A two-scale approach towards a multi-agent based model to predict High-speed-line (HSL) diffuse impacts on biodiversity

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Abstract

HSL disrupt plant and animal populations and cause impacts on biodiversity. Diffusion models have been proposed, using landscape mosaics or graph-based theory in order to predict cumulated impacts on species populations or barrier-effects of a linear infrastructure on ecological species connectivity. However, avoidance-reduction-repair impact measures implemented during development projects are poorly taken into account. Our approach aims to build a multi-agent based model about "indirect" impacts of a HSL, the Bretagne – Pays-de-la-Loire (BPL) project, trying to take into account mitigation measures. First step is to map potential impacts of barrier-effects or species invasion at short-term or long-term, first not taking into account ecological or human landscape discontinuities. Second step will be to calibrate the model at a certain spatial extent around former HSL projects. Final step will be to try to build the complex mechanisms of diffuse impacts from one ecosystem to another through some interspecific and environmental relationships with a multi-agent program.

Keywords: biodiversity; diffusion; impact; scale; rail; project

Les LGV perturbent les populations végétales et animales et causent des impacts sur la biodiversité. Des modèles de diffusion ont été proposés, utilisant une mosaïque paysagère ou la théorie des graphes afin de prédire les impacts cumulés sur les populations d'espèces ou les effets de coupure d'une infrastructure linéaire sur la connectivité écologique d'espèces. Cependant, les mesures d'évitement-réduction-compensation (ERC) des impacts, mises en œuvre lors des projets, sont peu prises en compte. Notre approche vise à construire un modèle multi-agent des impacts « indirects » d'une LGV, le projet Bretagne – Pays-de-la-Loire (BPL), en essayant de prendre en compte les mesures d'ERC. La première étape consiste à cartographier les potentiels effets-barrières ou d'espèces invasives à court ou long-terme, par-delà les discontinuités écologiques ou humaines du paysage. La deuxième étape consistera à calibrer l'extension spatiale du modèle autour de projets de LGV plus anciens. La dernière étape consistera à construire, avec un programme multi-agent, les mécanismes complexes de diffusion parmi les écosystèmes à travers quelques relations interspécifiques et environnementales.

Mots-clés : biodiversité ; diffusion ; impact ; échelle ; rail ; projet

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Nomenclature

APB arrêté de protection de biotope (*prefectural order for biotope protection*)
BPL bretagne – pays-de-la-loire (project)
DUP déclaration d'utilité publique (*declaration of public interest*)
ERE eiffage rail express (company)
GIS geographic information system
HSL high-speed-(railway-)line
INPN inventaire national du patrimoine naturel (*national inventory of natural heritage*)
RB réserve de biosphère (*world biosphere reserve*)
RNN réserve naturelle nationale (*national nature reserve*)
SIC site d'intérêt communautaire (*site of community importance*)
ZICO zone d'importance pour la conservation des oiseaux (*important bird area*)
ZNIEFF zone naturelle d'intérêt écologique, faunistique et floristique (*natural zone of interest for ecology, flora and fauna*)
ZPS zone de protection spéciale (*special protection area*)

1. Introduction

Long-term impacts of high-speed-lines (HSL) on biodiversity engage complex mechanisms of diffusion from the first impacts of the project on vegetal and animal populations to "indirect" impacts which may eventually fade into landscape evolutions or, on the contrary, might cumulate their effects with former impacts or impacts from other development projects. Therefore diffuse impacts of a HSL on biodiversity need complex modelling.

1.1 HSL impacts on biodiversity and mitigation measures

The notion of impact is ambiguous, as suggested by studies led on the impact relation between major transport infrastructures (such as HSL) and biodiversity (Vanpeene-Bruhier et al. 2013). HSL are both planning projects and hardware infrastructures. They product noticeable impacts on biodiversity which can be grouped as follows (Tourjansky-Cabart & Galtier 2007):

- Destruction of biota and habitat change;
- Fragmentation of the landscape (habitat alteration);
- Introduction of alien species;
- Urbanization and landscape consolidation.

