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PERSPECTIVE

Manifesto for multidimensional ecological networks: a perspective to better account for the complexity of habitat loss and fragmentation

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Abstract

Context Ecological networks (i.e. sets of connected natural habitats) emerged in the 1980s and have been implemented worldwide. They have been developed as a land-use planning tool that enables to ensure both habitat amount and landscape connectivity in response to ground based physical anthropogenic drivers (e.g. forest cuttings, roads, dams).

Objective We wanted to highlight some gaps in this conception of habitat loss and fragmentation that led to potential lacks in the current methods and approaches to design and manage ecological networks, with a view to suggest a way of improving the situation for a more comprehensive consideration of biodiversity.

Methods We compared new scientific knowledge about habitat loss and fragmentation with a critical assessment of feedback from ecological networks, in order to highlight bottlenecks. On this basis we formulated proposals for a new framework and discussed the operational implications for designing and managing broader ecological networks.

Results Airscape or soils—key compartments for activities and movements of species—appear to be rarely considered in ecological networks, as well as sensory pollutants—i.e. artificial light at night, man-induced sounds and odors—while they have been demonstrated to disturb nightscapes, soundscapes and odorscapes.

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Conclusion We invite landscape designers and decision-makers to transition to multidimensional ecological networks, developing specific infrastructure against habitat loss and fragmentation, in particular an aerial infrastructure for flying species, a brown infrastructure for soil wildlife, a dark infrastructure for darkness at night, a noise-free infrastructure and an olfactory infrastructure to deal with anthropogenic odors.

Keywords Corridors · Light pollution · Noise · Olfactory · Underground · Windfarms

Introduction

For decades, territory planning—whether through urban, intensive agriculture or transport infrastructure spreading—has led to a deep transformation of landcover, resulting in a vast decrease of natural habitats (Kleinschroth et al. 2019; Simkin et al. 2022). Habitat loss reduces species ability to complete their life cycle in habitat patches, affecting foraging (Buchmann et al. 2012), breeding (Homan et al. 2004) and survival (Kotze et al. 2021). Habitat degradation, rather than loss, can also be detrimental (Fontúrbel et al. 2022), as it impacts demography (Moreno-Opo 2020), distribution (Botello et al. 2015) and viability (Zhang et al. 2018) of populations and causes damages at the ecosystem level, e.g. on species diversity (Vellend 2003) or species interactions (Spiesman and Inouye 2013).

In addition to being reduced in area, relictual habitat patches are becoming disconnected from each other, generating an anthropogenic habitat fragmentation (Fahrig 2003). Habitat fragmentation may also be due to specific barriers with no significant loss of habitat amount—such as fences or walls in farmland or gardens (McInturff et al. 2020). Habitat fragmentation has many consequences for species and ecosystems (Saunders et al. 1991). It can generate direct or indirect attrition of individuals (e.g. roadkills) which have to move through inhospitable environments between habitat patches (Medrano-Vizcaíno et al. 2022) and then affect demography (Glista et al. 2008). Habitat fragmentation has also long-term effects by limiting gene flow between populations, for animals (Keyghobadi et al. 2005) or plants (Cristóbal-Pérez et al. 2021). This may lead to isolated populations, eventually causing their extinction due to inbreeding depression and stochastic demographic factors (Andersen et al. 2004). Lastly, fragmentation can impede the spatial adaptation of species to changing climatic conditions (Opdam and Wascher 2004) and condemn certain populations under unfavorable climates (Holyoak and Heath 2016).

Habitat loss and fragmentation have been identified as major threats to biodiversity (Moulatlet et al. 2021; Kuipers et al. 2021). As a consequence, maintaining substantial areas of optimal habitats and improving landscape connectivity (i.e. the degree to which a landscape allows or impedes movements among resource patches (Taylor et al. 1993)) have been regarded as key measures to enhance biodiversity (Hyseni et al. 2021; Timmers et al. 2022; Cerda-Peña and Rau 2023). Connectivity appears to be a factor that facilitates dispersal, migration and gene flow in fauna—for various taxa: mammals (Coulon et al. 2004), amphibians (Todd et al. 2009), birds (Radvan et al. 2023), insects (Ouin et al. 2008)—and in flora (Sork and Smouse 2006).

To address these concerns, a new concept based on landscape ecology principles, has emerged in the 1980s: ecological networks (ENs), defined as sets of natural or semi-natural habitats whose diversity, composition and configuration enable to ensure both activities and movements of species within the landscape (Jongman 1995; Bennett 2004). ENs are composed of cores closely-spaced or physically linked by linear habitats named corridors (such as hedgerows, watercourses, riparian forests) (Hilty et al. 2006). Role of corridors in facilitating the movement of species in the landscape has been observed or demonstrated by numerous studies (Beier and Noss 1998; Bolger et al. 2001; Gutiérrez-Chacón et al. 2020).

Ecological networks has brought two major innovations in nature conservation while allowing a degree of human use of the landscape: 1/ More than just a network of protected areas: they go beyond the preservation of habitat amount to include landscape connectivity as a goal (Battisti 2003); 2/ A generalized land management tool: they can be used in both natural or urban contexts (Samways and Pryke 2016; Hamid and Tan 2017). Moreover, in the range of adaptation measures to be implemented in the face of climate change, ENs are among those most recommended by scientists (Heller and Zavaleta 2009; Prober et al. 2019). Indeed, they enable species to

adjust their range in altitude or latitude (Rüter et al. 2014; Su et al. 2021).

