Title: DISENTANGLING EFFECTS OF LOCAL AND LANDSCAPE VARIABLES ON
ATTRACTIVENESS OF RESTORED GRAVEL-SAND PITS FOR BAT FORAGING
ACTIVITIES

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PITS

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Abstract

Despite the impacts of extraction activities, quarries have great potential for conservation of biodiversity, and their restoration can be considered a major task in restoration ecology. A particularly important issue is to quantify the roles of the following various factors that may influence biodiversity and restoration success: (i) local variables, (ii) landscape variables and (iii) ecological management. Following a multi-model inference we identify which variables were the most useful predictors of bat activity in gravel-sand pits. We used data from 21 French gravel-sand pits provided by the biodiversity-monitoring scheme, ROSELIERE. Our results suggest that within these restored gravel-sand pits, landscape variables appear to be better predictors of the attractiveness of restored gravel-sand pits for the foraging activity of bats than local variables. Species or community indexes appeared to be more sensitive to

landscape variables measured at a large scale (i.e., 1000 m). Among local variables, the time elapsed after operation was a better predictor of bat foraging activity than the description of the habitat itself. The effect was more obvious within a site with an elapsed time since operation greater than 10 years. Our findings suggest that to increase the attractiveness of gravel-sand pits for bat foraging activities, planning policies should consider not only the intrinsic characteristics of a project (i.e. local variables) but also the surrounding environment (i.e. landscape variables).

Keywords: bat community; gravel-sand pit, quarry rehabilitation; time of restoration; scale effect

Introduction

The large number of abandoned quarries represents a challenge for the restoration of these impacted habitats (Yuan *et al.*, 2006). Quarrying operations have profoundly altered preexisting ecosystems: the original topography has changed, the organic soil has been removed and hydrological regimes could have been perturbed (Khawlie *et al.* 1999; Shaban *et al.* 2007). In many sites, the previous ecological functions have been irreversibly disrupted (Milgrom, 2008), and trying to restore the past state may sometimes be impossible (McDonald and Dixon 2018). By offering substitution habitats, postmining sites may provide a haven for various taxa (Benes *et al.* 2003, Bizoux *et al.* 2004, Brändle *et al.* 2000, Dekoninck *et al.* 2010, Dolezalova *et al.* 2012, Harabis, 2016, Kerbirou *et al.* 2018b, Krauss *et al.* 2009, Šálek, 2012, Tropeck *et al.* 2010, Vojar *et al.* 2016), particularly in intensively human-dominated landscapes (Tropeck *et al.* 2010). According to the potential conservation value of these postindustrial sites, restoration management of quarries is now an important task in global restoration ecology (Tischew and Kirmer, 2007).

Restoration intervention can vary along a gradient from passive approaches based on unassisted regeneration to active approaches, including seeding, planting native species or restoring topography or hydrological regimes (Holl and Aide 2011). In terms of management, several studies have underlined that ecological gains were greater in the case of passive restoration based on natural evolution than when restoration was essentially based on human intervention through reclamation works (Brändle et al. 2000; Hodacova and Prach, 2003; Prach et al. 2011; Šálek, 2012; Tropek and Konvicka, 2008; Tropek et al. 2012). Some authors highlight expensive costs associated with active restoration (Catteral and Harrison 2006), while others suggest that passive restoration is laden with unrecognized costs and only slowly reaches its objectives (Zahawi et al. 2014). The debate is still ongoing, but Prach and del Moral (2015) suggest that criteria to choose between passive, intermediate (Uebel et al. 2017) and active restoration may depend on the landscape. Yet, relatively few studies have simultaneously considered within-site (i.e. local variables such as habitat, age, etc.) and landscape variables (surrounding habitats, distance to habitat source, landscape connectivity...etc.) (see Tropek et al. 2010). A better understanding of the relative importance of local and landscape variables could help to mediate the choice between passive and active restoration and to define targets while taking into account the surrounding landscape.

In addition to the restoration strategy, success also depends on target species and their specific traits: rareness, habitat or food specialization (Bezombes et al. 2019, Kraus et al. 2009, Tropek et al. 2010). Some studies highlight the importance of the time since the end of the exploitation as a criteria of recovery success on species richness, such as birds (Šálek 2012), terrestrial plants (Prach et al. 2011, 2013) or butterflies (Benes et al. 2003), while some others did not detect any age-related effect; see Brändle et al. (2000) on dwelling beetle richness or Krauss et al. (2009) on wild bee richness, which identified a habitat variable as the best predictor of recovery success.

Disentangling the relative effects of local and landscape variables could allow a better account of the cumulative impacts on species and habitats resulting from the additive effects of several projects operating in the same region (Bezombes et al. 2017). Such information could improve the sizing of offset measures according to the choice of the restoration processes, their efficiency and the surrounding landscape (Bezombes et al. 2019). We determined which variables, local- (i.e., age, habitat type) or landscape-scale (i.e., surrounding habitat areas or distance to a major resource), were the most useful predictors of bats activity (species relative abundance, richness, community specialization indexes) in 21 French gravel-sand pits. We chose to focus on bats, this group being increasingly threatened worldwide (Mickleburgh et al. 2002). In the European Union, all bat species are strictly protected by the Habitats Directive (Council of the European Union 1992), throughout the life cycle of a development project -including quarries-, developers must demonstrate that they will establish mitigation measures to prevent, reduce and compensate for impacts that result in any loss of bat foraging habitats (Bezombes et al. 2017). The purpose of this study is therefore to highlight the most important variables to consider during the rehabilitation of quarry sites to optimize the biodiversity potential.

Materials and methods

Study area

The study was conducted in France between 2009 and 2013 and involved the survey of 21 gravel-sand pits (Figure 1). Data were provided by ROSELIERE, a biodiversity-monitoring scheme implemented in quarries (for more detail see Supporting Information: Appendix S1 and Kerbiriou et al. 2018b).

