


Review

Working with Inadequate Tools: Legislative Shortcomings in Protection against Ecological Effects of Artificial Light at Night

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Abstract: The fundamental change in nocturnal landscapes due to the increasing use of artificial light at night (ALAN) is recognized as being detrimental to the environment and raises important regulatory questions as to whether and how it should be regulated based on the manifold risks to the environment. Here, we present the results of an analysis of the current legal obligations on ALAN in context with a systematic review of adverse effects. The legal analysis includes the relevant aspects of European and German environmental law, specifically nature conservation and immission control. The review represents the results of 303 studies indicating significant disturbances of organisms and landscapes. We discuss the conditions for prohibitions by environmental laws and whether protection gaps persist and, hence, whether specific legislation for light pollution is necessary. While protection is predominantly provided for species with special protection status that reveal avoidance behavior of artificially lit landscapes and associated habitat loss, adverse effects on species and landscapes without special protection status are often unaddressed by existing regulations. Legislative shortcomings are caused by difficulties in proving adverse effect on the population level, detecting lighting malpractice, and applying the law to ALAN-related situations. Measures to reduce ALAN-induced environmental impacts are highlighted. We discuss whether an obligation to implement such measures is favorable for environmental protection and how regulations can be implemented.

Keywords: regulation; standardization; environmental law; outdoor lighting; specially protected species; habitat protection; key biodiversity areas; key biodiversity organisms

1. Introduction

Artificial light at night (ALAN) is an indispensable tool. It can facilitate outdoor activities after dusk, it improves traffic safety and the sense of safety and security, and it can provide object and face recognition in the dark for all types of road users—drivers, pedestrians, and cyclists. Even though it is controversially debated to what extent public outdoor lighting is associated with protection against crime and beneficial to road safety [1–3], pedestrians seem to feel safer with uniform illumination allowing color vision [4,5]. The subjectively perceived safety and security is an important value, since it significantly affects the use of public space after sunset and outdoor activities for all groups of society.

However, approximately 30% of all vertebrates and over 60% of all invertebrates known today are nocturnal. Specifically, more than 60% of all known mammals are adjusted to the ecological niche of the night [6]. Nocturnal animals adapted their sensory systems to the nocturnal low-light conditions. Therefore, they can be directly affected if the low-light conditions are altered by ALAN,

but diurnal animals are also known to be affected [7,8]. The duration and intensity of perceived daylight, the course of twilight, and the natural light during night time, in particular moonlight provide signals for orientation and rhythms and thus represent important information for most organisms. ALAN can disturb natural night light and thus, e.g., the signal of the moon rhythm can become “polluted” [9]. Hence, the term light pollution was introduced to describe the part of ALAN, which causes adverse effects on nature and humans in a spatio-temporal context [10,11]. An increasing number of studies indicate that light pollution has great spatial distribution and thus consequences for wildlife, in particular for crepuscular and nocturnal but also for diurnal animals and plants even in far distance to urban settings (e.g., [12,13]). Even humans can be adversely affected by light immissions, as they often unconsciously suffer stress symptoms caused by artificial light with constant night-time exposure [14,15]. Especially in Europe, key biodiversity areas are threatened by the impact of ALAN, which are specially protected by European environmental law. Eighty-one percent of these areas experience brightening of the nightscapes due to skyglow [16].

Although technical lighting solutions target energy efficiency and sustainability goals, the illumination levels of nocturnal landscapes (hereafter nightscapes) increase globally by around 2–6% per year, according to modelling and ground-based luminance measurements [11] and upward radiance measured by satellite imagery (visible infrared imaging radiometer suite day/night band sensor) [17]. For example, nightscapes in Germany brightened in the years 2012–2016 similarly to the global trend. While the night sky brightness declined in a few federal states, such as Thuringia (−17%) and Saxony-Anhalt (−5.6%), it increased considerably in other federal states, such as Bavaria (+35%) and Hamburg (+29%) [18]. The development of efficient lighting solutions is thwarted by rebound effects [11,19]. Such rebound effects occur if the costs to apply artificial light decrease, probably leading to more installed lighting than initially required. Higher efficiency rates of light sources often result in higher brightness levels instead of the desired energy savings.

ALAN is a rapidly developing research field. This raises doubts as to whether the adverse effects known today are legally addressed. Hence, the question arises if existing legislation, which is designed to protect from the above-mentioned impacts, is applicable in an ALAN context. The legal framework could either be limited in scope, causing protection gaps, or be difficult to apply. Additionally, legal obligations required by environmental law provisions could be ineffective, making legislative reform necessary.

We hypothesize that environmental regulations are insufficient to provide comprehensive protection in ALAN-related contexts. Although protection is provided for species and landscapes with special protection status, there might be a lack of protection due to the omnipresence and breadth of biological impacts of ALAN, including skyglow. The paper aims to analyze the existing regulations in Germany and Europe on potential ALAN-specific protection gaps in order to find solutions to overcome these shortcomings.

2. Materials and Methods

The review uses an interdisciplinary approach. In a first step, the applicable legal framework is outlined. The legal protection and frameworks vary between states. Here, German federal environmental law is used as an example. The analysis is based on Huggins and Schlacke [20]. The European legal framework is included to broaden the scope of the legal analysis and to make the results at least within the jurisdiction of the European Union comparable. Additionally, it enables an analysis of legal protection gaps, since the European Union has enacted several legal acts that are related to ALAN and the relevant European law provisions are in part directly applicable in all European member states. Hence, the question arises whether protection gaps also exist at the European level. In a second step, the study puts existing regulations in context with a systematic review on the impacts of ALAN on various taxa, discussing how the studies fit in the specific legal context. In the last step, recommendations for technical solutions for reducing the adverse effects of outdoor lighting systems are discussed in the context of the legal framework.

2.1. Legal Analysis of Regulation Regarding ALAN

Legislation on the use of artificial light was examined by a legal analysis through legal interpretation and evaluation of court decisions. The analysis included German federal law as well as German state law. Emphasis was put on the Federal Nature Conservation Act (Bundesnaturschutzgesetz, hereafter BNatSchG), while the Federal Immissions Control Act (Bundesimmissionsschutzgesetz, hereafter BImSchG) and the German Federal Building Code (Baugesetzbuch) were also reflected. The review of the relevant provisions included an analysis of the relevant German court decisions. As far as German law provisions are prescribed by European law, relevant judicial findings of the European Court of Justice were considered. The literature research focused on the relevant publication in the field of Nature Conservation Law, Immission Control Law and European Environmental Law. To broaden the legal perspective, European environmental law provisions were analyzed, emphasizing on the Flora-Fauna-Habitat Directive and the Wild Birds Directive and its corresponding court decisions by the European Court of Justice. Additionally, European emission control legislation was considered including the International Plant Protection Convention (IPPC) Directive (2010/75/EU) and the Ecodesign Directive (2009/125/EC).

2.2. Literature Research on the Impact of ALAN on Flora and Fauna

For the impact of ALAN on flora, fauna and habitat, literature research using the method of Pullin et al. (2016) was conducted [21]. The systematic review was organized according to the PRISMA checklist and flow chart [22]. A keyword-based search was conducted using first “Web of Science” and then “Google Scholar” and additional experts advice. The key word search for ALAN focused on outdoor lighting containing the words “artificial-,” “street-,” or “nighttime light.” The taxon search used English and scientific names of animal and plant orders. On the publications that corresponded to the keyword search a title filter was applied. Only titles that contained both a reference to lighting, (artificial, natural, or darkness) and the taxon of interest were selected. Furthermore, an abstract filter was applied by reading the abstract of the publications and selecting only those presenting data from fieldwork or lab experiments or monitoring and excluding reviews and opinions. Furthermore, interviews with experts from the Loss of the Night Network LoNNe (COST ACTION ES1204) were conducted and studies added, which were not found using the mentioned search engines. The selected publications were listed according to where the studies were conducted, the type of study or monitoring, the studied taxa, and the responses. The resulting table was put into context to the legal analysis literature research. For the identification of specially protected species, the species of the references were compared to the list of Habitats Directive (92/43/EEC) edited version (2007) [23].

2.3. Designation of Technical Measures in the Context of the Legal Framework

Technical solutions and the application of sustainable parameters can mitigate the adverse effects on the environment and, thus, prevent violations of legal obligations. The parameters for the guidelines of sustainable use of outdoor illumination were elaborated in several workshops with experts of LoNNe. Experts from different scientific disciplines such as astronomy, chronobiology, ecology, lighting engineering and physics discussed the necessity and feasibility of different lighting parameters. Here we summarize the results of these workshops [24].

3. Results

The German and European Environmental Law contains several legal protective regimes to prevent or minimize negative effects on habitats, specimen of protected species and landscapes, namely the Flora-Fauna-Habitat Directive 92/43/EEC (hereafter Habitats Directive), the Wild Birds Directive 2009/147/EC (hereafter Wild Birds Directive), and the German Federal Nature Conservation Act (BNatSchG). These regulations also apply if adverse effects of outdoor illuminations are concerned. The European directives are of particular importance. They prescribe member states’ environmental

laws, i.e., they define minimum protection requirements applicable in all EU member states. European law is outlined in the results without focus on any specific member state. Relevant provisions are the prohibition to kill or disturb specimen of protected species and the prohibition to deteriorate or destruct breeding sites and resting places (art. 12 Habitats Directive, art. 5 Wild Birds Directive; § 44 para. 1 BNatSchG), the protection of Natura 2000 sites (art. 6 Habitats Directive; §§ 33, 34 BNatSchG), and the general obligation to protect nature and landscapes (§§ 13-15 BNatSchG). Additionally, the German Federal Immission Control Act subjects light emitting installations that have detrimental effects on flora and fauna, habitats, and living environments to obligations to prevent or minimize the detrimental impact.

