Can linear transportation infrastructure verges constitute a habitat and/or a corridor for vascular plants in temperate ecosystems? A systematic review

**Abstract**

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# Background

For the last decades, human activities have resulted in a global continuous loss of biodiversity [1], and transportation was identified as one of the ten major threats faced by threatened or near-threatened species [2]. Linear transportation infrastructures (LTIs) have led to habitat loss and degradation, fragmentation and barrier effects, light and noise disturbance, chemical pollution and direct mortality (e.g. road kill, electrocution) [3–8] . In particular, the splitting of natural habitats and ecosystems into smaller and more isolated patches (i.e. fragmentation) and the associated loss of habitat have negative effects on biodiversity [9]. For instance, LTIs have induced a decrease in wildlife species abundance at local and large scales [10]. And, through barrier effects LTIs can restrict wildlife movements, disrupt gene flow and metapopulation dynamics, and lead to the genetic isolation of populations over several generations [*e.g.* 11].

Considered transversally, LTIs thus generate a demonstrated negative fragmenting effect on biodiversity, but considered longitudinally, LTIs have the potential to constitute a habitat and/or movement corridors for biodiversity by their semi-natural verges [12]. Indeed, inside the LTI boundaries there is generally a transportation lane (road, railway, pipeline, powerline, river or canal) and verges which are most often covered with vegetation (road and railway embankments, strips of grass under power lines or above buried pipelines, or waterway banks, etc.). Studies assessing the potential of LTI verges as habitat and/or corridor for wildlife species have provided contrasted results. For instance, road verges sometimes contain significant portions of the remaining populations of rare plant species [13,14]. On the other hand, the alteration of the original habitat induced by the construction of transport infrastructure can favour the establishment and spread of exotic plants [*e.g.* 15,16]. The potential of LTI verges as habitat and/or corridor for wildlife species may also vary with verge management practices, as one practice (e.g. mowing) can be beneficial for some species (e.g. disturbance-tolerant species) but not for others (e.g. woody species) [17,18].

Knowing the role of LTI verges as habitat and/or corridor for biodiversity is of importance as verges might contribute to ecological networks. In the last decades, ecological networks of terrestrial and aquatic continuities (blue-green infrastructures) aiming to decrease fragmentation have received much attention from scientists and policymakers [19]. Meta-analyses of corridor effectiveness showed that, overall, corridors increase movements of plants, vertebrates and invertebrates between habitat patches, but that corridor effectiveness varies among taxa [20,21]. Maintaining such a network of ecological corridors might be beneficial on the long term in the context of climate change by facilitating species dispersal to newly suitable areas [22]. In France, the concept of green and blue infrastructures led to the development of a public policy named “Trame Verte et Bleue” (meaning green and blue ecological network) launched by the French Ministry of Ecology in 2007. Accordingly, French administrative regions have identified ecological networks and they conduct action plans for preserving and restoring these continuities, for biodiversity. At a smaller spatial scale, i.e. townships, it has also to be considered in local urban planning.

## Topic identification and stakeholder input

In France, the LTI network is very dense. For instance, the road network is the longest (over a million kilometres long, ¼ of the European network) and one of the densest (1.77 km/km²) of the European Union. As a comparison, Spain, which has an area close to the one of France, has a road density six times lower (0.32 km/km²). The railway network is also one of the longest in Europe with more than 30,000 kilometres of railway lines in use. Thus, such a dense LTI network means a considerable inherent surface of verges and LTI managers might substantially contribute to ecological networks. Furthermore, in the literature, the potential for LTI verges to be a habitat and/or a corridor for biodiversity seems to exist, but a comprehensive understanding of the conditions where this is true remains, as far as we know, unavailable. Seminal reviews on this question were previously published [*e.g.* 8,17,23] but they focused on roads and do not fulfil the standards of a systematic review [24]. This situation motivated several French LTI managing companies and the French Ministry of Ecology to request a systematic review on this issue, at the heart of the green and blue infrastructure public policy. The French LTI managing companies are gathered in an informal group, named “Club des Infrastructures Linéaires & Biodiversité” (CILB), aiming at acting for biodiversity conservation. The motorway, railway, power line, pipeline and waterway French stakeholder companies who are members of the CILB were specifically interested in evaluating whether their LTI verges could contribute to green and blue infrastructures to improve the management of these verges for that purpose. The systematic review was assumed to be a relevant scientific method to provide a sound answer to this practical questioning from LTI managers. A call for tender for a systematic review was thus launched by the French Ministry of Ecology and the French Agency for Environment and Energy Management (ADEME) through its research incentive program related to transportation ecology, named “Infrastructures de Transport Terrestre, Écosystèmes et Paysage” (ITTECOP), supported by the CILB and the “Fondation pour la Recherche sur la Biodiversité” (FRB), a French foundation supporting research in biodiversity. The French National Museum of National History (MNHN) was then chosen for conducting the project, in collaboration with the Franch National Institute of Research, Agriculture and Environment (Inrae), the University Pierre and Marie Curie (UPMC, Paris 6), the French Centre for Studies and Expertise on Risks, Environment, Mobility, and Urban and Country Planning (Cerema). At the beginning of the project, the LTI managers funding the study were met to list the types of verges they own and the management practices they apply on those, to define the components of the review question.

