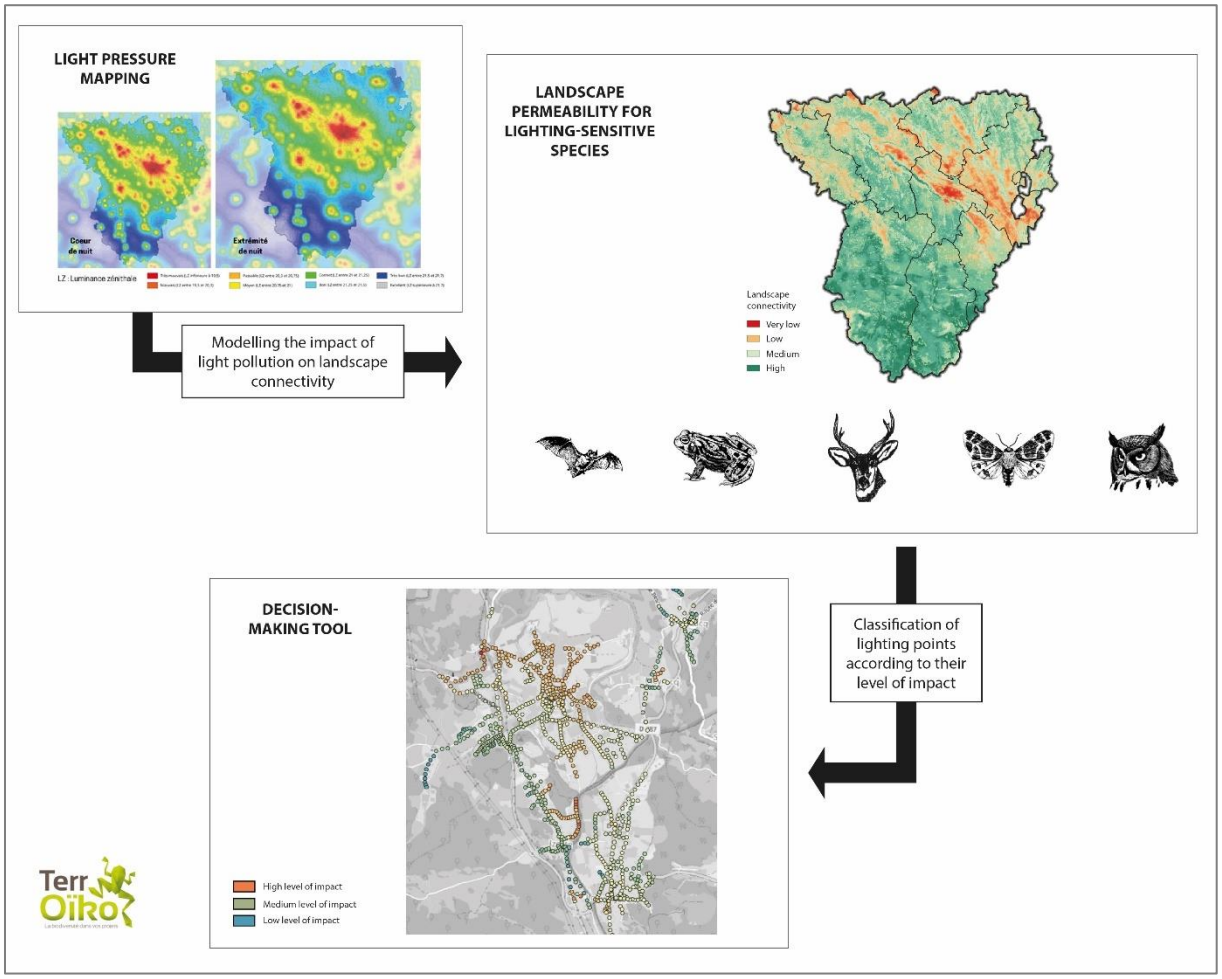
Additional File 1

Examples of projects carried out in France to take account for additional dimensions into Green infrastructure

In France, various initiatives have already been carried out to take account for additional dimensions into Green infrastructure. The most developed is the Dark infrastructure, but several exploratory projects have been completed to deal with White infrastructure, Aerial infrastructure and Brown infrastructure. In this document, we shortly introduce a few examples to show the diversity of approaches and methods.