These regulations are in most cases applied by administrative authorities. Questions whether these provisions are applicable usually arise in two situations: A project could be determined inadmissible during approval procedures [20] (p. 223 et seq.) or administrative authorities could decide to issue subsequent orders if a non-compliance is later discovered [20] (p. 118 et seq., p. 174 et seq.). The decision of the administrative body is in both cases subject to judicial review. Thus, a violation of these provisions is—if contested—ultimately determined by court ruling.

3.1. Nature Conservation Law

Relevant legal protective regimes are prescribed by European nature conservation directives, in particular the Flora-Fauna-Habitat Directive 92/43/EEC and the Wild Birds Directive 2009/147/EC. In contrast to regulations (such as the EC Regulation on the trade of protected specimen (No. 338/97/EC)), European directives are not directly applicable but require implementation into national law by each member state. The German Federal Nature Conservation Act (BNatSchG) contains provisions that required implementation and was for this reason amended extensively in 2010 and last revised in 2017 [25]. The act regulates species and area protection, landscape planning, compensation for interventions in nature and landscape, natural habitat network and interconnectedness, marine nature conservation, recreation in nature and landscape, and the participation of recognized nature conservation associations in certain decision-making procedures [26]. It is supplemented by state law regulations of the 16 German federal states, which predominantly specify the federal law to enhance its application.

3.1.1. Prohibition to Kill Specimen of Protected Species

The prohibition to kill a specimen of protected species is prescribed by European law: art. 12 para. 1 lit. a of the Habitat Directive requires that “member states shall take the requisite measures to establish a system of strict protection for the animal species listed in Annex IV (a) in their natural range, prohibiting: all forms of deliberate capture or killing of specimens of these species in the wild”. Protected species listed in Annex IV (a) are wild birds and bats, certain Lepidoptera species, amphibians, and mammals, among others, e.g., the Eastern Eggar (*Eriogaster catax*), the European Green Toad (*Bufo viridis*) and the Eurasian otter (*Lutra lutra*). In both cases, deliberate killings of a specimen are forbidden. The European Court of Justice (hereafter ECJ) has clarified the meaning of the word deliberate. An action is deliberate if the author of the act intended the killing of the specimen or, at the very least, accepted the possibility of such killing (ECJ C-221/04 mno. 71). As a result, the application of these European provisions has broadened substantially. The ECJ held in a case against the Hellenic Republic that the lack of enforcement of national regulations known to the authorities is sufficient to establish a deliberate act (ECJ C-103/00 mno. 25 et seq.). To put it more simply, a deliberate act includes conscious risk taking (such as the risk of a lighting installation to kill protected insects) but does not go any further [27] (p. 1161).

Germany adopted the regulation to ban the killing of such specimens in § 44 para. 1 no. 1 BNatSchG. Nevertheless, there is one important difference between the European prohibition (as it is adopted in many European member states) and the German Nature Conservation Law. The killing of a specimen is prohibited regardless the intent of the liable person, while the European directive

only includes “all forms of deliberate” killings. The prohibition is thus not limited to actions (factums), e.g., shooting down a bird. It is also applicable if the killing is an inevitable consequence of a lawful act such as the approval of a road construction project or the erection of wind turbines [28] (mno. 91). However, there is one distinction between undertaken actions of a person and projects: while it is sufficient that an animal is harmed by the action of a person, it is not enough that a single individual is killed by a project. As far as projects, such as the construction of lighting installation, are concerned, the German Nature Conservation Law prohibits projects only if one of two requirements are not met. The project realization is prohibited if it either causes “significant” killing risks to one or several protected specimens or its detrimental effects are not minimized through adequate and from a nature conservation perspective necessary mitigation measures [29].

Whether a project causes a “significant” killing risk is the major test. The number of potential killings is not necessarily relevant [28] (p. 302). The criteria of significance evaluates whether the project creates a risk for the species concerned that is significantly, i.e., considerably, higher than the killing risk that the species is suffering in a natural environment [30]. Therefore, a significant killing risk depends in particular on the robustness of the species, such as the ability to adjust to individual losses [31]. Mammals, e.g., the greater mouse-eared bats (*Myotis myotis*), are considerably less resilient to individual losses than insects e.g., European hornets (*Vespa crabro*). Therefore, a project causing the death of a small number of bats has to be considered a significant killing risk, while the same number of killed hornets might not be sufficient to pass the “significant killing risk” test.

The other requirement that projects must meet is the application of mitigation measures (see Section 3.4) if these are effective and from a nature conservation law perspective necessary. This requirement is not uncommonly overlooked by and demands that projects implement measures that prevent or minimize detrimental environmental effects.

3.1.2. Prohibition to Disturb Specimen of Protected Species

The European Habitat Directive forbids any deliberate disturbance of protected species, particularly during the period of breeding, rearing, hibernation and migration (art. 12 lit. b Habitat Directive). A disturbance is any adverse effect on the mental state of a specimen, which manifests itself in anxiety, flight or fright reactions [32]. This includes optical stimuli, such as light emissions, and impacts that cause fragmentation effects [20] (p. 102).

Under art. 12 para. 1 lit. b Habitats Directive and art. 5 lit. d Wild Birds Directive disturbances are prohibited if caused deliberately. The meaning of the word deliberate is identical to the prohibition to kill a protected specimen (see Section 3.1.1) [33] (§ 11 mno. 122). As a result, the person who caused a disturbance acts deliberately if the person is aware of the detrimental adverse effects on a protected specimen. While the Wild Birds Directive has a significance requirement (art. 5 lit. d), the Habitats Directive does not. The significance criterion as stipulated in art. 5 of the Wild Birds Directive is linked to the directive objectives, which is the conservation of all naturally occurring bird species. Hence, the requirements in the Wild Birds Directive align with the German implementation with the exception that the Wild Birds Directive does not require a deterioration of a local population. Thus, specimens with no link to a local population, for example migrating birds, are equally protected [20] (p. 105).

Under the German law the prohibition to disturb protected specimens is regulated in § 44 para. 1 no. 2 BNatSchG. Its scope of application is limited to strictly protected species in comparison to the prohibition to kill specially protected specimens. Strictly protected species include those whose protection is prescribed by European law (Habitats and Wild Birds Directive) [32] (§ 44 mno. 19). According to German law, a disturbance is significant if the conservation status of the local population of the affected species deteriorates. Disturbances are more likely to be significant, if the population size of the affected specimen is small. The prohibition to disturb is particularly relevant during the migration period of light-sensitive animals (e.g., migratory fish, amphibians, or birds) and for roosts of bats. If a significant disturbance exists, a violation can be averted by reducing the effects of artificial

light to such an extent that deterioration of the conservation status is prevented by mitigation measures (see Section 3.3).

3.1.3. Prohibition to Deteriorate or Destruct Breeding Sites or Resting Places

Special species protection law includes, in addition to the prohibition to kill or disturb protected specimen, a prohibition to deteriorate or destruct breeding sites or resting places. According to art. 12 lit. d Habitats Directive, member states are required to prohibit the deterioration or destruction of breeding sites and resting places. Reproduction sites are places necessary for the successful reproduction of a species, including mating and rearing sites. Resting places are places to which specimen retreat for regeneration and shelter, such as resting and sleeping [32]. This provision does not require a “deliberate” act, thus increasing the protection compared to the provisions mentioned above (ECJ C-98/03 mno. 55). Art. 5 lit. b Wild Birds Directive prohibits deliberate destruction of or damage to nests and eggs. In comparison to the Habitats Directive art. 5 Wild Birds Directive is restricted to nests only and requires a deliberate act, thus, limiting the legal protection of the Wild Birds Directive significantly.

Under the German Nature Conservation Act, deterioration or destruction of habitats of protected species is forbidden (§ 44 para. 1 no. 3 BNatSchG). A deterioration occurs, if the ecological function of the habitat deteriorates, causing a loss in reproductive success or a decline in resting opportunities [23] (p. 4) [34] (§ 44 mno. 18). The prohibition also applies if the deterioration is only gradual or caused by an indirect effect [34] (§ 44 mno. 18). A destruction occurs if the ecological function of the site or place is completely lost. The concept of damage or destruction is not limited to the physical impact on a breeding site, e.g., cutting a tree on which a bird’s nest is located, but also includes adverse effects which limit or disable the ecological function of the concerned site [20] (pp. 110 et seq.). However, according to the German Nature Conservation Act, the provision is not violated if the ecological function of the affected site or place is safeguarded in close vicinity.

This provision overlaps, at least as far as ALAN is concerned, to some degree with the prohibition to disturb protected specimens. For example, light emissions can disturb bats and cause flight reaction or avoidance behavior. This raises the question, whether ALAN that impairs a bat roost is a disturbance of the specimen or a deterioration of breeding sites. The distinction is rather unclear, but there is much to suggest that the prohibition to disturb takes only effects on the specimen itself into account, while the prohibition to deteriorate or destruct breeding sites and resting places protects the physical and functional integrity of the affected site [32] (§ 44 mno. 22). The prohibition to deteriorate or destruct offers advantages and disadvantages in conservation protection in comparison to the prohibition to disturb. One advantage is that the prohibition to deteriorate or destruct is not limited to especially sensitive periods in which specimens are typically vulnerable (e.g., during hibernation). The other is that this provision protects sites and places from both gradual and complete loss of its ecological function, while the prohibition to disturb is only applicable if the disturbance is significant [32] (§ 44 mno. 22).