The protocol of the systematic review was published in 2016 [25]. Because the question encompasses all biodiversity, a very large number of articles were collected. The review process was thus split by taxa in three stages. A first systematic review focusing on insects was published in 2018 [26]. A second systematic review on vertebrates (mammals, birds, amphibians and reptiles; organisms like fishes that are not living on or using verges but exclusively live in or use the LTI itself were not considered in this review) was published in 2020 [27]. Regarding insects, our systematic review revealed that their abundance was generally not statistically different between LTI verges and away from LTIs. Insect abundance was even higher on non-highway road verges than away from roads. Regarding vertebrates, highway verges had higher abundance of small mammals but both lower abundance and species richness of birds than away from highways. The opposite pattern was found howerver for bird species richness and abundance along waterways. Here, we propose a third systematic review on flora to complement the two previous ones.

## Objective of the review

The general aim of the review was to determine if LTI verges can provide habitats or dispersal corridor for flora (i.e. all vascular plants except stricly aquatic plants). This work exclusively focused on the longitudinal effect of LTI verges without considering the transversal effect of LTIs such as barrier effects. The review also aims at assessing the effects of managements practices (e.g., mowing), as well as of the characteristics of the surrounding landscape, on the potential of LTI verges for vascular plants.

### Primary question

The primary question of the review is: can linear transportation infrastructure verges constitue habitats and/or corridor for vascular plants in temperate ecosystems?

### Secondary questions

The approach in this review consisted in splitting the above primary question into six specific questions detailed in Table 1. This subdivision was used during study validity assessment and the synthesis of evidence.

We defined LTI verges as the area up to 30 m from roadways, waterways or railways, or the area (whatever the width) below power lines or below/above pipelines. We considered the surrounding landscape to be at, at least, 1 km around the LTI.

### Components of the primary question

Population: All vascular plant (except strictly aquatic plants) species and communities.

Exposure: LTI verges; i.e. road, railway, powerline and pipeline verges and waterway banks. Regarding the latter, as our systematic review focused on LTIs, we only considered navigable waterways (navigable rivers and canals) as relevant exposures.

Intervention: Management practices (e.g. mowing) or human-induced disturbances (*e.g.* waterway channelization) on LTI verges.

Comparator: Temporal and/or spatial comparators, including but not restricted to ecosystem present before versus after infrastructure construction (LTI verge creation), LTI verge before versus after management intervention), LTI verge versus nearby similar habitats away from LTIs, LTI verge managed with one practice versus unmanaged LTI verge or LTI verges managed with a different practice.

Outcomes: All outcomes relating to species presence or species dispersal, including but not restricted to species richness, abundance, community composition and species dispersal.

Context: Because the funders requested an evidence synthesis applicable to western Europe, we restricted our synthesis to temperate zones.

# Methods

The methods are described in details in an a priori systematic review protocol [25]. We summarize it here and present the small deviations from this protocol that we made when conducting the review. The methods follow the Collaboration for Environmental Evidence (CEE) Guidelines and Standards for Evidence Synthesis in Environmental Management [28] unless noted otherwise.

## Search for articles

### Search strings

The review team identifed English search terms to be combined in search strings. For all keywords listed wild-cards may be used to allow the use of derivations of the word’s root and to account for the possibility of finding a word in various spellings (English from Great Britain or from the United States) and with various endings (singular or plural).

We tested a first search string combining some of the search terms with Boolean operators of Web Of Science Core Collection (with search on “Topic”). To assess the comprehensiveness of the search string, we compared the search hits to the articles of the test list indexed in the database (see Additional file ***XXX*** for the list of articles of the test list and how it was constituted). Then, we modifed the search string by removing some of the search terms and including new ones, to increase the number of articles of the test list retrieved [25]. At last, the search string that produced the highest efficiency (i.e. total number of search hits as low as possible with the highest number of articles from the test list retrieved) was a set of four sub-search strings displayed in Table 2.

