departments must take the lead in reducing the impact of artificial light, as for investing in more efficient lighting (Bruce-White & Shardlow, 2011). One of the main objectives of the LIFE Natura@night project is to gain more efficient and targeted public lighting by conducting municipal plans for public lighting. The project's partner municipalities will obtain help from a company with extensive experience in this field (Fluxo de Luz) to contribute to technical solutions for LP reduction along with the achievement of more efficient management and greater energy efficiency, saving large amounts of public money. For example, Santa Cruz municipality in Madeira has achieved great results since its implementation.

The elaboration of public lighting plans consists of a complex process, which involves creating legislation at a regional level and creating and implementing (for each municipality that is part of the project) a Public Lighting Master Plan that helps to manage public lighting and achieve larger savings in public money, ensuring greater energy efficiency.

In addition to the technical information that needs to be collected and presented to support these decisions, political will is essential, which will be most represented, once citizens show more concern about the issue of light pollution. That is why these changes require a major awareness-raising effort from the relevant policymakers and authorities themselves. The positive relationship between companies, municipalities and NGOs is a priority in order to carry out these actions.

4. Beneficial changes in ALAN

Light pollution is a growing threat to wildlife worldwide. It is important to take measures to reduce light pollution and protect biodiversity. Natural darkness has conservation value and should be protected in the same way as other natural resources. Whereas urban lighting continues to expand generating important benefits, it is mandatory to achieve plausible changes to protect nature (Figure 3).

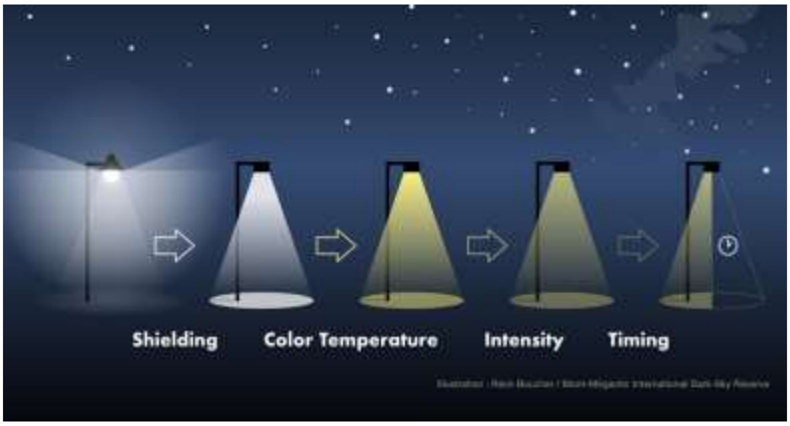

Figure 3 | Changes in ALAN, quality lighting designs. Illustration Rémi Boucher – Mont-Mégantic International Dark-Sky Reserve.

This can be achieved through good-quality lighting designs, and the negative effects of LP can be reduced to a large extent (Commonwealth of Australia, 2020).

As mentioned, misguided lighting design in lighting installations produces LP, detrimentally affecting the natural conditions of the night environment. Nonetheless, artificial lighting is essential in urban and specific rural areas where is needed at night to maintain adequate living conditions. It is also indispensable for a large number of leisure, commercial and productive activities, and is necessary to guarantee industrial safety in certain installations. The key issue that emerges is how to maximize the benefits of artificial night-time lighting whilst limiting the environmental, well-being and economic costs (Gaston *et al.*, 2015).

Energy efficiency and energy savings are priority objectives for any modern society. Although new developments in LED provide long-lived energy efficiency, this technology is known to have negative impacts on wildlife because of its spectral composition peaks. According to Bolliger *et al.*, (2020a), it was seen that dimming street lights by up to 35% had positive effects on insects and bats and was the best way to mitigate light pollution. Promising changes can be acquired by adjusting their intensity (dimming) and spectral output (custom colours and filters).

4.1 Best practice lighting design principles

In recent years, the intensity of artificial lighting has increased dramatically with a negative effect on ecosystems and human health. As urbanized areas are also growing, artificial lighting extends its negative impact to increasingly more ecosystems. Developing intelligent streetlight systems is a significant step toward safer artificial light output at night (Shroer & Hölker, 2017). These systems must be made affordable for communities and further developed to react to weather conditions, seasonal changes, and biological activity.