- **Example of Dark infrastructure**

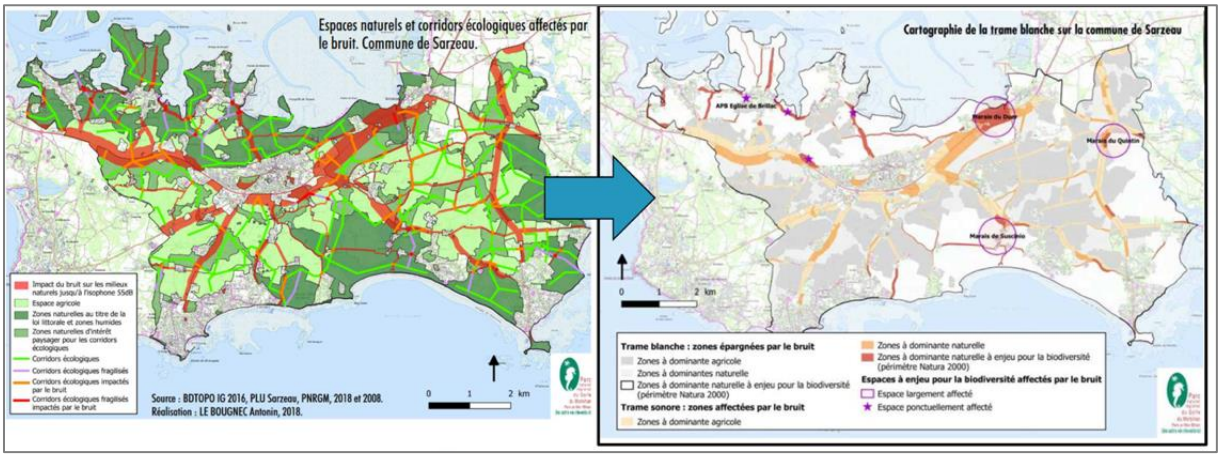
The 'Pays du Béarn' (8 groups of municipalities, totalling 390 municipalities) has carried out a study of Dark infrastructure. First, a diagnosis of light pressure was established by combining remote sensing data and data about public lighting points. Secondly, taxa that are particularly sensitive to night-time lighting (owls, amphibians, bats, non-flying mammals and moths) were selected and their ability to persist and move within the landscape was modelled using SimOïko[1] in order to assess the impact of light pollution on population viability analysis and connectivity. On this basis, priorities for action were identified for each lighting point, classified into three categories (high, medium and low impact). This mapping provides a decision-making tool to spatialize public lighting modernization.



[1] A species life modeling tool developed by TerrOïko, see the platform http://www.simoiko.fr

- **Examples of White infrastructure**

➢ A pioneering initiative of White infrastructure was carried out in 2018 by the Regional Nature Park of Golfe du Morbihan (29 municipalities). The first stage involved identifying the anthropogenic noise pressure that is disturbing and fragmenting (semi-)natural habitats. A theoretical framework was established and applied operationally to 3 municipalities in the Park, focusing on road noise, which is easier to assess. Average daily road noise (Lden) was mapped within these areas using field survey. This mapping of road noise pressure was then cross-referenced with the mapping of the ecological network, using the 55 dB(A) isophone as the threshold (a threshold often used as a maximum acceptable exposure limit for humans). The result was the identification of areas and corridors that are relatively unaffected by noise (White infrastructure to be preserved) and those that are more affected (White infrastructure to be restored where mitigation measures are needed). At the same time, a bioacoustic survey was performed based on 8 avian species to further analyse the soundscape and potential conflict with anthropogenic noise.