Given their benefits, ENs have long been promoted by nature conservation policies worldwide against habitat loss and fragmentation (Hilty et al. 2019; Keeley et al. 2019). Following the Convention on Biological Diversity of Rio 1992, the EU Member States have committed themselves to the constitution of a pan-European ecological network, to enable the conservation of ecosystems and habitats in Europe, to be implemented at the national, regional or local levels. In 2002, the Johannesburg Summit provided an action plan which aim is to « *promote the establishment of ecological networks and corridors at the national and regional levels*», to ensure the conservation and sustainable use of biodiversity (target 44.g).[1] Then, Aichi Biodiversity Targets 2011–2020 included the following objective: « *By 2020, […] degradation and fragmentation is significantly reduced*.» (target 5).[2] To meet these objectives, many states of the world have implemented public policies for ENs (Jongman et al. 2004) that can take various names—such as '*Trame verte et bleue*' (France), '*Biotopverbund*' (Germany), '*Wlaams Ecologisch Netwerk*' (Belgium Flanders), '*Green Network*' (Estonia), '*National Ecological Network*' (Hungary). These public policies often result in maps of natural and semi-natural habitats and connections to be preserved and restored. For instance, in France 15,7 million hectares of core areas of habitats (29% of French continental territory) and 50,717 km of linear corridors have been identified (Billon and Sordello 2017). Therefore, ENs provide a decision-making tool for land-use planning that makes it possible to take biodiversity into account in political trade-offs at various levels, from local to international (Wickham et al. 2010; Pietsch 2018), particularly in countries where landscapes are constrained by all types of artificialisation.

EN is a flexible concept and approaches for EN design and management are manifold. The theoretical basis of ENs (i.e. including habitat amount and connectivity) offers the greatest opportunities to design multidimensional and comprehensive ENs, considering all types of environments and all types of anthropogenic disturbance. However in practice, several vital dimensions to biodiversity functioning—such as aerial/soil habitats or sensory disturbance—seem to be regularly omitted. In the context of biodiversity shrinking on Earth, immediate action is urgently needed to deal with these issues—and ENs implementation make part of them—given that a quarter of terrestrial species is estimated to live in soils (Guerra et al. 2021), that 64% of invertebrates organisms are active at night (Holker et al. 2010) and that Earth's natural soundscapes are vanishing (e.g. 70% of the soundscapes recorded by Bernie Krause since the 1960s would have disappeared today). Even if scientific knowledge on these topics remains incomplete, we are sufficiently informed to take action now.

In this article, we want to highlight gaps both in the conceptualization and the implementation of ENs in various aspects. Our aim is to address both scientists and practitioners communities:

- researchers (e.g. landscape ecology, sensory ecology): identifying overlooked characteristics in the conceptualisation of habitat loss and fragmentation and highlighting key research gaps that would require further primary studies.

- landscape designers and decision-makers: inviting them to transition to more comprehensive ENs implementation, by providing them with operational guidance and examples of projects already completed.

First, we will demonstrate the limitations of the current implementation of ENs worldwide, that are based on the usual conception of habitat loss and fragmentation. Second, we will organize the argument on the requirement to overcome current bottlenecks in EN implementations, stressing the need to consider new forms of habitat loss/fragmentation in the light of scientific knowledge development. Third, we will propose to implement multidimensional ecological networks by suggesting that the concept of *Green infrastructure* could be a solution and by naming six specific infrastructure to be developed: aerial, soil, dark, man-induced noise-free, and anthropogenic odour-free. Fourth, we will discuss the operational implications for designing and managing ENs within the broader conception we recommend and we preconized a framework for this process. In this article, France is the starting point for our reflection because it is the country we know best, and we use this case

[1] https://ise.unige.ch/isdd/IMG/pdf/plan-action_johannesburg.pdf

[2] https://www.cbd.int/doc/strategic-plan/targets/T5-quick-guide-en.pdf

study to generalise, because this proposal to extend ENs is valid for many other countries, particularly all urbanised and industrialised countries.

Limitations of the current implementations of ecological networks

Considering the various methodological guides for practitioners to design ENs and the feedback reports (e.g. Bennett et al. Bennett and Mulongoy 2006; Naumann et al. 2011; Science for Environment Policy 2012; Sordello et al. 2017; European Commission 2019; Hilty et al. 2020), some potential limits can be addressed about how ENs are currently designed: ENs seem to mostly focus on above ground ecosystems and mainly consider the physical drivers of habitat loss and fragmentation.

First, ENs are often implemented at various spatial levels, from the municipality to an entire continent, including regions or states. This multiscale process enables to take into account a great diversity of species' life history traits (e.g. dispersal distances, home range sizes). It allows to cover a wide range of spatial variability in ecological processes, from large movements (e.g. migration of a big mammal over several kilometers) to very short movements (e.g. a small mammal that moves over a few dozen square meters). In contrast, ENs usually forget the temporal axis of ecological processes; e.g. circadian rhythm based on day/night cycle.

Second, ENs generally include several sub-networks according to different types of habitats which are often described in terms of terrestrial/aquatic compartments and patterns of vegetation; e.g. forests, hedges, wetlands, grasslands. ENs also deal with watercourses, to preserve or restore aquatic and sedimentary flows. As a result, ENs are mainly interested in what happens on the ground while aerial and underground habitats are more ignored. To take two examples: 1/ Voigt et al. (2018) underline that conservation strategies for bats focus almost exclusively on ground-based habitats (habitats for foraging, hibernation or reproduction) while aerosphere is under-represented; 2/ Mony et al. (2022) highlight that microorganisms—closely linked to soils—form the dominant proportion of biodiversity on earth while they are systematically forgotten in ENs policies.

ENs have mostly emerged to respond to habitat fragmentation caused by linear transportation infrastructure. The latter have been considered for several decades as the most evident landscape barrier (Forman and Alexander 1998; Coffin 2007), maybe because of their linear features that clearly generate a structural landscape cutting. Urbanization has also been identified as a major source of habitat loss and fragmentation for a long time (e.g. Dickman 1987), making ENs a regularly used tool in urban planning to create a spatial coherence in urban greening (Voghera and La Riccia 2019). Farming and forestry intensification can also lead to ruptures in the landscape (e.g. destruction of hedges, clear-cutting) (e.g. Van Apeldoorn et al. 1992; Grashof-Bokdam 1997) and ENs are used to dealing with these issues (Schmidt and Hauck 2018). Dams, weirs and other obstacles on watercourses were also very early the object of particular attention (e.g. Gehrke et al. 2002). The main drivers considered in ENs are hence currently 'physical' landscape features while sensory pollutants are barely included.

