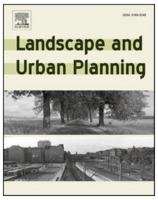
Landscape and Urban Planning 219 (2022) 104332

Contents lists available at ScienceDirect

Landscape and Urban Planning

journal homepage: www.elsevier.com/locate/landurbplan



A plea for a worldwide development of dark infrastructure for biodiversity – Practical examples and ways to go forward

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HIGHLIGHTS

- Light pollution is an increasing worldwide pressure for biodiversity, especially contributing to habitat loss and fragmentation.
- Green infrastructure (i.e. ecological networks policies) should consider nighttime darkness.
- A 4-step operational process could be adopted to identify, preserve, restore and assess dark infrastructure.
- Several dark infrastructure were already identified in both urban and natural areas, although some knowledge gaps still need to be filled.

ARTICLE INFO

Keywords:
ALAN
Green infrastructure
Corridor
Connectivity
Nature conservation
Planning

ABSTRACT

Artificial light at night (ALAN) has been massively deployed worldwide and has become a major environmental pressure for biodiversity, especially contributing to habitat loss and landscape fragmentation. To mitigate these latter, green and blue infrastructure policies have been developed throughout the world based on the concept of ecological networks, a set of suitable interconnected habitats. However, currently, these nature conservation policies hardly consider the adverse effects of ALAN. Here, we promote the integration of darkness quality within the 'green and blue infrastructure', to implement a 'dark infrastructure'. Dark infrastructure should be identified, preserved and restored at different territorial levels to guarantee ecological continuities where the night and its rhythms are as natural as possible. For this purpose, we propose an operational 4-steps process that includes 1)

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https://doi.org/10.1016/j.landurbplan.2021.104332
Received 18 December 2020; Received in revised form 29 November 2021; Accepted 2 December 2021

Mapping of light pollution in all its forms and dimensions in relation to biodiversity, 2) Identifying the dark infrastructure starting or not from the already identified green/blue infrastructure, 3) Planning actions to preserve and restore the dark infrastructure by prioritizing lighting sobriety and not only energy saving, 4) Assessing the effectiveness of the dark infrastructure with appropriate indicators. Dark infrastructure projects have already been created (for example in France and Switzerland) and can serve as case studies for both urban and natural areas. The deployment of dark infrastructure raises many operational and methodological questions and stresses some knowledge gaps that still need to be addressed, such as the exhaustive mapping of light pollution and the characterization of sensitivity thresholds for model species.

1. An emergency for nocturnal biodiversity on Earth

1.1. *ALAN as a major threat to biodiversity, including in protected areas*

In only a few decades, light pollution, i.e. the emission of artificial light at night (ALAN) has become recognized as a worldwide phenomenon (Bennie et al., 2015; Falchi et al., 2016). ALAN usually generates a very pronounced skyglow over the cities that can scatter within the atmosphere and be visible tens or even hundreds of kilometres away from the source of emission (Duriscoe et al., 2018; Jechow et al., 2020). Consequently, light pollution not only concerns urban regions (e.g. airports, city centers) and industrial areas (e.g. oil platforms, mines, plants, logistic centers) but also areas with limited human activities (Davies et al., 2016). Thus, it was shown that between 1992 and 2010, dark areas (i.e. with no, or almost no light pollution) have decreased by 15% in Europe, including in the protected areas (Gaston et al., 2015). Then, we are facing a threat against which spaces dedicated to the preservation of biodiversity (National Parks, Reserves, Natura 2000 areas) are very poorly protected or not protected at all (Mu et al., 2021). On an almost similar period of time (1992–2012), 3624 terrestrial mammal species experienced an increase in mean light intensity within their ranges worldwide, while only 41 species experienced significant decreases (Duffy et al., 2015). ALAN is also identified as one of the main factors accounting for the distribution of several bat species (Azam et al., 2016). Other studies suggest that ALAN could be one of the causes of the collapse of insect populations noted worldwide (Grubisic et al., 2018; Owens et al., 2020). As a clue for this, recent results of a monitoring study on the impact of ALAN on nocturnal moth populations indicated that some demographic effects can be identified after a 3-years duration (van Grunsven et al., 2020). This type of example is becoming more and more common in the existing literature.

1.2. *The plethorous and detrimental effects of ALAN on living organisms*

The scientific literature on this topic has become substantial during the past decade (e.g. Davies & Smyth, 2018; Falcón et al., 2020), even if some effects have been known for more than a century and are still relevant, such as collision mortality of migrating birds (Lao et al., 2020; Longcore et al., 2013). Today, impacts are demonstrated on flora (Segrestin et al., 2021) and most groups of animals, encompassing both nocturnal species; i.e. adapted to darkness (Elgert et al., 2021) and diurnal organisms (e.g. because artificial lighting unintentionally prolongs their activity phase into the night). For instance, ALAN-exposed wild great tit had on average 49% lower melatonin levels than the dark-night birds, leading to an alteration of innate immune response (Ziegler et al., 2021).

ALAN acts at different levels of life (e.g. genes, individuals, populations, ecosystems) and different life-history traits (e.g. growth, survival, fecundity, mobility) (Sanders et al., 2021) (Fig. 1). For instance, for one given species *Bufo bufo*, ALAN causes gene deregulation (Touzot et al., 2021) as much as it alters its reproduction (breeding behaviour, fertilization) (Touzot et al., 2020). ALAN decreases melatonin production in many organisms and thus the ability to synchronise diurnal and nocturnal metabolic processes (Grubisic et al., 2019). It unbalances interspecific relationships (Maggi et al., 2020), such as predator–prey interactions (Gomes, 2020) or competition between native and alien

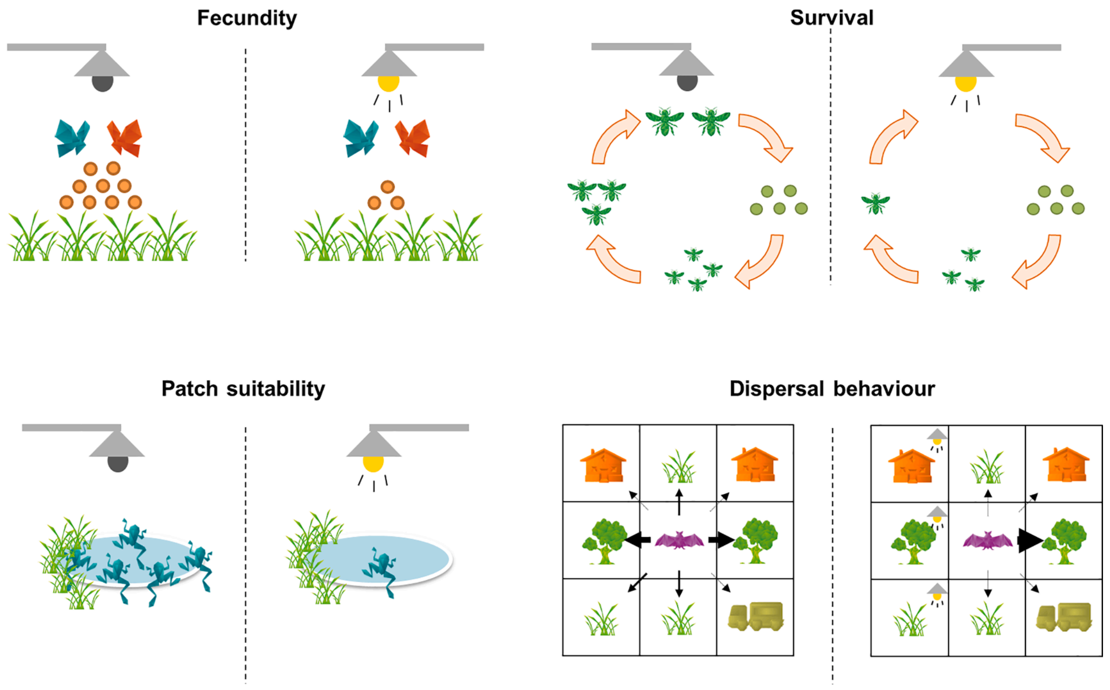


Fig. 1. Examples of mechanisms of ALAN effects on biodiversity.