The exploitation of these gravel-sand pits often results in the formation of a water body due to the underlying presence of the water table. The aquatic surface represents an average of 42% of the total pit area.

The dataset included quarries at different stages of their life cycle, allowing for the testing of the influence of local characteristics: 17% were quarries under operation, while the others were quarries under rehabilitation, with an ecological purpose (Table 1). Rehabilitation was based on passive restoration, and a spontaneous succession process occurred, leading to the presence of various semi-natural habitats, such as grasslands, wetlands, bushes, and woods.

In order to maintain an equal sampling effort between sites, we adjusted the number of sampled points per site (from 1 to 5 points, mean 3.6 ± 0.3) according to the sites size (mean $74.8 \text{ ha} \pm 2.1$). Therefore, the density of points sampled by sites is of the same order of magnitude as that recommended by the French Bat Monitoring Program (for more detail on the FBMP count point survey see Kerbiriou et al. 2019a). Points were spaced out by 200 meters to avoid, as much as possible, contacting the same bat at different points. Sampled points were relatively close to aquatic habitats (mean average distance to water $202 \text{ m} \pm 68$ (SE)). Between 2009 and 2013, a total of 547 samples were performed.

Local and landscape variables

We tested the effect of environmental variables on bat activity using variables describing local characteristics and variables describing the surrounding landscape.

Local characteristics, which relate to the different stages of the quarries' life cycle and vegetation dynamics, were noted in the field in a homogeneous patch of habitat (within a radius of 50 m around the recording point, in accordance with the maximum distance of detection for the most commonly contacted species in this region, Kerbiriou et al. 2019b). They were defined in two ways: (i) as a categorical variable with five categories of seminatural habitats (bare soil, seminatural grassland, bush (shrubs smaller than 7 m),

woodlands (trees taller than 7 m), and water bodies (with water present predominantly over the year)) and (ii) as a categorical variable with four categories describing the gravel-sand pit state (during quarrying and three categories of rehabilitation according to the time elapsed after operation (<5 years; 5 years<<10 years; >10 years)).

At the landscape scale, we selected land-use variables that are known to influence bat activity. We computed the proportion of the following 9 land-use variables in a 1000-meter buffer around the recording points using CORINE Land Cover (<http://www.eea.europa.eu/data-and-maps>): (1) discontinuous artificial surfaces and (2) mineral extraction sites are expected to negatively influence bat activity due to the loss of semi-natural habitat (Russo and Ancillotto 2015; Kerbiriou et al. 2018a); (3) arable land is related to agriculture intensification and is identified as one of the major pressures on bats (Wash and Harris 1996; Jaberg and Guisan 2001; Azam et al. 2016); (4) pastures, (5) heterogeneous agricultural areas, (6) land principally occupied by agriculture with significant areas of natural vegetation and (7) broad-leaved forest were included because they include different proportions of semi-natural habitat that could potentially benefit bats (Wash and Harris 1996; Boughley et al. 2011, Azam et al. 2016); and two variables describing aquatic habitats – (8) water courses (in the study area, the main water course was channeled) and (9) bodies of water – because they are identified as key habitat for many bat species (Rainho 2007; Salvarina 2016; Wash and Harris 1996). These continuous variables represent the most important habitats of the studied area, covering an average of 96% of the total 1000 m buffer area [min 71% max:100%]. According to the fact that distance to water is among the variables regularly identify for improves drastically the accuracy of bat abundance modelling (Rainho and Palmeirim, 2011; Santos et al. 2013; Sirami et al. 2013), we included in our analysis the distance to nearby water bodies or rivers using BD Carthage (IGN, <http://professionnels.ign.fr/bdcarthage>).

Design Sampling

Bat sampling

Bats were surveyed using standardized echolocation recordings, a robust method for assessing the relationship between bat activities and the corresponding habitat (Stahlschmidt & Bruhl 2012). We followed a similar protocol to the one designed for the French Bat Monitoring Program (see Kerbiriou et al. 2018a). Echolocation calls were automatically detected using a Tranquility Transect Bat detector (Courtpan Design Ltd, UK) and recorded over 6 min on a Zoom H2 digital recorder (Samson technologies, USA) at a sampling rate of 96 ks/s from the two possible outputs of the detector: time expansion (1.28 s of sound at x10 time expansion) and high frequency. Bat activity was assessed using the high frequency output and the time expansion output was used only for species emitting echolocation calls > 48 kHz. All ultrasound detectors were previously calibrated by the French National Museum of Natural History in order to have the same sensitivity levels and enable the detection of echolocation calls while minimizing background noise due to wind or insects (for more detail see Kerbiriou et al. 2018a). In each plot, echolocation recordings were carried out in two visits corresponding to peaks of bat activity: once during the 15th June to 31st July period, during which females are expected to feed their offspring; and second, during the 15th August to 30th September period, during which individuals are expected to be less dependent on their reproductive roost. All points of a site were sampled during the same night. Within each site, the sampling of each 6 minutes points occurred early in the night (not earlier than thirty minutes after dusk and no later than three hours after dusk, thus corresponding to peak bat activity, with such design, time effect on bat abundance is drastically reduce, see Pauwels et al., 2019, Mimet et al. 2020). Observers sampled bats only when weather conditions were favorable (no rain, temperature higher than 12°C and wind speed lower than 5 m/sec).

Bat identification

We used Adobe Audition and Syrinx software version 2.6 (Burt 2006) for spectrogram and spectral analysis. We manually identified bat echolocation after isolating each bat vocalization and extracting relevant parameters (for more details see Kerbiriou et al. 2018b) using Scan'R (Binary Acoustic Technology, 2010). Species were identified at the species level except for two genera: *Plecotus* sp., for which there is a lack of consensus about the acoustic criteria for identification at the species level (Obrist et al. 2004; Barataud 2015) and *Myotis* sp. because of the very low occurrence of each single *Myotis* species and some uncertainties in acoustic identification at the species level (Obrist et al. 2004; Barataud 2015).

