METHOD FOR EVALUATING EFFECTS OF ROAD PROJECTS ON ECOSYSTEM FOR DEVELOPMENT OF PLANNING TOOL

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ABSTRACT

Some major modifications in natural environments are related to road construction, use and management. Despite the legal protection, natural areas continue to be degraded. In France, environmental assessments take place relatively late in the decision-making process for road projects and their contents are based on qualitative data which do not take into account the concept of ecosystem. This can be explained by the lack of synecological assessment tool, by the absence of quantitative ecosystem indicators available at an early stage projects. Similarly to techno-economic software, this tool could become a referential to plan land use... Exhaustive understanding of sources of disturbance, modifications of local conditions, and effects induced by road projects on natural environment are a necessary first step to develop relevant ecosystem indicators. A synecological evaluation method of projects is proposed in this article, applied to four types of natural environments : forests; wetlands and banks; meadows and lawns; cultures, fields and hedgerows. The major dysfunctions are identified and provide ways to search relevant quantitative indicators about the key ecological functions that maybe impacted. An example is developed regarding the construction phase.

1. INTRODUCTION

Almost all terrestrial ecosystems have been, and continue to be significantly disrupted because of human activities [1]. Some major modifications are related to road construction, to their use and maintenance. Road infrastructure affects structure, dynamics of ecosystem functioning, and has direct effects on its components, including fauna and flora species. The increasing attention of scientists to ecological effects of roads has led to the emergence of a science: "road ecology" [2].
In France, a road construction project (design, implementation) is framed by a complex legal process involving environmental assessments (impact assessment, Natura 2000 incidences and water law documents). These environmental assessments have allow progress, but they have failed to reduce the natural environment degradation. Indeed, they essentially study environmental aspect in a human sense; firstly impacts on air quality and human health; then noise, vibration and finally landscape. The part regarding natural environment is only based on legal instruments of protection (Natura 2000, biotope judgement,...), mainly from the presence of rare species.
In 2004, natural areas subjected to regulatory protections accounted for 11.5% of world surface [3]. These areas appear as isolated islands in a "matrix" composed of other ecosystems, sheltering many common species [4]. A growing number of researches emphasises the essential role of the latter in ecosystems functioning [5]. Variations in abundance of common species can lead to acute consequences [6]. Thus, these actual legal protections are not necessarily indicative of sites ecological interest. Besides, evaluations are based on specialised inventories of flora and fauna, and do not take into account the complexity of ecological systems. They are inherently incomplete.

Infrastructure planning and biodiversity conservation must be thought in consistency, and at an early stage of the decision making process, in order to provide sound debatable alternatives. Thinks to that type of protection, the conservation of biodiversity is not simply limited to threatened populations, but allows considering the whole system, that means, all the life organisms exploiting natural habitats. Reasons for inadequacy of evaluation are among others, lack of technical skills, difficult accessibility to ecosystem concept, and the absence of practical tools to support decision making.

Techno-economic evaluation software, such as HDM-4 [7], are available at an international level, to help decide on the opportunity of road projects. Until now, there is no comparable tool for all environmental issues. Only eco-comparators based on life cycle analysis, such as Eco-COmparator Roads Construction Maintenance software (ECORCE), are developed [8], but without including impacts on natural environment.

Ecosystems are complex. The exhaustive understanding of road project effects on natural environments is an unavoidable step to develop such an assessment tool. It must be based on relevant quantitative indicators regarding by key ecological functions. However, nowadays there's no approach considering the whole effects on all the ecosystem targets, through the different phases of road projects.

This paper presents a method for the assessment of major ecosystem dysfunction induced by major road projects in order to identify quantitative indicators necessary for the tool. It is applied to four types of common natural environment. Results are used to identify tracks for the development of ecological sensitivity indicators. One of these tracks is investigating up to an example indicator.

2. METHOD

2.1. Principle of the assessment tool

For any road project between two locations *X* and *Y*, different types of natural environments, showing different sensibilities to the disturbances generated by the road project, are likely to be crossed (eg, A, B, C and D environments showed on Figure 1).

In order to quantitatively assess the effects of a given project, the study area must be divided into elementary cells (eg hexagon meshing on Figure 1). The sensibility of the different natural environment types depends on their vulnerability and their scarcity [9]. The total environmental cost (TEC) of a given project is provided by the formula :

$$TEC = \sum_{i=1}^{n} c_i Se_i$$

Where Se_i is the sensibility indicator of environment *i,* and c_i is the number of cells of environment *i* crossed by the line project (estimated length within environment *i* by means of Geographic Information System).

The *TEC* of different variants of road horizontal alignment, more or less respectful of the most sensible environments (Se_i), and more or less long (c_i), can be compared (solid, dashed and dotted lines on Figure 1).

The *TEC* is not a monetization. It is defined as the estimated value of sensibility of different ecosystem types functioning, based on comparison between before and after project situations.

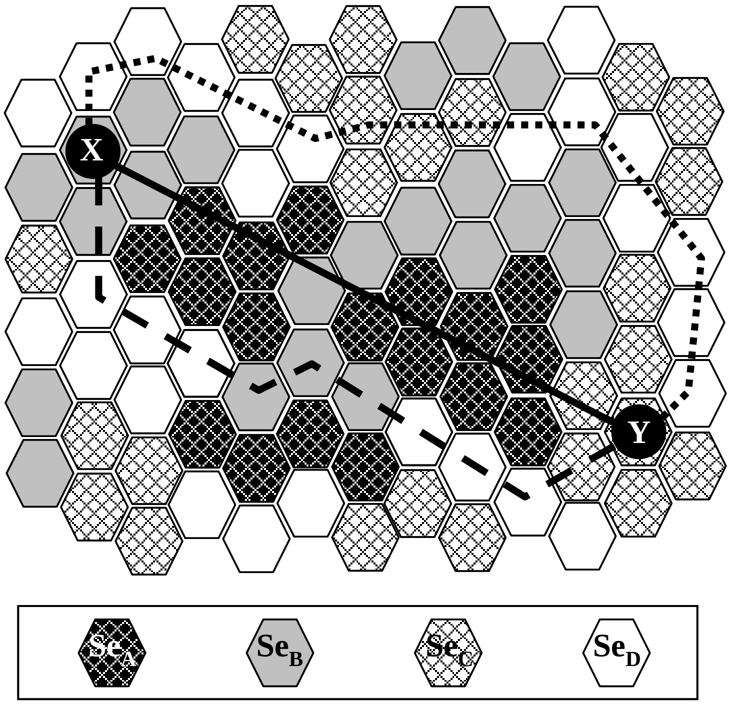


Figure 1. Horizontal alignments variants between X and Y in the meshed study area.

2.2. Pressure-State-Response approach

The synecological evaluation method developed here is a first step toward the creation of a tool designed to choose a road plotting at the lowest ecological cost, and this at an upstream stage of road projects.