In return, biodiversity represents a financial stake and a branding issue for project owners and supervisors of the HSL (Vandevelde 2013).
Impacts of a HSL on biodiversity in France are defined according to the 1976 Law on environmental impact assessment. In the process of a democratic development project leaded by a Déclaration d'utilité publique (DUP) (Public utility assessment), impact studies are designed to characterize the environment of the development project and to provide the most comprehensive information to the public. Impacts on biodiversity are not directly discussed in the impact studies but the "Natural Environments" chapter of the studies aims to prioritize environmental issues according to protected species and landscapes.
The mitigation measures thus concern the designing of the line, the bounding of pollutions and the recreation of specific environments. Since 1976 emerged the theory of avoidance-reduction-repair impact on the environment that comprises biodiversity. Avoidance and reduction are integrative part of development projects while compensation implies special issues because it generates additional environmental changes that need be examined in a comprehensive way (Regnery et al. 2013).

1.2 Indirect, cumulative and diffuse impacts

Parallel to the avoidance-reduction-compensation theory, researchers and developers questioned the existence of "indirect" ("induced") impacts as opposed to "direct" impacts of a development project (CETE 2012), though this distinction would not allow differentiating indirect impacts that occur as a result of one project from the impacts generated by neighbouring projects.
That is why a second distinction seemed necessary between any impacts on the one hand and "cumulative" impacts from different projects on the other hand. Finally, it is said that indirect impacts occur remotely through a complex path while the cumulative impacts include direct and/or indirect impacts from different projects crossing in one place, at one time (Pernon 2012).

Furthermore, actuality of biodiversity protection issues despite progress in mitigating environmental impacts around HSL, some of which are currently under construction like the Bretagne – Pays-de-la-Loire High-speed-line (BPL-HSL), led the state as well as some contractors to question the existence of "unanticipated residual impacts" by the HSL project (MEEDAT & RFF 2009). Modelling "diffuse" impacts consists in modelling indirect impacts of a HSL project while trying to take into account avoidance-reduction-compensation measures implemented all along that project.

1.3 Long-term impacts and diffusion models

The diffusion of HSL impacts on biodiversity has been questioned in different manners. The concept of diffusion has been proposed to estimate the maximum spatial extent of impacts on biodiversity in landscape mosaics. In a space as regular hexagonal grid, representing landscape mosaics, one can imagine a superposition of direct and indirect impacts. A second issue is the possibility of vegetal or animal population scattering. It is therefore needed to think about neighbouring host environments. The issue of population scattering leads to seek "potential ecological landscapes" according to various hierarchized factors (Pissard 2012). Another approach consists in modelling impacts on connectivity at a country's scale (Mancebo Quintana et al. 2010).

According to both approaches, a methodology has been developed to calculate the spatial extent of the barrier-effects of a linear transport infrastructure among species populations according to their ecological connectivity. The development of the Graphab software based on a landscape graph and the mapping of potential species habitats, according to connectivity (Girardet et al. 2013) based on ecological traits (Tournant et al. 2013) have allowed to predict the loss of probability to inventory one species with a proportional decrease of that loss to the distance from linear infrastructure.

At last, diffusion of HSL impacts on biodiversity can be considered in a chronological sequence acquisition of impacts by the landscape mosaics or as an alternative time to help guide the search for diffusion processes, from a reduced vision to a study of the pervasion mechanisms at local scale. This latter approach enables to model impacts occurring all along a HSL project such as the BPL project. First step of modelling is to map potential impacts of barrier-effect or of species invasion at short-term or long-term, first not taking into account ecological or human landscape discontinuities. The present article shows concepts and methods used for this two-scale approach towards a multi-agent based model, plus some results of this first step.

2. Concepts for modelling diffuse impacts of a HSL project

Concepts for modelling diffuse impacts of a HSL project follow a three-time approach from a reduced vision of the diffusion mechanisms to a calibrating of the impact spatial extent around former HSL projects and to a multi-agent based model of the mechanisms.