Evening and morning hours have the highest demand for artificial outdoor light. These, unfortunately, collide with the highest biological activity of many species (Shroer & Hölker, 2017). It is our responsibility to adapt outdoor lighting to respect the surrounding habitat, installing artificial lights only where needed.

According to the Commonwealth of Australia (2020), best practice lighting can be divided into three components according to the benefits to society: benefits for wildlife, energy saving and provision of economic benefit.

The majority of literature gathered confirms that operating time, illuminance, direction, and spectral appearance of light sources can alter night and day cycles and the actual physical nightscape.

The following are some examples of bad practice lighting design:

- Excessive luminaire densities.
- Different types of luminaire support.
- Excessive light sources.

- no uniformity/incoherence between light types.

Promising Principles of Good Outdoor Lighting Practice:

To conceive a good lighting practice is essential to elaborate and organize a lighting schedule. Basically, it is important to know when the off-peak hours, seasons, and events for artificial light are and to act accordingly, reducing intensity or turning off in off-peak hours.

Based on the information given by the IDA (International Dark-Sky Association) and Commonwealth of Australia (2020) the following eight principles are defined:

1. **Enjoy natural darkness.** Question the real needs and add light only for specific purposes, avoid over-illumination. The key is to lower the light intensity gradually. Once eyes are accustomed to darkness, is not necessary to over-light.
2. **Illuminate only what is necessary for a functional minimum**. Only light the areas or objects that are required to be lit. Artificial light should only be added for specific and defined purposes and only for the demanded location and specified duration.

    - Reduce the number of light fixtures to those that are strictly necessary. Make a critical analysis, and turn off light points that are not needed.

    - Ornamental lighting. Reduce the number of lamps and direct the light only to the structure that is desired to be illuminated (i.e. gardens, statues, monuments, sculptures). Historical monuments could have direct light with appropriate fixtures and timed illumination.
    - Decrease the number of luminaires, the intensity of light, or the hours of operation in illuminated signs (i.e. advertising, pharmacies, billboards).

3. **Lights should be kept at low altitudes, directed, shielded, and low in intensity and brightness.** These measures can be extremely effective, in reducing sky-glow too.

    - Existing lights can be easily modified by installing a shield using "*full cut off*" streetlights (without screens), lower height lighting (closer to the ground), directing the light and also avoiding intensive light. If shielded, use transparent and smooth glass, oriented downwards and with a top cover, so that the light beam only points where it is needed. Lenses with a "back shield" can also be added to reduce light dispersion. Ports and harbors with shielded light for the docks and motion-activated lighting.

Lights that emit a broad spectrum of light with a high UV component should be avoided. The majority of insects and other invertebrates are most sensitive and responsive to the short wavelength end of the light spectrum.

4. The bad setting or improper application of artificial light may over-illuminate the sky when luminaries emit unnecessary light towards the sky. It is important to **orientate the light** to pedestrians, too brightly lit areas are counterproductive, as they have

the opposite effect as what was intended. Too much light becomes darker and gloomy after a few metres from the intense light, making it a more insecure place.

Lamps should not emit light at more than 70° angle. Instead of using more luminaires, place light reflector fittings. The use of internal *louvres* in the luminaire allows the reduction of direct lighting, basically increasing the energy efficiency of the luminaire.

5. **Use adaptive light controls**. There is other type of light-regulating devices as motion sensors, dimmers adaptive luminaries with remote management to manage light timing and intensity with smart control technology. By modest changes such as modifying public lights using sensors, timers and adjustable lighting in road areas, street lighting, in towns and green areas, major positive changes can be achieved.

Motion detectors can be used to turn off lights completely when there is no human activity nearby. It is more recommendable with LEDs as traditional bulbs have a long warm-up cool-down period so LEDs provide instant light. In places where the switch-off is not possible, an additional reduction of the flow in periods of less outdoor activity should be a priority.

- Use of timers.
- Decrease the number of fixtures during this period.
- Close the curtains to decrease the amount of luminosity on the outside.
- Define if there are periods when light is not needed in a particular place.

6. **Use appropriate lighting**. Consider the intensity of light produced rather than the energy required to make it, use low-glare lighting.

Lamp type

- Use a yellow colour wavelength greater than 500nm.
- It is recommended to use fluorescent lamps with a temperature lower than 3000k.
- LED lamps with yellow colour (less than 3000K) are a possible option.