Sensory pollutants include anthropogenic disturbances caused by waves or volatil compounds, such as artificial light at night (ALAN), man-induced noise and odors. There are very few international conservation strategies to reduce ALAN at the landscape level (Schroer et al. 2020; Jägerbrand and Bouroussis 2021). For example, an assessment of French regional ENs performed in 2015 showed that they did not include ALAN (Sordello 2015). Regarding noise pollution the European Commission has recommended the identification of quietness areas since 2014 (European Environment Agency 2014) but a real promotion of a noise-free EN is still lacking. Even less actions exist concerning odorscapes. Indeed, attention paid to odors is currently limited to ecological engineering measures, for instance to reduce wildlife damage; manipulating odours to protect crops from unwanted animals (Baker et al. 2008; Hansen et al. 2017).

Various dimensions that ecological networks should embed

Air and soil compartments

Many species fly, especially birds, bats, insects and all aerial planktons (Fig. 1). Some of them may follow well identified 'flight routes' (Barchi et al. 2013) and some of these flyways can concentrate thousands of individuals (Fülöp et al. 2018). Yet, the aerosphere is full of obstacles (Drewitt and Langston 2008; Loss et al. 2015). Buildings such as telecommunication towers, maritime lighthouses and skyscrapers are a considerable source of mortality for flying species; this has been assessed especially for avifauna (Loss et al. 2014). Wind farms cause casualties for bats and birds (Cabrera-Cruz et al. 2020), via collisions or barotrauma (i.e. trauma due to the extreme speed of the blades which generates a sudden drop in atmospheric pressure in their vicinity) (Baerwald et al. 2008). This issue is becoming more and more concerning regarding wind farms expansion in the context of climate change and renewable energy deployment. Powerlines can lead to damage, by collisions or electrocutions (Sergio et al. 2004). Aircraft are a factor of mortality for birds (Desholm 2009). Other aerial sources of collisions may exist although they are not well assessed yet, e.g. all types of cables (wood longshoring cables, ski lift, telecommunication cable). For instance, a study on 252 skiable domains between 2000 and 2004 in France counted close to 240 birds killed by ski-tow, ski lifts and cable cars (Maillard 2009). Therefore, it seems obvious that airscape fragmentation requires a dedicated strategy (Sordello et al. 2022b).

The soil is also an habitat for many taxa (Fig. 1), such as bacteria, fungi, invertebrates (nematodes, springtails, earthworms, …), mammals (rodents, insectivores, carnivores and other burrow builders, galleries) or plants (root system) (Bardgett and Cook 1998; Wolters 2001). For all these organisms, the soil is both a place to live and to move (Auclerc et al. 2009; Eijsackers 2011). Some species live exclusively in the soil and have only this compartment to move. For instance, some springtails are repelled by light and live completely in the soil at depths of around thirty centimetres (eu-edaphic species) (Eisenbeis and Wichard 1987). Trees may also need to exchange nutrients among each other via their roots (Klein et al. 2016). Yet, soil wildlife may encounter many man-induced obstacles: housing foundations, transportation networks for energy (e.g. gas pipelines) or people (e.g. subway). In cities, many green areas—for example, on streetsides—are limited to large, unconnected bins of soil. Some human activities, such as material extraction or agriculture, threaten soil quality (Menta et al. 2014; Falco et al. 2015) and may generate barriers to wildlife movements, either physical (e.g. compacted soil due to intensive agricultural practices) or chemical (e.g. virtual

Fig. 1 Aerosphere and soil are key compartments for biodiversity to live (habitats) and move (connectivity)—with specific man-induced threats—while ecological networks generally focus on above ground issues (road, dams, land-use)

"wall" of toxic substances within a polluted soil). The soil is not just a surface but a compartment made up of different strata which—when the soil is excavated and moved elsewhere—are mixed together, destroying the way the soil functions.

Aerosphere is a compartment where take place ecological and biochemical processes that are essential to life on Earth, providing a vital resource, including for humans: pure and oxygenated air (Khonyongwa et al. 2023). Soil performs numerous ecological functions (e.g. nutrient and water cycles, carbon storage, degradation of organic matter) and also provides crucial benefits for our societies (e.g. climate regulation, recycling, food provisioning) (Adhikari and Hartemink 2016; Banwart et al. 2019). As a result, habitat loss and fragmentation in airscapes and soil should be considered in ecological networks. For the moment this consideration remains limited, and restricted to roads; e.g. crossing passages for soil wildlife (worm bridges) and aerial fauna (bat bridges and gantries) (Berthinussen and Altringham 2012; Claireau et al. 2021).

Sensory pollutants

Species are sensitive to visual, auditory or olfactory stimuli which play a key role to seek habitats (e.g. finding refugia, identifying food resources, detecting an available partner (Conover 2007; Goerlitz et al. 2008; Jiang et al. 2015)) and to move (e.g. pursuing prey, fleeing predators, memorising its way (Bee 2007; Reddy et al. 2022; Freas and Spetch 2023)). Nowadays, human activities emit artificial stimuli which interfer with natural ones (Dominoni et al. 2020) and that can combine with each other (Willems et al. 2022; Ichikawa and Kuriwada 2023).

Nighttime lighting has expanded substantially worldwide over the past decades, exposing all living organisms to light pollution (Falchi et al. 2016). Artificial light at night (ALAN) has been demonstrated to cause many damage on fauna, flora and ecosystems (Falcón et al. 2020; Sanders et al. 2021). It can alter habitat quality (Picchi et al. 2013; Ciach and Fröhlich 2019) and act as a barrier in the nightscape (Zeale et al. 2018; Vowles and Kemp 2021; Korpach et al. 2022).