2.1 A reduced vision of the diffusion mechanisms

The complex evolution of a landscape depends on both changes in physical conditions of the biotope and in life-rhythms of the biocenosis. The calculation of physical and biological variables can explain the evolution of the landscape in terms of bifurcation (Couvet & Teyssèdre-Couvet 2010) following processes according to the percolation theory (Baudry & Burel 1999). It is so possible to imagine the diffusion of the impacts on populations in the landscape in a simplified way based on ecological knowledge acquired about ecosystem operations and pervasion of the impacts from one species to another within an ecosystem, finally causing dramatic changes (Scheffer et al. 2001). This reduced vision seems relevant thanks to the idea that there is a link between the emergence of a small-scale phenomenon and the existence, at scale, of an underlying intermittent phenomenon (Metzger et al. 2009) (Ye et al. 2012) (Jarić & Cvijanović 2012). It is reasonable to think that hotspots of biodiversity by the infrastructure or spatially remote represent together axes of high probability of diffuse impact because of their relative species richness which leads to assume that many more scattered impacts and many more captured impacts may transfer along those axes.

Impacts of infrastructures on biodiversity are generally of two types (Flavenot et al. 2013): fragmentation or connectivity. At small scale, it seems relevant to differentiate two types of HSL impacts: barrier-effects or species invasions. These barrier or invasion impacts among species do not necessarily imply a change in the ecosystem running, since several species may play similar roles (Gamfeldt et al. 2008), less their expression is assumed to be carried out at lesser or upper scale (in time and space) in a diverse or monotonous landscape (Peters et al. 2007). Indeed, ecological studies generally show that diverse landscapes resist better rapid invasions than monotonous ones, so that the former look less sensitive to species invasions impacts due to HSL while the latter seem exposed to rapid alien species invasions. Reversely, at long-term, it is assumed that in a

diverse landscape many components can connect to one another and probably produce species invasions (not regarding at first landscape ecological or human discontinuities) (Rilov et al. 2012) while noticeable barrier-effects of a HSL on biodiversity in a monotonous landscape shall fade rapidly into landscape evolutions once the infrastructure has been set-up (Ewers & Didham 2006).
Besides, reduced vision of the environment around a transport infrastructure implies to distinguish different sectors of the designed linear infrastructure according to their position in the global project. Indeed, the shape of the HSL route and the physical settlements of the infrastructure depend on global conditions (constraints of high speed, such as minimum bend radius etc.) and local stations (travellers or maintenance-stations, bifurcations etc.) (Ollivro 1994). The location of the HSL project way-points (stations or waypoints between HSL and former network) defines areas of uncertainty concerning the nature of future impacts: avoidance difficulties exerted near these way-points at different stages of the project (for the choice of location of the route, as well as building double-ways for connection) lead to assume that there is a greater number of impacts on wild populations (including protected and ordinary species).

2.2 Calibrating the model around former HSL projects

Second step of modelling consists in calibrating the two-scale (time and space) model of diffuse impacts around former HSL projects. It seems relevant to compare former existing HSL to the BPL-HSL in order to choose two study-areas similar to the BPL-HSL in terms of impact on the environment despite differences between HSL local environments, because every HSL in France are parts of the TGV network transportation project. Comparison can be achieved by calculating a ratio that expresses the number of connections at the time of route choices divided by the HSL length, which is equivalent to the project gait or structural look of the HSL. Indeed, HSL geographical designs are due to the project global constraints (high-speed-transportation) and to the project local constraints (way-point options). Therefore, considering that straight-line is a first option, sweeping design of a HSL expresses a balance between global and local constraints of the project, which implies some similarity between HSL whatever be their environments.
After two HSL of different ages are selected as they have a close ratio to the one of the BPL-HSL, the same procedure as the one used to set up potential diffusion axes and scale-types of impact around the BPL-HSL can be applied to former HSL projects. Then around each former HSL, we may choose two sites, one in a monotonous landscape and one in a diverse landscape. Finally, the combination of the landscape relative richness and the scale-type of impact (species invasion on short-term or long-term, and barrier-effect on short-term or long-term) should allow to search for specific impacts –though as it is hardly possible to get strong modelling of such complex ecological processes, main research shall concentrate on landscape change.