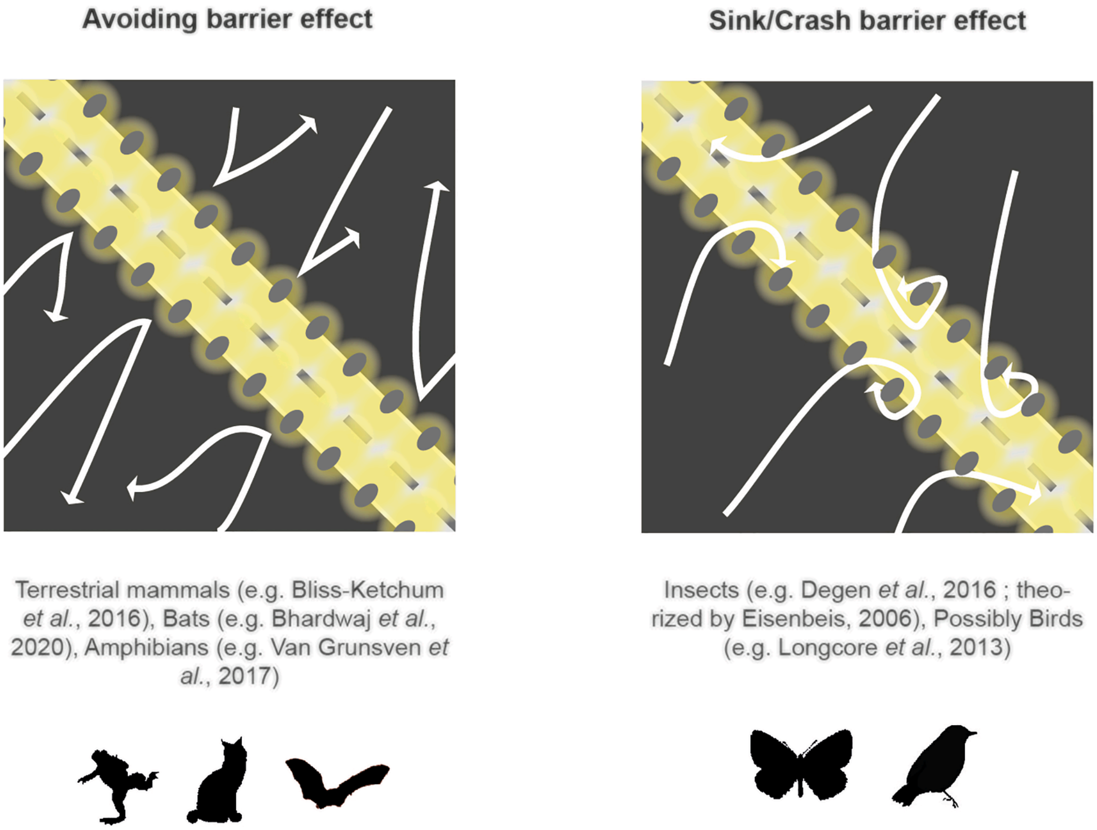
species (Speißer et al., 2021). It also disrupts the biological rhythms of both plants (Lian et al., 2021) and animal species (Bumgarner & Nelson, 2021). It decreases species richness (Mena et al., 2021), alters communities (Grubisic & van Grunsven, 2021) and generates cascading effects within ecosystems (Fleming & Bateman, 2018). Finally, ecosystem functions and services can be degraded or impeded, such as litter consumption in aquatic ecosystems (Czarnecka et al., 2021), both nocturnal and diurnal pollination (Giavi et al., 2021; Knop et al., 2017) or carbon mineralization (Hölker et al., 2015). ALAN can also interact with multiple environmental stressors, including other sources of pollution (e.g. noise), thereby exacerbating them (Dominoni et al., 2020).

1.3. ALAN leads to habitat loss and fragmentation

ALAN influences wildlife mobility by altering spatial cues (Vowles & Kemp, 2021). It is particularly true for species (e.g. insects, birds) that orient using natural celestial light sources (i.e. Moon, Milky Way, stars) during migration or 'daily' travels (Foster et al., 2018). ALAN can also affect the movement of individuals through phototaxis, which can be either positive (this may result in trapping and even mass mortalities of animals such as migrating insects or birds; e.g. Boyes et al., 2021; La Sorte & Horton, 2021) or negative (avoidance, on bats, seabirds, terrestrial mammals, reptiles; e.g. Saldaña-Vázquez & Munguía-Rosas, 2013). This mechanism can have an impact on population dynamics and demographic rates, like mortality and fecundity, by altering immigration/emigration movements (Gaston & Bennie, 2014). It can also affects the photic characteristics of natural habitats at the landscape level, due to an avoidance (Ditmer et al., 2021) or a sink/crash effect (Eisenbeis, 2006; Rodríguez et al., 2021) (Fig. 2).

A major concern of these consequences is that ALAN can further amplify habitat loss and fragmentation for many organisms. Studies showed that light pollution can affect the quality of natural habitats reducing the attendance of sensitive species (Ciach & Fröhlich, 2019; Picchi et al., 2013), alter activity along linear landscape features (Barré et al., 2020) and disrupt dispersal (Beier, 1995; Camacho et al., 2021; Wilson et al., 2018). It can also have indirect effects on space use due to a reduction of available resources (Luo et al., 2021), a modification of predation (Czarnecka et al., 2019) or an increase of competition (Salinas-Ramos et al., 2021), which may ultimately lead to isolated populations in relictual dark areas (Sordello, 2017a) (Fig. 3). Studies have confirmed that illuminated areas can be difficult to be crossed by some animals and then act as physical barriers: including facilities built to restore functional connectivity (Bhardwaj et al., 2020; Bliss-Ketchum et al., 2016). Lighted infrastructure (e.g. roads, bridges, buildings) can affect insect or bat movements (Degen et al., 2016; Hale et al., 2015; Málnás et al., 2011), slow down or even stop toads migrating to and away from their breeding grounds (van Grunsven et al., 2017), and more generally alter organism flux across ecosystem boundaries (Manfrin et al., 2017). On the scale of the United-States, light pollution fragmented most mammal ranges and resulted in isolated dark refugia from 2012 to 2018 (Ditmer et al., 2021).

All major habitats are concerned by these ALAN consequences: terrestrial (e.g. street lightings lead to significant changes in biomass and plant cover of dominant grass species on road verges and advance or delay flowering by 4 to 12 days (Bennie et al., 2017)), aerial (e.g. artificial light is avoided by nocturnally migrating passerines crossing the North Sea (Rebke et al., 2019)) and aquatic. ALAN affects organisms living in freshwater (e.g. exposure of a stream section to 10–12 lx of ALAN results in a decrease of 16% in family richness and 76% in mean body size of freshwater emergent insects [1 lx is a unit defined relative to human daytime vision] (Meyer & Sullivan, 2013)), wetlands (e.g. ALAN disrupts toad activity at juvenile-stage and reduces post-metamorphic toad growth by 15% (Dananay & Benard, 2018)) and marine areas (e.g. juvenile survival of a salt marsh keystone species – the crab Neohelice granulata – can be decreased up to 61% when exposed to ALAN compared to natural dark conditions, due to increased predation (Nuñez



Avoiding barrier effect

Sink/Crash barrier effect

Terrestrial mammals (e.g. Bliss-Ketchum *et al.*, 2016), Bats (e.g. Bhardwaj *et al.*, 2020), Amphibians (e.g. Van Grunsven *et al.*, 2017)

Insects (e.g. Degen *et al.*, 2016 ; theorized by Eisenbeis, 2006), Possibly Birds (e.g. Longcore *et al.*, 2013)

Fig. 2. Example of habitat loss and fragmentation caused by avoiding (left) and attractive (right) effects of ALAN.