NB: because this project was developed in France and that we do not have access to the original files to translate them, the figures is in French but we have given as many explanations as possible in English in the caption below..

Left: Green infrastructure was mapped and cross-referenced with anthropogenic noise. Cores or corridors shown in green colors are the least concerned by noise. Noise polluted corridors are indicated in purple, orange or red colors according the level of noise pollution (from the lowest to the highest)

Right: Noise-free infrastructure was mapped according to land cover (farmland, natural habitats). Areas shown in white/grey colors are unaffeccted by noise while orange/red colored areas are the noise polluted parts of the infrastructure. Pictograms in purple highlight the most polluted sites (star: isolated sites, circle: extensive sites)

Reference: Le Bougnec A. (2018). *La Trame sonore. Elaboration d'une méthode d'identification sur le territoire du Parc Naturel Régional du Golfe du Morbihan*. 79p.

➢ Another project is currently in progress, in an urban context, in the Lille metropolitan area (671,90 km2 ; > 1 million inhabitants). This territory has already implemented a Green/Blue infrastructure, including a Dark infrastructure. The aim is now to take account for noise in these ecological networks. Here, the White infrastructure has been defined as « *One of the natural frames that contribute to ecological continuity, composed of areas unaffected by noise pollution where all living things, people and nature, can communicate easily and coexist in acoustic balance* ». To identify it, the project is currently focusing on noise mapping, by compiling existing data and taking field measurements using recorders set up at various sites. These soundscape recordings will enable to better quantify and qualify biophony (targeting avian species) and anthropophony. This diagnosis will allow to identify the ecological network (cores and corridors) where soundscape is optimal or, on the contrary,

disturbed, and to subsequently propose an action plan. This project in a dense urban environment also aims at raising awareness among inhabitants by highlighting the links between healthy soundscapes and human well-being.

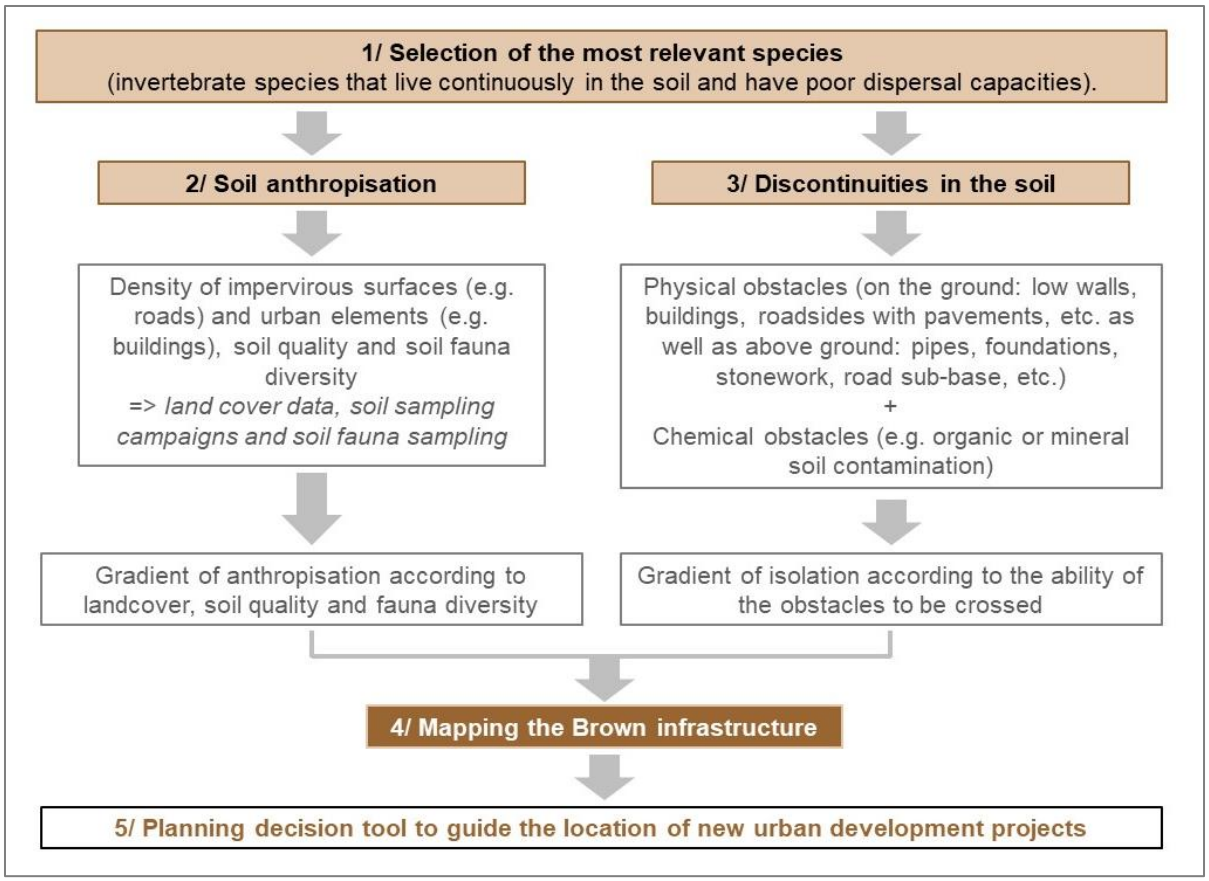
Reference: Pichard O. (dir.), Deléarde M., Pot G., Perissere C. (2025). *Trame blanche urbaine de Lille : Restaurer et maintenir des paysages sonores favorables à la biodiversité et aux habitants de Lille, Lomme, Hellemmes. Phase 1 : Diagnostic et état des lieux*. Cerema Hauts-de-France. 97p.