Human activities also generate sounds whose impacts on biodiversity are extensively documented (Sordello et al. 2020); for instance industry (Mason et al. 2016), roads (Grade and Sieving 2016), aircraft (Injaian et al. 2021), wind farms (Keehn and Feldman 2018), recreation activities (Payne et al. 2012). This noise pollution affects animal communication—whether in predator/prey or mating interactions (Roca et al. 2016; Duquette et al. 2021)—behavior or foraging (Klett-Mingo et al. 2016; Mancera et al. 2017). It alters species occurrence (Luscier et al. 2023) and ultimately ecosystem composition (McClure et al. 2017; Sangermano 2022). In the same way as ALAN does, anthropogenic noise degrades habitat quality (Francis et al. 2011; Ware et al. 2015; Luo et al. 2018) and is likely to fragment natural soundscapes. For example, traffic noise represents an acoustic barrier for owl hunting (Senzaki et al. 2016).

Less attention has been paid to date to the impacts on wildlife of odors emitted by human activities such as transportation, industry or agriculture. However, we know that odors also contribute to sensory landscapes in the form of an odorscape within which many taxa interact (Conchou et al. 2019; Finnerty et al. 2022). Thus, anthropogenic odors are likely to interfere with the olfactory communication of living organisms, by decreasing the intensity of signals or by luring individuals with wrong information (Lurling and Scheffer 2007; David et al. 2022; Jiang et al. 2023). Potentially, these man-induced odors can degrade the quality of natural habitats, or even constitute areas of disruption, for example in the context of linear infrastructure (Girling et al. 2013; Jürgens and Bischoff 2017).

Therefore, nature conservation would benefit from considering the sensory perception of species (Madliger 2012; Elmer et al. 2021), including at the landscape level (Little et al. 2022). This raises the need for ecological networks to include sensory pollutants, at least starting with artificial light at night (Sordello 2017), man-induced noise (Moulherat et al. 2023) and anthropogenic odors (Renou et al. 2021). This means we have to stop considering landscape features solely from a tangible point of view. For instance, a road is not only a physical issue (e.g. impervious surface, traffic, fences) but also a multisensory polluting infrastructure (Fig. 2). Healthy natural sensory landscapes are also essential for human beings; e.g. artificial light at night disturbs human health (Cupertino et al. 2023) and five million people in the European Union suffer from major chronic sleep disorders caused by noise according to European Environment Agency.

Caption: A road combines both physical—such as impervious ground, fencing, verge management (Ouédraogo et al. 2020)—and sensory threats—such as artificial light at night (Davies et al. 2012), man-induced noise (Bautista et al. 2004; Bee and Swanson 2007) and odors (Girling et al. 2013). These sensory pollutants are likely to reduce the effectiveness of road crossing structures (Bliss-Ketchum et al. 2016; Sołowczuk 2019; Bhardwaj et al. 2020) and widen the road ecological footprint. For instance, ALAN was shown to act on bats up to 50 m (Azam et al. 2018) and noise effect on decreasing bird density was true up to 100 m (Wiącek 2023).

Green infrastructure: a solution to implement multidimensional ecological networks?

For decades, several tools have been developed for ecological planning, using the term '*infrastructure*'.

'*Ecological infrastructure*' was firstly introduced in 1984 in UNESCO's Man and Biosphere Programme to promote « *a natural landscape and natural areas as the framework for spatially organising the city*» (UNESCO 1984). Then, during the 1990s, '*Ecological infrastructure*' relatively equated with '*Ecological Networks*'—both terms focusing on nature conservation (Ahern 1995). In recent decades, new terms have been flowering, such as '*Urban Ecological Infrastructure*' (UEI) or '*Green*