2.2.3. Bat activity measurements

Distinguishing individuals from echolocation calls is currently impossible, so, we measured an index of relative bat activity defined as the mean number of bat passes per species over 6 minutes (following Kerbiriou et al. 2019a for the definition of a bat pass). This definition of bat activity is a commonly used measure of relative bat abundance. Although a bat could be detected more than once, bat activity measured over a short time (6 minutes) is highly correlated with the number of recorded individuals flying at a site (Mimet et al. 2020). The response variables were (1) relative abundance of bat passes of the most abundant species recorded (*Pipistrellus pipistrellus* (Schreber, 1774), *Pipistrellus kuhlii* (Kuhl, 1817), *Pipistrellus nathusii* (Keyserling & Blasius, 1839), *Nyctalus noctula* (Schreber, 1774), *Nyctalus leisleri* (Kuhl, 1818), and *Myotis* ssp.), (2) total relative abundance of bat passes, (3) species richness, (4) Community Habitat Specialization Index (CSI) and (5) Community Specialization to Forest (CSF).

The CSI is a mean trait community index based on the average habitat specialization of each species present in the community. Each species was characterized for habitat

specialization through the calculation of a Species Specialization Index (SSI). The SSI varied between 0.54 and 3.86 (Supporting Information: Appendix S2 Table S2). The Community Specialization Index (CSI) is calculated as the arithmetic mean of the SSI of the detected species weighted by their relative abundances (Supporting Information: Appendix S2). We calculated the Community Specialization to Forest (CSF) index as the arithmetic mean of the species specialization to forest habitat (SSF) weighted by their relative abundances. The SSF was the average density of a species in forest habitats divided by its average density in non-forest habitats. It was calculated using the French Monitoring of Bat Populations data, (see Regnery et al. 2013, Supporting Information: Appendix S2).

Data Analysis

We tested the effect of local and landscape variables on bat activities using a generalized linear mixed model (GLMM, R package lme4). The response variable was either species relative abundance ($n = 7$ taxa) or bat community metrics (total relative abundance, richness, CSI, CSF). The explanatory variables were the two local variables (seminatural habitat and gravel-sand pit state) and the ten landscape variables (9 land-use variables and the distance to closest water). We added as covariables the temperature, the season and the year (as a factorial variable) because we assumed that bat activity might be influenced by weather conditions (Ciechanowski et al. 2007) and because we can expect changes in bat relative abundance among periods of the bat life cycle and between years. We also hypothesized that close points, even if their habitats are different, may likely have a similar bat population density due to similar climatic conditions or large-scale landscape compositions. Thus, we included a site effect, and we added an autocovariate (i.e., a distance-weighted function of neighboring response values; Dormann et al. 2007, function autocov_dist package spdep, Bivand R. et al.) with the aim to account for spatial autocorrelation. According to the hierarchical structure of our sampling design (same sites were sampled year to year), we

treated the variable “site” as a random effect, while considering the other explanatory variables as fixed effects (Zuur et al. 2009). For the total relative abundance, rather than summing in an unique metric the raw data of abundance of each species, we included species identity as random intercepts to account for non-independence of observations corresponding to the same species (see Donald et al. 2007; Gamero et al., 2017; Pierret & Jiguet 2018). The explanatory variables were centered and standardized so that the regression coefficients were comparable in magnitude (Schielzeth, 2010). According to the nature of the response variable (i.e., count data), we used a negative binomial error distribution (Zuur et al., 2009) to model relative abundance, total relative abundance, and richness. Because the *N. noctula* model did not fit well, we transformed the response variable (i.e., relative abundance) to presence/absence and then used a binomial error distribution. For CSI and CSF, we used a Gaussian error.

Thus, our global models were structured as follows:

[Bat activity] ~ local variables + landscape variables + season + temperature + year + autocovariate + 1|Site

where bat activity could be the relative abundance of a bat species (n=7) or total relative abundance, or richness or CSI or CSF.

Following a multi-model inference (Burnham et al. 2011; Grueber et al. 2011), we generated a set of candidate models containing all possible variable combinations. We ranked them using the Akaike information criterion corrected for a small sample using the *dredge* function (R package MuMIn). We only built models complying with the following conditions: (i) models do not include more than five variables to avoid overparameterization, (ii) models do not include simultaneously correlated covariates ($R^2 > 0.5$ or non-independent variables such as habitat or gravel-sand pit state, i.e. there is rarely water bodies and woodland at the state "during carrying", while when rehabilitated > 10 years the more common local habitats are

water bodies and woodland see Supporting information S1). For each set of candidate models, we did multi-model inference averaging on a delta AICc <2 using the *model.avg* function (Table S3) to obtain an averaged regression coefficient for each fixed effect (R package MuMIn). Finally, we performed variance-inflation factors (VIF, vif function, package car) on each top model (Fox and Monette 1992). Because all variables showed a VIF value <3 and the mean of VIF values was <2, there was no striking evidence of multicollinearity (Chatterjee et al. 2000). All analyses were performed using R statistical software v 3.1.5

Results

A total of 1542 bat passes belonging to 11 species were recorded on the 21 gravel-sand pit sites (Table 2). According to the recording sampling (547 records of 6 minutes each), the mean bat activity was 28 bats passes/hour [min:0 – max: 850 bat passes/hour]. The majority of echolocation calls from the 11 bat species came from three *Pipistrellus* bat species (Table 1).

Effects of local variables

Among the two local variables, only the gravel-sand pit state appeared in the set of the top models (Table 3, see also Supporting Information: Appendix S3). When this variable was selected, the relative importance was only of concern for community metrics (richness, CSI and total relative abundance) and not for taxa except for the *Myotis spp.* group (Table 3). The difference between the “during quarrying” state and the three other states was only significant for the older state (>10 years elapsed after operation), which exhibited greater relative abundance (Figure 2).