- **Example of a Brown infrastructure**

Since 2021, the Limoges metropolitan area (20 municipalities covering more than 500 km2) has been implementing a Brown infrastructure, defined as « *all the soil cores and corridors that ensure ecological continuity for biodiversity living in the different soil horizons* ». To this end, a field survey is underway to characterise both the degree of anthropisation and the discontinuities in the soil, by setting up soil sampling campaigns and soil fauna sampling.

The method mainly targets invertebrate species that live continuously in the soil (geobiont species) and have poor dispersal capacities (absent or very reduced locomotor appendages), grouping together mesofauna (mites, springtails) and macrofauna (mainly earthworms, gastropods, isopods, myriapods). These legless and wingless organisms are directly affected by urban development, with no way of escaping, and their distribution is therefore directly conditioned by urban form.

Soil discontinuities will be defined as physical obstacles (on the ground: low walls, buildings, roadsides with pavements, etc. as well as above ground: pipes, foundations, stonework, road sub-base, etc.) and chemical obstacles (e.g. organic or mineral soil contamination) that may restrict the movement of soil fauna. Therefore, a gradient of isolation will be described according to the ability of the obstacles to be crossed. Finally, the Brown infrastructure will be mapped to serve as a planning tool to guide the location of new urban development projects.



References:

Cluzeau D., Maréchal J., Auclerc A., Joussein E., Soubrand M., Dom O., Sowa-Doyen J. (2022). *Trame brune de Limoges Métropole. Phase 1 : Approche méthodologique. Développement expérimental d'une trame brune sur le territoire d'un EPCI*. 42p.