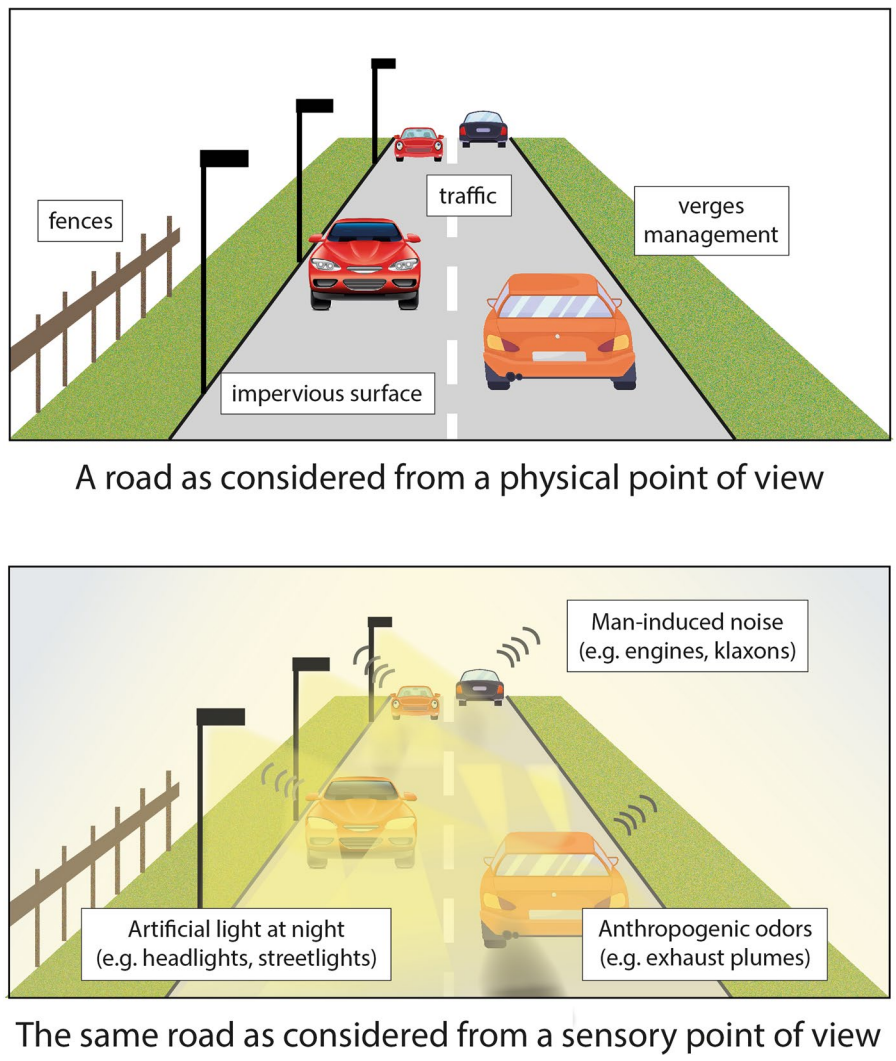


Fig. 2 A road is a multi-modal landscape feature that addresses both physical and sensory habitat loss and fragmentation

Infrastructure' (GI) (Childers et al. 2019; Sun et al. 2020). Today, while GI spontaneously refers to 'green' components of ecosystems, it has emerged as the more inclusive and commonly used name, whatever the environement (terrestrial or aquatic) and the context (natural or urban), among natural resource professionals (Benedict and MacMahon 2002). In recent years, GI have been spreading on a variety of territory levels, including urban contexts (e.g. in London (Jones and Somper 2014), Madrid (Velázquez Melero and Rodríguez-Espinosa 2023), New-York (Meerow 2020), Tokyo (Aleksejeva et al. 2022)). On a broader level, the European Commission has been developing a GI strategy since 2013,[3] which is now part of the EU Biodiversity Strategy for 2030.

However, since GI originate from a variety of disciplines including ecology, urban planning or civil engineering (Ying et al. 2022), a kind of confusion exists about what they really aim at (Silva and Wheeler 2017). Some conceptions emphasise the more anthropogenic objective—i.e. improving human well-being (Li et al. 2017)—while other definitions focus on biodiversity persistence (Science for Environment Policy 2012; Mell 2014). Some definitions are hybdrid but give priority to human benefits; for instance, European Commission defines GI as « *A strategically planned network of natural and semi-natural areas with other environmental features, designed and managed to deliver a wide range of ecosystem services, while also enhancing biodiversity*».[4]

Here, we refer to *Green Infrastructure* assuming a conception focused primarily on biodiversity while benefiting humans, taking the definition of Benedict & MacMahon (2002): « *an interconnected network of green space that conserves natural ecosystem values and functions and provides associated benefits to human populations* ». Hence, we consider GI as the practical implementations of ENs. As a result, we preconize that GI also transition to encompass multidimensional ENs.

In France, a process has already been started to expand GI to other ecosystem dimensions. Especially, designers are now invited to take into account light pollution to ensure that ecosystems function properly at night, leading to the emergence of a Dark infrastructure (Sordello et al. 2022a). Recently, the European Commission promoted the extension of GI to night-time environment (European Commission 2023).

To continue in this direction, we suggest to decline GI according to various dimensions that affect ecological networks. Namely, an aerial infrastructure for flying species, an underground infrastructure for soil wildlife (that could be named 'brown infrastructure' in reference to soil color), a dark infrastructure for darkness at night, a noise-free infrastructure (that could be named 'white infrastructure' in reference to 'white noise'; i.e. sound emitted to mask surrounding noise) and an olfactory infrastructure to deal with anthropogenic odors (see Fig. 3). In France, such new infrastructure have begun to be implemented. Indeed, dark infrastructure are proliferating across the country (Sordello et al. 2021), a noise-free infrastructure has been undertaken in a French regional nature Park (Le Bougnec 2018) and the French metropolises of Limoges and Nancy have been involved in a brown infrastructure (Cluzeau et al. 2022; Vincent et al. 2022). Moreover, projects that combine these several dimensions to achieve a more comprehensive Green infrastructure are emerging. Details of such exploratory projects are given in Additional File 1.

Exploratory practical concerns

Multidimensional ecological networks and their implementation in GI are a practical challenge: how can this complexity be taken into account while remaining operational and readable? We suggest here two practical outlets: designing and management—and we preconize a framework that could be operationalized by managers and decision-makers to process multidimensional GI (Fig. 4). We also highlight key knowledge gaps that would need further research, detailed in Additional File 2.

Designing from extended ecological networks to multidimensional GI

The design of ecological networks (i.e. identifying cores, corridors and barriers) is an essential first step to identify which areas are still preserved and which

[3] https://environment.ec.europa.eu/topics/nature-and-biodiversity/green-infrastructure_en