Effects of landscape variables

Among the 11 bat activity metrics tested, the proportion of mineral extraction sites within a radius of 1000 m had a strong negative effect on *N. noctula*, a slight negative but non-significant effect on the total relative abundance and a positive effect on *Myotis* spp. (Table 3, see also Supporting Information: Appendix S3); however, it is noteworthy that the relative importance of this variable for *Myotis* spp. was very weak (Table 3). For the other highly anthropized habitats present in the sites' surroundings (proportion of discontinuous artificial surfaces), we identified a strong negative effect on *N. leisleri* and *Myotis* spp. While the distance to water had a strong negative effect on *P. pipistrellus*, *P. nathusii*, *P. kuhlii*, *Myotis* spp., *N. leisleri*, and *N. noctula*, (Table 4). Therefore, the farther away the surrounding water was from the site, the lower the relative abundance of those species. However, we did not detect any effect of the distance to water on bat community metrics (Table 4). Surprisingly, the proportion of watercourses exhibited a strong negative effect on *P. pipistrellus*, *P. kuhlii*, and all the community metrics (Table 4). Moreover, bodies of water never exhibited any strong effect, except on *N. noctula*. Arable land negatively influences *E. serotinus* relative abundance, whereas land principally occupied by agriculture with significant areas of natural vegetation positively influences *P. kuhlii*, *P. nathusii*, and *E. serotinus*, and heterogeneous agricultural areas positively influenced *P. pipistrellus*, *Myotis* spp. and richness. Pastures had a weak positive effect on *Myotis* spp. Finally, broadleaved forest exhibited a positive influence on *E. serotinus* only.

Discussion

Local variable effect

The local variable based on habitat type was not a good predictor of bat activity, whereas the gravel-sand pit state appeared to be a better predictor but mainly for community metrics. This result suggests that within these gravel-sand pit sites in the process of rehabilitation, the time

elapsed after operation is a better predictor of bat activity and gives more information than the description of the habitat itself. Whatever the bat activity considered - relative abundance of *P. pipistrellus* or *Myotis spp.*, richness, Community Habitat specialization index, the total relative abundance of foraging calls - the effect is more obvious within a site with an elapsed time since operation of greater than 10 years.

This result found in previous analysis (Kerbiriou et al. 2018b) is still robust when this effect is adjusted to landscape variables. This result is consistent with other studies that also highlighted the positive influence of aged quarries on the richness of species such as birds (Šálek 2012) or terrestrial plants (Prach et al. 2011, 2013), but it contrasts with studies that found a negative effect, such as Benes, et al. (2003) on butterflies, or studies that did not detect any age-related effects (Brändle et al. (2000) on dwelling beetle richness, Krauss et al. (2009) on wild bee richness. In the latter, although the authors tested an age gradient of over 120 years, effective habitats were the best predictors. These contrasting findings among taxa are probably linked to their habitat requirements, and bee and butterfly communities are most likely favored by open habitats such as grasslands present in the early stages of succession; while birds and bats need more wooded habitats that require more time to develop. In our study, the bat guild did not include open specialized species: habitat-specialist species were linked to wetlands (*M. daubentonii*, *P. nathusii*) or woodlands (*N. noctula*). In addition, as trees grow and age, they may have cavities that birds or bats could use to nest and harbor insects that are prey for these insectivores (Regnery et al. 2013). The time lag (<10 years) to detect a significant effect on bat activity highlights the need for offset policies to consider the dimension of time between project impacts and gains provided by offset measures (McKenney and Kiesecker 2010). Such results highlight the need of proactive approaches that assess ecological possibilities very far upstream of development projects are needed to better adapt development projects to

ecological equivalence principles (i.e. equivalence between impact sites and offsets sites, Bezombes et al. 2017).

Landscape variable effect

At the landscape scale, distance to the closest water body or river (*Dist. water*) and the proportion of watercourses channeled in a 1000-meter buffer (*Channel*) are among those we identified with the greatest number of strong effects and relative importance (Table 3 & 4). Numerous studies based on acoustic methods, and carried out on the species studied here, identified aquatic habitat as favorable and where species relative abundance is greater (Rainho and Palmeirim 2011; Russ and Montgomery 2002). However, in our study, the three variables linked to the aquatic habitat showed contrasting effects: (1) the proportion of bodies of water in a 1000-meter buffer (*Water bodies*) did not exhibit any strong effects on bat activity, (2) the proportion of water courses channeled in a 1000-meter buffer (*Channel*) exhibited a strong negative effect and no positive effect and (3) the distance to the closest water body or river (*Dist. water*) exhibited a strong negative effect, i.e. the greater the distance to water, the lower the bat total relative abundance. These results seem somewhat contradictory. The effect of distance to the closest water body or river is congruent with many studies (Rainho and Palmeirim, 2011; Barré et al. 2019). The apparent contradiction between distance to water (*Dist. water*) and the proportion of water courses channeled in a 1000-meter (*Channel*) could be explained by the fact that, in our study, the proportion of water courses was extracted from the CORINE Land Cover shape where the water courses digitalized are mainly wide, channeled rivers (i.e., with artificialized banks) and consequently probably of lesser ecological interest (see Corbacho and Sánchez 2001). Second, the accuracy of the two types of variables used was not similar: *Channel* are assessed using CORINE Land Cover, whose precision is very limited (minimum unit of 25 ha), whereas the distance to water was calculated using BD Carthage with a metric spatial resolution. Thus, differences in response

patterns could be linked to spatial data quality or to the lack of precision concerning the ecological characteristics of the water courses or bodies analyzed (small ponds with natural banks are considered by the distance of the water variable vs. the proportion of water habitats variable, which includes only large bodies of water or channeled rivers).