#### Publication databases

We first listed the databases to which the members of our review team had access. The database selection was then based on three criteria [25]:

* Topic: the database(s) had to cover ecology;
* Accessibility/reproducibility/sustainability: the database(s) had to be accessible by the whole review team, and by researchers all over the world (as a guarantee of reproducibility and further reviewing);
* Comprehensiveness: number of articles indexed in the database(s) among the articles of the test list (Additional file ***XXX***)

These criteria led us to select two databases: Web Of Science Core Collection (with subscriptions: Science Citation Index Expanded 1956-present, Social Sciences Citation Index 1975-present, Arts and Humanities Citation Index 1975-present, Conference Proceedings Citation Index-Science 1990-present, Conference Proceedings Citation Index-Social Science & Humanities 1990-present, Book Citation Index-Science 2005-present, Book Citation Index-Social Sciences and Humanities 2005-present, Emerging Sources Citation Index 2015-present, Current Chemical Reactions 1985-present, and Index Chemicus 1993-present; 86 articles indexed out of the 102 articles of the test list) and Zoological Records (subscribed timespan 1864-present, 51 articles out of the 102 articles). Searches on these two databases were made on “Topic”.

#### Search engines

We performed additional searches using three search engines:

* Google Scholar (https://scholar.google.fr/);
* BASE (Bielefeld Academic Search Engine, https:// www.base-search.net/);
* CORE (https://core.ac.uk/). Because these search engines could only handle a limited number of search terms and did not allow the use of all wildcards, the search strings used for publication databases were simplified. We thus developed a search string for each of the five LTIs (Additional file 3). In Google Scholar, results were sorted by relevance, with the boxes “include patents” and “include citations” unchecked. In BASE, results were sorted by relevance, with the box “boost open access documents” unchecked and the box “Verbatim search” checked. For each of the five search strings, we retrieved the first 20 hits.

#### Specialist websites

We searched for links or references to relevant articles and data on 11 specialist websites including a journal special issue on transportation ecology (Additional file 4).

#### Supplementary searches

To retrieve grey literature, we contacted by email national and international experts of transportation ecology, through the Ecodif (now SFEcodif), Transenviro, Wftlistserv and IENE mailing lists and by posting a call on social media (https://fr.linkedin.com/). SFEcodif is a French mailing list about ecology and evolution which counted around 7000 subscribers (https://www.sfeco logie.org/sfecodif/), and Transenviro, Wftlistserv and IENE mailing lists are international mailing lists about transportation ecology. Together, the Transenviro and Wftlistserv mailing lists (http://www.itre.ncsu.edu/CTE/ Lists/index.asp) gathered about 600 contacts and the IENE mailing list (http://www.iene.info/) counted around 300 contacts. All these mailing lists were accessed on 22 September 2015. Eventually, we contacted nearly two thousand people (N=1902) by individual email. Organizations funding the systematic review also provided us with their unpublished reports. As well, some experts spontaneously sent us documents on flora after having heard about our project (see below).

#### Dates of literature searches

Literature searches were performed in three stages. First, we performed searches in Web Of Science Core Collection publication database, in Zoological Records publication database, and in Google Scholar search engine on April 27th 2015, February 1st 2016, and March 4th to 9th 2016, respectively. The call for grey literature was performed on April 21st 2015. All articles published in 2016 were not considered during these first searches.

Second, searches were updated on June 15th 2018 for Web Of Science Core Collection and Zoological Records publication databases, and on November 6th 2018 for Google Scholar, to retrieve articles published from 2016 onward until these dates (Additional file 4). New searches on specialist websites were conducted from November 26th 2018 to December 4th 2018, and searches on BASE and CORE search engines were updated on November 7th and 8th 2018, respectively.

Third, we performed an update from articles published between 2018 and 2020 on March 3rd, 2021 for Web Of Science Core Collection (N=6193 articles) and Zoological Records publication databases (N=1240 articles). Due to time restriction, no update was conducted however for the other sources of literature (Google Scholar, CORE, BASE). There was no update of the call for grey literature either, but we received spontaneously documents from experts by emails: on 20th October 2021 from Mayenne Nature Environnement (N=10 articles) and on the 15 November 2021 from Frédéric Hendoux, director of the Conservation Botanique National du Bassin Parisien (N=4 articles).