[4] https://biodiversity.europa.eu/green-infrastructure

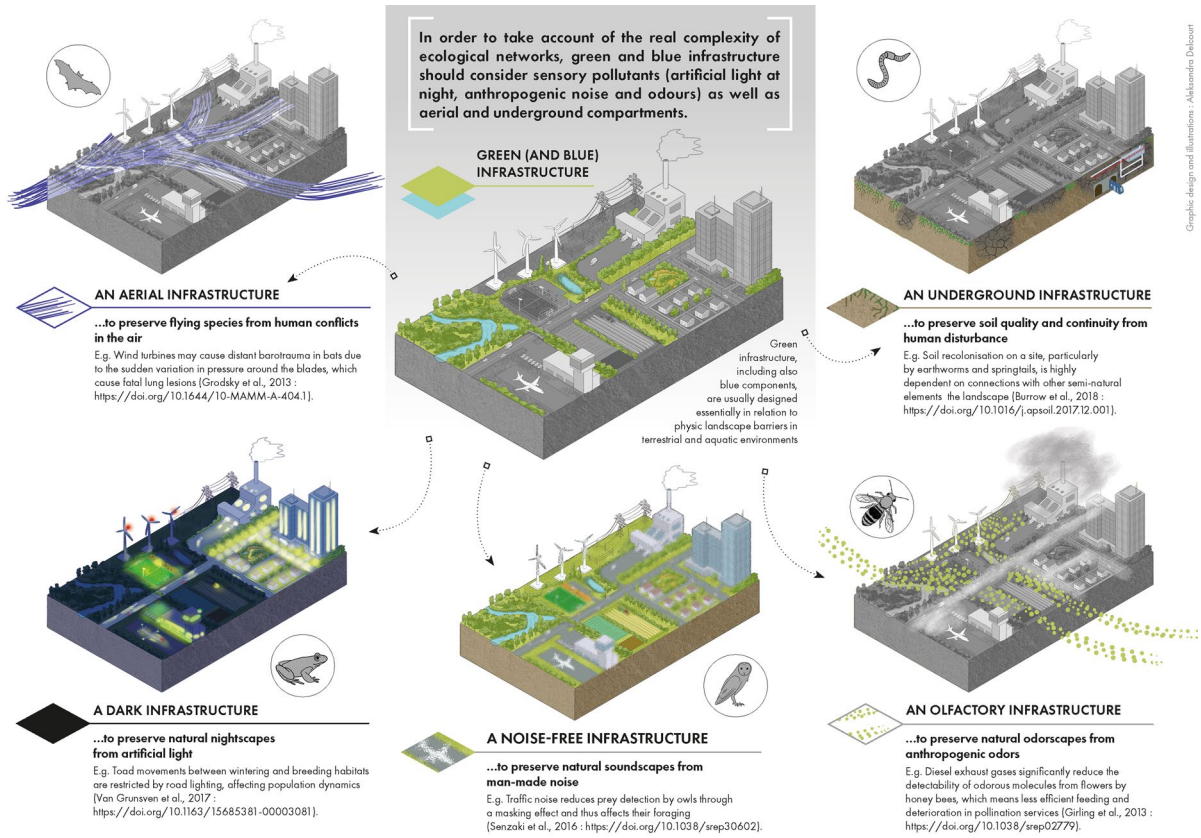
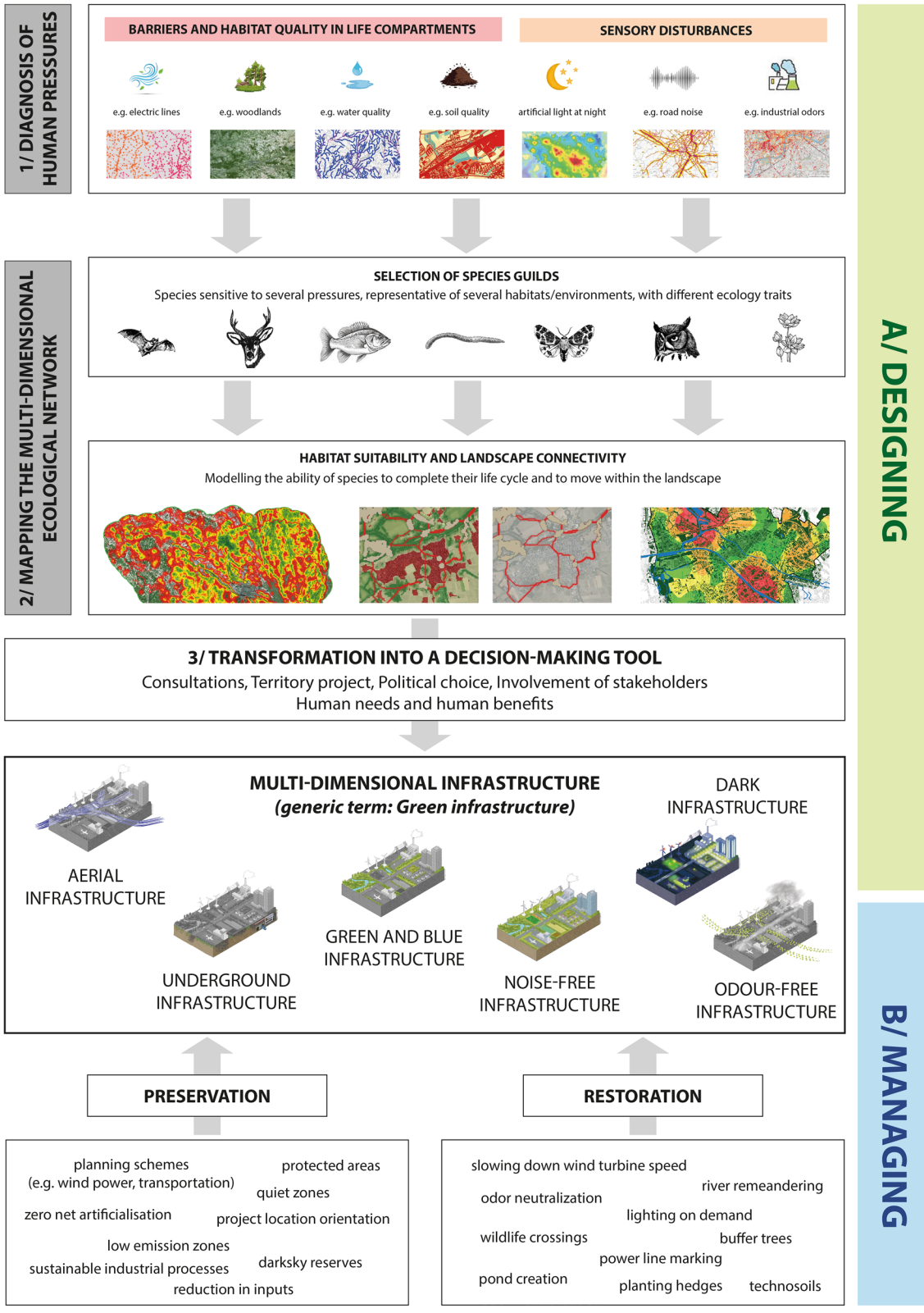