However, the provision has a drawback by limiting the spatial scope of its protection to breeding sites and resting places. The spatial extent of the protection is, according to the European Commission, determined by the characteristics of the affected species. If the species’ home range is rather small, a wider understanding of the spatial scope is used, while the understanding is narrower for wide-ranging species [23] (p. 45). The protected sites and places do not include in either case migratory routes between different protected sites or between foraging areas and the protected places.

3.1.4. Protection of Natura 2000 Sites

Natura 2000 sites are a network of protected areas established under the European Habitats Directive. The network aims to protect habitats of endangered species and natural habitat types by building a network of protected areas to ensure a good conservation status. It consists of areas protected under the Habitats and Wild Birds Directive. As of 2016, the Natura 2000 network stretches over 18% of European Union’s terrestrial areas and close to 6% of its marine territory, making Natura

2000 the largest coordinated network of protected areas in the world [35]. The European Union passed legislation to protect Natura 2000 sites from activities that could deteriorate the site, obligating member states to implement necessary conservation measures. A project (construction or operation of a lighting system, light show, etc.) shall not significantly affect the conservation objectives or the integrity of the site.

Art. 6 para. 4 of the Habitats Directive requires any plan or project likely to have a significant effect on the site, either individually or in combination with other plans or projects, to be subject to appropriate assessment of its implications [36] for the site in view of the site's conservation objectives. A project is defined as the execution of construction works or of other installations or schemes or other interventions in the natural surroundings and landscape including those involving the extraction of mineral resources (ECJ C-226/08 mno. 38). Such a project could be the construction or operation of a lighting installation [20] (p. 60). The European Union uses a rather strict protection approach utilizing unique legal tools: the directive does not distinguish between the adverse effects of different projects or plans. Hence, it is irrelevant whether the project or plan caused the impact individually or in combination with other plans and projects. If the result of the comprehensive assessment indicates a deterioration of the site, the plan or project is inadmissible. Another unique characteristic of the Natura 2000 protection is that the application of the protective provisions is not geographically limited. Thus, projects and plans are subject to the assessment even if they are located outside of the Natura 2000 site. Whether a plan or project is prohibited depends only on the impact on the site not where the plan or project is located.

The German Federal Nature Conservation Act contains a general prohibition to cause a significant deterioration of a Natura 2000 site (§ 33 BNatSchG). Of greater importance is § 34 para. 2 BNatSchG, which requires projects (and plans) to undergo an assessment of its implications for the site if it is likely that the projects cause a significant deterioration on the site concerned. The project is inadmissible if that assessment reveals a significant deterioration of the conservation objectives or the integrity of the site.

3.1.5. Nature and Landscape Protection under German Law

The German Federal Nature Conservation Act establishes a general protection of nature and landscape in §§ 13 et seq. BNatSchG. It is a specific German conservation law approach that is neither prescribed by European law nor exist equivalent European legal obligations [37] (p. 317). In contrast to Natura 2000 sites, this legal regime is not geographically restricted and functions as a minimum standard of protection for nature and landscape. It aims to prevent significant detrimental effects of the performance and functionality of ecosystems or the landscape image.

The German protection of nature and landscape consists of a set of provisions containing graduated legal obligations (a so-called cascade of legal effects) [37] (p. 318). These are applied if an alteration of an area (impact) occurs. An alteration or impact refers to any changes affecting the shape or use of areas, or changes in the groundwater level associated with the active soil layer, which may significantly impair the performance and functioning of the natural balance or landscape appearance (§ 14 para. 1 BNatSchG), e.g., new street lighting installations. A significant impairment is determined by examining whether the affected species or habitats are still present in approximately same number and quality as before [38]. In the case of an impairment, the author of the impact is primarily obliged to avoid the significant detrimental effect by applying appropriate mitigation measures (§ 15 para. 1 BNatSchG; see also Section 3.4) [37]. If the detrimental effect is either only avoidable through inappropriate measures or inevitable in itself, a subsequent obligation applies: The obligation to compensate or offset the decline in performance or functionality (§ 15 para. 2 BNatSchG) [37] (p. 319). If these measures are also unfeasible, the person who caused the detrimental effect is required to pay offset payments if the project causing the detrimental effect is approved by the competent authority.

3.2. Immission Control Law

Immission Control Law addresses immissions, which are, according to the German Immission Control Act, defined as air pollution, noise, vibration, heat, radiation, and light. It creates a legal regime in case of detrimental effects on human beings, animals, and plants. For this review, the legal analysis is restricted to adverse effects of ALAN on animals and plants.

3.2.1. European Law

Emissions are subject to multiple European laws. Despite the extensive legislative activity, comprehensive legislation of all emission sources has not yet taken place (see overview [39], § 1 mno. 26 et seq.). Important legislative acts concern, e.g., industrial emissions (IPPC Directive 2010/75/EU) but light emissions are only in part regulated by European law. The European Parliament and the Council issued Directive 2009/125/EC, establishing a framework for the setting of eco-design requirements for energy-related products. Under this umbrella legislation the European Union enacts regulations (regulations are legislative acts which have direct binding effect in all member states), which govern specific energy-related products in detail, such as Regulation (EC) No. 245/2009 on fluorescent lamps. This regulation considers both “light pollution” and “obtrusive light”. Light pollution is defined by Annex II as the sum of all adverse impacts of artificial light on the environment, including the impact of obtrusive light. Obtrusive light is to be understood as the part of the light from a lighting installation that does not serve the purpose for which the installation was designed (Annex II of the Regulation). It includes light, which is improperly falling outside the area to be lit, diffused light in the neighborhood of the lighting installation and sky glow, which is the brightening of the night sky that results from the direct and indirect reflection of radiation (visible and non-visible), scattered from the constituents of the atmosphere (gas molecules, aerosols, and particulate matter) in the direction of observation. Though light pollution and obtrusive light are addressed by the regulation, it does not propose binding obligations. It describes indicative (i.e., non-binding) benchmarks for best-performing products for office and public street lighting (art. 6). In this context, best-performing products should not be confused with best available techniques: Operators of certain industrial installations are required to apply the best available techniques under the art. 11 of the Integrated Pollution Prevention and Control Directive (2010/75/EU), whereas the use of best-performing products is not required by European law. In conclusion, European law does not prescribe binding obligations to limit ecological adverse effects of artificial light, although the European Union has the legislative power to regulate ALAN and has identified “light pollution” as an issue to be addressed.

3.2.2. German Immission Control Act

German immission control law is primarily regulated by the Federal Immission Control Act (BImSchG). It contains, in addition to nature conservation law, obligations for operators of exterior lighting systems. Outdoor lighting is in most cases not subject to approval procedures under the German Federal Immission Control Act. Nevertheless, operators of lighting systems are obliged to avoid and minimize harmful environmental effects caused by light emissions. According to the definition, light immissions are harmful environmental effects, if they are, by their nature, extent or duration, likely to cause hazards, significant disadvantages or significant nuisances for the general public or the neighborhood (§ 3 para. 1 BImSchG). The protection includes humans, animals and plants, soil, water, atmosphere as well as culture and other material assets (§ 1 BImSchG). Thus, the German Federal Immission Control Act offers a wide scope of protection, which includes all adverse effects of ALAN.

The legal obligation for operators of exterior lighting systems, as set forth by the Federal Immission Control Act, depends on whether the operator needs an immission control permit to construct and operate his or her installation. If the installation is subject to approval, e.g., wind energy plants with a total height of at least 50 m (see 4th BImSchV)—stricter obligations apply, including the requirement to

comply with the precautionary principle by implementing the state-of-the-art techniques (§ 5 para. 1 (1) no. 2 BImSchG). In most cases, exterior lighting does not require such a permit, e.g., commercial lighting. Operators of such installations are obliged to prevent detrimental environmental impacts caused by the light emissions by applying the best available techniques (§ 22 para. 1 (1) no. 1 BImSchG). If the detrimental effect is inevitable, the operator is subsequently obliged to limit the detrimental impact to a minimum level (§ 22 para. 1 (1) no. 2 BImSchG). However, the scope of these obligations are limited. Operators are excluded from these obligations if their exterior lighting system serve non-commercial purposes, such as garden illuminations (§ 22 para. 1 (3) BImSchG). Public street lighting is also not subject to these obligations, if operated by the municipality [20](pp. 161 et seq.). The design and operation of municipal street lighting are heavily influenced by the technical standard EN 13201. In Germany, the DIN Standards Committee Lighting Technology (FNL) carries out the specifications for the national standard. The FNL is composed of about 66% industry representatives and mirrors the work of ISO/TC 274 “Light and lighting” at the national German level and the European level of CEN/TC 169 “Light and lighting” [40]. The standardization-committee ensures that the standards reflect the state of the art and that the national positions and interests of all stakeholders in lighting technology in Germany are considered. The standardization-committee thus provides recommendations for minimum requirements for public lighting, though the committee is a private association. Therefore, the committee lacks democratic legitimacy and it has—as a private association—no legislative power, thus, the standardizations do not create legal obligations (BGH, NJW 2008, p.3775, mno 18.). They only specify the technical prerequisites necessary to meet existing legal requirements [41].