The approach is enrolled in the *PER* model [10] in which indicators are divided into three categories: pressure (P) - state (E) - response (R) (Figure 2). The activities during the different phases, which are sources of disturbance, create pressures on local environment whose state is modified. As a response, the actors (producers, financials, managers) intervene on disturbances by changing the pressures on environment.

Sensibility indicators must be able to illustrate the major ecosystem dysfunctions. They will allow searching relevant quantified values to assess these dysfunctions. Response indicators will allow determining the most relevant integration measure (Figure 2), notably preventive ones acting directly upon sources of disturbance. These actions types are the most relevant ones because it is much more difficult to restore natural environment than to continue to conserve it.

The observed effects on natural environments are usually complex and result from a mix of disturbances. At each step of road life, this implies to identify in an exhaustive way the different types of disturbances sources which produce specific effects on ecosystem functioning.

For each natural environment, a confrontation is carried out between the phases of typical road project and, the characteristics of a given natural environment, in order to analyze the potential effect of road upon the environment. It permits to analyze the potential effects of disturbance sources on each ecosystem target: microclimate, surface water, groundwater, soil, flora, soil fauna and terrestrial fauna (Figure 2).

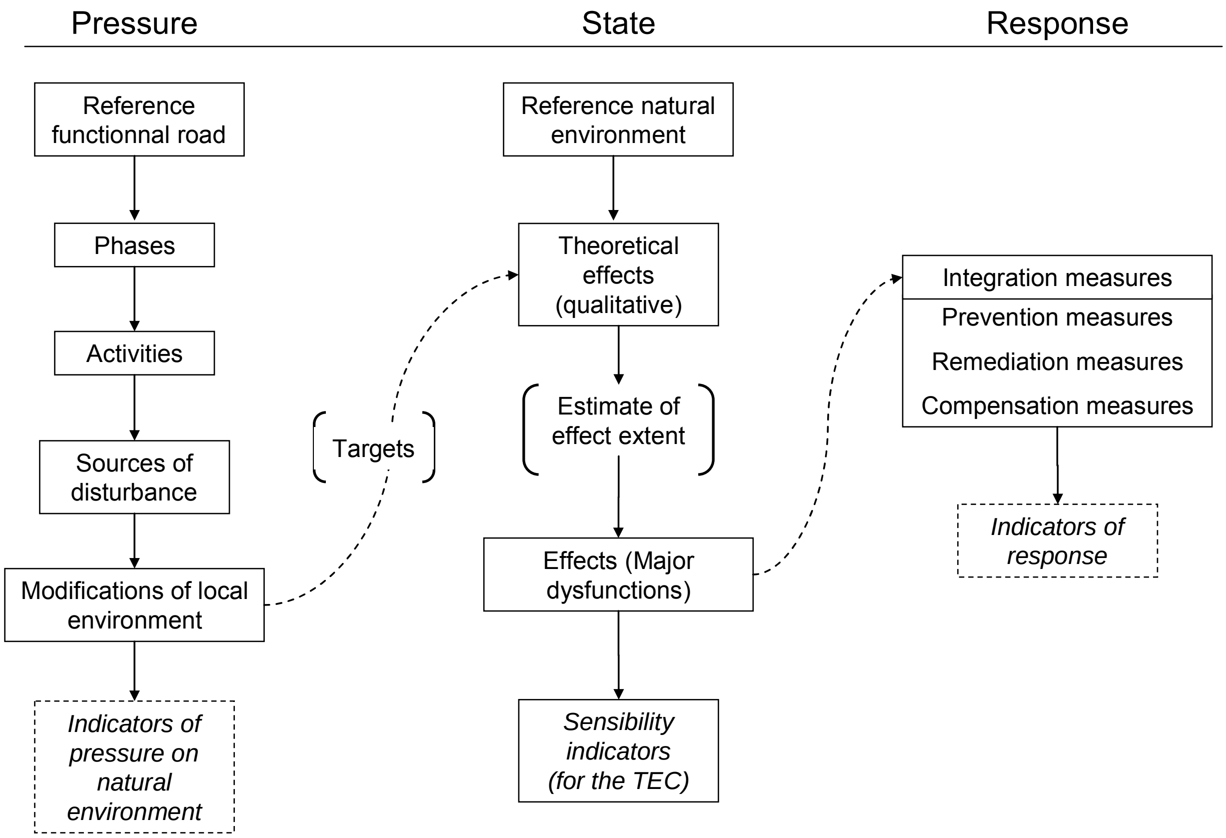


Figure 2. Method for analyzing the effects of road and to searching indicators.

Natural environment reference is defined by a good ecological state with maximum vital attributes, a large area, a hilly topography and a landscape unaffected by human disturbance other than those produced by road.

The road reference is defined by the minimal operations necessary to obtain a functional road, excluding compensation arrangements usually integrated to the road infrastructure (revegetation, fencing, fauna passages,...). This gives the opportunity to completely rethink integration measures and gives the opportunity for innovation.

Then, effect dimensions are assessed with four variables *Dt, Ds, Dv, Di* :

- *Dt* temporal dimension, related to the evolution of plant succession after a disturbance until the climax. Climax refers to the time necessary for vegetation to come back to a stable natural state, without human intervention: for example, 5 years from a bare soil until a hayfield, 20 years for a moor, and 50 years for a forest [11].
- *Ds* spatial dimension, effect propagation on an elliptic surface,
- *Dv* degree of likelihood or degree of occurrence, a probability that the effect happen,
- *Di* intensity level of effect, e.g. sound level undergone,

The mix of variables *Dt, Ds, Dv, Di* is normalized by their maximum values which result in an index representing the extent (An) of each effect. The extent of the ecosystem dysfunctions ranges between 0 and 1. It allows ranking major effects and then determining "indicators of sensibility".

2.3. Studied natural environments

Terrestrial natural environments are defined by means of typology unit of physiognomic relationship of vegetation grouping, and by means of landscape elements easy to identify [12].

On global climate scale, Metropolitan France is divided into 3 main climate zones: Mediterranean climate, oceanic climate and mountain climate. At national scale, France is subdivided into finer climatic zones corresponding to the bio-geographical areas defined in the Natura 2000 database. This multitude of climate, associated with landform and soil type diversity, is result in a great botanical richness and thus a great part of the habitats existing throughout the World: from lichens and mosses of arctic and alpine types, to semi-tropical species, such as olive and orange trees...

The typology terrestrial environment chosen for this study is a compilation of data from Corine Biotopes [13] and Switzerland natural environment handbook [12]. Among these natural environments, four were analyzed in this study: 1) Forests 2) banks and wetlands, 3) meadows and lawns and 4) cultures, fields and hedgerows. Forests include flooding forests, broad-leaved trees forests, conifer forests and peat bogs. Banks and wetlands gather banks vegetation, low swamps, wetlands, peat bogs. Meadows and lawns are formed by natural vegetation and artificial dry meadows, wet meadows and wildlands of grass family. Cultures, fields and hedgerows are the association of all types of cultures from woody plants, herbaceous plants to hedges surrounding these agro-ecosystems.