Fig. 3 The green (and blue) infrastructure could be a relevant lever to encompass multidimensional ecological networks, including specific infrastructure concerning aerial and underground compartments and sensory pollutants

ones are degraded (i.e. have to be restored) and then to achieve in the end to a planning and decision-making tool, the multidimensional GI (see Fig. 4—Part A/Desiging). In a perspective of more comprehensive ENs, such mapping should involve airscapes and soils and include sensory drivers of habitat loss and fragmentation—artificial light, noise and olfactory disturbances (see Fig. 4—Step 1). Preserved areas should benefit from protection to prevent the spread of pressures in all these dimensions in the future, for example to avoid the implantation of wind farms on aerial migratory corridors (wind power is growing every year and will continue to do so (GWEC 2023)) or the extension of night lighting in areas of relict darkness (ALAN is estimated to grow by 2% a year (Kyba et al. 2017)).

Ecological networks are often designed based on habitat amount (ensuring population viability) and landscape connectivity (ensuring ability of species to move). This step involves species to be selected as biological model to represent a diversity of ecology and environment. Hence, the aim will be to diversify the species guilds—e.g. to include soil fauna, flying species, species sensitive to ALAN, with different traits (dispersal distance, etc.) (see Fig. 4—Step 2). Next, population viability and landscape permeability can be assessed, for instance by including new drivers (ALAN, noise, odors) as additional parameters in spatial models through the coefficients determining habitat quality and land cover resistance (Hale et al. 2015; Pauwels et al. 2019; Moulherat et al. 2023) (but see the issue about data availabity, below).

Another question is how to use existing maps of ecological networks supported by policies to go further. This is an important issue to avoid giving the impression, particularly to local elected representatives, that the works they have undertaken to date are now obsolete. In this respect, it is possible to start


1/ DIAGNOSIS OF HUMAN PRESSURES
BARRIERS AND HABITAT QUALITY IN LIFE COMPARTMENTS
SENSORY DISTURBANCES
e.g. electric lines
e.g. woodlands
e.g. water quality
e.g. soil quality
artificial light at night
e.g. road noise
e.g. industrial odors
2/ MAPPING THE MULTI-DIMENSIONAL ECOLOGICAL NETWORK
SELECTION OF SPECIES GUILDS
Species sensitive to several pressures, representative of several habitats/environments, with different ecology traits
HABITAT SUITABILITY AND LANDSCAPE CONNECTIVITY
Modelling the ability of species to complete their life cycle and to move within the landscape
3/ TRANSFORMATION INTO A DECISION-MAKING TOOL
Consultations, Territory project, Political choice, Involvement of stakeholders
Human needs and human benefits
MULTI-DIMENSIONAL INFRASTRUCTURE
(generic term: Green infrastructure)
AERIAL INFRASTRUCTURE
UNDERGROUND INFRASTRUCTURE
GREEN AND BLUE INFRASTRUCTURE
NOISE-FREE INFRASTRUCTURE
DARK INFRASTRUCTURE
ODOUR-FREE INFRASTRUCTURE
PRESERVATION
planning schemes (e.g. wind power, transportation)
protected areas
quiet zones
zero net artificialisation
project location orientation
low emission zones
sustainable industrial processes
darksky reserves
reduction in inputs
RESTORATION
slowing down wind turbine speed
river remeandering
odor neutralization
lighting on demand
wildlife crossings
buffer trees
power line marking
pond creation
planting hedges
technosoils
A/ DESIGNING
B/ MANAGING

◂**Fig. 4** Framework from diagnosis to action to design and manage multidimensional GI

from these already designed ecological networks by coupling them with pressure maps in order to identify the parts of the ecological networks that also meet the additional criteria; e.g. regarding night-time darkness (Ranzoni et al. 2019) or acoustic environment (Le Bougnec 2018).

Regardless the method, data (e.g. pressure, occurrence) and knowledge (species sensitivity thresholds, life traits) may not all be available today. For instance, the design of an 'aerial infrastructure' requires first of all a good knowledge of the migratory axes and the behavior of flying species (flight heights, frequency of movements, etc.), which is only partially known today (Dokter et al. 2011; Péron et al. 2017). The integration of sensory drivers would require a good knowledge of the sensitivity thresholds of species to light, noise and olfactory pollutants. However, these thresholds are barely known for artificial light at night (Gaston et al. 2013), much less for anthropogenic noise (Kunc and Schmidt 2019) and totally unexplored for man-made odors. Research is hence required on these topics (see Additional File 2). Identifying such thresholds (i.e. operational quantified knowledge) may require primary studies and/or secondary research (systematic reviews, meta-analyses) to synthesize available knowledge. Knowledge should evolve rapidly in certain areas; for example, soundscape ecology, which is currently undergoing strong development, offers very promising prospects based on landscape acoustic indices (Farina and Gage 2017).

Finally, the ecological network—a scientific result—will have to be transformed into Green infrastructure—a planning map based on a political project (see Fig. 4—Step 3). This implies to involve various stakeholders through consultations in order to develop a territorial project that attracts support. Human needs and human benefits are taken into account here. This stage requires education, but it also needs a strong political will to ensure that the GI is as close as possible to the EN in order to maintain the same ambition to protect biodiversity.

Management to reduce disturbances

Mitigation measures to reduce pressures, disturbances and landscape barriers must be implemented every where it is possible. However, GI offer a guidance which allows to prioritize actions within crucial areas (cores and corridors) (see Fig. 4—Part B/Managing). These measures will contribute to improve the quality of habitats, re-establish or create corridors, remove barriers or reduce the hostility of the landscape matrix, resulting in the enhancement of ecological network functionality. Several measures have already been applied for a long time in the context of GI (e.g. planting hedges, river remeandering, wildlife crossings). Such measures are relevant but in multidimensional GI new aspects have to be considered (e.g. aerial obstacles, soil disturbance, light pollution). Given the wide range of possible actions, we will only introduce some solutions for each topic:

1/ Aerial infrastructure: The blades of wind turbines can be lowered or stopped to reduce mortality during specific periods (migration, agricultural works likely to attract birds, etc.) (Smallwood and Bell 2020). Concerning aircraft, since most collisions occur at less than 150 m above ground (Dolbeer 2006), a strategy is to reduce the attractiveness of airport verges to wildlife or to introduce scare tactics as a preventive measure (Villers 2019).