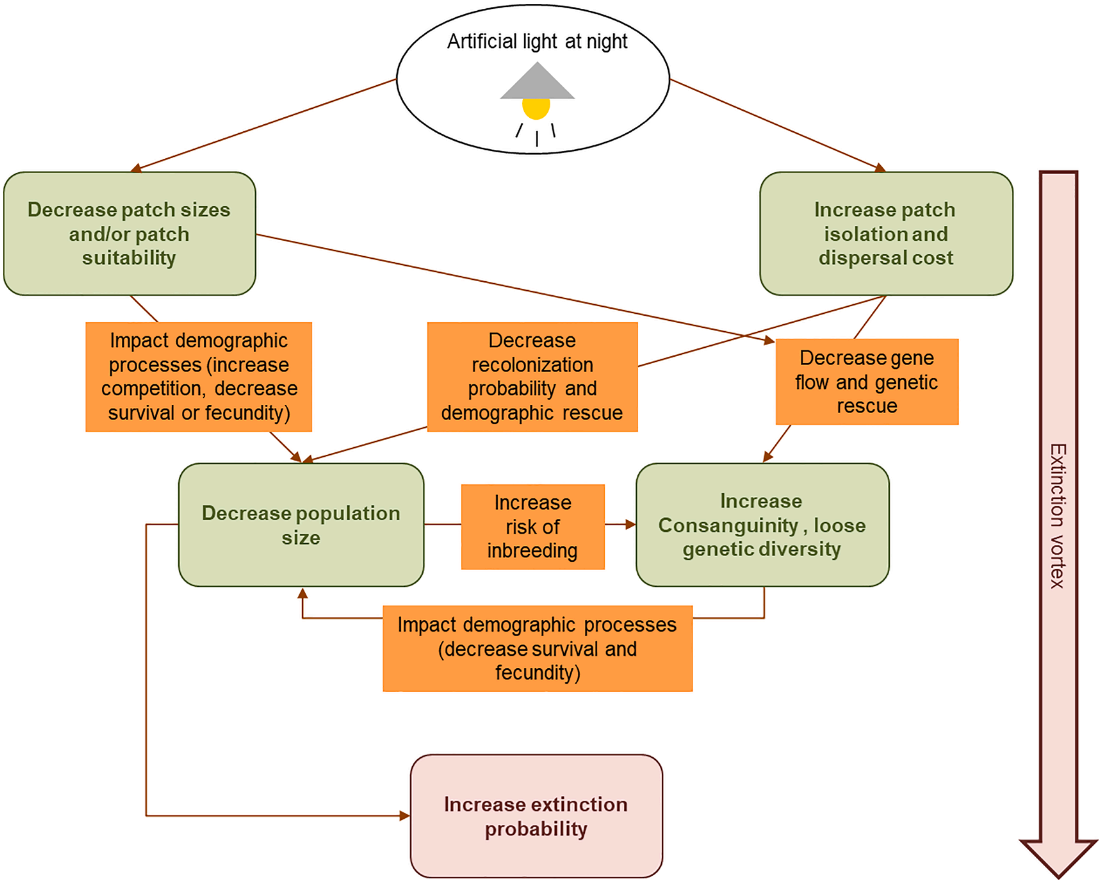


Fig. 3. Framework for understanding the effects of ALAN on ecological networks.

et al., 2021)).

2. Development of 'dark infrastructure' as a solution to protect biodiversity

2.1. Current ecological network policies: green and blue infrastructure

Over the past few decades, biodiversity protection strategies have increasingly integrated ecological networks (Battisti, 2003; Keeley et al., 2019), through green infrastructure, defined by the European Environment Agency as '*a strategically planned network of natural and semi-natural areas with other environmental features designed and managed to contribute to maintain biodiversity in fragmented landscape and deliver a wide range of ecosystem services.*' (Green Infrastructure (GI)—Enhancing Europe's Natural Capital, 2013). The term 'blue infrastructure' is sometimes used to specifically refer to aquatic habitats (Silva and Wheeler, 2017), but, in practice, the term 'green infrastructure' can be generic and include both terrestrial and aquatic habitats. Many Member States have implemented green infrastructure projects since the late 90's (European Commission, 2019), e.g. Belgium (Wlaams Ecologisch Netwerk, Flanders and Structure Ecologique Principale, Wallonia), Estonia (Green Network), France (Trame verte et bleue), Germany (Biotopverbund), and Hungary (National Ecological Network).

Green infrastructure remains a schematic (cores + corridors) and theorical approach, but it can lead to protecting and connecting remaining natural spaces, notably within a landscape where nature has been highly artificialized and fragmented. In this application, green infrastructure can especially play an essential role in the protection of biodiversity in industrialized countries, as shown by the deployment of public policies for green and blue infrastructure worldwide (Linehan et al., 1995). Globally, the International Union for Conservation of Nature (IUCN) promotes green infrastructure as a key spatial planning tool for nature conservation (Bennett, 2003; Hilty et al., 2020). The concept of ecological connectivity is also implicit in several international conventions such as the Ramsar convention (1971) and the Bern convention (1979), European agreements (habitats and species directive) and related EU policy implementation (Natura 2000). Testifying its relevance, green infrastructure initiatives have also been developed at the international level, notably in Africa (e.g. The Tri-Dom Ecological Network, Cameroon-Gabon-Congo), Asia (e.g. The Arakawa River Ecological Network, Japan), North America (e.g. Southern Rockies Wildlands Network, USA), South America (e.g. The Vilcabamba-Amboró Conservation Corridor, Peru/Bolivia) (Moore & Shadie, 2007) and Oceania (e.g. Australia (Kilbane, 2013)).

2.2. Considering darkness: switching from 'daytime green and blue' to 'nighttime green and blue'

Today, nearly all international conservation strategies take little or no account of darkness. As a rare exception, we can note the resolution adopted in 2020 by the international Convention on the Conservation of Migratory Species, recognizing that ALAN is an emerging issue for wildlife (UNEP/CMS/Resolution 13.5, 2020). In Europe, the environmental protection of European Union and laws of individual Member States do not specifically protect nocturnal species from the negative effects of ALAN, with rare exceptions (Schroer et al., 2020). However, policies should reduce ALAN and its pressure on ecosystems worldwide. Particularly, mitigation solutions at the landscape level appear to be lacking (Jägerbrand & Bouroussis, 2021) whereas it is essential to spatially plan night lighting in order to differentiate its management according to the biodiversity issues in a territory.

Thus, a possible way, relevant in our opinion - particularly from a practical point of view - could consist in including darkness within green and blue infrastructure, resulting in a 'dark infrastructure' where biological and ecological processes required during nighttime are possible (Sordello, 2017d). Challéat et al. (2021) recently proposed this approach from a socio-ecological perspective. Here, we take the definition of dark infrastructure from Sordello (2017c) and Sordello (2017d) as the approach of integrating light pollution into the identification of ecological continuities for different habitats. The result is an ecological network - formed by cores connected by corridors - in which darkness is an additional quality criterion (Sordello et al., 2018b). For instance, to identify green infrastructure for farmland with hedges (*bocage*), the criteria analyzed until now mainly referred only to sufficiently dense network of hedges with good quality hedges (wide, with old trees, multistratified vegetation, *etc.*). Henceforth, a *bocage* dark infrastructure would require all of the green infrastructure criteria but also the level of darkness (Sordello, 2017d). IUCN adopted a motion on light pollution during the world IUCN congress held in France in September 2021, voted by a very large majority, which promotes the deployment of dark infrastructure around the world based on this definition (IUCN, 2021).

Without restricting corridors to physical and contiguous structures (they can be airborne), dark infrastructure is one of the possible responses to mitigate the impacts of artificial light at night on biodiversity and specifically on habitat loss and fragmentation and wildlife movements (Pauwels et al., 2019; Zeale et al., 2018). This approach would integrate the stress caused by ALAN on the physiology and behaviour of organisms, population dynamics, and species interactions at night. Dark infrastructure may help to limit the multiple impacts of light pollution on biodiversity with a global vision on a territory (Sordello, 2017c). This enables going beyond case-by-case management of light sources and going further than protected area networks by envisaging the actual connection of natural and semi-natural habitats, according to landscape ecology concepts. It leads to consideration of the cyclic rhythms for biodiversity (e.g. day-night, seasonal) within green and blue infrastructure policies (Sordello, 2017b).