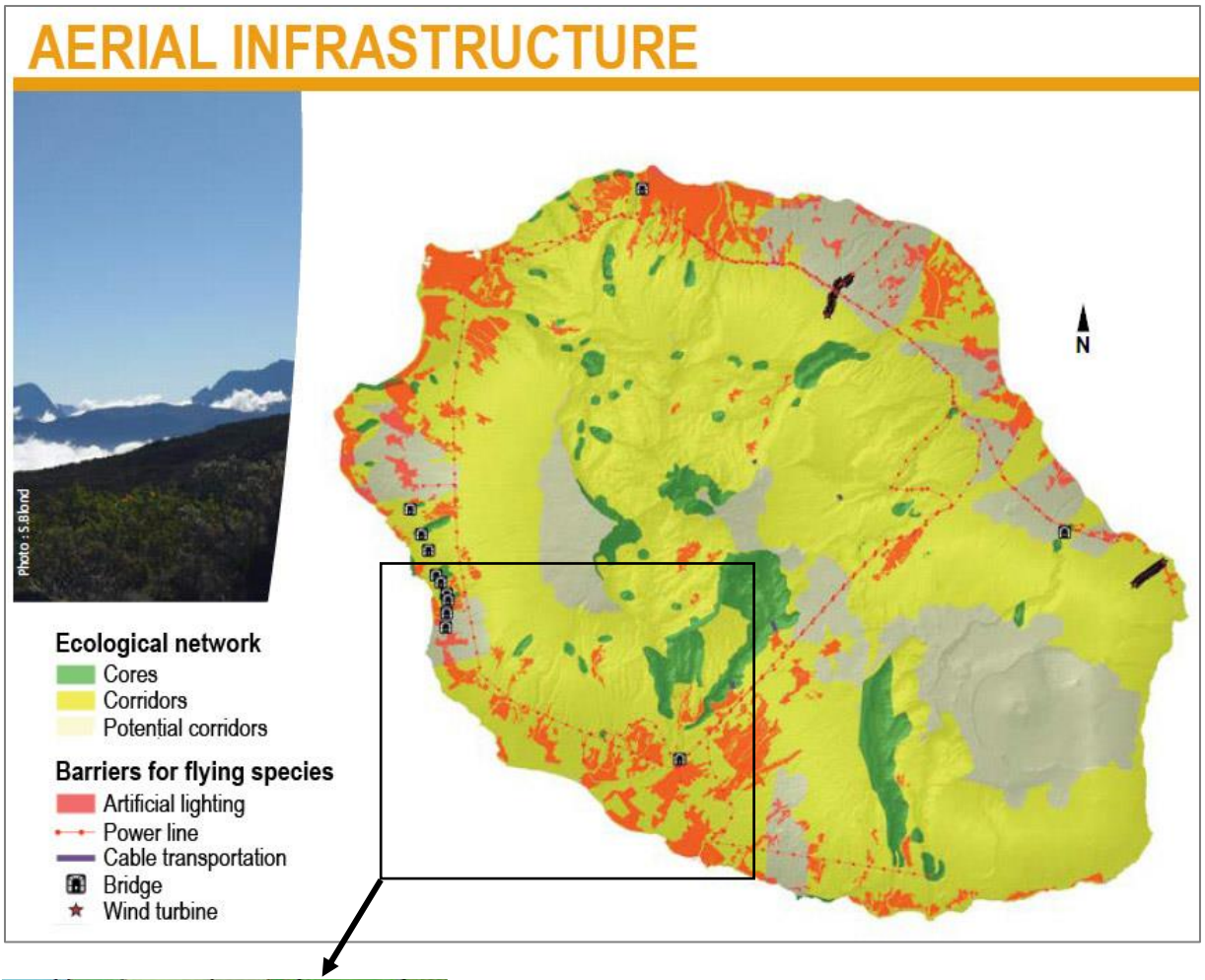
Maréchal J., Hoeffner K., Lénack E., Marie X. & Cluzeau D. (2025). Caractérisation de la trame brune urbaine. ProjetTram'BioSol. *Techniques de l'Ingénieur* GE 1077:(1-26).

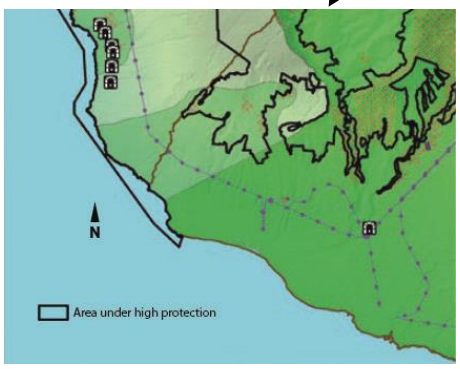
Sowa Doyen J. & Monod K. (2023). Trame brune et planification urbaine. *Biodiversité, des clés pour agir* (7):11-14.