2.3 A multi-agent based model applied to BPL-HSL

Final step for modelling diffuse impacts around BPL-HSL is to build a few scenarios of complex diffusion from an ecosystem to another through some interspecific and environmental relationships. Once our model is calibrated around former HSL projects at two different time-scales, we may choose some invasive species and species sensitive to barrier-effects around BPL-HSL. It shall then be possible to set-up a multi-agent program, for example with the Cormas software (Bousquet et al. 1998), in order to model spatial extent of the impacts among selected species. Thus, pervasion mechanisms of the impacts among species communities do not imply continuous landscape pervasion, although we may check that landscape structures do not produce special features in the relationships between communities. Indeed, diffusion of the impacts may have different shape whether in field, hedgerow or wooded landscapes.

3. Methods for modelling diffuse impacts of a HSL on biodiversity with a reduced vision

Mapping or highlighting global axes of significant diffuse impacts can be achieved by selecting high potential of impact scattering (nearby the infrastructure) and high potential of impact capturing (remote from the infrastructure) areas along the HSL route in order to draw axes of high-potential impact diffusion, then by defining scale-types of impact according to the landscape relative richness and finally by localizing areas of uncertainty about the nature of future dominant impacts.

3.1 Global axes of diffuse impacts

High-potential of impact scattering areas can be highlighted by calculating species richness along the high-speed-railway line. Calculation of protected species richness at the municipality level in the impact studies

perimeter (700 meters large centred on the line between Cesson-Sévigné and La Milesse then 200 meters aswell between Neuville-sur-Sarthe and Connerré) (n=57) seems relevant since protected species are assumed to be mostly impacted and since municipality is the tiniest level of land management (Raymond et al. 2012). After calculation, selection of all values higher than the mean value leads to locate areas of high potential for dispersal. Census realized for the DUP (2006 for BPL-HSL) shall be available at the French regional public services, while second census realized for post-DUP studies perimeter (2011) is given by the Eiffage Rail Express (ERE) company, project supervisor.
Spatial distribution of sensitive areas for biodiversity can be obtained by combining different scanned areas of interest or protection for nature in a single layer of a geographic information system (GIS). Information is available on the website of the Inventaire National pour la Protection de la Nature (INPN) (*National inventory for nature protection*). The COMBINATION tool of the ArcGIS software can be employed for this task (Esri 2011). Combination is limited to the three French departments (Ille-et-Vilaine, Mayenne and Sarthe) included in the BPL project. So following areas are combined:

- Zone naturelle d'intérêt écologique, faunistique et floristique (ZNIEFF 1 and 2);
- Zone d'importance pour la conservation des oiseaux (ZICO);
- Site d'intérêt communautaire (SIC);
- Zone de protection spéciale (ZPS);
- Réserve de biosphère (RB);
- Réserve naturelle nationale (RNN);
- Arrêté de protection de biotope (APB).

It should be added "semi-natural" and "natural" landscapes according to the Corine Land-Cover typology (codes 311 to 412). Calculation of distances of each nearest area to the infrastructure is achieved with the tool NEAR of the ArcGIS software. Finally, selection of areas of high richness of protected species and sectors near sensitive areas leads to locate sectors representing global axes with high potential for scattering and capturing diffuse impacts on biodiversity. Cross-selection is made with the ArcGIS software selection tools.

3.2 Scale-types of diffuse impacts

Localizing scale-types of diffuse impacts on the map can be achieved by calculating richness of the landscape based on the European Corine Land-Cover typology. Land-cover typology can be applied as a proxy for ecological habitat typology (Kienast et al. 2009) in an integrative approach of biodiversity and territory (Julliard 2012). 57 sectors corresponding to the ones identified for species richness calculation are first created from two buffer zones (700m and 200m) around the digitalized map of the HSL route, with the BUFFER ZONE tool of ArcGIS. Then with the INTERSECTION tool, we intersect buffer zones with the map of French municipalities which is available on the Institut Géographique National (IGN) (National geographical institute) website.