State law plays also a role in obligations to lighting operators. For example, federal laws do not contain an obligation for mandatory street lighting in Germany, though a few federal states (Bavaria, Berlin and Baden-Wuerttemberg) require street lighting within urban areas if (financial) appropriate. However, federal states have on the other hand enacted legislation to protect flora and fauna from adverse effects of ALAN, though the legislation enacted so far has only addressed specific issues related to ALAN. The most comprehensive provisions were introduced in 2019 as desired by a federal state petition [42]. It stipulates an obligation to avoid impacts (as described in Section 3.1.5) outside of urban areas on the insect fauna by adverse effects of ALAN (art. 11a BayNatSchG). This obligation is flanked by the obligation to determine the impact that the outdoor lighting installation has on insect fauna, if installed outside of urban areas. Furthermore, art. 11a BayNatSchG allows outdoor lighting installation in proximity of protected landscape and natural habitat types only in exceptional cases. At the same time Bavarian state law prohibits façade lighting of public buildings (e.g., castles, churches, town halls and administrative buildings) between 23:00 and dawn (art. 9 BayImSchG) [42]. In addition, two federal states (Bavaria and Baden-Wuerttemberg) prohibited skybeamer outside of urban areas (art. 11a (2) BayNatSchG; § 21 para. 1 (2) LNatSchG BW).

3.3. Application of the Nature Conservation and Immission Control Law Regarding Effects of ALAN

We reviewed 303 papers to set the impact of ALAN into context of the existing law. The studies were listed according to the treated taxa in studies treating amphibians, bats, birds, fish, insects, mammals, and plants (Table 1).

Table 1. Number of articles analyzed within the review for different taxa. After applying a Web of Science search, including a title plus an abstract filter, further cross checking of literature databases was conducted, using Google Scholar (GS) and the ALAN literature database (ALAN) (<http://alandb.darksky.org>). Experts were additionally approached from the Loss of the Night Network (LoNNe) COST Action 1204 (<http://www.cost-lonne.eu/>).

Number of Articles	Literature Source	Bats	Birds	Insects	Mammals	Amphibians	Fish	Plants
Topic search		170	677	688	873	348	1404	3505
Title filter	Web of Science	55	141	70	20	52	73	150
Abstract filter		39	43	36	14	11	31	2
Add papers from cross checking	GS/ ALAN/ LoNNe	3	9	33	39	4	17	22
Total		42	52	69	53	15	48	24

3.3.1. Prohibition to Kill Specimen of Protected Species

The prohibitory effect applies if light-sensitive specimen of protected species can be injured or killed. The application of ALAN situations to the prohibition is limited in scope due to three reasons. First, the prohibition to kill specimen of protected species covers only specific species (see Annex IV (a) Habitats Directive and § 7 para. 2 no. 13 BNatSchG). These include all bat species, European wild bird species and 41 butterfly species, but not nocturnal light-sensitive organisms per se. Among light-sensitive and threatened taxa are especially amphibians, bats, birds and nocturnal Lepidoptera [12]. In our literature research we found only one paper that explores the effects on a specially protected species as listed in Annex IV (a) Habitats Directive (92/43/EEC) except for the studies on bats and wild birds. This study addresses the effects of illumination on an amphibian, the brown frog tadpoles (*Rana temporaria*) [43]. Two thirds of all the studies (202 articles) indicate severe impacts of ALAN on a very broad range of taxa, but these impacts are difficult to apply to the prohibition to kill or disturb specimen, because the tested organisms do not belong to the list of specially protected species.

Secondly, the killing risks need to be determined as significant. Significance is given if specimens are affected, which, because of their behavior, may be exposed to uncommon increased risks through the effects of the lighting system and if these risks cannot be prevented by mitigation measures [20] (pp. 91 et seq.). The significant killing risks criterion requires knowledge of the community composition and the light-sensitivity of the species concerned; both can be hard to obtain [20] (p. 98). The difficulty that arises under the Habitat Directive is similar. The act to be prohibited (e.g., the installation and the operation of a lighting system) has to be deliberate. This also requires knowledge of potentially affected protected species in the vicinity of the lighting system as well as knowledge of their sensitivity to ALAN.

The insect order of Lepidoptera, for example, is declining in rapid numbers [44,45] and from this group especially those seem to be threatened that are providing greater eye size for capturing low intense night time lighting [46]. In the UK and Ireland light pollution accounted for 20% of the variation in long-term changes in moth abundance [45]. In addition, ALAN is still successfully used in pest management of insects [47,48]. Further indications of the significance of ALAN on the decline are still lacking. However, there is strong evidence that flight-to-light behavior of nocturnal insects can directly or indirectly increase mortality. Lepidoptera attracted to street lamps have been shown to be less able to execute their normal evasive flight behavior [49,50] and often stay trapped flying around the lamps until they die of exhaustion or as prey.

The third difficult criterion for the application of the prohibition is that the injury or death of the specimen must be a direct consequence of the lighting system's light emission (BVerwG, NVwZ 2009, p. 302 mno. 91). A deterioration of a habitat, for example, due to a decline in available food sources or other ecological functions (as described above) on the specimen is not sufficient to prohibit the light emission under this provision.

3.3.2. Prohibition to Disturb Specimen of Protected Species

ALAN affects animals during the period of breeding, rearing, hibernation, and migration. Bats are a positive example where the prohibition to disturb could be applied. Their responses to ALAN can be divided into three groups: opportunistic, neutral and avoiding. The latter is mostly observed within almost all species at roosts (day and winter) and when drinking [51]. The behavior of light-sensitive bats can be impaired within the radius of up to 50 m distance to the light source, even if the luminance level is as low as 1 lux [52,53]. High intensity lighting can create a barrier to movements at foraging transfer flights across illuminated streets to even relatively common and opportunistic or neutrally behaving bats, such as the common pipistrelle (*Pipistrellus pipistrellus*) [54]. The avoidance of lit passages can lead especially to disturbed drinking behavior for many bat species [51,55]. While slow flying species such as *Myotis* and *Plecotus* spp. avoid ALAN, fast flying species, e.g., *Pipistrellus* spp. can be attracted especially to white and green lights [56] and become distracted by phototaxis from their migration routes [57]. Thus, both groups experience negative impacts of ALAN. Azam et al. (2016) judge the effects of ALAN on bat populations as being more impacting on the occurrence and the activity of bats than the factor land surface sealing [58]. These behaviors exist during periods in which specimens are typically vulnerable. It is likely that bats due to their avoiding behavior abandon habitats, which causes a decline in the local population. If such development is likely, the prohibition applies.

However, only one third of the studies were conducted on listed protected species like bats. Effects of disturbances caused by ALAN are manifold and affect a broad spectrum of species (Table 2). An omnipresent disturbance of various taxa is the suppression of circadian or seasonal rhythms when the natural signal of light is disguised by ALAN and hormone performance is affected [7].

Field monitoring for the shift in the reproduction period of a strictly seasonal wild mammal due to ALAN is yet not well documented. A leading example is an outdoor study in Australia. The study was conducted on a kangaroo species, the Tammar wallaby (*Macropus eugenii*), observing a temporal shift in the reproductive cycle between animals living in unlit bushland and animals living on an illuminated and fenced naval base. The animals were tagged with light sensors, which recorded a 20-fold higher light exposure of the animals on the naval base [59]. The animals in the bushland experienced less light and a moonlight dependent cyclical change in light levels during the night. The natural illumination of the nocturnal environment is ten times less intense than the constant nocturnal ALAN exposure at the naval base. While over 70% of the female kangaroos gave birth in December and January in the bushland, the period for births at the naval base was delayed until late April. This study is only one example of how ALAN can impact the reproduction cycle of seasonal species. Similar shifts in the seasonality of reproduction have been documented, e.g., the gray mouse lemur (*Microcebus murinus*), which is affected by ALAN causing earlier readiness for mating [60,61]. For goats (*Capra hircus*), which mate in autumn, the signal for reproductive organ development was disguised and the organs remained smaller [62]. It has been further observed that lighting in winter caused stagnant reproductive development and caused early growth and hair change toward the summer type in dwarf hamsters (*Phodopus sungorus*) [63,64].

Street lighting next to a water body suppressed in fish (perch and roach) the gene expression of gonadotropins (follicle-stimulating and luteinizing hormones) and the content of sex steroids (17 β -estradiol, 11-ketotestosterone) [65] at 13 to 16 lux at the water surface and 6.5 to 8.5 lux at a depth of 50 cm [66]. This could hamper the reproduction success of these common fish species.

Also, artificial lighting can change the seasonal behavior of birds. Molting and sexual maturity, for example, occurred in laboratory tests using low light levels (0.3 lux, comparable to a bright full moon) during night time up to three weeks earlier than in birds examined in absolute darkness during the night [67]. The fitness-relevant effects of extended daily and seasonal activity of birds have not been sufficiently studied. Likewise, to extended day use, the extended seasonal activity can potentially be beneficial to birds as more time can be spent on foraging per day and the season can be elongated. However, the advantages can be reversed if the supply of food is low due to frost in the spring [67] and if the daily extended foraging time is at the expense of the immune response [68].