3. RESULTS AND DISCUSSION

3.1. Modification inventory

Each road life phase, construction (P1), exploitation (P2) and maintenance (P3) is described by a series of actions (named activities), allowing its implementation (A1 to A8). Each activity can be a source of disturbance (S1 to S18), of modification of local environmental conditions (M1 to M93) (Table I to III).

3.1.1. Construction phase

The construction phase is characterized by a sequence of four activities that generate 12 sources of disturbance of local environmental conditions. This induces a series of 65 potential modifications of local environment. Noise and vibration production, dust and particle emissions, oil leak risk, and vehicle displacement, are typical modifications of field preparation (A1). It is the same for the next activity, to which luminous pollution of life areas and technical areas are added. Earthworks especially introduce disturbances related to topographic modifications and to potential soil treatment. The pavement implementation induces potential modifications associated with emissions of hydrocarbon substances (liquids and gases) due to materials and machines. Finally, the new road induces permeability modification, absorption of solar radiations and land use, due to the change of in land use.

Table I. Activities, sources of disturbance and modifications in construction phase.

Activities	Sources	Modifications of local environment
A1 Field preparation	S1 Water table lowering (pumping)	M1 Soil drying M2 Noise and vibrations (drilling and pumping machines) M3 Hydrocarbon leak (machines) M4 Emission of fine metal particles (mainly heavy metal by machine fumes) M5 Translation of machines (low speed movements)
	S2 Surface water discharge (drainage)	M6 Soil drying M7 Noise and vibrations (digger) M8 Hydrocarbon leak (digger) M9 Emission of dust and fine metal particles (mainly heavy metal digger fumes) M10 Translation of diggers (low speed movements)
	S3 Clearing of tree layer and shrub layer	M11 Linear destruction of trees and shrubs M12 Emission of wood shavings M13 Noise and vibrations (saws) M14 Emission of dust (clearing machines) M15 Hydrocarbon leak (clearing machines) M16 Emission of fine metal particles (clearing machine fumes) M17 Translation of machines (low speed movements)
	S4 Clearing of topsoil	M18 Baring of the mineral soil M19 Noise and vibrations (clearing machines) M20 Emission of dust (machines) M21 Hydrocarbon leak (machines) M22 Emission of fine metal particles (machine fumes) M23 Translation of machines (low speed movements)
A2 Setting of life areas and technical areas on about 10 000m^2 (after A1)	S5 Gravelling, concreting, liner implementation	M24 Artificial covering of the soil M25 Noise and vibrations (machines for the setting of areas) M26 Emission of dust (machines for the setting of areas) M27 Hydrocarbon leak (machines) M28 Emission of fine metal particles (machine fumes) M29 Translation of machines (medium speed movements)
	S6 Working of life and technical areas	M30 Artificial lighting (starlight at night) M31 Wastewater sewage (grey and black waters) M32 Production of non dangerous solid wastes (households) M33 Leak of noxious wastes: hydrocarbons, solvents, binders
A3 Earthworks	S7 Cuts	M34 Lowering of contour lines M35 Noise and vibrations (extraction machines) M36 Emission of dust (extraction machines) M37 Hydrocarbon leak (extraction machines) M38 Emission of fine metal particles (extraction machine fumes) M39 Noise and vibration (use of explosives) M40 Emission of dust (use of explosives) M41 Emission of mineral blocks (use of explosive)
	S8 Fills	M42 Raising of contour lines M43 Noise and vibrations (fill machines) M44 Emission of dust (fill machines) M45 Hydrocarbon leak (fill machines) M46 Emission of fine metal particles (fill machine fumes)
	S9 Displacements of machines between working areas	M47 Noise and vibrations M48 Emission of dust M49 Hydrocarbon leak M50 Emission of fine metal particles (fumes) M51 Translation of machines (medium speed movements)
	S10 Soil treatments	M52 Emission of reagent fine particles (basic, oxidizing, binding)

Activities	Sources	Modifications of local environment
	(lime and cement)	M53 Noise and vibrations (soil treatment machines) M54 Emission of dust M55 Hydrocarbon leak M56 Emission of fine metal particles (fumes of soil treatment machines) M57 Translation of machines (medium speed movements)
A4 Pavement implementation	S11 Implementation of pavement layers	M58 Release of bitumen M59 Emission of volatile hydrocarbons M60 Noise and vibrations (pavement machines) M61 Hydrocarbon leak (pavement machines) M62 Emission of fine metal particles through fumes (pavement machines)
	S12 Implemented pavement	M63 Change of the superficial permeability M64 Absorption of solar radiations by the dark surface M65 New occupation of soil surface

3.1.2. Exploitation phase

This phase is characterized by two sources of disturbance (S13 and S14) and nine potential modifications of local environmental conditions. This includes the pour of various substances from vehicles, the fire risk, and noise production, vibrations, light pollution related to translation of high speed vehicles.

Table II. Activities, sources of disturbance and modifications in exploitation phase.

Activities	Sources	Modifications of local environment
A5 Road use	S13 Road traffic	M66 Translation of vehicles (high speed movements) M67 Luminous vehicles at night M68 Noise and vibrations M69 Emission of organic pollutants (hydrocarbon leak and tire wear) (grease and diesel engines) M70 Emission of fine metal particles (fumes) M71 Solid wastes (households) left by users
	S14 Accidents	M72 Pour of hazardous wastes (freight) M73 Pour of hydrocarbon (freight and tanks) M74 Accidental fire

3.1.3. Maintenance phase

This phase is characterized by three activities (A6-A8), four sources of disturbance and 19 potential modifications of local conditions. This includes especially the reduction of vegetation by mechanical maintenance or chemical maintenance and nuisances due to these operations occur. The winter maintenance induces modifications related to snow removal, the use of de-icing or abrasive substances, and disturbance related to machine translation (medium speed movements). Modifications related to maintenance of the wearing course are of the same nature as those due to road implementation (A4).

Table III. Activities, sources of disturbance and modifications in maintenance phase.

Activities	Sources	Modifications of local environment
A6 Maintenance of TTI verges	S15 Mechanical maintenance	M75 Reduction of plants' size M76 Noise (cutting and shearing machines) M77 Translation of machines (low speed movements)
	S16 Chemical maintenance	M78 Emission of herbicides M79 Emission of growth inhibitors M80 Translation of treatment machines (low speed movements)
A7 Road winter maintenance	S17 Snow clearance and de-icing of the road	M81 Supply with salt (reference NaCl) M82 Supply with sand M83 Removal of the snow cover M84 Noise and vibrations of the snowplow M85 Hydrocarbon leak (snowplow) M86 Emission of fine metal particles (snowplow fumes) M87 Translation of snowplow (medium speed movements)
A8 Road structural maintenance	S18 Maintenance of the road wearing course	M88 Release of bitumen from the new pavement M89 Release of volatile hydrocarbons from the new pavement M90 Noise and vibrations M91 Hydrocarbon leak (milling machines) (grease and diesel engine) M92 Emission of metal particles (milling machines) M93 Artificial lighting (starlight for night works)

3.2. Inventory of effects

For each natural environment, road effects are deductively analyzed from ecosystem functioning, based on published knowledge available in basic and applied ecology.