Finally, articles from a previsouly published review on roadside management were included into our review (Jakobsson 2018).

## Article screening and study eligibility criteria

### Screening process

The articles collected from online publication databases were screened by several member of the review team for eligibility (according to the criteria described in the next section) through three successive stages : first on titles (performed by SV, AV, AJ, RS, MV, EG, EM, VR, LP), second on abstracts (performed by SV, AV, AJ, RS, MV, EG, EM, VR, AC, YB, LP), and third on full-texts (performed by LP, VF, VR, SV, AV, AJ, AC, DYO, EG, EM, MV, RS, PP, VA, YB, YR). The number of articles screened by each member of the review team is detailed in the supplementary file ***XXX***.

The screening is conservative at each stage : in cases of doubt, articles proceed to the next stage for further assessment. The agreement between screener was assessed before beginning a screening stage (title, abstract or full-text screening stage) by computing a Randolph’s Kappa coefficient [25] on a number of references randomly sampled among the database of articles about flora. These randomly sampled articles were screened by each of the reviewers independently of each other. We considered 200, 20 and 50 randomly sampled references to be sufficient to assess the agreement between screeners during title, abstract and full-text screening, respectively. It is a relatively small proportion of the total number of references to be screened, but these numbers were based on our experience with the previous systematic reviews published on insects and then on vertebrates [26,27]. A minimal coefficient of 0.6 was considered an acceptable level of agreement between reviewers. All disagreements were discussed by reviewers, so that diferences in screeners’ understanding of eligibility criteria could be resolved. When the coefficient was lower than 0.6 the operation was repeated until reaching a coefficient larger than 0.6.

### Eligibility criteria

At each stage of screening, article eligibility was based on a list of selection criteria. At the stage of title screening, these criteria mainly encompassed both the subject (ecology and related disciplines) and the population and exposure/intervention of the article (Table  3). The same criteria were applied at the stage of abstract screening, to which we added criteria regarding the exposure/intervention, the comparator, the outcomes or the study type (Table  4). Articles without abstract were discarded due to their high number and time constraints, and as this protocol was followed for the previous two reviews of our project. Finally, the same criteria as for the abstract stage were used for the stage of full-text screening, to which we added new inclusion criteria regarding the language, the climate, the type of publication or the specifc questions covered (Table 5). We considered that a study was not relevant to the purpose of the review, and thus discarded it, if the comparator was inappropriate (comparison between diferent seasons, comparator difcult to interpret for the purposes of this review, high contrast of habitat with the comparator (e.g. herbaceous vegetation compared to forest), etc.], if the sampling was not strictly done on verges (we defined LTI verges as the area up to 30 m from roadways, waterways, or railways, or the area (whatever the width) below power lines or below/above pipelines), or if—for questions Q5 and Q6—the landscape scale was below 1 km. As our review focused on transportation infrastructures, we also made sure at full-text screening stage that only paved roads and navigable rivers and canals were included. This information is unfortunately rarely provided for waterways, so we included all articles with Strahler [29] stream order above three, canals and rivers, and we excluded all articles with stream order equal or below three and articles with no information on stream order.

To identify whether study area was in the temperate climate we used the Köppen–Geiger Climate Classifcation (Cfa, Cfb, Cfc, Csa, Csb, Csc, see <http://people.eng.unimelb.edu.au/mpeel/koppen.html> for the GoogleEarth layers of the Köppen–Geiger Climate Classification). When a study area overlapped temperate and non-temperate climate with no possibility to extract the data regarding only the temperate climate the study was discarded. Similarly, studies were excluded if the results included biological groups and/or exposures that were not under the scope of the review, with no possibility to extract results scoping the review (e.g. results combining aquatic and riparian flora, or combining vascular flora and lichen or bryophytes, results combining paths and paved roads, results combining streams and rivers). We also checked for data redundancy (data already published in another article included in the review) and added this factor as an exclusion cause. Articles about non vascular plant species were set aside during the three stages of title, abstract and full-text screenings.