The same applies to plants. Premature bud formations are mainly observed in illuminated areas [69]. It seems that rather light signals trigger this phenomenon than temperature conditions. Accordingly, early bud formation rather occurs in illuminated than non-illuminated, warm urban areas. The changes in flowering times cause adverse effects if they take place outside the flying times of pollinators and only a few or no insects are available for the propagation of these affected wild plants. Since plants react with different sensitivities to light and differences in day length [70], artificial lighting can lead to the loss of sensitive species and consequently to a reduced supply of flower forms, which in turn can affect the occurrence and diversity of pollinating insects [13,71].

Table 2 lists the results of the literature research for disturbed seasonality and reproduction performance by ALAN. Suppressed seasonality can worsen the conditions for reproduction and affect the response on environmental stressors such as chemical pollutants and climate change.

Yet, it remains unclear whether a shift in seasonality in reproduction causes a negative effect on population dynamics. The effects of ALAN indicate a disturbance of the organisms and thus presumably a relevant stressor to these species. However, the prohibition to disturb specially protected species only applies in very specific cases: disturbances of hormones are often neither expressed in anxiety, flight, nor in fright reactions nor hormonal stress responses, such as increased cortisol. Hence, the impact of outdoor lighting often cannot be recognized as a stressor to light exposed organisms (e.g., in perch [72]). Only if light is applied at very high intensities, evidence for stress symptoms such as anxiety can be observed, e.g., salmon exposed to 160 lux [73]. In a diurnal toad (*Melanophryniscus rubriventris*), stress symptoms were observed when exposed to ALAN throughout the whole night analyzing the leukocyte composition in blood samples [74] and the stress hormone corticosterone of nesting great tits (*Parus major*) was increased [75]. The proof of the stress level in the wild bird required blood samples, which makes it difficult to provide evidence to determine stress levels and, subsequently, to apply the prohibition to disturb protected specimen. Except for the wild bird (*Parus major*) neither the toad nor the fish species discussed above are listed as protected species in Annex IV (a) Habitats Directive.

Table 2. References for potential disturbances caused by ALAN of various taxa indicating suppressed hormone performance, shifted seasonal or circadian rhythms or impact on reproduction behavior or growth.

Taxa	# Articles	Disturbance Effect	References
Amphibians	10 (1 *)	Development of juveniles, growth and reproduction, mortality, male courtship calls, shifted predator–prey ratio	[74,76–84]
Bats	1 *	Development of juveniles	[85]
Birds	26 *	Sleep disruption, reduced reproductive hormone secretion, altered seasonal rhythm	[67,68,75,86–108]
Fish	17	Timing for hatching and initial swim bladder filling, reduced expression of reproductive hormone secretion, reproduction failure, suppression of circadian rhythm, social interactions	[72,109–124]
Insects	8	Shifted diapause induction, shifted timing of gender occurrence, disturbed communication to find mates, impaired immune function, prolonged juvenile development time, reduction in pheromone quantity and quality, extended season, activity, and fecundity	[125–132]
Mammals	30	Shifted circadian and seasonal rhythms, decreased foraging	[59–64,133–156]
Plants	16	Delayed leaf fall, early bud burst, decreased stomatal movements, shifted community compositions, accumulation of superoxide radicals, triggered stress responses, soybean maturation delay, changed photo-physiology, increased crop yields	[69,157–171]

* References considering taxa listed on Annex IV.

In conclusion, the prohibition can be used for the protection of species that show evident avoidance behavior and belong to the strictly protected species of the Annex IV list. However, the lack of anxiety, flight or fright reaction against ALAN makes the provision hardly applicable, thus, creating a protection gap. The same applies as far as disturbances are concerned on a broad range of taxa, which are not listed in Annex IV (Tables 2 and 3).

Table 3. References indicating disturbance caused by ALAN of various taxa indicating avoidance behavior and interference by phototaxis.

Taxa	# Articles	Impact	References
Amphibians	5	Habitat selection and changes in behavior during migration and breeding season	[76,79,172–174]
Bats	36 *	Light avoiding behavior at roosts, community routes and drinking habitat, shifted predator-prey ratios, shifted community structures,	[49,52–57,85,175–202]
Birds	16 *	Changed migratory behavior and collisions of coastal birds due to phototaxis, habitat avoidance for nesting	[95,203–217]
Fish	19	Community structures, migration behavior, fry dispersal, changed light avoiding behavior of an invasive crayfish with potential impact on the ecosystem, increased sediment swirl by crayfish	[218–236]
Insects	37	Aggregation at lit places, avoidance of lit places, shifted predator-prey interactions, shifted plant-herbivore interactions, aquatic insect drift, reduction in pollination performance, population decline, shifted oviposition sites	[45,46,237–271]
Mammals	9	Shifted activity patterns and space use, shifted predator-prey relations	[136,141,142,272–277]

* References considering taxa listed on Annex IV.

3.3.3. Protection of Natura 2000 Areas and Protected Breeding Sites and Resting Places

Light has been introduced in places, times and at intensities at which it does not naturally occur [278]. Thus reproductive and resting places and other light-sensitive habitats, including Natura 2000 areas, experience increasing disturbances due to (a) direct artificial light irradiation [279], (b) scattered light from illuminated spaces outside the habitats [280,281], and (c) skyglow from distant urban areas, caused by reflection of ALAN at atmosphere molecules, aerosols, and especially clouds [282]. Nightscapes can be affected by skyglow from urban settlements in the far distance [283,284]. The impact is highly dependent on light intensity and shielding of luminaires [283]. Guette et al. discussed that despite the establishment of buffer zones around nature reserves, core areas of the protected sites are increasingly affected by ALAN [285]. In Europe, special protected natural habitats are increasingly threatened by skyglow and the sources for the disturbance are often unknown [16].

ALAN can significantly change nightscapes and have detrimental effects on the ecological functions of the affected site. It can increase the spatial resistance, cause habitat fragmentation for various organisms (Table 3) and deteriorate the suitability of habitat for migrating species (Table 4). While there is empirical evidence from laboratory and experimental studies that light level comparable to urban skyglow has adverse effects on organisms (e.g., references [86,109,286]), there is as of yet only limited evidence from field monitoring (e.g., references [253,287]).

The responses to ALAN depend on the species and their developmental stage. For example, amphibians can perceive light intensities as low as 10^{-5} lux [288]. Due to their high adaptation capability to low light conditions, amphibians can easily be blinded and stay immobile against threats such as predators or cars when suddenly exposed to light [76,172,289,290]. A study by Grunsven et al. indicated that migrating toads stopped to migrate when exposed to ALAN [173]. This behavior is light color-dependent: red lighting did not prevent toads from migration, while green and white light emissions interrupted migration until dawn, when the lights were switched off.

Birds have an extraordinarily good visual performance and many species are highly attracted to light sources and are therefore threatened to fatal collisions by ALAN. Migrating birds as well as many sea birds and petrels have been observed to collide with buildings or coastal formations when strongly illuminated [208,212–216]. Cabrera-Cruz et al. argue that the global migratory behavior of birds could be adversely affected by illuminated landscapes and that the birds can be at risk of approaching non suitable habitats in urban settings instead of wetlands for their resting on migratory routes [291].

Migrating fish can also be disturbed by ALAN. Mature silver stage European eel (*Anguilla anguilla*) are highly light-sensitive. For example, flume experiments demonstrate a strong avoidance reaction of silver eels to ALAN [292]. This can result in a reversed, upward migration against the current when lights are directed upstream [293]. Although salmon (*Salmon salar*) is more apt to adjust to ALAN, hatchery studies reveal that juvenile specimens are attracted to ALAN and stay in lit areas for a long period while delaying their dispersal [220]. Thus, the spatial resistance of a landscape increases with ALAN and the migration becomes more time and energy consuming, which can jeopardize the natural synchronized reproduction especially for long distances migratory species such as eel or salmon [294].

Nocturnal Lepidoptera (moths) may substantially suffer from landscape deterioration and fragmentation by nightlights. Degen et al. calculated that the attraction radius for moths to streetlights is 23 m or more [258]. When street lighting is installed with lighting points of for example 40 m distance to each other, the illumination can become a barrier to the insect dispersal. However, other flying organisms are also affected. The giant water bug (*Lethocerus deyrollei*), for example, lost the habitat when illuminated. In a field study in Korea, Choi et al. found that the giant bugs could no longer be detected in a radius of 700 m around artificial light sources and anthropogenic influences and their occurrence was considerably limited within a radius of 3 km around the light sources [260]. Perkin et al. described altered flight behavior in up to 40 m distance to a light source for other aquatic insects [251].

Studies indicate that biodiversity seems to be reduced in close vicinity of streetlights. Although 70% more moths were found at streetlights than at unlit sites, the diversity of moth species decreased by more than 25% [247]. Moreover, the moths carried plant pollen from a smaller number of different plants than in natural darkness. In addition, moths were found to produce fewer pheromones under illumination, possibly decreasing their reproductive performance [128]. Thus, the attraction and altered behavior of insects in lit areas can hamper the provision of food sources for many animals, such as bats, birds and fish, including threatened species.

Illumination can further impair the ecological function of nighttime pollinators with severe consequences on the vegetation as a food source for daytime pollinators [237]. The seed dispersal from fruit-eating bats was also observed to be reduced [198]; this study does not affect European landscapes, because it examines tropic species, but is a vivid example of how an ecological function (here seed dispersal) could be disturbed with unknown consequences for the surrounding vegetation and landscapes.