7. Choose lights that emit light with **no violet or ultraviolet wavelengths**. That is, reduced or filtered out blue (such as orange, red or amber-coloured lights) to which wildlife are generally less sensitive, causing minimal harm. Also, this would contribute to reducing sky glow as short-wavelength light scatters more readily than long-wavelength light.
8. **Choose darker, non-reflective surfaces** to prevent light from reflecting into nature or the sky.

- Asphalt road surfaces near waterbodies should be made non-polarising by incorporating a rough top layer or white granules that scatter light. New buildings should not include glass that produces horizontally polarised light.

- Painting buildings pale grey or white is been seen to attract evening and nocturnal insects. For example, these painted surfaces can result in diverting pollinators away from flowers and attracting their predators.

The lighting installation will be deemed a success if it meets the optimal lighting principles mentioned above. Residents and visitors would benefit from natural and dark nights and creating environmentally friendly well-planned lighting. Thanks to good lighting designs, the areas of interest can be seen by humans clearly, easily, safely and without discomfort (Commonwealth of Australia, 2020).
For several decades the population has been forced to dispose of light 24 hours a day, disregarding the impacts of light emission on the atmosphere jointly with the imposition of the use of efficient LED technology on society without explanation of its disadvantages. White LEDs with 3000K colour temperature have been found to negatively impact ecosystems and, in some cases, have been banned. There are promising alternatives with lower impacts, but equally efficient, such as LEDs with orange or yellow tones (amber LED pc, white LED with a yellow filter, where the wavelengths below 500nm corresponding to blue are absent or residual).

- According to (Haarman, 2022), independent of colour, flashing lights also attract fewer birds than continuous lighting. Short light intervals also reduced avoidance behaviour. These alternatives should therefore be explored further and could yield great results, thus current data on colour and light patterns suggest the use of red flashlights in windmills, and oil platforms.

It is mandatory to ensure that changes in public lighting do not cause difficulties for the population. It is proposed to reduce or eliminate unnecessary lights, setting limits on light emission in terms of quantity and quality, and turn off some lights in the most critical places, days and times that affect social well-being (i.e. road insecurity caused by glare) and the environment (according to Bolliger *et al.,* (2020a), dimming the lights was found to have positive effects on insects and bats.

One of the reasons for refusing to remove luminaires or reduce lighting is because of safety concerns. However, more artificial light is not synonymous with greater safety. Recent studies in the UK show that turning off lights at night (between midnight and five a.m.) not only did not increase crime but actually decreased some types of crime, such as car break-ins. When lighting is switched off after midnight, offenders might consider that the costs of committing a crime, such as using a torch, would likely raise suspicion among residents and risk being witnessed, outweighing the benefits. Also, when the streets are likely to be in near darkness, the offenders might find it challenging to detect any valuable items left unsecured in vehicles, so they may choose to move elsewhere to fulfil their intentions (Tompson *et al.,* 2022).

The main sources of stray or deflected light that contribute most to light pollution are advertising signs, lighting in commercial areas, illuminated parks and gardens, seasonal or punctual scenic lighting (buildings lighting, through floodlights, discos and monuments, outdoor lighting), nursery/horticultural lights lit all night long, lighting of industrial areas, airports, sports facilities. Light installations with less reach but considerable local impact are promenade lights or path lights and lighting of roads and highways.

- Scenic and outdoor lighting should be switched off after midnight. This statement can be transposed to all public lighting that does not compromise safety.

4.2 Other mitigation measures

In addition to all the measures mentioned throughout this chapter, it would be interesting to consider the following:

- Support the work of professionals who protect the environment.
- Use public money to invest in designers, architects and NGOs who work on eco-designs to reduce the impact on the environment.
- Undertake artificial light auditing. For example, Portugal would benefit highly if there was a body that certifies if the luminaires meet the specific optimal criteria.
- Consider artificial migration in both economic and environmental terms. Insects attracted to light posts in planes and ports, could be then transported to other areas/countries where they could become pests (Bruce-White & Shardlow, 2011).
- Manage Natura 2000 sites for butterflies and biodiversity. Managing habitat variety across a landscape is essential to conserve the full range of typical species. Avoid uniform management habitat, and plan as mosaics to deliver wider benefits for biodiversity and environmental gains.

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