Disentangling the relative importance of local and landscape variables

Among the 11 bat activity measures, local variables performed equally than landscape variables for *Myotis* spp. and total relative abundance and never performed better than landscape variables (Table 3). Thus, in our study, landscape variables appear to be better predictors of the attractiveness of gravel-sand pits for the foraging activity of bats than local variables. This importance of landscape variables is consistent with the requirements of the species studied. Indeed, their home range matches with a radius ranging from 400 m to 1000 m (see Davidson-Watts & Jones, 2005 for *P. pipistrellus* and Flaquer *et al.*, 2009 for *P. nathusii*). Lacoëuilhe *et al.* (2016) studied the effect of landscapes on bat activity and showed a positive scale effect: the set of species we studied here appeared to be more sensitive to large-scale variables (i.e., 1000 m) rather than ones at a smaller scale. Our findings suggest that, with the aim of increasing the attractiveness of rehabilitated gravel-sand pits for bat foraging activities, planning policies should consider not only the intrinsic characteristics (i.e. local variables) of a new quarrying project but also the surrounding landscape (i.e. landscape variable), particularly when defining the conditions for the restoration process. One way of doing that could consist of adopting a proactive approach for the implementation of offsets. In such frameworks, biodiversity offsets of different projects could be used jointly with the aim to restore connectivity between those postexploitation sites and seminatural or natural habitats at the landscape scale and, in turn, reach a functional level of this restored habitat (i.e., a size in accordance with home-range requirements, see Quétier *et al.* 2014). Bearing in mind that different companies finance these individual quarry projects, so the provision of connectivity

by aggregation and layout of biodiversity offsets of different projects requires the existence of an efficient coordination at the landscape/regional scale. Such coordination could potentially be effective through the implementation of a “market” type nature mitigation banking system (Vaissière & Levrel 2015), however several studies provide empirical evidence of the risks of this system (BenDor et al. 2011, Robertson and Hayden 2008, Robertson 2009; Hannis and Sullivan 2012). Another way could be to mobilize tools dedicated to land-use planning by national/regional governments, such as regulations regarding ecological corridors at national scale (e.g. Polish legislation in an amended Nature Conservation Act of 16 October 1991, Koziel et al. 2010; and French regional ecological coherence scheme Act of 12 July 2010, Billon et al. 2017) or at the EU scale.

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Supporting Information

The following information may be found in the online version of this article.

Appendix S1: Detailed information on ROSELIERE program and site survey

Appendix S2: Species Specialization Index and details on the assessment of the Habitat

Specialization Species Index, Community Specializations Indices and Community

Specialization to Forest.

Appendix S3: Additional information on models

694 Table 1. Local characteristics of sites sampled

<i>Seminatural habitat</i>	
bare soil	80
seminatural grassland	211
bush	19
woodland	35
water body	202
<i>Gravel-sand pit state</i>	
during quarrying	95
restoration states <5 years	77
restoration states 5 years<<10 years	164
restoration states >10 years	211

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697 Table 2. Species detected and number of contacts

Species	Number of contact(s)
<i>Myotis alcathoe</i>	1
<i>Myotis brandtii/mystacinus</i>	1
<i>Myotis emarginatus</i>	2
<i>Myotis daubentonii</i>	40
<i>Myotis</i> sp.	83
<i>Myotis</i> spp. total	127
<i>Nyctalus leisleri</i>	106
<i>Nyctalus noctula</i>	82
<i>Eptesicus serotinus</i>	21
<i>Pipistrellus kuhlii</i>	50
<i>Pipistrellus nathusii</i>	86
<i>Pipistrellus pipistrellus</i>	829
<i>Plecotus</i> spp.	4

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699 Table 3. Relative importance of each variable (i.e., relative values of each variable calculated as a sum of the AICc weights over the set of top
700 models in which the term appears). Abbreviations: discontinuous artificial surfaces (*Disc. artificial*), mineral extraction sites (*Min. extraction*),
701 arable land (*Arable*), pastures (*Past.*), heterogeneous agricultural areas (*Hetero. Agri.*), land principally occupied by agriculture, with significant
702 areas of natural vegetation (*Agri. natural.*), broadleaved forest (*Wood.*), water courses, in the study area, the main water course is channeled
703 (*Channel*), bodies of water (*Water*) and distance to closest water bodies or river (*Dist. Water*).

	<i>P. pipistrellus</i>	<i>P. kuhlii</i>	<i>P. nathusii</i>	<i>E. serotinus</i>	<i>N. leisleri</i>	<i>N. noctula</i>	<i>Myotis spp.</i>	Richness	Total relative abundance	CSI	CSF
Local landscape variables											
<i>Seminatural habitat</i>	-	-	-	-	-	-	-	-	-	-	-
<i>Gravel-sand pit state</i>	28	-	-	-	-	-	88	92	100	100	-
Landscape scale variables											
<i>Disc. artificial</i>	-	-	-	17	24	-	82	10	5	-	-
<i>Min. extraction</i>	-	31	-	-	14	100	22	-	78	-	-
<i>Arable</i>	-	-	-	70	-	-	-	15	-	-	-
<i>Past.</i>	-	-	64	22	-	67	19	8	20	-	-
<i>Hetero. Agri.</i>	24	17	-	46	-	33	88	100	49	-	-
<i>Agri. natural.</i>	-	100	44	100	48	-	-	-	-	-	-
<i>Wood.</i>	-	-	-	35	-	-	-	-	-	-	-
<i>Channel</i>	100	18	17	-	-	-	24	100	100	100	33
<i>Water bodies</i>	-	-	-	70	11	100	-	-	17	-	-
<i>Dist. water</i>	72	100	100	-	89	100	-	-	-	-	-
Covariables											
<i>Autocovariate</i>	-	100	40	-	100	-	19	9	15	100	100
<i>Year</i>	100	-	100	-	-	-	-	100	-	-	-
<i>Season</i>	100	56	100	66	100	100	72	12	36	-	-
<i>Temperature</i>	76	54	6	49	90	-	-	10	13	-	-

710 Table 4: Conditional average estimate and adjusted SE of the effect of landscape variables on bat activity. For abbreviations, see Table 3 legend.

711 (*** P < 0.001, ** P < 0.01, * P < 0.05, . P < 0.1).