Ecological functions in riparian areas can be similarly affected. Grubisic et al. found that direct LED lighting on aquatic freshwater bodies can interfere with the communities of periphyton, the primary growth of plants, presumably due to the high emission of blue light [157–159].

Furthermore, skyglow can reduce the vertical migration of algae consuming zooplankton in freshwater lakes [287]. If *Daphnia* no longer migrate to the upper layer of the water column at night due to ALAN, algae will be released from *Daphnia* consumption. As a result, algae biomass and cloudiness of the lake may increase, although the nutrient load is unchanged [294]. Aquatic insects can be attracted to the light sources in high numbers after emerging the water body [294]. Reproduction is further reduced by the strong signal of lighting amplified by artificial, reflective surfaces near water, which can disguise the natural signal, and prevent aquatic insect ovipositioning in suitable habitat [295,296]. Outside of suitable aquatic habitats, the offspring can be threatened to drought.

Flying insects are attracted to streetlights in high numbers, ALAN captivate insects from their natural habitats and deprive their ecological function, an impact which can be described as a vacuum cleaner effect [297]. Both, exhausted and dead insects that accumulate on the ground are a food source

for insectivorous predators or scavengers [250,297,298]. Naturally nocturnal spiders, carrion beetles and slugs have been observed to extend their foraging until late in the day—presumably to benefit from higher abundance of exhausted or dead insects in the area of the lamps [249,298].

Other distortions in ecosystems appear because some diurnal species such as fish or birds can use lit areas to extend their daily activity into the night: Some predatory fish species have higher foraging success [218,299]. Feeding places for songbirds are being visited longer [217] and in higher numbers [300]. Prolongation of the daily activity of songbirds was observed [67,97,101,103,104], and the extended activity phase correlated with the level of luminance in many birds such as robins, chaffinches, blackbirds, great and blue tits [286]. At lit beaches, waders have been observed hunting for sandworms even after dark [95]. A prolonged activity phase can be beneficial to the foraging success, but it can be detrimental to the immune system of higher vertebrates in the long term [68], altering predator–prey relationships and distorting whole food webs [249].

In conclusion, the impact of lighting systems can be calculated by the detrimental impact on landscapes (Table 4), the disturbance of species in their circadian and seasonal performance (Table 2) and changed behavior due to avoidance and phototaxis (Table 3). The deterioration of conditions for protected and other species are in most cases due to natural landscape deteriorations produced by lighting systems outside of Natura 2000 and resting- and breeding sites [285]. However, the distance up to which skyglow effects have an impact on light-sensitive species remains unclear. Therefore, evidence for a significant impairment of the conservation objectives of the respective protected area is lacking. Hence, the aim of European law to ensure a strict protection regime for special areas of conservation under the Habitat Directive falls often short in ALAN-related situations. The same applies to the general protection regime of nature and landscape under German law. Although it does not distinguish between protected and unprotected species and has in general a broad spatial scope of application, it requires a substantial impact from a single lighting source.

In order to minimize the direct light immission in sensitive habitat, two regulations have been recently enforced. In France, any direct light emission towards water bodies is prohibited [301], while Bavaria require to avoid light emission on insect habitat [42] (art. 11a Bavarian Nature Conservation Law).

Table 4. References indicating fragmentation and deterioration of landscapes due to distorted food webs for various organisms.

Landscape Deterioration Effect	Taxa Concerned	References	#	References with Taxa Listed on ANNEX IV	#
Barrier in aerial habitat or avoidance	Bats Birds Insects	[53–55,57,102,178–180,182,184,185,188,189,195,197,211,213,214,216,241,251,253,258,260,269,291,302–304]	29	[53–55,57,178–180,182,184,185,187,189,195,197,214,216,291,303,304]	19
Terrestrial habitat avoidance or disorientation, avoidance behavior at roosts	Amphibians Bats Birds Mammals	[85,133,136,173,174,176,203,207,272–274,305–307]	14	[85,176,203,207,307]	5
Distorted food webs	Amphibians Arthropods Slugs	[79,173,240,249,250,298]	5	–	0
Barriers in freshwater bodies and aquatic habitat avoidance	Fish Insects	[222,225,228,244,293,308]	6	–	0

3.4. Measures to Reduce the Detrimental Effects of Flora and Fauna

Technical mitigation measures concerning lighting situations are particularly relevant. Such measures can thus prevent a violation of environmental law obligations such as the prohibition to disturb protected specimens (see Sections 3.1 and 3.2). For example, the application of lower light levels, can reduce adverse effects to an extent that killing or disturbance risks [51,58,180,195,303]

and deterioration effects of landscapes [283] can be avoided. In addition, the existence of effective mitigation measures is important to determine whether the legal obligation to avoid adverse effects is an adequately functioning legal tool.

Adverse effects of ALAN are not persistent in contrast to the detrimental effects of chemical pollutants. Similar to noise, ALAN can be eliminated immediately when turned off and limited if the light emission is spatially and temporally restricted to its purpose. Adequate and sustainable lighting systems are defined as (a) energy efficient and consume demonstrably little electricity, (b) increase visibility, security and safety, (c) are aesthetically appealing, and (d) its environmental impacts are minimized. Hereafter, we list relevant technical parameters to mitigate the adverse effects of illumination on flora, fauna, and landscapes.

3.4.1. Light Intensity

The required illuminance level depends on the one hand on the demand and the other on the possible negative environmental impact of the illumination. We advocate for an “as much as necessary and as little as possible” approach for outdoor lighting, or using the term of the Green Public Procurement Report [309]: to apply light levels “as low as reasonable achievable”. This principle aims to avoid adverse effects and results in energy and cost savings. There is still a need for additional research to determine minimum thresholds for numerous applications. However, one of the most effective methods to limit or reduce the adverse effects of ALAN is to reduce the light intensity. (e.g., references [54,286,303]).

Requirements for street lighting result from the visual performance to detect obstacles and to provide orientation. The perception of objects is facilitated if contrast is increased. Low light levels can be supported in the choice of high contrasts of the street surface, for example, highlighting pedestrian and cyclist lanes in different colors than the road for motorized traffic. Another factor to safely reduce illuminance levels in areas with light-sensitive organisms and residential areas is the reduction of traffic velocity either completely or at least during the dark phase. It is necessary to determine the traffic volume at specific times during darkening and night hours of different seasons to determine adequate street lighting levels. Technical measures should be used to avoid inflexible light levels, which illuminate the streets during the dusk, night and dawn in intensities that would be only necessary for high traffic volumes.

Light sources that emit higher intensities than surrounding streetlights cause glare and the incautious distraction of the eye towards the light source (psychological glare), which triggers a constant adaptation of the eye to light intensity differences. Falchi et al. therefore recommend to define a maximum illuminance for specific administrative areas [310], enacting regional lighting concepts or master plans [311]. An example of a comprehensive municipal lighting concept is the recently developed lighting plan for the city of Fulda, which was part of the application to become the first certified German dark sky community [312].

In lighting concepts, the communities are recommended to set upper limits for the luminance of self-luminous or light reflecting surfaces, for example, billboards or facades. Regional laws of Italy (e.g., Abruzzo, Lazio, and Lombardy) and the national law of Slovenia limit surface luminance to 1–2 cd/m². While these low limits are reasonable for light-sensitive ecosystems and landscapes, much higher levels are applied in lighting concepts of various cities. The lighting master plan of the city of Lucerne limits roof advertising to a maximum of 110 cd/m² [313]. Likewise, in the “advertising context for the urban image of Berlin”, a maximum of 500 cd/m² is permitted. This maximum value can further be limited down to 14 cd/m² depending on the respective area type, background brightness, time of day and types of light sources [314]. Luminance of 100 cd/m² can achieve visual acuity [315]. Thus, it is recommended to reduce the luminance of signs and billboards accordingly and to implement curfew hours, for example between 23:00 and 06:00, during which the signs need to be dimmed or turned off [316].

3.4.2. Radiation Geometry

The ratio between the total emitted light and the part that is released into the sky can be calculated as a percentage, the so-called upward light output ratio (ULOR), or upward light ratio (ULR) if the radiation of the luminaire into the sky is calculated by the emitted direct light plus the reflection from the ground [317,318]. Upward radiation should be limited to a minimal amount by limiting light emission in the upper half and the horizontal as the shielding of light emission has significant impact on the distribution of light and sky brightness by skyglow [283,319]. Downward directed radiation of outdoor luminaires should be applied in an angle of less than 70° (the angle of 0° describes the area directly below, the 90° angle the area in the horizontal, and 180° straight above the light source). If radiation geometries with larger angles are necessary, the light beam should be shielded, permitting no stray light beyond the lit object itself. In particular in the vicinity of nature protected and riparian areas, the strictest light geometry criteria should be applied and lighting of objects—for example monuments or churches—should be avoided or regulated in time and intensity (see regional regulations in France and Bavaria in Section 3.3).

3.4.3. Light Color

Substantial color rendering is important for detecting traffic signals and color coding of signs. Color correlated temperature (CCT) values of below 1800 Kelvin (K) only allow limited human color recognition and some colors can be hardly distinguished under such conditions. With increasing CCT the color rendering improves. Above 3000 K, color detection of the human eye increases to 100%. However, the potential of color detection in foggy conditions is reduced if the portion of blue light spectra increases. In addition, the dark adaptation of the human eye is limited at higher color temperatures or higher proportion of blue. Hence, Jin et al. recommend a color temperature of 3000 K for streetlights, which allows high color rendering, provides low dispersion to foggy conditions and still allows a relatively good dark adaptation of the human eye [320].