3.2.1. Effects distribution according to natural environment

The distribution of *An* values relative occurrence (with a step of 0.1) shows the completeness of the method (Figure 3). The method takes into account the whole panel of road effects on natural environments down to the smallest ones. These small effects can pile up at long time and can lead to consequences on ecosystems : for example, at a certain critical threshold, oils can not be self-purified by natural environment. It is important to consider these small effects in the indicator search.

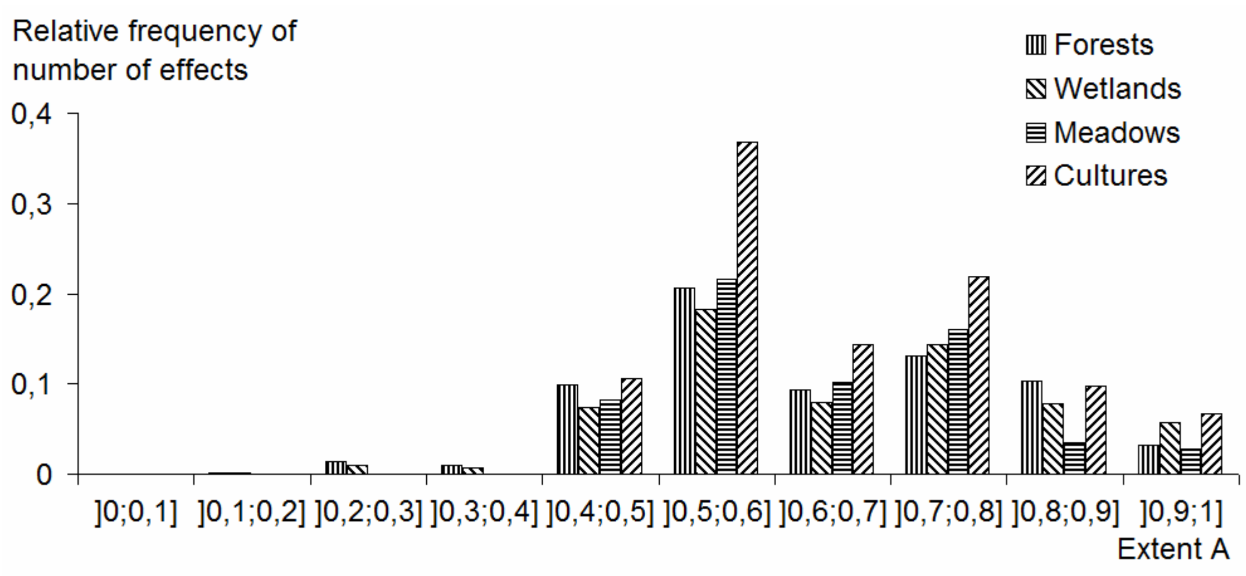


Figure 3. Relative frequency of effect numbers according to *An* class and natural environment.

3.2.2. Similarity of sensibility between natural environment

On the Principal Component Analysis graph (fig. 4a), variables (natural environments) are projected onto a factorial plane to the edge of the unit radius circle : they are reliably represented. The circle represents the correlation between *An* values of natural environments. The F1 axis is represented by the variable Forests (27% of contribution) and the F2 axis by Meadows (35% of contribution). The variables Cultures and Meadows constitute a correlation group (ρ = 0.72), Wetlands and Forests another group (ρ = 0.75) confirmed by hierarchy ascending classification (Fig. 4b).

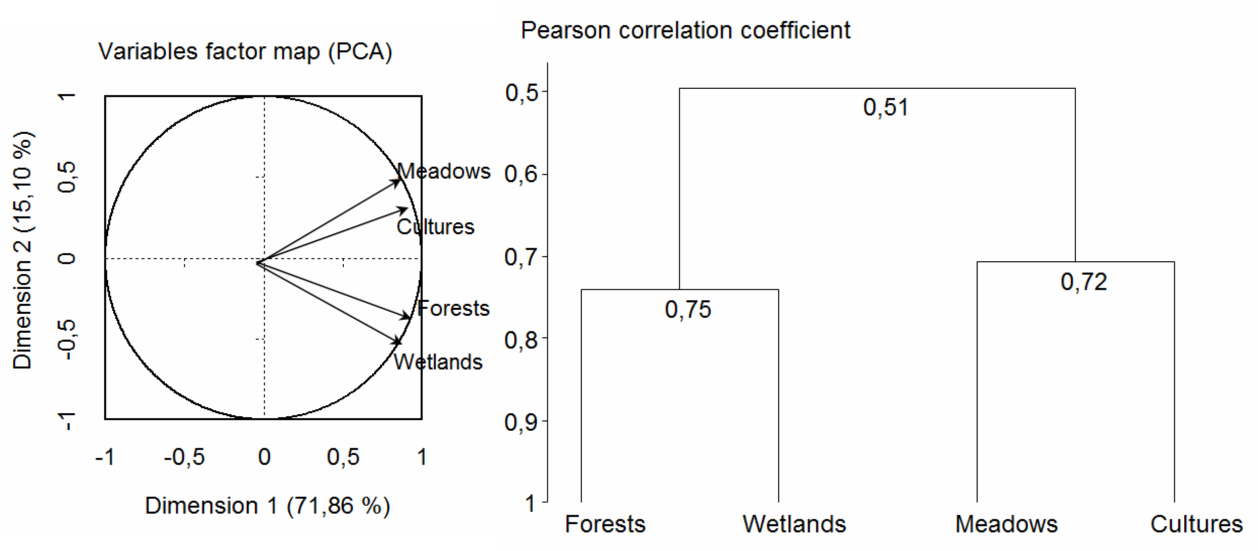


Figure 4. Projection variables "natural environments" on PCA correlation circle (Fig. 4a) and hierarchy ascending classification (fig. 4b).

3.2.3. Effects distribution according to phases

Radar graphs represent *An* values distribution per phases in chronological order of the road projects progress. The construction phase corresponds to white area, the exploitation phase to light gray area and the maintenance to dark gray area (Figure 5).

From a general point of view, forests and wetlands are distinguished by a greater number of dysfunctions shared between the three road life phases (Forest 8%, 5.9% Wetlands, Meadows 3.4%, Cultures 3.9%). The visualization of effects distribution according to phases confirms the similarity groups of dysfunctions *Forests-Wetlands* and *Meadows-Cultures*. Radar graphs allow a detail analysis of these similarity groups (Figure 5).

The *An* values of sources of disturbance *S1 Water table lowering* and *S2 Surface water discharge* do not act regarding *Meadows* and *Cultures*, which can be explicated by the natural environment typology choice (Figure 5).