Cléach E. & Cluzeau D. (2020). Du ver pour la Trame verte et bleue. *Espaces naturels* (72):28-29.

- **Example of Aerial Infrastructure**

On Réunion Island, the various anthropogenic aerial structures likely to conflict with the movements of flying species have been identified: cables, bridges, wind turbines, power lines, as well as light pollution. These aerial obstacles have been mapped in relation with cores and corridors of the ecological network, identified in particular for seabirds (petrels and shearwaters), highly endangered endemic species that spend part of the year in the open sea and return to nest in the heights of the island. Night-time lighting disrupts the flight of these seabirds by disorientating them, leading to strandings and high levels of indirect mortality, particularly when young birds are fledging. Civil engineering structures crossing the ravines, high-voltage power lines and, potentially, wind turbines also constitute aerial obstacles.





Aerial infrastructure identified on Réunion Island.
Top: Ecological network (cores and corridors) cross-referenced with several types of airscape barriers.
Left: Zoom on cores mapped for seabirds (Bourbon black petrels) on a piece of territory. Green colors show several levels of priority for this species.

Reference : Direction de l'environnement, de l'aménagement et du logement de la réunion (2014). *Etude préalable d'identification et de cartographie des réseaux écologiques à la Réunion*. 27p.

- **Example of a multi-dimensional infrastructure**

A project was conducted on the Regional Nature Park of Scarpe-Escaut (55 municipalities) to integrate additional life compartments - aerosphere and soil - and human drivers - artificial light at night and anthropogenic noise - through a single process of Green infrastructure.

1/ A first step was to assess and map several human pressures; i.e. aerial obstacles, light pollution and noise pollution and anthropogenic landscape (road, urban, farming activity).

Infrastructure	Pressure taken into account	Data used
Green infrastructure	road, urban, farming activity	ING's BD TOPO
Dark infrastructure	Artificial light at night	A light pollution map was produced by DarkSkyLab (https://www.darkskylab.com/; https://darkskylab.com/light-pollution-platform/). It was cross-referenced with the ecological networks of all species.
Noise-free infrastructure	Anthropogenic noise	A map of roadside noise pollution was provided by the Département du Nord. It was cross-referenced with the ecological networks of all the species.
Aerial infrastructure	Wind turbines, airports, high-voltage lines	Data on overhead obstacles was obtained from the ING's BD TOPO (high-voltage lines, airports) and from the Direction régionale de l'Environnement, de l'Aménagement et du Logement (wind turbines). They have been cross-referenced with the ecological networks of airborne species.

2/ Secondly, 18 species representative of different types of habitats (wooded, open, wet, soil) and with sufficiently heterogeneous ecological traits were selected to cover different types of life cycles, dispersal capacities and population densities. Data from several inventory databases were compiled and analyzed.

Infrastructure	Taxonomic group
Green and blue infrastructure	Amphibians Mammals Birds Fish Butterflies Reptiles Orthopterans Odonates
Dark infrastructure	
Noise-free infrastructure	
Aerial infrastructure	Flying species such as birds and bats
Underground infrastructure	Soil biodiversity (e.g. annelids, small mammals living underground)

The ability of these species to complete their life cycles and disperse through the Park was modelled. To this end, estimates of population sizes, population viability and flows of individuals were obtained using SimOïko.

Example of simulation provided for a soil species (*Talpa europaea*)

3/ The third challenge was to integrate all the results into an operational decision-making tool, so that a multitude of stakeholders can work together on the biodiversity protection and restoration measures to be implemented. Several maps were provided to deal with sensory pollutants and aerial/soil compartments.