2.3. *Incorporating natural light levels*

We need to mention that the term 'black infrastructure' could also be used, but 'dark' seems more appropriate since it encompasses several levels of darkness. Under natural conditions, the night is not totally black, since the starry sky - and particularly the moon for most of nights - produce an ambient luminosity that is bright enough for nocturnal species thanks to their large eyes or numerous photoreceptive cells (Clarke, 1983; Dice, 1945; Somanathan et al., 2008; Veilleux & Cummings, 2012). Moreover, the term 'dark' may appear less tense for operational actors and users than the term 'black', which suggests that the aim of such a planning strategy should be to eliminate artificial lighting all the time and everywhere, whereas we know that this is utopian. Here, the goal is to preserve and restore an ecological network with a level of darkness that is as natural as possible and allows maintainence of biodiversity. The level of natural light at night changes cyclicly, due to lunar phases, which is a source of synchronization of biological rhythms and activity for organisms (Battaglia et al., 2017; Grant et al., 2009; Norevik et al., 2019). We know that the full moon illuminance - around 0.05 to 0.1 lx at temperate latitudes during the summer (Kyba et al., 2017) - is already a sufficient level to cause biological effects for some organisms (Clarke et al., 1996; Linley et al., 2021; Prugh & Golden, 2014). Consequently, ALAN should not reach light intensity that disrupts biological or ecological processes. This means that nighttime brightness (natural + artificial) should never exceed the level of the full moon and lower levels are required to avoid any impact, particularly in dark infrastructure since it involves diverse species, some of which highly sensitive to light pollution (Simons et al., 2021). We raise here the fact that the management of night lighting should consider the external parameters that influence the ambient luminosity (the moon phase, but also the weather for example), by reasoning in relation to a global level of 'natural + artificial' light conditions (van Hasselt et al., 2021).

3. Identifying, preserving and restoring dark infrastructure: a 4-steps process

Conceptual studies on the usefulness of dark ecological networks as a social-ecological framework to limit the impacts of light pollution on biodiversity were recently published, pointing out the challenges of articulating organizational levels for a bottom-up approach of the dark ecological network (Challéat et al., 2021). Dark infrastructure must be identified, preserved and restored at several administrative levels (municipalities and intermunicipal councils, departments, regions, states or associations of states such as the European Union), as well as biological/ecological levels (e.g. biogeographic zones, perimeters of natural areas with or without regulatory protection status, landscape patches or local sites). The link between levels should reconcile 'top-down' (upstream framing for subsequent application in local planning schemes) and 'bottom-up' (feedback from local experiences to feed into a broader, national or international framework) insights on ALAN regulation.

Here, we propose an operational 4-steps process to identify, preserve and restore the dark infrastructure (Fig. 4).

3.1. *STEP 1: Mapping 'darkness quality'*

First of all, it is essential to carry out a diagnosis of light pollution in the form of a map of the territory under consideration (Marcantonio et al., 2015). This mapping must allow the identification of spatial distribution of the quality of the night environment in the form of different classes (Fig. 4). This quantitative indicator will be one of the essential input for the identification of the dark infrastructure, by crossing with biodiversity data (Xue et al., 2020). Light pollution mapping can be done starting with satellite images (Jechow & Hölker, 2019), nocturnal orthophotography (Schirmer et al., 2019), field data (geolocation of lightings associated with their technical characteristics: power, light spectrum, *etc.*) or metrology (*in-situ* measurement of light pollution by various devices such as luxmeter, sky quality meter, *etc.* (Garratt et al., 2019; Secondi et al., 2017)). The strengths and weaknesses of each data source will depend on the scale considered (national, regional, municipal, neighbourhood). France has just published a national map of light pollution constituting a quantitative indicator of the light diffused in the middle of the night in clear weather using satellite data (ONB, 2021).

3.2. *STEP 2: Identifying the dark infrastructure*

According to quantitative indicators previously developed, dark infrastructure must be identified, including cores and corridors for different types of environments (e.g., forests, grasslands, wetlands, freshwaters, shores) (Fig. 4).

A first vision of dark infrastructure is to consider that it corresponds to optimal areas, where the nighttime environment remains sufficiently undisturbed for biodiversity (= *'Reference conditions'*, to make a parallel with Water Framework Directive implementation – WFD). Such optimal areas must be identified as soon as possible because light pollution continues to increase and threaten them (Guetté et al., 2018). Then these areas will form the basis of the dark infrastructure. A second vision may include in the dark infrastructure areas of lesser quality, whose nocturnal functionality is impeded (i.e. where the threshold of 'Reference conditions' is not reached but still good). This minimal light threshold could be selected according to the most sensitive species (which might be always low) or depending on conservation goals and ecosystems. Indeed, this threshold will determine which areas will have to be preserved and which areas will have to be restored. In France, 'Pyrenees National Park' determined a threshold of sensitivity to light, using data previously collected on *Rhinolophus* and *Myotis* bats. The results show that, whatever the bat species observed, from a level of light

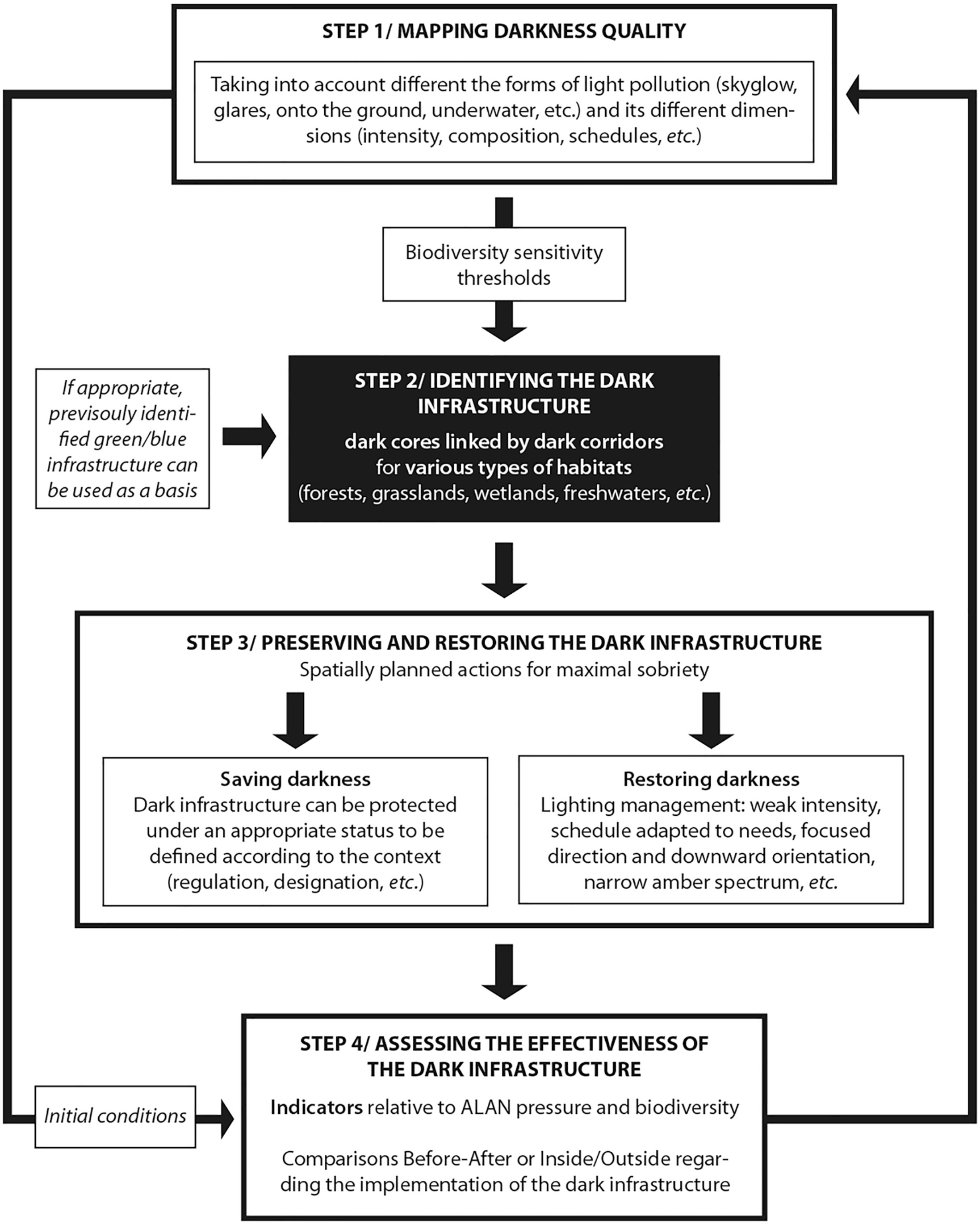


Fig. 4. 4-steps process of implementation of the dark infrastructure whatever the scale of territory considered, from the elaboration of the diagnosis until the assessment.