2/ Brown infrastructure: Reducing the impervious areas and increasing open ground in urban green spaces is an essential step to enhance soil biodiversity (Maher et al. 2022) and soil functions such as carbon storage (Yan et al. 2023) or water flows (Strohbach et al. 2019). Moreover, *constructed Technosols* are a very promising field of ecological engineering to rebuild soils by recycling mineral waste (e.g. rubble from demolition, sediments from dredging, waste from quarries) (Ivashchenko et al. 2021; Minixhofer et al. 2022; Ouédraogo et al. 2024). In rural landscapes, shift farming practices towards a more extensive agriculture (e.g. agroforestry, permaculture) may contribute to restore a brown infrastructure (Domínguez et al. 2023).

3/ Dark infrastructure: A lot of practices can improve night quality (Gaston et al. 2012; Sordello 2018). Lighting should be reduced to the strict minimum, which may involve eliminating unnecessary light sources or reducing lighting time; e.g. part-night lighting (Azam et al. 2015), motion-activated lighting

(Bolliger et al. 2020), dimming protocols (Merckx et al. 2023). Yellow/amber/red closed light spectrum, considered less damaging for wildlife, should be preferred (Longcore et al. 2018).

4/ Noise free infrastructure: Reducing man-made sources of noise appears to be the first response (e.g. developing silent engines). Anti-noise barriers, including vegetative, may be a solution (Halim et al. 2015) and quiet zones can be defined, both in rural or urban context (Cerwén and Mossberg 2019).

5/ Olfactory infrastructure: The best strategy seems to be a reduction of anthropogenic odors at source (e.g. reducing the use of agricultural inputs and fossil fuels). When volatile compounds are in the environement, it is difficult to neutralize them (i.e. destroy them, transform them, cover them up). Biofilters, odor-neutralizing materials (e.g. activated carbon), chemical scrubbers, essential oils are interesting ideas but very little feedback are available. For the moment, they are being tested in industry, to reduce olfactory disturbances inside buildings, and in agriculture, to reduce odour nuisance for neighbours. For instance in France, following a complaint from neighbours, a farmer installed raspberry essential oil foggers to cover up the odours caused by his duck farm. The feasibility and effectiveness of transposing such techniques to odorscape restoration for nature conservation has yet to be fully assessed. Landscape management (e.g. tree buffers, hedgerows) might also help to reduce propagation of volatile compounds (Tyndall and Colletti 2007) but assessments show a limited effect (Hernandez et al. 2012). Scent manipulation could become a promising avenue to counterbalance the negative effects of man-made odours, to enhance landscape restoration (e.g. wildlife crossings) or to prevent roadkills (Bíl et al. 2018).

It should be noted that the panel of available measures is uneven between topics (for example, mitigating odors remains entirely exploratory to date). Moreover, measures have varying degrees of efficiency, sometimes not assessed, and can lead to undesirable consequences (e.g. introducing noise to avoid a collision; exposing trees to sensory pollutants to build 'natural barriers'). Research is therefore needed on these emerging topics (see Additional File 2) (Madliger et al. 2016). However, the need for more knowledge must not be paralizing since reducing pressures can only go in the right direction for biodiversity protection; then wide range of actions can be implemented without delay and without regret (no-regret strategies; i.e. measures that can be started now without being certain of everything, because they have no detrimental effect) such as reducing nighttime lighting, limiting noise or decreasing the amount of impervious surfaces.

The implementation of these actions requires a cross-sectoral coordination by the Green infrastructure project manager. Long-term monitoring protocols are needed to assess the efficiency of GI implementation by measuring changes in both human pressures and biodiversity responses (i.e. habitat amount, quality and connectivity). In the light of this monitoring, it is recommended that the Green infrastructure (design and/or the action plan) be updated periodically (every 5 years, for example).

Conclusion

Scientific knowledge about human impacts on wildlife activities and movements is constantly increasing. New threats to species have been identified as diverse as windfarms, man-induced sounds or light pollution. This increase in the awareness of anthropogenic disturbances on biodiversity raises the number of parameters that should be accounted for when implementing ecological networks. To be more comprehensive, we encourage ecological network public policies to cover different living compartments—from soil to air—and more drivers—both physics and sensory—that lead to habitat loss and fragmentation. To this end, extended Green infrastructure could be a relevant solution. They should include several specific infrastructure, especially an aerial infrastructure for flying species, a brown infrastructure for soil wildlife, a dark infrastructure for darkness at night, a noise-free infrastructure to deal with anthropogenic sounds and an olfactory infrastructure to deal with anthropogenic odors. Transitioning to multidimensional ecological networks is an enormous challenge for societies that will involve more stakeholders in the process of design and management of GI. A lot of actors have now to feel concerned by such public policies, far from transportation managers, farmers or water stakeholders, such as the aviation or wind power sectors, technosol engineers, lighting engineers or noise and odor emitting industries.

Although knowledge is still incomplete, there is an urgent need for action on these issues without delay, for biodiversity and for us. Indeed, this challenge is essential for our societies since a vast literature highlights the benefits of a dark night environment (Wang et al. 2023), healthy soils (Hassan et al. 2022) and quiet spaces (Hahad et al. 2024) for our well-being. Then, the gain of a healthy environment for humans and non-humans go in the same direction, which is underlined by the « *One health* » concept currently developed by the United Nations (ONU 2022).

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Declarations

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