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	<i>P. pipistrellus</i>	<i>P. kuhlii</i>	<i>P. nathusii</i>	<i>E. serotinus</i>	<i>N. leisleri</i>	<i>N. noctula</i>	<i>Myotis</i>	Richness	Total relative abundance	CSI	CSF
	β_{cond}	β_{cond}	β_{cond}	β_{cond}	β_{cond}	β_{cond}	β_{cond}	β_{cond}	β_{cond}	β_{cond}	β_{cond}
Disc. artificial				0.441±0.433	- 0.557±0.284*		- 0.527±0.204*	-0.056±0.070	0.008 ±0.130		
Min. extraction		-0.486±0.278			-0.427±0.288	- 0.446±0.213*	0.333±0.132*	0.019±0.060	-0.198±0.105		
Arable		.		- 1.016±0.467*				-0.067±0.052	.		
Past.			-1.394±0.716	0.621±0.414		-1.109±0.890	0.859±0.430*	0.053±0.086	0.225±0.178		
Hetero. Agri.	0.079±0.157*	0.384±0.284	.			-0.376±0.238	0.949±0.211*	0.150±0.066*	0.217±0.136		
Agri. natural.		0.733±0.186*	0.400±0.156*	0.738±0.319*	-0.515±0.262				-0.020±0.088		
Wood.		**		0.964±0.449*							
Channel	- 0.566±0.168*	0.497±0.409	-	0.614±0.308*			-0.436±0.274	- 0.239±0.081*	- 0.562±0.139*	- 0.207±0.072*	- 0.036±0.013*
	**							*	**	*	*
Water bodies				-0.878±0.469	0.430±0.318	- 0.452±0.197*			0.103 ±0.124		

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723 Figure 1. Map of the gravel-sand pits sites of ROSELIERE program and sampled points

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725 Figure 2. Predicted difference of bat activities between the state “during quarrying” (i.e., the

726 intercept) and the three gravel-sand pit restoration states (<5 years; 5 years<<10 years and

727 >10 years). *P. pipistrellus* relative abundance (A), *Myotis* spp. relative abundance (B),

728 richness (C), community habitat specialization index (D), and the total relative abundance of

729 foraging calls (E). (***) $P < 0.001$, (**) $P < 0.01$, (*) $P < 0.05$, (.) $P < 0.1$).

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Supporting information, Appendix S1: Detailed information on ROSELIERE program and site survey

The ROSELIERE program (<http://programme-roseliere.fr/node/21>), is a biodiversity monitoring scheme, implemented with the aim to (i) assess the level of biodiversity on a large number of quarries nationwide, (ii) assess the success of gravel-sand pits restoration, (iii) understand the basic processes that promote or reduce the conservation effectiveness of these restoration programs.

Table S1: Number of sampled points according to habitat and state

State	Water bodies	Bare soil	Semi-natural grassland	Bush	Woodland
During quarrying	6	70	15	4	0
Rehabilitated <5 years	30	8	39	0	0
Rehabilitated 5 years << 10 years	66	2	88	4	4
Rehabilitated > 10 years	100	0	69	11	31

Supporting information, Appendix S2: Assessment of Habitat Specialization species index, Community Specializations Indices and Community Specialization to Forest
Habitat Specialization species index were assessed using data provided the French Monitoring of Bats population (see Kerbiriou *et al.*, 2018).

Assessment of specializations indices

In the French national bat monitoring volunteers were involved in collecting habitat variable on a detailed and adapted basis. Habitat information is recorded on the first reconnaissance visit to the circuit. The appropriate habitat codes are chosen from an established hierarchical system allowing to describe more than 950 habitat types, which is very similar to widely used habitat code in bird monitoring schemes (see Crick 1992 for the UK and Barnagaud *et al.* 2012 for the French monitoring), but adapted to take account of bat foraging specifics and particularly linear elements (for more details about the French Bat monitoring see the website [<http://vigienature.mnhn.fr/page/relevés-d-habitats>]). Habitat classes are collected in a radius of 100 m around the sampled point and grouped into 18 classes in order to obtain sufficient number of sample per class (for more methodological information see Julliard *et al.* 2006; DeVicor *et al.* 2008; Kerbiriou *et al.* 2019).

Specialization species index (SSI)

We quantified the species specialization index (SSI), which is the degree of habitat specialization for a species, as the coefficient of variation (SD/mean) of its densities across habitats following Julliard *et al.*'s approach (2006). SSI is thus independent to species habitat preferences. However, it is also possible to assess the species specializations to forest habitats by calculating the average density of a species inventoried in forest habitats divided by the average density in non-forest habitats.

Table S2: Species Specialization Index

Bat species	Species Specialization index (SSI)	Specialization to forest (SSF)
Barbastelle (<i>Barbastella barbastellus</i>)	3.64	0.61
Serotine bat (<i>Eptesicus serotinus</i>)	1.50	0.51
Greater mouse-eared bat (<i>Myotis myotis</i>)	3.19	0.24
Daubenton's bat (<i>Myotis daubentonii</i>)	3.48	0.07
Whiskered bat (<i>Myotis mystacinus</i>)	3.86	0.51
Natterer's bat (<i>Myotis nattereri</i>)	2.40	0.67
Lesser noctule (<i>Nyctalus leisleri</i>)	0.95	0.42
(<i>Nyctalus noctula</i>)	1.58	0.49
Kuhl's Pipistrelle (<i>Pipistrellus kuhlii</i>)	0.75	0.17
Nathusius's pipistrelle (<i>Pipistrellus nathusii</i>)	3.06	0.39
Common Pipistrelle (<i>Pipistrellus pipistrellus</i>)	0.54	0.20
Soprano Pipistrelle (<i>Pipistrellus pygmaeus</i>)	1.79	0.12
Lump-nosed bats (<i>Plecotus sp.</i> , mainly <i>P. austriacus</i>)	1.36	0.11
Mouse-eared bats (<i>Myotis sp.</i>)	1.83	0.23
Savi's Pipistrelle (<i>Hypsugo savii</i>)	3.19	0.06

Assessment of bat community specializations indices

- The Community Specialisation Index (CSI)

The CSI is calculated as the arithmetic mean of the species specialization index (SSI) of the species detected, weighted by the relative abundances (Julliard *et al.* 2006) (Eq. (1)).

$$CSI_j = \frac{\sum_{i=1}^n a_{ij} (SSI_i)}{\sum_{i=1}^n a_{ij}} \text{ (Eq. 1)}$$

where n is the total number of species recorded, a_{ij} is the abundance of individuals of species i in plot j , and SSI_i its specialization index.