pollution of about 19.8–20.5 mag/arcsec^2, the number of contacts established with each species decreases (Fresse, 2018). Then, to design their dark infrastructure, three classes of darkness quality were retained: poor (15.9 to 20 mag/arcsec^2), average (20.1 mag/arcsec^2 to 21.3 mag/arcsec^2), good (>21.3 mag/arcsec^2)

Once the cutoff threshold is chosen to characterize the dark infrastructure, in practice, two options of implementation are possible (Sordello et al., 2021): 1) either taking ALAN into account in an existing green and/or blue infrastructure; i.e. when the work to define the ecological network has already been done but without considering darkness (e.g. applied in Geneva, Switzerland by Ranzoni et al. (2019); see Fig. 5F), or 2) integrating ALAN in the design of a new green and/or blue infrastructure (e.g. applied in 'Pyrenees National Park', France). The first option would enhance existing efforts, as it is expected to upgrade the functionality of the ecological network; however, its appropriateness must be considered on a case-by-case basis because green and blue infrastructure are generally defined on the basis of target species chosen independently of their sensitivity to ALAN. For the second option, ALAN can be an additional parameter in spatial models (see Fig. 5D); i.e. the estimation of roughness/resistance coefficients for ecological networks modelling (Hale et al., 2015; Pauwels et al., 2019) or used to downgrade the rating of cores and corridors, ultimately leading to the exclusion (or planning restoration) of elements that are of low quality (Sordello et al., 2018b).

(A)

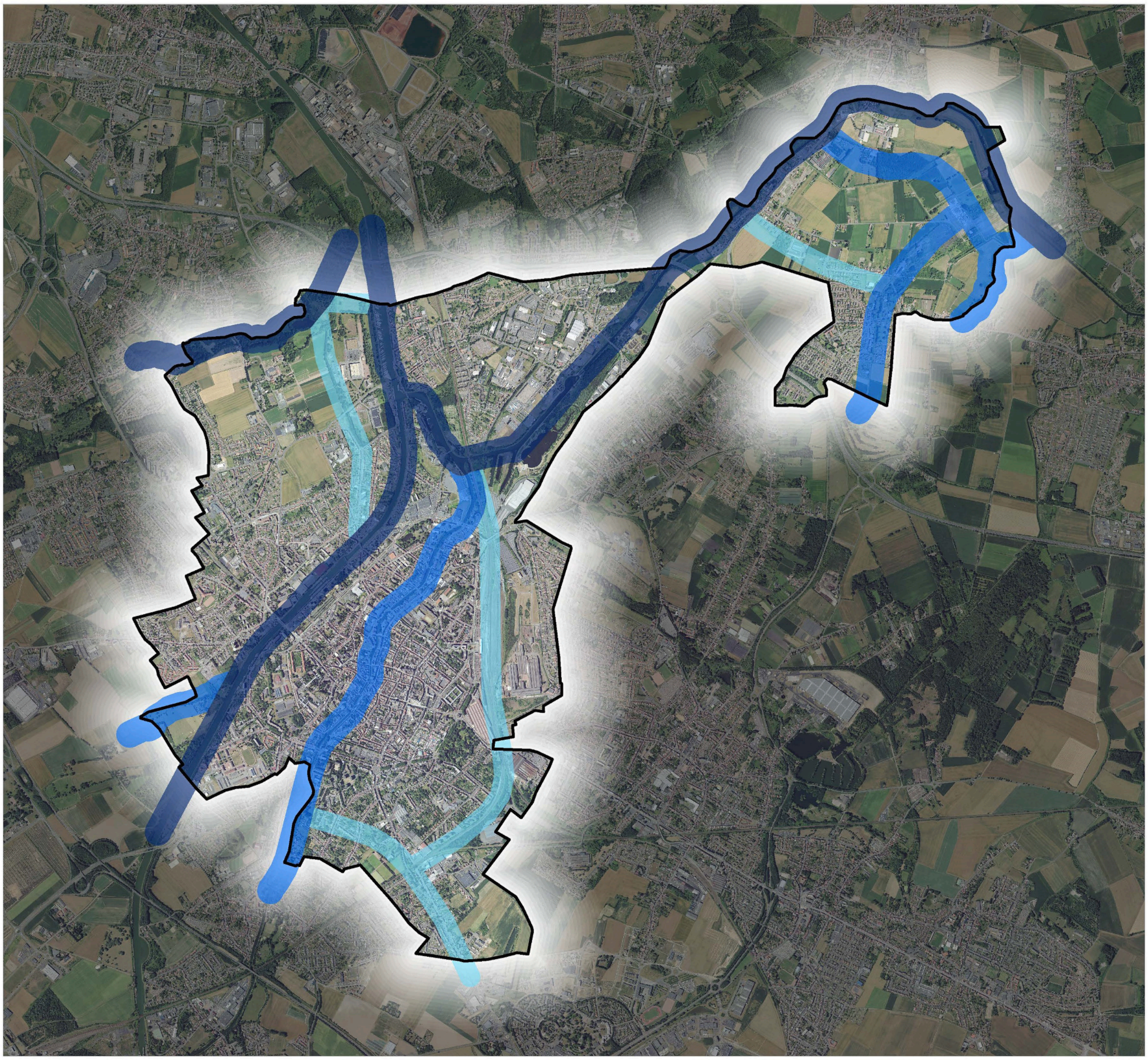


Fig. 5. Examples of dark infrastructure already in place in France, Switzerland and United-States. A) In the town of Douai (France), a dark infrastructure was identified using an acoustic bat survey (80 points in June 2018) throughout the commune territory. Here, the dark infrastructure was not translated into cores and corridors but into a set of dark ecological continuities. These have been drawn with three levels of issues represented by shades of blue on the map, in order of importance from the least dark to the darkest (tertiary, secondary, main). These levels are directly related to the intensity of bat activity. They allow to prioritize the further actions of preservation and restoration of the dark infrastructure. B) Identification of nocturnal corridors for several bat species in the 'Métropole Européenne de Lille' (France). This summary was obtained after random stratified sampling (bats were recorded on 399 sampling points; one entire night per sampling point) and species distribution modelling. A least-cost modelling approach was finally applied to identify nocturnal corridors. These nocturnal corridors correspond in large part to the canals and watercourse ('Deule', 'Roubaix', 'Marque'). C) Dark infrastructure in Metz Métropole (France). The grey-black shape indicates the impact of ALAN on the core functionality (extinction probability) and the shades from red to blue give information about the impact of ALAN on corridor functionality (dispersal flow). The result provides a decision-making tool for scientists, conservation managers and policy-makers to plan ecological networks where ALAN is taken into account. D) In greater Los Angeles (United States), the 'darkest path' corridors (light colored lines) between natural habitats was calculated, using high-resolution data from a small satellite (Aerospace Corporation; see Pack et al., 2017). Light pollution levels range from low (blue) to medium (red) and high (yellow). After transforming the raw data, the least cost paths between four parks were calculated with brightness as the resistance value to demonstrate the links between protected areas occupied by mountain lions, which are known to be averse to moving across lighted landscapes. The results were consistent with known corridor locations and illustrated the need to protect the remaining tenuous dark paths and to restore a dark infrastructure for wildlife movement. E) In the 'Parc Naturel Régional de l'Aubrac' (France) landuse data were crossed with light pressure data at the extremities of the night (i.e. the least favourable conditions, before possible public lighting extinctions). This work was performed for the different sub-ecological networks identified in the 'green and blue infrastructure' of the Park. Here the map shows the result obtained for woodland habitats. The shades of colour indicate the quality of the night sky in this dark wooded infrastructure (see the caption on the image). F) Raster map resulting from the analysis of the viewshed - visibility of the light sources of the Geneva basin (Switzerland). The color gradient highlights the areas most heavily impacted by light pollution, such as built-up areas, road networks or open areas. The darker areas represent the areas from which the light nuisances are less visible or nonexistent, such as forest areas, valleys and bocage structures (dark blue). Open areas without structures such as hedgerows or forests, are thus more exposed to light pollution.