Table 1 : Scale-types of diffuse impacts in a diverse landscape

Impact / time-scale	Short-term	Long-term
Barrier-effects	*Strong*	*Weak*
Species invasions	*Weak*	*Strong*

Table 2 : Scale-types of diffuse impacts in a monotonous landscape

Impact / time-scale	Short-term	Long-term
Barrier-effects	*Weak*	*Strong*
Species invasions	*Strong*	*Weak*

Then, selection of all values higher than the mean value or all values lower than the mean value, with ArcGIS selection tools, leads to locate two different scale-types of diffuse impact departure areas, according to the typology as described in table 1 (diverse landscape) or table 2 (monotonous landscape).

3.3 Uncertainty areas about the scale-type of diffuse impacts

Throughout the course of a HSL project, it is possible to identify areas where avoidance has been made more difficult by the constraints of the local choices for passenger-stations or way-points to the former railway network (the latter constraint is a particular trait from the TGV network). Among the 57 sectors identified for diffusion potential and scale-type of impact, sectors near way-points are assumed to present a greater number of potential impacts on different species because of avoidance difficulties, regardless to the environment. Empirical data on BPL-HSL shows that between three or four municipalities are generally concerned with those way-points. Selection of the corresponding sectors leads to locate areas of uncertainty about the nature of future dominant impacts (of barrier-effect or of species invasion).

4. Results for modelling diffuse impacts with a reduced vision

Mapping global axes of diffuse impacts then their scale-type areas and the areas of uncertainty about their scale-type finally shows where significant impacts (and what sort of potential impact) may be attributed to the HSL despite mitigation measures or gradual fading of the impacts over time.

4.1 High potential areas of scattering and capturing diffuse impacts (global axes of diffusion)

The number of protected species by sector is slightly variable. We sought some landscape factors that would explain this variability (area of sector, proportion of land-cover areas in each sector, land-cover richness, density of the hedgerow network, seniority of landscape consolidation) but no factor showed real significance (correlation coefficients no better than 0.35). The distance to the closest sensitive environments varies between 0 to 4431 meters. A dozen sectors, located within 400m of a sensitive environment, which is almost a quarter of the line, partly corresponds to the “conflict spots” identified in the BPL impact studies.
The selection of protected species richness values above mean value (7.7 species) and the selection of distance to sensitive areas values below mean value (821m) give 32 sectors, which are about 56% of the total sectors. The selection rate thus means that about half-part of the line generates significant impacts on the HSL environment, which is satisfying in the absence of any other criteria. Selected sectors are grouped in four continuous sets, but no sector appears west of the Torcé sector, which leaves six sectors quite out of range. The boundaries of the selected sets of sectors cover no noticeable ecological or human discontinuities.
At last, it is to be mentioned that all inventoried species are protected under various statuses. In two sectors (Changé and Coulans-sur-Gée), there is a significant difference between the number of protected species and the equivalent value weighted by the protection status (simple value when regional status, multiplied by two when national status and multiplied by three when European or international status). These gaps are due to the presence of a majority of internationally protected species: six to eleven species in Changé (comprising European otter and beaver which are uncommon in the project perimeter) and nine species upon eleven in Coulans-sur-Gée (including seven species of bats).

4.2 Scale-types of diffuse impacts and sectors of uncertainty map

We combined on a single map the three selections of barrier-then-invasion impact dominated sectors, invasion-then-barrier impact dominated sectors and sectors of uncertainty about the type of impact, among all sectors corresponding to global axes of diffuse impacts.