To calculate the *Myotis* group CSI, we used the sum of identified *Myotis* species' calls and the average of the CSI known of identified *Myotis* species.

The CSI reflects the relative abundance of more or less specialized species in local assemblages and is therefore expected to decrease following the relative declines of specialists (species with a high SSI). For the analyses, we kept only sites with a non-null abundance because a null CSI does not describe a generalist community.

The Community Specialization to Forest (CSF).

The CSF is calculated as the arithmetic mean of the species specialization to forest habitats (SSF) weighted by the abundances. The SSF is the average density of a species inventoried in forest habitats divided by its average density in non-forest habitats. Contrary to SSI, here we consider species from the most to the least habitat dependent to forest habitats. So far, the degree of habitat specialization was based on expert knowledge in bats, but here we could use species and community indices from standardized monitoring methods. The species specialization index was systematically checked with the literature to confirm the forest-dependency gradient among bat species (Table S1). Finally, we calculated the mean specialization to forest habitats using the same equation model as for community specialization index (see Eq. (1)).

For CSI and CSF relative abundance, so this measure was corrected by species distance of detection (Barataud 2015), species bat activity was weighted by the multiplicative inverse of the distance of detection squared, thus a species with a great distance of detection contributes less for total relative abundance than a species with a small distance of detection.

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Supporting information, Appendix S3: Additional information on models

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Table S3: Set of top models for species and communities metrics, with df, log-likelihood, AICc, Δ AICc and 'Akaike weights. Abbreviations: Gravel-sand pit state (State), Semi-natural habitat (Habitat), discontinuous artificial surfaces (*Disc. artificial*), mineral extraction sites (*Min. extraction*), arable land (*Arable*), pastures (Past.), heterogeneous agricultural areas (*Hetero. Agri.*), land principally occupied by agriculture, with significant areas of natural vegetation (*Agri. natural.*), broad-leaved forest (*Wood.*), water courses, in the study area, the main water course is channelled (*Channel*), bodies of water (*Water*) and distance to closer water bodies or river (*Dist. Water*), Temperature (*Temp.*).

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Model	df	log-likelihood	AICc	delta	weight
<i>P. pipistrellus</i> (error distribution: Negtive binomial)					
Channel + Dist. Water + Year + Season + Temp.	11	-779.28	1581.05	0.00	0.48
Channel + Year + Season + State + Temp.	13	-777.71	1582.10	1.06	0.28
Hetero. Agri. + Channel + Dist. Water + Year + Season	11	-779.96	1582.41	1.37	0.24
<i>P. kuhlii</i> (error distribution: Negtive binomial)					
Min. extraction + Agri. natural + Dist. Water + Season + Autocovariate	8	-76.73	169.74	0.41	0.14
Min. extraction + Agri. natural + Dist. Water + Autocovariate + Temp.	7	-77.90	170.00	0.68	0.12
Agri. natural + Dist. Water + Season + Autocovariate	7	-77.91	170.03	0.70	0.12
Agri. natural + Dist. Water + Autocovariate + Temp.	8	-77.08	170.42	1.09	0.10
Agri. natural + Dist. Water + Season + Autocovariate + Temp. Temp.	8	-77.09	170.46	1.13	0.10
Hetero. Agri. + Agri. natural + Dist. Water + Autocovariate + Temp. + Temp.	8	-77.18	170.62	1.29	0.09
Agri. natural + Channel + Dist. Water + Autocovariate + emp. + Temp.	8	-77.18	170.62	1.30	0.09
Agri. natural + Channel + Dist. Water + Season + Autocovariate + Temp.	8	170.97	170.97	1.65	0.07
<i>P. nathusii</i> (error distribution: Negtive binomial)					
Agri. natural + Dist. water + Year + Season + Autocovariate	11	-162.83	348.16	0.00	0.17
Past. + Channel + Dist. water + Year + Season	11	-162.88	348.25	0.09	0.17
Past. + Agri. natural + Dist. water + Year + Season	11	-162.96	348.42	0.26	0.15
Past. + Dist. water + Year + Season + Autocovariate	11	-162.98	348.46	0.29	0.15
Agri. natural + Dist. water + Year + Season	10	-164.30	349.01	0.85	0.11
Past. + Dist. water + Year + Season	10	-164.40	349.22	1.06	0.10
Dist. water + Year + Season + Autocovariate	10	-164.73	349.87	1.71	0.07
Past. + Dist. water + Year + Season + Temp.	11	-163.83	350.14	1.98	0.06
<i>Nyctalus noctula</i> (error distribution: Binomial)					
Dist. water + Min. extraction + Past. + Water + Season	7	-118.74	251.68	0.00	0.67
Dist. water + Min. extraction + Hetero. Agri. + Water + Season	7	-119.45	253.11	1.43	0.33
<i>Nyctalus leisleri</i> (error distribution: Negtive binomial)					
Agri. natural + Dist. Water + Season + Autocovariate + Temp.	8	-171.78	359.83	0.00	0.27
Min. extraction + Dist. Water + Season + Autocovariate + Temp.	8	-172.40	361.06	1.23	0.14

Disc. Artificial + Dist. Water + Season + Autocovariate + Temp.	8	-172.45	361.16	1.32	0.14
Dist. Water + Season + Autocovariate + Temp.	7	-173.53	361.27	1.43	0.13
Agri. natural + Season + Autocovariate + State + Temp.	10	-170.58	361.57	1.74	0.11
Water+ Dist. Water + Season + Autocovariate + Temp.	8	-172.66	361.58	1.75	0.11
Disc. Artificial + Agri. natural+ Dist. Water + Season + Autocovariate	8	-172.75	361.76	1.92	0.10