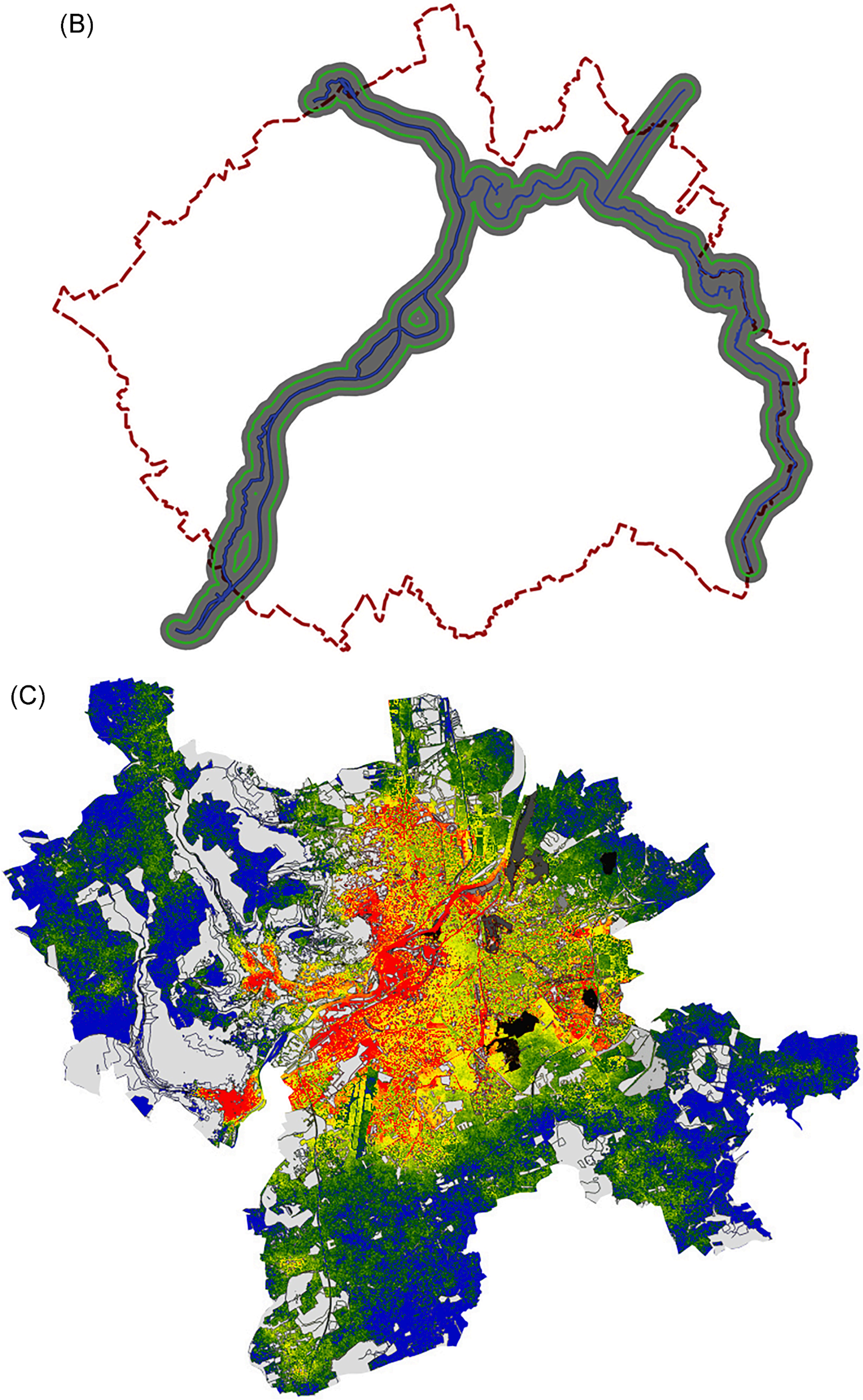


Fig. 5. (*continued*).

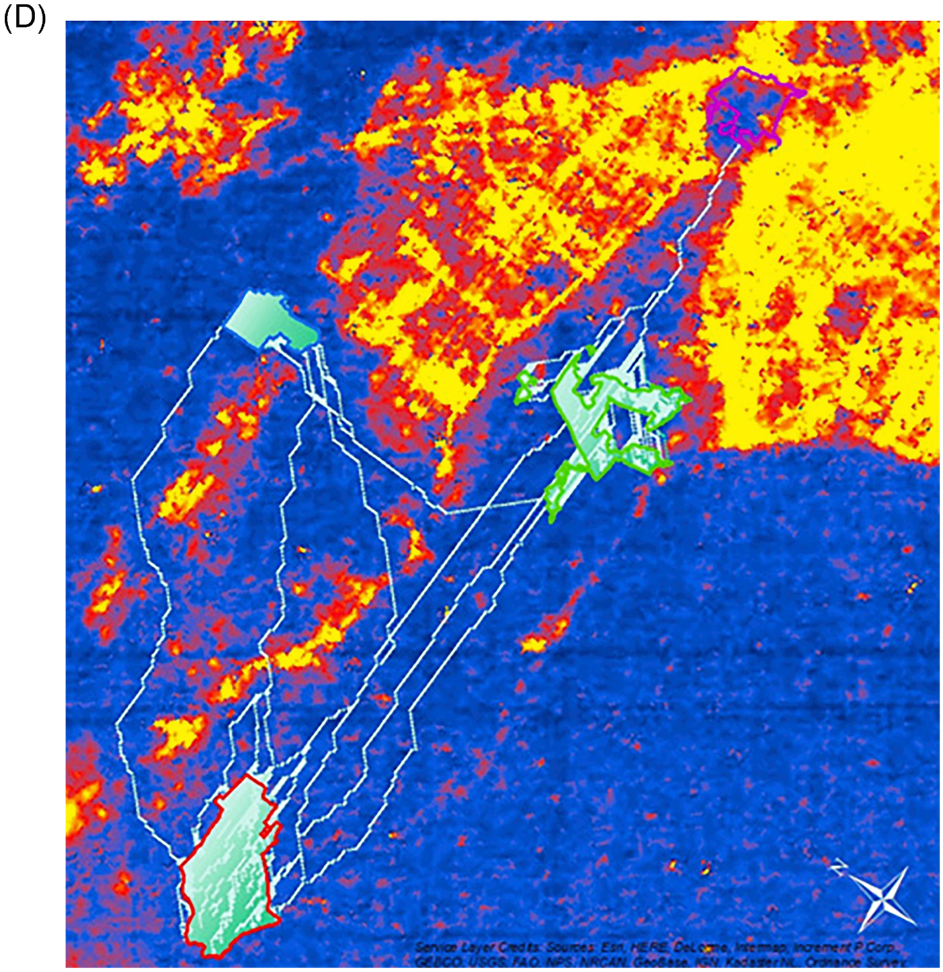


Fig. 5. (*continued*).