## Study validity assessment

We conducted a critical appraisal of the studies and assigned them a low, medium or high risk of bias. To define the criteria of this appraisal, eight external experts in landscape connectivity and transportation ecology were gathered and consulted during a 1-day workshop with seven scientists of our review team [25]. During the workshop, we discussed about the gold standard protocol of an ideal study answering our primary question with unlimited resources (unlimited money, time, workforce, etc.). We considered that a study was unreliable because of a high risk of bias, and therefore excluded it from the review, if there was/were:

* A total absence of replications;
* An inadequate methodology (for example for question Q4 on the role of corridor of verges, a statistical analysis of dispersal data that did not allow to distinguish LTI verges from other habitats);
* A method description strongly insufficient (i.e. when it was not possible to know where the sampling was done: within or outside LTI verges);
* Major confounding factors (e.g. strong difference in sampling effort between treatment and control)

We considered that a study had a medium risk of bias if it had the following characteristics:

* Absence of transparent and systematic procedure for the selection of sample plot location (i.e. randomization, fixed distances, grids);
* Control–Intervention and Before–After–Intervention study designs (as opposed to Before–After– Control–Intervention study designs) for the specifc questions involving verge management (questions Q1 and Q3);
* Absence of true spatial replication of the study (for example study with repetition of measures on a unique site);
* Attrition bias (difference in the loss of samples between control and treatment);
* Method description slightly insufcient (some minor details were missing but did not challenge our understanding of the methods).

Finally, we considered that a study that did not have a high or medium risk of bias had a low risk of bias. Studies with a high risk of bias were discarded from synthesis. In the narrative synthesis, the results of studies with a low risk of bias were first synthesized and then the consistency of the results of studies with a medium risk of bias was assessed. In the meta-analyses, the infuence of the level of bias (low or medium) on effect sizes was furthermore tested. For articles dealing with more than one specifc question (Table 1), we performed critical appraisal for each question separately, that we considered being different studies. The critical appraisal was performed as follows: first, each study was critically appraised by one reviewer (VF). Then, a second reviewer critically appraised again the uncertain cases. We compared conclusions of the two reviewers, and when they differed, they discussed disagreements until reaching a consensus and asked for a third reviewer if necessary. All reviewers never had to critically appraise article they authored by themselves. Although it is a CEE standard that at least two people independently critically appraise each study, it was not possible in this study due to the high number of articles and time constraints.

## Data coding and extraction strategy

### Extraction of meta-data

We used the coding tool displayed in Table 6 to produce an easily searchable database of the studies included after critical appraisal (i.e. with low and medium risk of bias). If an article dealt with more than one of our specific questions, we coded each question in a different row.

### Extraction of data for narrative synthese

For all specific questions except Q2 (for which data was extracted for meta-analyses only), we first extracted into tables the statistically tested results of all studies with low and medium bias. For each species or group of species we extracted the effects of exposure/intervention and categorized them as positive, negative or neutral. Neutral effects referred to comparison between control and treatment that were statistically not signifcant (*i.e.* no statistically signifcant difference between the two, α=0.05). Where necessary, we assessed whether the differences were statistically signifcant using the confidence intervals reported by the authors. Data extraction was performed by VF (Q3, Q4 and Q6) and HM (Q1 and Q5).

### Extraction of data for meta-analyses

For each primary study, and for both LTI verges and control sites away from LTIs, sample sizes, outcome means, and measures of variation (standard deviation, standard error, or confidence interval) were extracted from tables, text, published raw data (e.g. in appendices), and graphics using the R package “metaDigitise” version 1.0.1. [30]. When outcome means or measures of variation could not be directly extracted from the published data, the sample size and any other measure that enable further imputation according to Lajeunesse [31] (e.g upper- and lower inter-quartile ranges, statistical tests parameters) were extracted. In case of uncertainty of the measure of variation reported (i.e. when it was impossible to know whether it was the standard deviation or the standard error that was reported), standard errors were assumed to obtain conservative estimates of the uncertainty around the effect sizes calculated. Abundance for either species groups or individual species were extracted. If a study reported the abundances for both a group and some particular individual species from the group we only used the former. Similarly, if total abundance or richness were given alongside data for specific subgroups (e.g. annuals, forbs, or ruderals), only global values were used except if the grouping concerned the native or exotic/invasive status of species, in which case results were also extracted in addition to the global ones. When studies measured the biodiversity of vascular plants at various distances from LTI verges we used values of the furthest distance as controls. When studies reported multiple measures along a distance gradient within the boundaries of the LTI verges, means and standard deviations were combined and used to compute a single effect size. Finally, if a study reported several sites that could serve as a control, the site with habitat most similar to LTI verges was chosen as control. Data extraction was performed by one reviewer (HM).