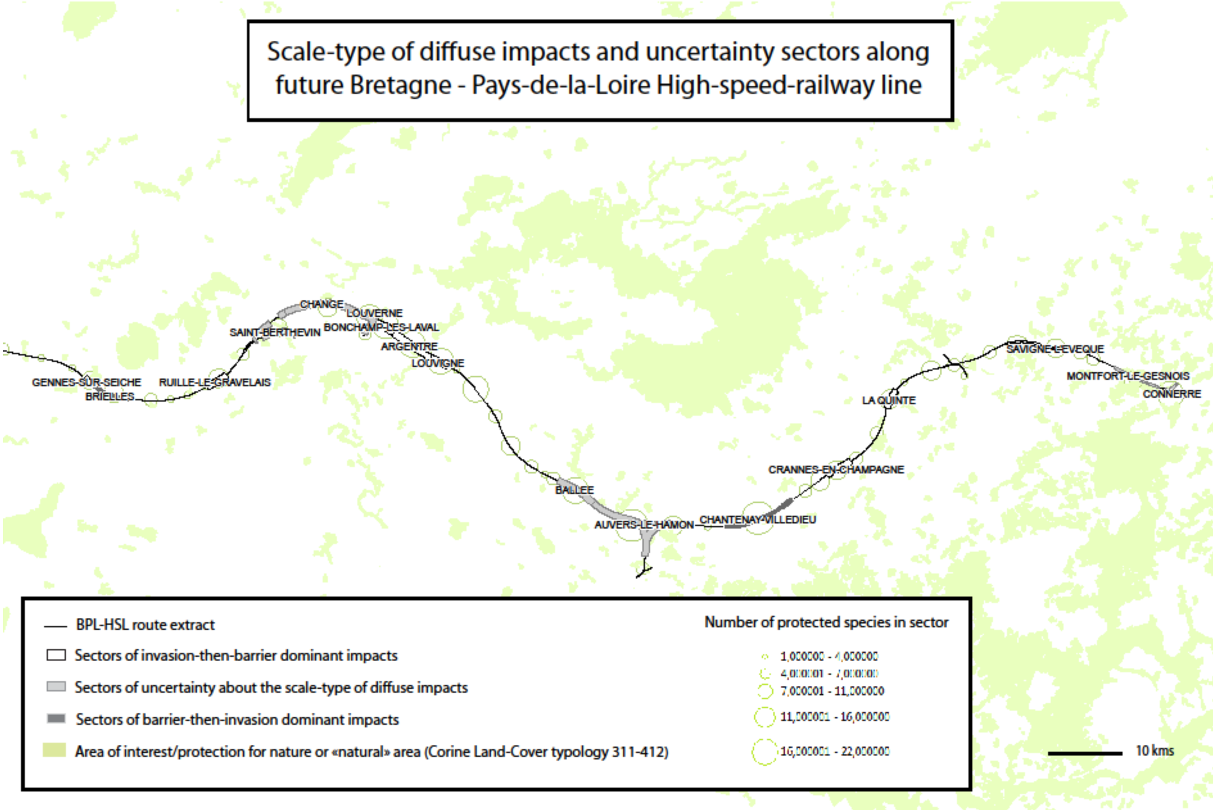

Fig. 1: Map of scale-type diffuse impacts and of uncertainty areas

Among the 32 sectors that present high-potential of diffuse impact, which are of a particular scale-type and/or uncertainty about the nature of future dominant impacts, 17 sectors present either a particular scale-type or uncertainty about the future impacts. Eight sectors correspond to invasion-then-barrier dominant diffuse impact areas, located in relative monotonous landscapes (maximum three different land-cover types in sector). Six sectors correspond to areas of uncertainty, covering four of the eight way-point areas of the BPL-HSL. And two sectors correspond to barrier-then-invasion dominant diffuse impact areas, located in diverse landscapes (minimum four land-cover types). They are almost regularly distributed along the line. The low number of diverse landscape sectors is due to the relative (estimated) abundance of monotonous landscapes. Landscape relative richness in the two diverse landscapes, which are barrier-then-invasion dominant impact sectors, is partly due to the presence of different woodlands.

5. Discussion of results and following methods

We mainly discuss our first results about mapping global axes of impact diffusion, scale-type diffuse impacts and uncertainty areas. Following methods for modelling diffuse impacts are briefly treated.