3.3. STEP 3: Preserving and restoring the dark infrastructure

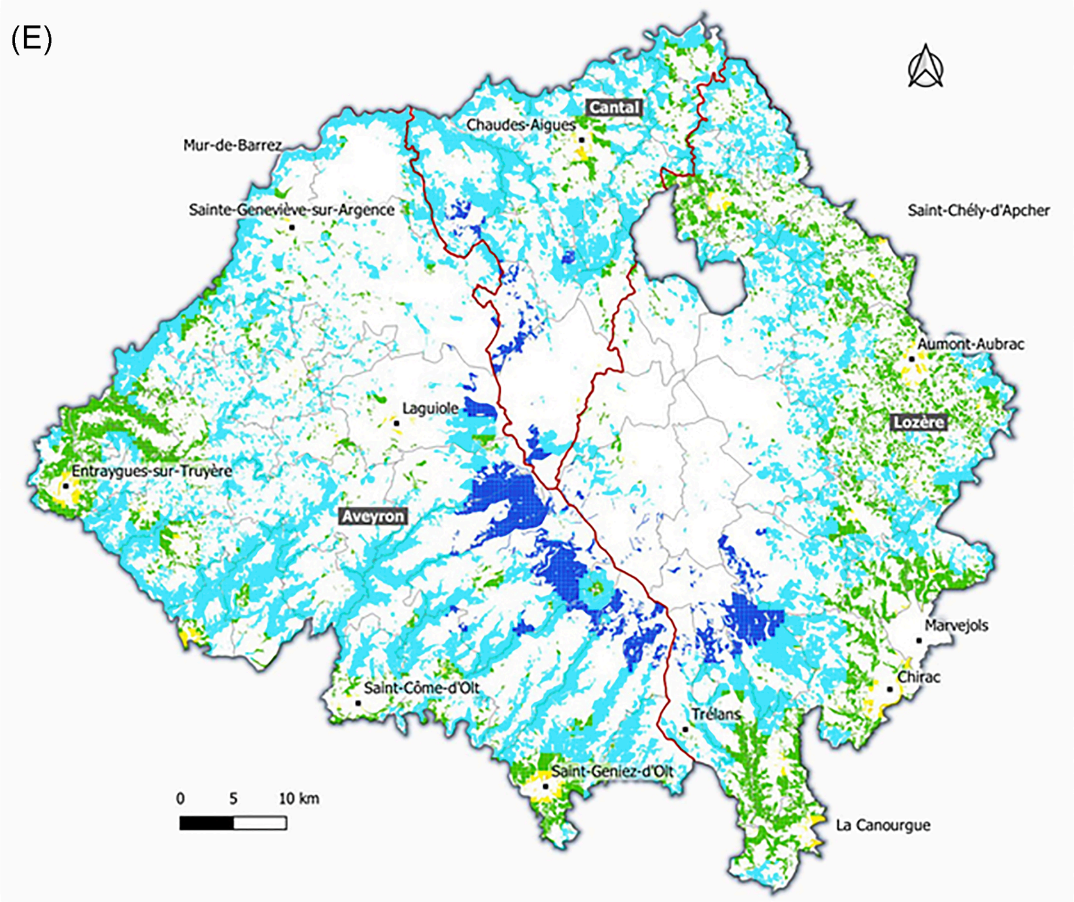
After being identified, dark infrastructure must be preserved to prevent light pollution, under a protection status to be defined according to the context (space that cannot be illuminated or even urbanized, protected areas, World Heritage recognition, designations such as those proposed by the International Dark Sky Association, *etc.*).

In areas where the dark infrastructure is considered 'degraded' compared to reference conditions (based on quantitative or semi-quantitative indicators), darkness should be restored by mobilizing various lighting management tools (Gaston et al., 2012; Sordello, 2018) (Fig. 4). The most effective and simple way is to suppress lightings or, at least, to turn off lights. However, light is needed for human activity at night; then it would be unreasonable to imagine a world without any outdoor lighting. Therefore, we must aim for sobriety, by lighting only when strictly necessary, by questioning the need for lighting in advance and by seeking alternatives as a priority (e.g. passive lightings, reflectors, headlamps, *etc.*). Also, the management of lighting should no longer be done by partitioning uses but by considering all light sources in a given site. For example, in a given street, lights illuminating sidewalks could remain off as long as signs and storefronts are still active and already providing a sufficient level of light for walking.

Restoration actions could be prioritized accordingly to the ecological stakes and the level of nuisances induced by ALAN, with the objective of optimizing the nocturnal space–time between humans and the rest of the living world. As the optimization of lighting has not been a concern until now, there is a great deal of scope for reducing light pollution (wasted light, unnecessary lighting, unsuitable time slots, *etc.*) without losing comfort and use for human activities. To this end, many lighting parameters can be modulated: e.g. adapting the level of illumination to use (Rydell et al., 2021), adapting the lighting periods (Day et al., 2015) or regulating the power to demand schedules (Bolliger et al., 2020), direct the lights downwards and specifically targeting the area to be lit. Concerning the color of the light, species have different sensitivities to light wavelengths, whether for vision, chronobiology or other functions (behaviour, physiology, activity, growth, *etc.*) (Alaasam et al., 2021; Musters et al., 2009). Therefore it is impossible to identify one color that would be impact-free for all organisms. Thus, the choice of lighting to be preferred in terms of its associated spectrum can be guided by the ecological context (Spoelstra et al., 2017; Syposz et al., 2021). However, a general advice is that broader spectra have broader impacts because they stimulate more photoreceptors in a species and affect more species (Diamantopoulou et al., 2021; Kernbach et al., 2020). In addition, at the moment, research results show that amber light (yellow/orange) have lower effects on wildlife than blue, green or even red, which leads to prefer low color temperatures (~1500–2400 K) (Deichmann et al., 2021; Longcore et al., 2018). Nevertheless it should be noted that even yellow/amber lights remain impactful for some taxa (Kühne et al., 2021; Van den Broeck et al., 2021).

3.4. STEP 4: Assessing the effectiveness of the dark infrastructure

Finally, as for other public policies, indicators are needed to monitor and assess the role and effectiveness of dark infrastructure in maintaining and, where appropriate, restoring darkness and ecosystem functioning at night (Fig. 4). This step will require comparisons before



	Zenithal luminance (mag/arcsec^2)	Number of stars visible to the naked eye on a clear sky		Zenithal luminance (mag/arcsec^2)	Number of stars visible to the naked eye on a clear sky
🟥	≤ 19.5	< 100	🟩	> 21.00 et ≤ 21.25	950
🟧	> 19.5 et ≤ 20.30	280	🟦	> 21.25 et ≤ 21.50	1200
🟨	> 20.30 et ≤ 20.75	520	🟦	> 21.50 et ≤ 21.70	2300
🟨	> 20.75 et ≤ 21.00	660	⬜	> 21.70	> 4000

Fig. 5. (*continued*).

and after implementation of the dark infrastructure, or comparing areas where it is implemented and those where it is not. The indicators should encompass pressure indicators (light pollution, as detailled above) and indicators related to biodiversity. For the latter, it will be necessary to combine different aspects, including species richness and abundance, community functioning (life traits, relationships between species), as well as functional connectivity in addition to structural connectivity. For this purpose, indicator species could be identified, among the most vulnerable nocturnal animal group to ALAN – such as bats, amphibians, nocturnal Lepidoptera, Lampyrid beetles, *etc.* – for different types of habitats/ecosystems.

4. First successful 'dark infrastructure' projects

Several dark infrastructure projects have already been carried out, notably in France, Switzerland and United-States by various actors (e.g. municipalities, metropolises, managers of protected areas, lighting specialists) (Fig. 5A–F). These projects consisted in identifying dark infrastructure in a given territory with various methodologies, covering the two options described in Section 3.2.

In France, many cities have already identified their dark infrastructure or are in the process of doing so (such as Amiens, Bordeaux, Douai, Lille (see Fig. 5B), Limoges, Marne-et-Gondoire, Metz, Nantes, Nice, Strasbourg). Five french 'National parks' ('Cévennes', 'Pyrénées', 'Port-Cros', 'Mercantour', 'Réunion') also conducted a joint project to map their light pollution (STEP 1) and their dark infrastructure (STEP 2). They are now in the process of implementing their action plans to restore darkness where it is degraded (STEP 3). The same is true for several french 'Regional nature parks' such as those in the 'Massif Central' (see an example of 'Parc naturel régional de l'Aubrac' in Fig. 5E).

Concerning option 1 or 2 previously presented to identify the dark infrastructure, we meet both in these projects.

In the transboundary region of the Geneva basin in Switzerland, the dark infrastructure was obtainded by intersecting low ALAN areas with