## Potential effect modifiers/reasons for heterogeneity

We recorded the following potential effect modifiers as stated in the protocol of the present review [25]:

* Geographic location;
* Biological groups studied;
* Site characteristics: type of LTI, type of habitat of the verge/comparator sites and level of contrast between them;
* Verge management practices (mowing, grazing, vegetation burning, pesticide use, etc.);
* Comparator type (spatial/temporal, etc.);
* Selection of sampling location (randomization, fixed distances or grids versus directed sampling). Although identified as a potential reason for heterogeneity in the review protocol, we eventually considered the absence of replicates as an important source of bias. Accordingly, those articles without replicates were discarded during critical appraisal.

# Results

## Literature search retrieval

### Literature searches and screening

Searches about the role of linear transportation infrastructure as habitat and/or corridor for biodiversity returned 93014 articles from 1972 to 2020 (74062 from the initial search retrieval and 18 952 from the actualisation in 2020). After the title screening stage, 10775 articles concerning vascular plants were accepted. During the abstract screening stage, we rejected 6778 articles from the corpus, yielding 3566 articles for full-text screening. We could not retrieve full-texts for 112 articles ( 3% ) and among the other articles, 433 were accepted for critical appraisal from the litterature search retrieval (see ROSES flow diagram in Figure **XXX**). For articles that were rejected at full-text screening, the most common reasons for exclusions were: that sites were not in the bioclimatic region of interest ( 45.5% ), that the type of a study was not appropriate (*e.g* a simulation study ; 14% ) and that there was no appropriate comparator ( 14% ).

A posteriori, some articles were included in the screening process (Figure **XXX**). Indeed, we considered 50 articles from the review of Jakobsson et al. (2018). This recent review assessed the role of ILT infrastructure management on the flora biodiversity. As it corresponds to our question Q1, we included articles which were not already in our corpus. One of them was lacking an abstract was and therefore excluded during abstract screening, no PDF could be obtained for 7 articles, 25 articles were excluded at the title screening stage and 17 articles were included in the critical appraisal stage. The exclusions of the 25 articles was either because studies were not conducted under a temperate climate (76%), or because the document was written in a language other than English or French (24%). Later in the search process, we also received 10 and four articles by mail from experts (Mayenne Nature Environnement and Conservatoire botanique national du Bassin parisien, respectively). However, these articles were all excluded from the screening process at the full-text stage. Indeed, four of them were reviews and the others were rejected because of the type of study or because the exposure criteria were not met.

Thus, at the end of the screening phase, 547 articles remained (Figure **XXX**). The articles rejected at full-text screening as well as those for which we did not find full-texts are listed in Additional file **XXX** with reason for exclusion (also detailed in Figure **XXX**).

### Study validity assessment

Because an article can answer to more than one of our specific subquestions, the 491 articles included in the review were split into 547 diferent studies that underwent critical appraisal. At this stage, 88 studies were excluded from further synthesis because they showed a high risk of bias. The reasons for a high risk of bias were a strongly insufficient description of the method ( 7% ), the presence a major confounding factor ( 4.57% ), an inadequate methodology ( 3.29% ), an absence of replication ( 0.55% ) and protocols varying between control and treatment ( 0.37% ) or between sites( 0.18% ). Thus, a total of 459 studies corresponding to 405 articles were retained after critical appraisal. Additional file **XXX** provides a list of all studies retained after the screening stage with coded metadata and their risk of bias assessed during critical appraisal. The number of studies of each level of bias for every subquestion and type of LTI is also given in Figure **XXX**.

After the critical appraisal stage, 72 studies with a low or medium risk of bias that reported statistical results for any subquestion except Q2 were further included in the narrative synthesis. The 83 studies with a low or medium risk of bias dealing with Q2 were scanned separately for means and error measures for control and treatment sites in order to compute effect sizes for a meta-analysis on the role of habitat of LTI verges. Among them, 46 studies provided the necessary data for *Species richness* and/or *Abundance*.

### Characteristics of the studies

Of the 261 with low or medium risk of bias, 31.48% had a low risk of bias (Figure **XXX**). The majority of studies dealt with the role of habitat of verges by comparing biodiversity within the boundaries of LTI verges to biodiversity in similar habitats away from the verges (Q2 ; 116 studies), and with the impact of management practices on the biodiversity hosted by comparing LTI verges under different management regimes or perturbation levels (Q1 ; 177 studies). A relatively high number of studies also investigated the effect of the surrounding landscape on the habitat role of verges (Q5 ; 66 studies). However, studies addressing the role of corridor of verges were very scarce. Indeed, there were only 3 studies on the role of corridor of LTI verges (Q4), 1 study on the impact of management practices on the role of corridor and 2 studies on the influence of the surrounding landscape.