5.1 Complex mechanisms of diffusion in a simplified way

First step of modelling diffuse impacts around a HSL project like the BPL-HSL does not yet lead to confirm or infirm hypotheses about the scale-types of diffuse impacts around such terrestrial transport linear infrastructures, mainly because such hypotheses need to be confirmed by searching for impacts around former HSL projects that may have generated real diffuse impacts since they have settled in their own environments several years ago. Our two-scale approach is rather supported by ecological evidence that impacts of a major transport infrastructure on vegetal and animal populations may pervade in the landscape through complex processes comprising both the species community (or ecosystem) level and the physical (or habitat) level. We assume that diverse or monotonous landscapes imply different scales (in time and space) of diffusion, so we deliberately did not try to define at first what size or spatial extent shall take such pervasion processes.

5.2 Spatial scales firstly without spatial extent

Our first spatial approach is but geometrical, though it is quite logical according to the complexity of diffusion and to the ecological experience. Selecting simple high-potential areas of impact scattering (because of species richness) by the concrete infrastructure and selecting high-potential areas of impact capturing (for same reason) at distance from the infrastructure highlight what areas shall be impacted in any way by a HSL project. There is no doubt that diffuse impacts might take place in those areas despite the numerous mitigation measures taken all through the BPL project course. Besides, modelling uncertainty areas following assumption of a greater number of impacts in the proximity of way-points leads not only to highlight emblematic parts of an HSL territorialized project but also opens to a comparison between latest HSL projects such as the BPL-HSL and former HSL projects that have different environments while sharing similar structures.

5.3 First step of modelling and diffusion mechanisms modelling

We shall select former existing HSL by calculating the ratio of the number of way-points at the time of designing the HSL over the route length. Around these “older” HSL, we will be sure to find real impacts. It is to be reminded that the BPL-HSL is yet not built, although a large part of the alleged impacts already occurred with clearings and building way-points in 2012 or will soon occur with excavations this year. Most professionals and researchers have highlighted the difficulty of evaluating early or late impacts such as landscape consolidation or cumulated impacts form other projects. Besides, impacts might be unnoticeable on the long-term.
We shall then concentrate on landscape analysis. Indeed, models based on ecological connectivity show that the gradient of barrier-effect extends to five or fifteen kilometres right of the line depending on the species (Clauzel et al. 2013). And phenology knowledge suggests that impacts among species populations pervade at a mean rate of one year time. Though modelling such complexity is but possible at that time. Additional search for barrier-effects or species invasions may also help showing evidence of diffuse impacts.
Furthermore, as information about biodiversity in former HSL projects’ perimeters is but homogenized, we may concentrate on protected or identified biodiversity areas and select the closet similar areas remote from the aged HSL. Nevertheless, archives of some French departments (which generally collect regional and prefectural documents) indicate that HSL public utility assessments (that contain impact studies) are searchable.

6. Conclusion

Our two-scale approach towards a multi-agent based model of HSL diffuse impacts on biodiversity aims to model impacts of a High-speed-railway line project, such as the Bretagne – Pays-de-la-Loire High-speed line (BPL-HSL), on surrounding biodiversity among indirect and/or cumulated impacts despite mitigation measures. Methodological proposals have already produced results on the barrier-effects of major terrestrial transportation infrastructures like HSL on connectivity at the species level. In order to take into account the avoidance-reduction-repair impact measures which are implemented during development projects and any other action, we propose to model the complex diffusion mechanisms of impacts in a simplified way at first, without regarding at first ecological or human discontinuities of the landscape. First step is to map global axes of impact diffusion around the HSL (considering high-potential of impact scattering areas by the infrastructure and high-potential impact capturing areas remote), plus barrier-effect or species invasion scale-types of diffuse impact at short-term or long-term (depending on relative richness of the land-cover) and uncertainty areas about the nature of future diffuse impacts (by HSL stations and way-points to former railway network as decided when designing the line and approved by public utility assessment). Second step will be to calibrate the model at a certain spatial extent around former HSL projects (after choosing former HSL projects quite similar to the BPL-HSL). Final step will be to try to build the complex mechanisms of diffuse impacts from one ecosystem to another through some interspecific and environmental relationships with a multi-agent program.

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