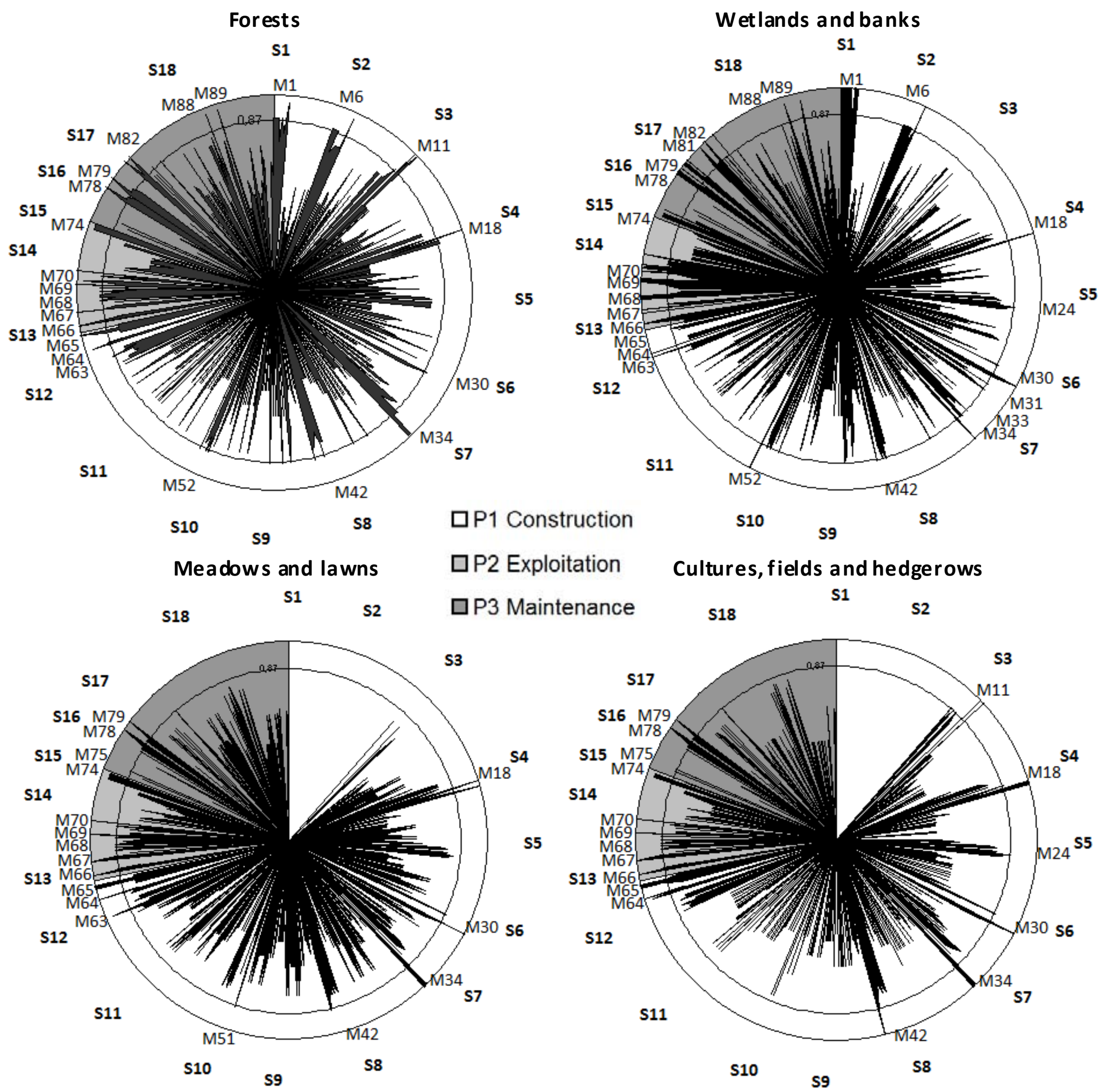


Figure 5. Radar graphs showing *An* values (817 effects) for each natural environment.

3.3. Majors effects identification

The ecosystem major dysfunctions threshold is defined by *An* ≥ 0.87 values. This threshold is determined in order to extract about 10% of the total effects and also in order to avoid low values of each variables *Dt, Dv, Ds, Di*.

The *An* ≥ 0.87 are associated to three phases, to sources of road disturbances (S_i) and to modifications of environmental conditions (M_i) (Figure 6).

3.3.1. Construction phase

During field preparation, among major dysfunctions, *Water table lowering* (Source of disturbance S1) and *Surface water discharge* (S2) can affect most ecosystem targets of Wetlands (thick peaks). If ecosystem is totally affected this can lead to the total destruction of the natural environment. Regarding Forests, the conclusion is similar. *Clearing of tree layer and shrub layer* (S3) affects specially Cultures and Forests. *Clearing of topsoil* (S4) affects the four natural environments. *The technical soil of life areas* and *technical areas* (S5 M24) affects Wetlands and Cultures by destroying biological connections. *Activities of technical areas* (S6) produce pollution from wastewater sewage, and induce risk of *leakage of noxious substances* (M33) affecting mainly wetlands. During earthworks (cuts S7 and fills S8), dysfunctions appear for the four natural environments. *The displacement of machines between working areas* (S9), as a vector of exogenous vegetal species, modifies Wetlands and Meadows. *Soil treatment with lime or cement* (S10) affects wetlands and forests. *The infrastructures itself* (S12) *modifies temperature* (M64) and land use regarding the four natural environments. For *S12*, forests and wetlands both differentiate by another modification : *Change of the superficial permeability* (M63).

3.3.2. *Exploitation phase*

Road traffic sources of disturbance (S13 and S14) affect the four natural environments, without distinction of specific modifications among them.

3.3.3. *Maintenance phase*

Chemical maintenance by means of herbicides and growth inhibitors (S16) disturbs all natural environments. The mechanical maintenance by means of cut (S15) affects Meadows and Cultures. *Winter maintenance* (S17) clearly affects Forests and Wetlands. The *new bituminous concrete* (S18) is a *source of hydrocarbons* (M88-89) that may propagate across the food chain of wetland and forest ecosystems.