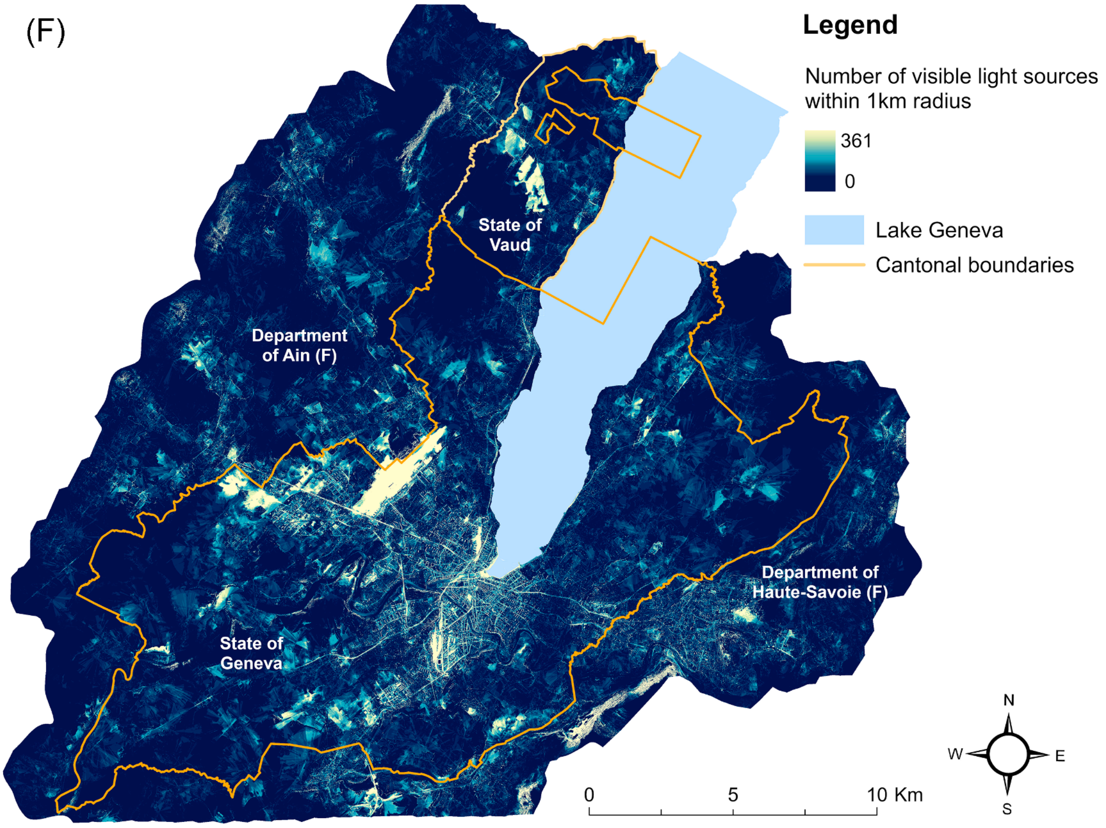


Fig. 5. (*continued*).

the existing green infrastructure (option 1) (Fig. 5F). To do this, an automated extraction of light sources from nocturnal high-resolution orthophotography was performed. These light sources were then used in a viewshed analysis where ALAN at any location was derived from the number of light sources within a 1 km radius.

In Douai (France), a dark infrastructure was identified 'from scratch' (option 2) (Fig. 5A). Firstly, a "bat activity map" for different groups (*Pipistrellus*, *Nyctalus*, *Serotinus* and *Myotis*) was established, using 80 bat sound recorders during two nights in June under good weather conditions. Then, a hierarchy of activity levels by quantiles allowed to identify the areas of highest activity, forming the dark infrastructure.

Option 2 was also applied in Metz Métropole (France) to identify its dark infrastructure (Fig. 5C). To do so, the probability of species extinction and the individual dispersal flow (see Fig. 2) were calculated taking into account the effect of ALAN on life-history traits (see Fig. 1) using the simulation tool Simoïko (Moulherat, 2014). A generic population viability analysis was used. The input data were obtained from the field, scientific literature, or expert opinion on 5 species.

These examples show that dark infrastructure is a tool that various stakeholders adopt to preserve and restore darkness, in both urban and natural contexts. The spatial scales are also variable, ranging from a single municipality or even a neighbourhood to vast territories. These pioneering projects will be a valuable aid for subsequent initiatives. For this purpose, a further work will be necessary to review the methods applied in these projects to characterize dark infrastructure, to identify the technical levers for implementing better lighting management in these spaces, and to list any difficulties encountered.

5. Research and development issues

Firstly, to identify the dark infrastructure, it is necessary to better map ALAN pressure in a given area. This is the stage of the factual diagnosis of darkness quality (STEP 1 in our timeline). Generally, existing maps only take into account the light level while the impacts on the species also depend on the schedules or the composition of the light. Moreover, the maps that are available with global coverage are based on light sources detected by satellites, which only detect light that is emitted upward. Satellite data allow modelling skyglow (indirect light pollution) and exclude a large part of the other forms of direct light pollution such as glare, light emitted towards the ground, light that penetrates the water or enters cavities, *etc.* which are also problematic (Wilson et al., 2021). Upward radiance and modelled sky glow correlate well with surface-level exposure, but mask large spatial variation in exposure (Simons et al., 2020). In addition, the light caught by the satellites will depend on the sensor spectrum sensitivity (500–900 nm for NASAS's VIIRS-DNB instrument, the most used currently), which can lead to the exclusion of a critical part of the spectrum (such as ultraviolet or infrared radiation and overall blue light that is increasing in LED-based lighting systems) (Elvidge et al., 2010; Kyba et al., 2015; Levin et al., 2020). Therefore, the objective is to create reliable maps taking into account all these considerations, in order to truly assess the global quality of the nighttime environment. This will allow to identify where we do not deviate 'too much' from a reference state (i.e. a natural night without ALAN), and a class system could be used for this (e.g. very good, good, average, poor and bad) as we do for water quality in Europe based on WFD.

Secondly, a major research issue is still to determine the lowest level of ALAN for which effects are observed on species or ecosystems (as commonly done in ecotoxicology); i.e. thresholds of light sensitivity (Hölker et al., 2021). In other words it deals with the cutoff point to say that we are in or out of the dark infrastructure (STEP 2 in our time line). This is necessary to state if darkness is sufficient or not for biodiversity and actually to inform the design of dark infrastructure. This question is very difficult to address because such thresholds are taxa-dependent (and sometimes even function of the sex or the age for a same taxon). Data already exist for some species but this knowledge remains incomplete even if we already know that impacts are detected at light levels far below 1 lx: e.g., 0.5 lx for fish swimming (Latchem et al., 2021), 0.3 lx for plant growth (Crump et al., 2021) and bird digestion (Sepp et al., 2021), 0.03 lx for amphibian locomotion (Secondi et al., 2021), 0.01 lx for insect diapause (Mukai et al., 2021). In addition, the different light parameters should be considered together because the impacting light level can vary according to the color as a result of the spectral sensitivity of species (e.g. young sea turtles are desoriented at 39 lx with red light, 10 lx with yellow light and 5 lx with green light (Cruz et al., 2018). A connected research issue is to better understand the combined effects of ALAN and other pressures (Ciach & Fröhlich, 2017) on biodiversity.

6. Conclusion

Green and blue infrastructure, which correspond to ecological networks (i.e. cores connected by corridors), are a strong measure to mitigate habitat and biodiversity loss. They have been implemented for many years by many states and supranational organizations around the world. The dark infrastructure stems from them, in order to take into account the necessity of natural periods of darkness for life on Earth. Dark infrastructure is one of the means of limiting the effects of light pollution on biodiversity at the landscape scale. In view of the continuously increasing light pollution levels worldwide, it is timely for institutions and society to take up such a planning tool, as they have done for green and blue infrastructure.

As a cautionary word, dark infrastructure should not become only the last remnants of an old dark-night world. Their implementation is not a justification for continuing to illuminate every spaces outside the ecological network without any restriction. On the contrary, they should contribute to reach the more general goal that is to limit ALAN everywhere and everytime possible, because saving energy will not systematically solve the problem of biodiversity loss. It can even worsen the situation in case of a rebound effect (more light emitted while consuming less energy) or harmful changes in emitted light spectrum that would be more energy efficient but more impactful for biodiversity. However, the dark infrastructure makes it possible to prioritize and spatialize the issues, as well as preservation and restoration actions, at a territorial level. The goal is to 'secure' the areas that are still of good quality for ecosystem functioning and to ensure that this dark infrastructure expands year after year.

The development of dark infrastructure will raise many practical questions for the scientific community and operational stakeholders in the coming years (e.g. lighting and biodiversity data availability, species sensitivity thresholds, modelling methods, governance, status of protection). In addition, their capacity to reduce the negative impacts of ALAN on biodiversity will have to be assessed through apropriate indicators (Sordello et al., 2018a).

Such an approach oriented towards the conservation of biodiversity in dark nocturnal conditions fits into a wider transdisciplinary field addressing various problems and approaches to the preservation of the night (Kyba et al., 2020; Moeschler & Achkar, 2020). The several crises of all kinds (social, economic, health) that our societies are going through can be an opportunity to raise awareness for the need to preserve nature, including at night because, at any given moment, half of the Earth's surface experiences night.

Acknowledgements

The authors would like to sincerely thank Prof. Kevin J. Gaston for providing fruitful comments on an earlier version of the manuscript, and Nina Noujdina that produced the darkest-path analysis in Fig. 5D with light data provided by Dee Pack (Aerospace Corporation) from an AeroCube small satellite.

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