### Publication year

The 327 articles retained after critical appraisal were published from 1977 to 2020 (**Figure XXX**).

### Source

Most of the 359 studies retained after critical appraisal were retrieved from Web Of Science Core Collection ( 320 articles). Only 3 studies came from Zoological Records and only 1 from Google Scholar. The call for grey litterature eventually led to 18 studies being included in the final corpus and

2 studies were also spontaneously sent to us. Lastly, 15 studies came from the review of Jakobsson et al. (2018) on the impact of management practices of road verges on biodiversity.

### Language and type of article

The vast majority of the studies included in the synthesis came from documents written in English ( 93.6% ), the remainder being written in French. Almost articles included came from scientific journal ( 93% ), but the review also included 17 technical reports, 3 PhD thesis chapters and 3 Master thesis chapters, as well as 1 Powerpoint presentation and 1 book chapter.

### Study location

At country level, most of the 261 were done in the United States ( 20.3% ) and France ( 15.6% ), then in Spain ( 7.8% ), Australia ( 7.5% ) or in the United Kingdom ( 5.8% ; see Figure **XXX** for a full list).

### Study design

Most studies included in the synthesis had a Control-Exposure (for questions Q2, Q4, Q5, Q6) or a Control-Intervention (for questions Q1 and Q3) design (respectively 50.7% and 42.9% of the studies). Only 6.4% of the studies however included a temporal control by assessing biodiversity both before and after the intervention/exposure.

### Exposures

The majority of the 261 studies were about roads ( 167 ). Waterways were the second most studied LTI with 141 studies. On the other hand, only 25, 6 and 5 studies were done along powerlines, railways and pipelines respectively.

## Data synthesis: quantitative syntheses

### Description of the data

We extracted quantitative data from 47 among the 459 with a low or medium risk of bias addressing the specific question Q2 (“Is tracheophyte biodiversity in LTI verges equal to, higher, or lower than in similar habitats away from the LTIs?”). Among the 205 extracted from these 47, 109 cases in 24 studies concerned species or group abundance, and 96 in 34 studies concerned species richness (Additional file ***XXX***).

We estimated the variance of cases with data imputation (*i.e.* filling missing variance by using the available data from the other studies) for 24 cases ( 15.6% of *Abundance* cases and 7.3% of *Species richness* cases). When several cases were extracted from the same study, this was because there was data for several species or group of species, for several sites, or for several years or seasons.

Most of the cases in our data were conducted along roads (highways 14.1% ) and non-highway roads ( 47.8% ), then along powerlines ( 19.5% ), pipelines ( 17.1% ) and railways ( 1.5% ).

Cases extracted for the meta-analysis were mostly from studies conducted in North America and Europe (North America: 40.5% , Europe: 39% , Oceania: 10.7% , South America: 4.9% , and Asia: 4.9% ).

### Meta-analyses and publication bias

For abundance, overall we found that vascular plants were marginally less abundant on LTI compared to similar habitats away from verges (grand mean effect size d=-0.78, 95% confidence interval (95% CI) [-1.56;0.01] ). However, this negative relationship could be attributed mainly to two highly influential cases (Cook’s distance above 0.5) and when they were removed, the overall grand mean effect size became positive but was not statistically different from zero ( d=0.21, 95% CI [-0.53;0.95] ). Hence based on this more robust estimate, abundance on the verges did not seem to differ from the one observed in reference sites. We also found high heterogeneity between effect sizes ( jkQ\_T=3603.5, p < 0.0001N=103 ), indicating that moderators could explain variations in effect sizes.

For species richness, the overall mean effect size was not statistically different from 0 ( d=0.1, 95% CI [-0.42;0.62] ), meaning that LTI verges and reference sites also exhibited similar numbers of species overall. Again, we found a statistically significant heterogeneity in the effect sizes ( Q\_T=1502.6, p < 0.001N=103 ).