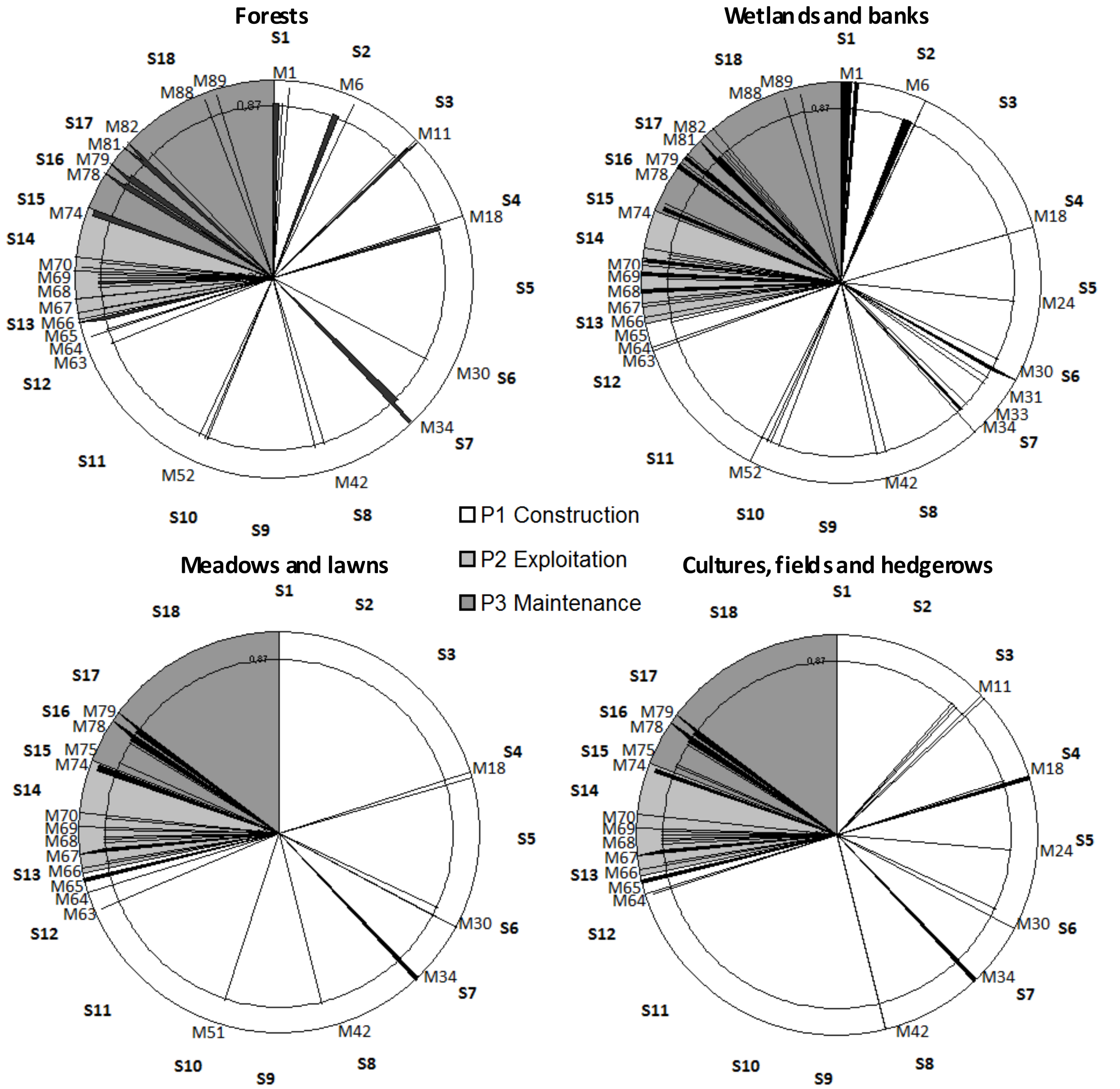


Figure 6. Radar graphs showing *An* ≥ 0.87 values effects for each natural environment.

3.4. Potential targets

Table IV presents, for each type of target (microclimate – Mc ; surface waters – E> ; groundwater E< ; soil – Sol ; flora – Flo ; soil fauna – Fs; terrestrial fauna – Ft) and for each of the four studied environments, the number of identified effects which extent (An) is above 0.87. The left hand side column indicates which modification (M) is at the origin of these effects. These modifications are ranked following the progress of road projects with their three phases (construction, exploitation, maintenance).

Table IV. Identification of major effects on targets according to the environment.

Modifications	Forests							Wetlands							Meadows							Cultures						
	Mc	E>	E<	Sol	Flo	Fs	Ft	Mc	E>	E<	Sol	Flo	Fs	Ft	Mc	E>	E<	Sol	Flo	Fs	Ft	Mc	E>	E<	Sol	Flo	Fs	Ft
M1	2	1	1	1	2		1	2	1	1	2	2		3														
M6	2	1	1	1			1	2	1	1	2	2		3														
M11					1		3															1	1		1			2
M18						1	2							2						1	1						1	2
M24														1														1
M30							2	1						2	1						2	1						2
M31												1		1														
M33														1														
M34			1	2	1	1	1			1	2	1		1						1	1						1	1
M42			1				1			1				1						1	1						1	1
M51												1							1									
M52				1	1		1				1	1		1														
M63							1					1		1					1									
M64							2							1							1							2
M65							2							2							2					1		3
M66					1		1					1		1					1		1					1		1
M67							2	1						2	1						2	1						2
M68							1	1						1	1						1	1						1
M69		1	1	1	1	1	1		1	1	1			1		1		1		1	1		1		1	1	1	1
M70			1		1	1	1		1	1	1	1	1	1						1	1							1
M74				2	1	1	2				2	1		1				2	1	1	2				2	1	1	1
M75																					1					1		1
M78		1	1	1	1	1			1	1	1	1		1		1		1	1	1	1		1		1	1	1	1
M79		1	1	1	1	1			1	1	1	1		1		1		1	1	1	1		1		1	1	1	1
M81		1	1	1	1	1	1		1	1	1	1		1														
M82							1		1		1			1														
M88							1							1														
M89							1							1														
Total/target	4	6	9	11	12	8	29	7	8	9	15	15	1	33	3	3	0	5	6	8	19	4	4	0	6	7	7	24
Total	79							88							44							52						

These results show that a single modification can lead to 2 or 3 effects on the same target (eg. M1, M6, M11 …). As a whole, Forests and Wetlands show a higher number of potential major effects than Meadows and Cultures (79, 88, 44 and 52 respectively).
Some modifications have a major effect (at least) on the 4 natural environments (eg. M18 – Bearing of the soil; M 34 – Modification of the topography…), while oppositely, some other only affect two environments (eg. M11 – Destruction of trees and shrubs regarding Forests and Cultures; M51 – Translation of machines between working areas regarding Wetlands and Meadows), or a single environment (eg. M33 – Pour of noxious substances from the life areas regarding Wetlands). Some modifications have major effects one numerous targets of a single natural environment, while they do not have any on others (eg. M1 and M6 – Soil drying; M81 – Supply with salt).
Whatever the type of natural environment, the Terrestrial fauna target appears as more frequently affected than others. Oppositely, groundwater (E<) do not undergo any major effect in Meadows and Cultures, as well as Soil fauna (Fs) in Wetlands.
Such display of the exact nature of the targets that are affected by modifications provides tracks for the development of sensibility indicators for the future evaluation tool.

3.5. Discussion about identified major effects

According to the ecosystem analysis, road life phases can directly and indirectly affect the structure, the composition and the dynamic of ecosystems. Wetlands and Forests are the most vulnerable. The synecological analysis based on effects' deduction is consistent with scientific studies in which some of the listed effects have been discussed. The major dysfunctions identified by means of our method are supported by some study examples.