Myotis spp. (error distribution: Negtive binomial)

Disc. artificial + Hetero. Agri.+ Channel + Season + State	10	-233.96	488.33	0.00	0.16
Disc. artificial + Hetero. Agri. + Season + State	9	-235.30	488.94	0.61	0.12
Disc. artificial + Min. extraction + Hetero. Agri. + Season + State	10	-234.42	489.25	0.92	0.10
Disc. artificial + Hetero. Agri. + Season + State + Disc. Artificial + Temp.	10	-234.52	489.46	1.13	0.09
Disc. artificial + Hetero. Agri. + Channel + State	10	-235.68	489.70	1.37	0.08
Disc. artificial + Hetero. Agri. + State	9	-236.77	489.81	1.48	0.08
Disc. artificial + Past. + Hetero. Agri. + Season + State	8	-234.76	489.93	1.60	0.07
Disc. artificial + Hetero. Agri. + Season + Autocovariate + State	10	-234.86	490.14	1.81	0.06
Disc. artificial + Min. extraction + Hetero. Agri. + State	9	-235.94	490.21	1.88	0.06
Past. + Dist. water + Season + Autocovariate	7	-238.01	490.22	1.89	0.06
Min. extraction + Hetero. Agri. + Season + State	9	235.96	490.26	1.93	0.06
Past. + Dist. water + Autocovariate	6	-239.06	490.28	1.95	0.06

Richness (error distribution: Negtive binomial)

Hetero. Agri. + Channel + Year + State	12	-637.18	1298.95	0.00	0.20
Min. extraction + Hetero. Agri. + Channel + Year + State	13	-636.40	1299.47	0.52	0.15
Hetero. Agri. + Channel + Year + Season + State	13	-636.64	1299.96	1.01	0.12
Disc. artificial + Hetero. Agri. + Channel + Year + State	13	-636.82	1300.33	1.38	0.10
Hetero. Agri. + Channel + Year + State + Temp.	13	-636.88	1300.44	1.49	0.10
Hetero. Agri. + Channel + Year + Autocovariate + State	13	-636.90	1300.47	1.52	0.09
Past. + Hetero. Agri. + Channel + Year + State	13	-637.00	1300.68	1.73	0.08
Hetero. Agri. + Channel + Year	9	-641.27	1300.88	1.93	0.08
Min. extraction + Hetero. Agri. + Channel + Year + State	13	-637.13	1300.95	2.00	0.07

Total relative abundance (error distribution: Negtive binomial)

Min. extraction + Channel + State	8	1988.07	3992.18	0.00	0.07
Min. extraction + Hetero. Agri. + Channel + State	9	1987.10	3992.26	0.08	0.06
Min. extraction + Hetero. Agri. + Channel + Season + State	10	1986.16	3992.38	0.20	0.06
Min. extraction + Past. + Channel + State	9	1987.17	3992.39	0.21	0.06
Min. extraction + Channel + Season + State	9	1987.23	3992.50	0.32	0.06
Min. extraction + Past. + Channel + Season + State	10	1986.31	3992.68	0.50	0.05
Min. extraction +Channel + Season + State + Temp.	10	1986.36	3992.78	0.60	0.05
Hetero. Agri. + Channel + State	8	1988.43	3992.90	0.72	0.05
Hetero. Agri. + Channel + Season + State	9	1987.48	3993.02	0.84	0.04
Min. extraction +Hetero. Agri. + Channel + Autocovariate +State	10	1986.59	3993.25	1.07	0.04
Min. extraction +Past. + Channel + Autocovariate +State	10	1986.72	3993.49	1.31	0.03
Min. extraction +Channel + Water + State	9	1987.77	3993.58	1.40	0.03
Min. extraction +Hetero. Agri. + Channel + Water + State	10	1986.78	3993.62	1.44	0.03
Min. extraction +Past. + Channel + Water + State	10	1986.80	3993.66	1.48	0.03

Min. extraction + Channel + State + Temp.	9	1987.87	3993.79	1.61	0.03
Hetero. Agri. + Channel + Autocovariate + State	9	1987.89	3993.83	1.65	0.03
Min. extraction + Past. + Hetero. Agri. + Channel + State	10	1986.89	3993.84	1.66	0.03
Hetero. Agri. + Channel + Season + Autocovariate + State	10	1986.90	3993.87	1.69	0.03
Min. extraction + Channel + Water + Season + State	10	1986.95	3993.96	1.78	0.03
Hetero. Agri. + Channel + Water + State	9	1987.97	3993.98	1.80	0.03
Disc. artificial + Min. extraction + Channel + State	9	1987.97	3993.98	1.80	0.03
Hetero. Agri. + Channel + Season + State + Temp.	10	1986.97	3994.00	1.82	0.03
Min. extraction + Channel + Autocovariate + State	9	1988.03	3994.10	1.92	0.02
Min. extraction + Hetero. Agri. + Channel + State + Temp.	10	1987.04	3994.14	1.96	0.02
Min. extraction + Agri. natural + Channel + State	9	1988.05	3994.14	1.96	0.02
Disc. artificial + Min. extraction + Hetero. Agri. + Channel + State	10	1987.06	3994.18	2.00	0.02
Hetero. Agri. + Channel + Water + Season + State	10	1987.06	3994.18	2.00	0.02

CSI (error distribution: Gaussian)

Chanel + Autocovariate + State	8	-637.85	1291.96	0.0	0.66
Chanel + Autocovariate	5	-641.58	-641.58	1.3	0.34

CSF (error distribution: Gaussian)

Chanel	4	288.76 -	-569.45	0.00	0.67
Channel + Autocovariate	5	289.09 -	-568.07	1.38	0.33

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