Multivariate Meta-Analysis Model (k = 104; method: REML)  
  
Variance Components:  
  
 estim sqrt nlvls fixed factor   
sigma^2.1 0.0000 0.0002 24 no Author\_date   
sigma^2.2 16.2300 4.0287 104 no Author\_date/Case.ID   
  
Test for Residual Heterogeneity:  
QE(df = 100) = 10219.5665, p-val < .0001  
  
Test of Moderators (coefficients 1:4):  
QM(df = 4) = 7.7145, p-val = 0.1026  
  
Model Results:  
  
 estimate se zval pval ci.lb   
ILT\_analysisHighway 0.0071 1.1302 0.0063 0.9950 -2.2080   
ILT\_analysisNon\_Highway\_road 0.1047 0.7787 0.1345 0.8930 -1.4216   
ILT\_analysisPowerline -0.9405 0.6932 -1.3567 0.1749 -2.2992   
ILT\_analysisPipeline -1.7845 0.7374 -2.4199 0.0155 -3.2298   
 ci.ub   
ILT\_analysisHighway 2.2222   
ILT\_analysisNon\_Highway\_road 1.6310   
ILT\_analysisPowerline 0.4182   
ILT\_analysisPipeline -0.3391 \*   
  
---  
Signif. codes: 0 '\*\*\*' 0.001 '\*\*' 0.01 '\*' 0.05 '.' 0.1 ' ' 1

Multivariate Meta-Analysis Model (k = 102; method: REML)  
  
Variance Components:  
  
 estim sqrt nlvls fixed factor   
sigma^2.1 2.2981 1.5159 24 no Author\_date   
sigma^2.2 2.5101 1.5843 102 no Author\_date/Case.ID   
  
Test for Residual Heterogeneity:  
QE(df = 98) = 2754.9376, p-val < .0001  
  
Test of Moderators (coefficients 1:4):  
QM(df = 4) = 3.1113, p-val = 0.5394  
  
Model Results:  
  
 estimate se zval pval ci.lb   
ILT\_analysisHighway 0.0029 1.0242 0.0028 0.9978 -2.0045   
ILT\_analysisNon\_Highway\_road 0.0668 0.5459 0.1223 0.9027 -1.0033   
ILT\_analysisPowerline 0.8993 0.6777 1.3270 0.1845 -0.4290   
ILT\_analysisPipeline -1.7845 1.5442 -1.1556 0.2478 -4.8111   
 ci.ub   
ILT\_analysisHighway 2.0102   
ILT\_analysisNon\_Highway\_road 1.1368   
ILT\_analysisPowerline 2.2276   
ILT\_analysisPipeline 1.2421   
  
---  
Signif. codes: 0 '\*\*\*' 0.001 '\*\*' 0.01 '\*' 0.05 '.' 0.1 ' ' 1

Multivariate Meta-Analysis Model (k = 78; method: REML)  
  
Variance Components:  
  
 estim sqrt nlvls fixed factor   
sigma^2.1 1.7094 1.3074 34 no Author\_date   
sigma^2.2 0.6491 0.8057 78 no Author\_date/Case.ID   
  
Test for Residual Heterogeneity:  
QE(df = 73) = 1163.7565, p-val < .0001  
  
Test of Moderators (coefficients 1:5):  
QM(df = 5) = 2.4166, p-val = 0.7890  
  
Model Results:  
  
 estimate se zval pval ci.lb   
ILT\_analysisHighway -0.5635 0.6019 -0.9361 0.3492 -1.7433   
ILT\_analysisNon\_Highway\_road 0.2867 0.3165 0.9057 0.3651 -0.3337   
ILT\_analysisPowerline 0.2101 0.6725 0.3124 0.7548 -1.1080   
ILT\_analysisPipeline -0.5034 0.8885 -0.5665 0.5710 -2.2448   
ILT\_analysisRailway 0.2620 0.8731 0.3000 0.7641 -1.4492   
 ci.ub   
ILT\_analysisHighway 0.6163   
ILT\_analysisNon\_Highway\_road 0.9070   
ILT\_analysisPowerline 1.5281   
ILT\_analysisPipeline 1.2380   
ILT\_analysisRailway 1.9732   
  
---  
Signif. codes: 0 '\*\*\*' 0.001 '\*\*' 0.01 '\*' 0.05 '.' 0.1 ' ' 1

There was no striking evidence of publication bias neither for abundance nor for species richness from the funnel plots and the plot of the cumulative meta-analysis by publication year (Additional file **XXX**). Egger’s regression test for funnel plot asymmetry indicated that there was no statistically significant asymmetry neither for abundance (P-value = 0.5) and species richness (P-value = ). Similarly, publication was not significantly correlated to publication year, neither for abundance (r=-0.00164995030535946, P-value=0.986672289827347), nor for species richness (r=0.0133252234793388, P-value=0.907818767753606). Finally, we did not detect any influence of the risk of bias of the study (low or medium) on effect sizes (after removing the effect of type of LTI) for none of the outcome category.

### Effects of moderators on abundance

### Effects of moderators on species richness

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