The following principle applies when environmental impacts have to be concerned—the wider the color spectrum of luminaires, the more organisms can potentially be affected. If the spectrum is limited, the question arises, which colors cause the least impact on flora, fauna, and humans and should therefore be preferred? Organisms respond highly variable and sometimes contrary to different color spectra [7,12]. Thus, optimal light color conditions for all applications cannot be generalized. However, there is evidence that adverse effects from cool white bulbs with a broad color spectrum and a relatively high proportion of short wavelengths (i.e., blue light) are more severe than light emissions that tend to emit longer wavelengths [321,322]. Since light emissions with a high blue content may affect more organisms [310], cold white light—with a high proportion of blue light (wavelength less than 490 nm)—should be avoided as far as feasible during the evening and night. Hence, outdoor lighting should have CCTs of 3000 K or less and if the installation is within or in vicinity of protected areas preferably less than 2400 K. Light-sensitive areas require the use of either low- or high-pressure sodium vapor lamps with light intensity regulation or LED with the lowest possible blue light component, such as narrow-band amber or phosphor converted (PC) amber LED. The illumination of freshwater systems, where the spectral composition of the water is altered by additional optically active constituents that absorb or scatter light, might be an exception because all colors seem to be detrimental [7,109,110].

3.4.4. Requirement Profiles for Lighting Systems

New lighting installations or the operation thereof should be designed and operated as defined in a requirement profile. It should include the purpose and scope of the illumination necessary. For example, the Office for the Environment in the Canton of Solothurn in Switzerland has compiled descriptive information materials for the construction planning of municipalities to avoid unnecessary light emissions [323]. Requirement profiles should determine parameters for illuminance, luminance, illuminated area, radiation geometry, color spectrum, and temporal illuminance control. The parameters

should be based on objective criteria: for example, visitor numbers of tourist facilities, color rendering requirements for specific purposes, usage numbers for infrastructures or requirements for hazardous situations such as pedestrian crossings or known accident black spots, which objectively justify specific illumination parameters. Of the various technical solutions for lighting systems, the one that causes the least adverse effect on the environment should be chosen by default. Lighting beyond the requirement profile can be energy-inefficient and damaging to biodiversity, result in additional costs, and can create non-compliance with legal obligations (see Sections 3.1 and 3.2).

4. Discussion

A significant number of studies indicate adverse effects of ALAN on light-sensitive species, natural habitats, ecological functions and landscapes. Technical measures exist to implement parameters for sustainable lighting solutions, namely the regulation of intensity, light color, and appropriate radiation geometry (see, e.g., reference [324]). However, although the awareness of the impact of ALAN increases and knowledge gaps between stakeholders and the scientific community are declining, more and more lighting systems with increasing intensities are installed [17]. This discernible trend is perpetuated and intensified by uniformly lit infrastructures, private illuminations and brightly lit commercial advertisement [325].

The adverse effects of ALAN interfere with environmental protection objectives. Light emissions can cause “broad” adverse effects, impacting a wide range of taxa or whole ecological systems. ALAN can also cause specific negative effects, disturbances to light-sensitive taxa such as bats. Some adverse effects of ALAN can be described as almost indiscernible, since disturbing effects in organisms can be hard to detect (e.g., reduction of hormone performance or the immune response) causing a decline of the species’ resilience. Due to these circumstances, artificial light emissions are relevant to habitat protection both in general and for special protection, to species protection and—as a technical installation—to immission control. Hence, adequate protection against the adverse effects of ALAN requires different legal tools.

European law addresses, similar to German laws, the adverse effects in two different fields of law. It uses a strict approach to protect specific species and selected habitats (nature conservation law) and it applies lighting installations to immission control laws. The tools often used in these legislative frameworks are subject to specific limitations. Adverse effects of ALAN must either affect specially protected species or habitats, cause significant impacts (e.g., population decline) or be caused deliberately by the person responsible of the light emission.

If the broad and indiscernible effects of ALAN are taken into account, it gives an indication why legal protection could be insufficient: broad effects impact species regardless of their conservation status; indiscernible effects do not manifest themselves in death or disturbances of specimens. This preliminary assessment suggests that only specific negative effects apply to current European (and German) law, leaving protection gaps for the remaining adverse effects. Positive examples for effective protection of specific impacts (on protected species) are the attraction of ALAN on birds, causing deadly collisions or the avoidance behavior of bats, resulting in a loss of habitat, e.g., roosts [20].

However, legal obligations are even in these specific cases often not applied. Considering the main legal characteristics and the results of our review—specifically the application of the law (see Section 3.3), we identified three sets of reasons as the most important obstacles why the application of the law is lacking and where legislative shortcomings cause protection gaps. These are a lack of expertise and awareness, including knowledge gaps, deficits in the scope of protective legal regimes, and deficits in applying adverse effects of ALAN to the law.

4.1. Knowledge and Awareness Gaps

So far, no conclusive thresholds of light intensities exist below which artificial light is not harmful to species and habitats. Laboratory studies indicate that even skyglow levels can affect organisms (e.g., references [7,326]). However, in outdoor field studies the light levels indicating effects seem to be

much higher [87,94,109]. Also, the impact of skyglow is yet not fully understood. It remains unclear to what extent and under which conditions light-sensitive species are threatened to lose habitat due to the brightening of landscapes. Landscapes can be brightened by skyglow to an extent which is several times higher than the natural night time brightness [327]. Nevertheless, standardized measurement methods of sky brightness to judge the impact of the skyglow from urban settings on landscapes and especially protected areas (e.g., Natura 2000) are lacking [328–330]. Similar to temperature and rainfall the data on the brightness of landscapes needs to be monitored and made publicly available (see also reference [331]). This causes protection gaps: As long as thresholds of harmful effects of ALAN are not identified, applications of ALAN cannot be defined as harmful or significant adverse effects which in turn make the application of the law impossible. Even if such information and knowledge gaps are covered it remains challenging (and often costly) to provide sufficient evidence if, for example, small species such as insects are affected since population loss is difficult to assess.

Studies present strong evidence that ALAN can distort food-webs. But it is currently not well known, how much natural darkness and which spatial extent of protection is necessary to safeguard fully functioning ecosystem services and food webs. Furthermore, the relevance of the factor ALAN cannot be rated in relation to other pollutants such as chemicals, pesticides, noise and impoverishment of landscapes due to land use. Studies indicate that deteriorated conditions due to pollution and climate change might become reinforced due to the impact of ALAN (e.g., references [69,118,153,332,333]). This calls for further research, as well as a strengthening of awareness and expertise, to establish fundamental knowledge to subsequently determine harmful effects and define necessary mitigation measures.

The trend to higher ALAN consumption and neglected expertise on the adverse effects urgently call for better legislative regulation. Regulating new lighting installations and modernizations of outdated lighting systems are suggested to safeguard compliance with environmental European law. A legislative approach by regulating the application of outdoor lighting is necessary not despite but precisely because of a lack of scientific knowledge. Legislation should, based on the precautionary principle as required by art. 191 Treaty on the Functioning of the European Union (TFEU) (ECJ C-157/96) [334,335] (mno. 26 et seq.), establish protective regulations for risks indicated by the studies presented (see also reference [336]). Such legislative action could be based on Art. 192 TFEU or be integrated into the legal framework of the Eco-design Directive such as the Regulation (EC) No. 245/2009, which stipulates energy efficiency targets but does not impose binding obligations to limit adverse effects of ALAN. Additionally, better energy efficiency of lighting products does not necessarily mitigate adverse effects of ALAN. On the contrary, it is likely that the trend to energy efficient, e.g., high CCT lighting substantially increases the adverse effects of ALAN for many species [321,322] and habitats in clear weather conditions [325,337]. Investment costs of adequate lighting management systems to restrict light intensities to the needs are often higher than the potential financial benefit. However, the investment in lighting control management is an important factor to save energy and protect biodiversity.

Despite the knowledge gaps some states have acknowledged the adverse effects of ALAN and adopted specific regulations. For example, the Senate of Mexico recently endorsed legislation that classifies light pollution as a form of environmental pollution. The new law makes light pollution subject to regulation under existing environmental laws. Australian environmental authorities have developed a draft for national light pollution guidelines that aim to raise awareness of the potential impacts of artificial light on wildlife and provide a framework for assessing and managing these impacts around susceptible listed wildlife.

4.2. Limitations in Scope of Application

European and German environmental law include the protection for specific species, the protection of selected habitats (Natura 2000 network) and legislation on light immission control. However, these provisions are limited (a) in its spatial and (b) material scope of application and (c) by its conditions for its application which results in shortcomings in legal protection.

- a. Adverse effects of ALAN do not only affect specific natural habitat types but can lead to impairments across all landscapes. However, a legal framework on European level for a general protection of landscapes is missing. Obligations to protect landscapes in German nature conservation law (§§ 13 et. seq. BNatSchG) are also limited in its spatial application. The spatial limitation is further reduced as far as special protected landscapes, such as areas belonging to the Natura 2000 network, are concerned. But even the strict protection approach of the Habitats Directive is in part not comprehensive since protection against skyglow effects is ineffective.
- b. Protection gaps occur because some light-sensitive species, such as bats, are protected due to their conservation status, but others are not. Limitation in scope can be justified since special species protection aims to provide protection only for endangered species or species for which a country bears particular responsibility.
- c. The prohibition to disturb protected species is only applied if ALAN has psychological adverse effects on the specimen, e.g., anxiety, flight or escape reactions. However, ALAN does not always trigger such stress levels but rather decreases the immune response, certain hormone secretion, and circadian and seasonal timing. Thus, impacts of ALAN often go unnoticed.