3.5.1. Effects on abiotic targets

Road network alters ecosystems' abiotic elements, affecting the biotic. Noise induced by vehicles [2] may disturb the perception of acoustic communication signals in animal populations (by masking them) and thus acts on their behaviour (example of frogs, [14]). Artificial light near road discomforts nocturnal wildlife [15]. Flammable vegetation of road sides constitutes a risk of fire spreading to adjacent natural environments [16]. During road construction, the mechanical drying of soil leads to impacts on soils, hydrology, vegetation [15] leading to the destruction of wetland ecosystems. Lime treatment disrupts numerous animal populations [17]. Close to roads, due to the introduction of chemical pollutants the water quality may be damaged [18]. These pollutants come notably from vehicles [19]. They are toxic, persistent in the environment [2] and may negatively impact animal communities [15] because of bioaccumulation in food chains [20]. Road salting damages groundwater quality [21]. This chemical pollution is notably involved in the decline of amphibian populations: the salt concentration increase induces a reduction of weight and locomotion performances of tadpoles [22], an increase of physical abnormalities and thus low survival [23].

3.5.2. Effects on biotic targets

Road network also affects biotic elements of ecosystems. The fragmentation due to road networks reduces and isolates ecosystems. Their ability to maintain their biodiversity is then altered [9]. Populations that are not able to access to resources on the opposite side of the road, end subdivided into isolated habitats [24]. The edge effect or the avoidance by fauna of road edges contributes to the creation of obstacles to migration and genetic fluxes [15, 25, 26]. Some species undergo a high mortality because of collision with vehicles [24] and because of predation due to the uncovering. If such effects are strong enough, road may contributes to the extinction of local species, as for example amphibians that undertake mass movements during showers [15]. Vehicles are also vectors of exogenous vegetal species [28], or even exotic [18]. Maintained road sides may be invaded and become conduits for exogenous species to adjacent ecosystems [29]. Even mature forests internal conditions are not able to limit such invasions [30].

3.6. Identification of relevant targets for indicators

3.6.1. Ecosystem functioning model

The hierarchy of major effects makes possible to highlight tracks for the search of "sensibility indicators". The *An* values are reported according to a simplified ecosystem pyramid (Table V).

Each natural environment, *Forests* (F), *Wetlands* (H), *Meadows* (P), *Cultures* (C), includes an ecosystem, a set of living organisms taking advantage of the natural environment, with interactions between species and their environment. Ecosystems are ecological entities characterized by [11] :

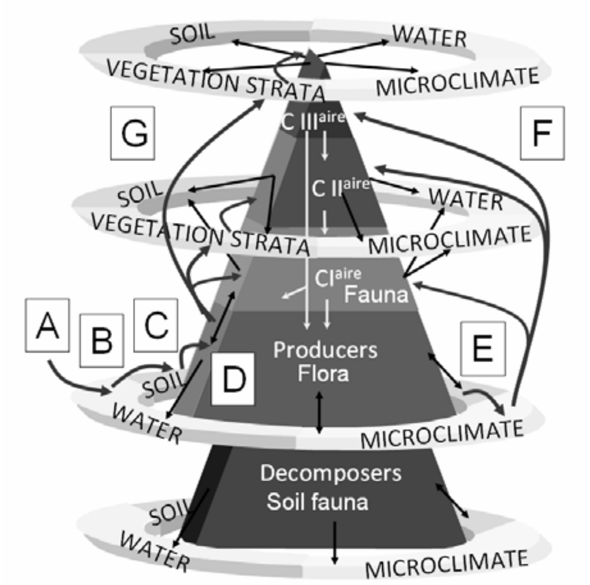
- a biotope, a geographical area submitted to homogeneous abiotic factors, and containing enough resources to allow the life support (microclimate, water, soil and vegetal strata),
- a biocenosis, a set of living organisms in relation into an autonomous trophic network, and depending on the biotope (straight black arrows, Table V).

The trophic network (straight white arrows) is made of organisms that are able to incorporate energy into the system (Producers), organisms that extract energy from others (Primary consumers or herbivorous or CI^{aire}; predators CII^{aire}; super-predators or $CIII^{aire}$), and organisms that are able to degrade the organic matter (Decomposers).

Curved arrows indicate the main consequence chains on targets (cib.) : micro-climate (Mc), surface waters (E>), groundwater (E<), flora (Flo), soil fauna (Fs), terrestrial fauna (Ft).

Table V. Example of consequences chain of major effects in inter-environment.

The pyramid represents ecosystem. Arrows indicate the major chains of consequences. Abbreviations: Cib .= targets. Bold values represent the *An* ≥ 0.87.

Modifications	Causal chains	Cib.	F	LH	P	C
M1 A Lowering of groundwater-surface soil → B Reduction of surface water → C soil drying → D destruction of flora hygrophobia → E Destruction of wet conditions microclimate→ F destruction and → et G loss of ecological niche for hydrophilia fauna → creation of banal environment		Mc	**0.87**	**1**	0	0
			0.87	**1**	0	0
		E>	**0.87**	**1**	0	0
		E<	**0.87**	**1**	0	0
		Sol	**0.87**	**1**	0	0
			0,76	**1**	0	0
		Flo	**0.87**	**1**	0	0
			0.87	**1**	0	0
		Fs	0,80	0,80	0	0
		Ft	0,80	**1**	0	0
			0,80	**1**	0	0
			0,96	**1**	0	0

3.6.2. Application to sensibility indicator search

From the ecosystem major dysfunctions, quantitative indicators are searched. An illustration is provided (Table V) regarding the relations between the various targets affected by modification M1 – Soil drying. This modification can strongly impact Forests and Wetlands. Almost all the targets of these natural environments are concerned. The sequence of impacted targets can be classified as follow: 1° surface water and groundwater; 2° soil; 3° microclimate; 4° flora; 5° fauna. The first targets are abiotic. In this sequence, targets are analysed in order to determine those allowing the identification of sensibility indicators. The latter have to be easy to measure and interpret, non-redundant, and integrators of the effects previously listed on all the affected targets. The selected indicators must also represent the fundamental characteristics of the natural environments: structure, composition and functioning of the ecosystem.

Developing an indicator from the lowering of the water table and the surcharge of surface water would necessitate computer modelling that may be expensive and require specific competences.

The soil target seems more suitable and accessible. The analysis of soil drying can be carried out from the measurement of soil hydromorphy intensity. Hydromorphy marks are sampled by means of core sampler. Redox patches are identified on cores to determine oxidized and reduced horizons. A right hydromorphy level is indispensible to the right functioning of wetlands and forest ecosystems.

4. CONCLUSION

Quantitative indicators can be searched from ecosystem major dysfunctions. Selected indictors will represent the fundamental characteristics of natural environments : structure, composition and ecosystem functioning. These indicators must be applicable in all countries at the upstream stage of the decision process, even where documentary sources and inventories of natural environments are shallow. Indicators must be easy to measure and interpret, non-redundant, and integrators of the effects listed thanks to the developed method. Thus future indicators will mainly be measured on abiotic targets (microclimate, surface water, soil...). Biotic targets being dependant from them, these indicators will allow synthesizing the complex phenomena observed on flora and fauna.

As far as possible, indicators will then have to be aggregated into a limited number of indices similar to a “print”. Indicators must be incorporated into a software so that all the environmental aspects, natural environments and life cycle analysis, are taken into account in the evaluation. They will have to be incorporated into a Geographic Information System (GIS) tool. This will allow to observe spatialized data and to propose different variants of road alignment.