The Immission Control Act also contains significant protection gaps, because lighting systems that are not used for commercial purposes or within an economic enterprise are exempted from the obligations under the German Federal Immissions Control Act. These are in particular privately used lighting systems such as home and garden lighting and street lighting systems operated by the municipality since these primarily serve public interests without economic purposes. However, private lighting of gardens, balconies, and house facades are increasing in quantity, amplifying the impact on the environment.

Additionally, technical standards such as the EN 13201 specify only minimum brightness levels in various traffic situations, based solely on light technology and energy efficiency, lacking expertise of the chronobiological or ecological adverse impacts of ALAN and upper maximum brightness levels. Due to a lack of specific light emission control legislation, vague environmental laws fade behind an effective industry standard, which is often misunderstood as legally binding.

4.3. Deficits in Applying the Law

Relevant protective provisions, such as the prohibition to kill or disturb specimens, use a strict approach, i.e., projects causing the death or disturbance of a protected specimen are prohibited. This “strict” approach could also be described as a rather “deep” than a “broad” approach. The scope of the provisions is limited in scope (see above) but when applicable they are designed to provide comprehensive protection. This approach has been effective to safeguard the conservation status of rare and endangered species, such as, e.g., the little owl (*Athene noctua*) [338]. Some of the adverse effects of ALAN are aligned to this approach offering effective protection if applied (e.g., bats), although the list of light-sensitive species in, for example, Annex IV of the Habitats Directive is short [23]. Other—possibly most—adverse effects of ALAN could, however, be described as rather “broad” than “deep”: ALAN affects a wide range of taxa adapted to the night niche, its effects vary but are often hard to measure. Similarly, ecosystems and food webs rely on ecosystem services of nightscapes regardless of its natural habitat type; adverse effects of ALAN inflict stressors on the ecosystems and food webs resulting in a deterioration of habitats and biodiversity by compromising the robustness against other stressors.

European nature conservation law, as provided by the Habitat and Wild Birds Directive, tackles such broad adverse effects by implementing, inter alia, two strategies. On the one hand is the legal framework, e.g., Natura 2000 protection, designed to protect against a broad range of adverse effects by prohibiting deterioration of the objective goals, such as the natural habitat type or protected species, subsequently providing a good conservation status of the respective ecosystem or food web (see [339]). This is flanked on the other hand by the requirement to ensure a good conservation status of habitats “involving, if need be, appropriate management plans” (art. 6 Habitats Directive) and other measures.

The latter is largely not utilized to benefit light-sensitive species since knowledge and awareness gaps persist (see above).

The objective goals include in addition to the protection of species also a good conservation status of natural habitat types [340]. Hence, adverse effects impairing such objective goals would be applicable under art. 6 Habitats Directive or §§ 33, 34 BNatSchG respectively. However, significant deficits in their application through the environmental impact assessment (not restricted to ALAN-related situations) remain [341]. The results strengthen this evaluation since there is only one paper available that treats species protected according to the Habitats Directive specifically. The lack of supplemental information creates substantial obstacles for the application of the law. Administrative bodies, which are assigned to evaluate the effects of lighting installations, lack sufficient evidence or expertise to assess the lighting systems' implications (see also Section 3.3.1). The European Commission has issued guidelines on the assessment of the implications [342], but they do not address light emissions specifically. The lack of evaluation standards and evidence in combination with prognostic uncertainties create substantial obstacles for applying the law.

Even if the obstacles to conduct an impact assessment are removed, it is questionable if instruments such as the assessment required by art. 6 (3) Habitats Directive are adequate legal tools. Lighting systems are typically not subject to approval procedures, in which such an assessment would take place. It seems very unlikely to conduct such an assessment on lighting systems if the legality does not require an approval procedure. The fact that one lighting installation alone typically does not constitute a significant deterioration of habitat supports this conclusion [20] (p. 75). Hence, the requirement that national authorities agree to the projects (i.e., lighting systems) only if the "conclusions of the assessment of the implications for the site" ascertain "that it will not adversely affect the integrity of the site concerned" (art. 6 (3) Habitats Directive) is an inadequate legal tool to provide comprehensive protection against adverse effects of ALAN.

These shortcomings also apply to the prohibition to kill or to disturb protected specimens. National authorities face similar difficulties in applying ALAN-related situations to the law. These obstacles may even be harder to overcome. While the protection of Natura 2000 sites prohibits deterioration regardless whether it is caused by a single or a combination of several light installations, while the prohibition to kill or disturb protected specimens only applies if a single person responsible, e.g., an operator of a lighting installation causes the significant adverse effect. Since skyglow is caused not by a single lighting source but by a high number of lighting systems, adverse effects caused by sky glow or by multiple lighting systems are inapplicable.

In addition, European special species protection provisions presuppose a deliberate act, thus, the provisions are only applicable if the constructor or operator of the lighting system accepted the possibility of the stipulated adverse effect (e.g., injury, death or disturbance) which is less likely as long as knowledge and awareness gaps last.

Concerning the German implementation of the prohibition to kill or disturb, both require a significant effect, which requires a considerable increase in killing risks of a specimen. A significant effect, however, can only be assessed if relevant information on the mortality of the species at issue is available. Such information is either scarce or difficult to obtain, hindering the effective application of the provisions.

In conclusion, the legal instruments available rely on legal tools that are in ALAN-related situations typically hard to apply and, thus, inadequate. These are the requirement to assess the implications on Natura 2000 sites, the criterion of significance, the lack of supplement legislation or guidelines and the necessary causation link between the light emission and the detrimental effect, which require a case-by-case decision. Instead, an approach should be used that creates ALAN-specific requirements, such as the application of certain illuminance levels, light colors, or light geometries (see Section 3.4), making a case-by-case decision obsolete.

Currently existing regulations specifically designed to address adverse effects of ALAN are regional and scattered. They lack a coherent strategy for providing, e.g., wildlife corridors. France

started such an attempt but only in one regional department [343]. Another example is a national act against light pollution in Slovenia (2007) that uses a strict approach (e.g., limiting ULOR to 0%) [344]. The Slovenian and some Italian regional regulations include restrictive measures, such as the limit of 1–2 cd/m² surface brightness. If European legislation against adverse effects of ALAN is adopted, it should—as the subsidiarity principle according to art. 5 of the Treaty on European Union (TEU) requires—not undermine existing national or regional regulations but safeguard minimum protection and enhance regional or national stricter approaches.

Optimized regulation against adverse effects of ALAN would require binding mitigation measures, e.g., similar to the South Korean Light Pollution Prevention Act 2013 [345], but should also offer flexibility as, e.g., provided by British regulations [316]. Furthermore, optimized regulations would restrict light emissions in residential areas and habitat of high diversity such as floodplains or urban green areas, as provided by the regulations in France [301]. On the contrary, in order to reduce effects such as skyglow, it is useful to apply universal parameters for all types of landscapes, including rural and urban areas. The limits for light emissions should not only focus on the lighting source itself but rather target unintended immissions outside the area where illumination is needed [346]. Lighting systems should be examined comprehensively, considering environmental contexts. The admission decisions should be based on the regional landscape conditions, the occurring of light-sensitive species, and the existing regional or local lighting concepts. Policy parameters for ALAN should be made transparent and publicly available. Planning instruments for outdoor lighting must provide descriptions of the location and the purpose of these installations. Permission to install or modernize lighting installations should, if required, be granted only if nature conservation requirements are met. This could include a lighting concept to justify and determine the lighting parameters as described above. Technical solutions should be considered based on their potential ecological harm, choosing sustainable lighting systems by default.

5. Conclusions

Adverse effects of ALAN impact a wide range of different taxa and habitats. Detrimental effects range from decrease in immune response and shifts in seasonality to avoidance and attraction behavior resulting in a loss of habitat or the death of specimens. However, the effects caused by ALAN require further research, which in turn creates a knowledge gap. To protect flora and fauna from impairments nature conservation law and immission control law provisions apply, although substantial shortcomings remain.

- a. The protection of habitats is spatially limited and even within its application it requires an individual impact assessment. However, assessments for lighting systems are so far not subject to approval procedures.
- b. The protection of specially protected species requires an adverse effect such as the injury, death, or avoidance behavior of a specimen, excluding most of the adverse effects of ALAN.
- c. Most provisions require either a significant increase in killing risks or a significant decline of a local population. Both criteria are in ALAN-related situations difficult to assess.

Hence, habitat and special species protection make a case-by-case decision necessary that relies on information that is typically hard to obtain. The provisions offer protection only for specific and well-documented species. Regarding immission control, ALAN-specific regulations are missing. European immission law provisions focus on energy efficiency, while the German Federal Immission Control Act does not impose legal obligations on lighting systems that do not serve an economic purpose, e.g., a municipality's street lighting.

In conclusion, the legal tools at hand seem to be substantially flawed and, hence, inadequate to provide comprehensive protection. Instead, specific regulations against the adverse effects of artificial light at night should be implemented. Such legislation should stipulate minimum protection requirements for the parameters light intensity, light color, and radiation geometry.

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