In France, at the upstream stage of the decision process of the road project, feasibility and opportunity studies consist in very limited environmental evaluations. The synecological tool would be integrated at this early stage so that all the variants could be discussed in order to obtain the road alignment with the lowest environmental cost (TEC). It could also be used for the next stages, from preliminary studies to environmental monitoring. The ecological expertise of the road projects with this tool could be more independent and objective.

The synecological assessment method developed in this study is an initial step in the creation of a road projects effects assessment tool. It should be extended to other natural environments types such as rivers, moor,... and to interaction between natural environments. Post-project measures of indicators will be modeled by defining the critical threshold values. Finally, the tool should also take into account railways projects in order to meet the needs of current environmental comparison between road and railway projects. The aim would be to formulate practical proposals for achieving better landplaning and natural environment protection.

REFERENCES

1. Millennium Ecosystem Assessment (2005). Ecosystems and Human Well-being: Biodiversity Synthesis. Washington, DC, E.-U.A., Island Press.
2. Coffin A. W. (2007). From roadkill to road ecology : A review of the ecological effects of roads. Journal of Transport Geography 15 : 396-406.
3. Cans C. et F. Clap (2008). Typologie des procédures de protection des espaces naturels. JurisClasseur Environnement et Développement Durable, Fasc. 4530.
4. Franklin J. F. (1993). Preserving Biodiversity: Species, Ecosystems, or Landscapes? Ecological Applications, 3(2) : 202-205.
5. Gaston K. J. et R. A. Fuller (2008). Commonness, population depletion and conservation biology. Trends in Ecology & Evolution 23 : 14-19.
6. Gaston, K. J. et Fuller, R. A. (2007). Biodiversity and extinction: losing the common and the widespread. Progress in Physical Geography, 31(2) : 213-225.
7. Kerali H.G.R. (2000). HDM-4 Highway Development and Management, Volume 1- Overview of HDM-4. The highway development and management series, AIPCR, Paris.
8. Sayagh S., Ventura A., Hoang T., François D. et A. Jullien (2009). Sensitivity of the LCA allocation procedure of BFS recycled into pavement structures. Resources Conservation and Recycling 54 : 348-358.
9. Genelleti D. (2003). Biodiversity Impact Assessment of roads : an approch based on ecosystem rarity. Environmental Impact Assessement Review 23 : 343-365.
10. OCDE (Organisation de Coopération et de Développement Économique) (1993). Jeu de base d’indicateurs de l’OCDE pour l’étude de performance environnementale. OECD Environment Monographs 83.
11. Fischesser B. et M.-F. Duipuis-Tate (1996). Guide illustré de l’écologie. Ed. de La Martinière – Cemagref Editions. 319 p.
12. Delarze R. et Y. Gonseth (2008). Guide des milieux naturels de Suisse. Rossoli, 2ème édition revue et corrigée, Bussigny, 425 p.

13. Bissardon M. et L. Guibal (1997). Corine biotopes, version originale types d'habitats français. Ecole Nationale du Génie Rural, des Eaux et des Forêts et GIP Atelier Technique des espaces naturels, 175 p.
14. Bee M. A et E. M. Swanson (2007). Auditory masking of anuran advertisement calls by road traffic noise. Animal Behaviour 74 : 1765-1776.
15. Laurance W. L., Goosem M. et S. G.W. Laurance (2009). Impacts of roads and linear clearings on tropical forests. Trends in Ecology & Evolution 24 : 659-669.
16. Curt T. et P. Delcros (2010). Managing road corridors to limit fire hazard. A simulation approach in southern France. Ecological Engineering 36 : 457-465.
17. Buckton S. T. et S. J. Ormerod (1998). Effects of liming on the Coleoptera, Hemiptera, Araneae and Opiliones of catchment wetlands in Wales. Biological Conservation 79 : 43-57.
18. Forman R. T. T., Sperling D., Bissonette J.A., Clevenger A.P., Cutshall C.D., Dale V.H., Fahrig L., France R., Goldman C.R., Heanue K., Jones J.A., Swanson F.J., T. Turrentine et T.C. Winter (2003). Road Ecology: Science and Solutions, Island Press, Washington.
19. Pagotto (1999). Etude sur l'émission et le transfert dans les eaux et les sols des éléments traces métalliques et des hydrocarbures en domaine routier. Université de Poitiers, Ecole des Mines de Nantes, Laboratoire Central des Ponts et Chaussées, Thèse : chimie et microbiologie de l'eau, 252 p.
20. Mariño F., Ligero A. et D. J. D. Cosin (1992). Heavy metals and earthworms on the border of a road next to Santiago (galicia, northwest of Spain). initial results. Soil Biology and Biochemistry 24 : 1705-1709.
21. Meriano M., Eyles N. et K. W.F. Howard (2009). Hydrogeological impacts of road salt from Canada's busiest highway on a Lake Ontario watershed (Frenchman's Bay) and lagoon, City of Pickering. Journal of Contaminant Hydrology 107 : 66-81.
22. Denoël M., Bichot M., Ficetola G. F., Delcourt J., Ylieff M., Kestemont P. et P. Poncin (2010). Cumulative effects of road de-icing salt on amphibian behavior. Aquatic Toxicology 99 : 275-280.
23. Sanzoa D. et S. J. Hecnar (2006). Effects of road de-icing salt (NaCl) on larval wood frogs (Rana sylvatica). Environmental Pollution 140 : 247-256.
24. Jaeger J. A. G., J. Bowman, Brennan J., Fahrig L., Bert D., Bouchard J., Charbonneau N., Frank K., Gruber B. et K. Tluk von Toschanowitze (2005). Predicting when animal populations are at risk from roads: an interactive model of road avoidance behavior. Ecological Modelling 185 : 329-348.
25. Delgado J. D., Arroyo N. L., Arévalo J. R., et J. M. Fernández-Palacios (2007). Edge effects of roads on temperature, light, canopy cover, and canopy height in laurel and pine forests (Tenerife, Canary Islands). Landscape and Urban Planning 81 : 328-340.
26. Andrews A. (1990). Fragmentation of habitat by roads and utility corridors: a review. Australian Zoologist 23 : 130-141.
27. Benítez-López A., Alkemade R. et P. A. Verweij (2010). The impacts of roads and other infrastructure on mammal and bird populations : A meta-analysis. Biological Conservation 143 : 1307-1316.
28. Zwaenepoel A., Roovers P. et M. Hermy (2006). Motor vehicles as vectors of plant species from road verges in a suburban environnement. Basic and Applied Ecology 7 : 83-93.
29. Gelbard J. L. et J. Belnap (2003). Roads as conduits for exotic plant invasions in a semiarid landscape. Conservation Biology 17 : 420-432.
30. Flory S. L. et K. Clay (2009). Effects of roads and forest successional age on experimental plant invasions. Biological Conservation 142 : 2531-2537.