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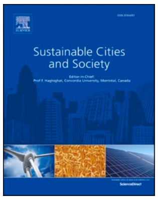

How the built environment influences pollinator diversity in urban landscapes: An analysis of French cities using participative data

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ABSTRACT

Most of our knowledge of the factors favoring pollinating insects in urban areas arises from studies focused on urbanization gradients. However, when it comes to differentiating among types of built fabric according to their capacity to host pollinators, few information can be found. In this paper, we study the influence of built fabric patterns on pollinating insects using open data from citizen science and covering the whole of France. With pollinator richness as the response variable in a model focused on urban agglomerations, we test the relevance of spatial metrics describing the building patterns while accounting for other drivers such as plant species, season, climate, and the connectivity of herbaceous habitats. We divide the data into subsets covering varying ranges of building densities, to explore those for which built fabric types exhibit the greatest differences. Our results show that only a focus on moderate building densities reveals clear differences between built fabric types. In this case, the areas with old individual housing appear to be more favorable than other patterns dominated by individual housing built in the post-war period and in the late twentieth century. These results outline the potential of the coupling of participative naturalist data with geographical data.

1. Introduction

Urban biodiversity has merged as a major concern in urban planning over the last decades, since urban areas are no longer perceived as biologically poor environments in contrast to their surrounding landscape (Savard et al., 2000; Spotswood et al., 2021) and they may even sometimes serve as refuge areas in response to extinction threats (Hall et al., 2017; Soanes & Lentini, 2019). The increasing concern for urban biodiversity has also been fostered in conjunction with the issue of the sustainability of urban environments (Wu, 2014) and with the growing interest in urban green spaces and their contribution to the residents' quality of life (Chiesura, 2004; Sadler et al., 2010), whether for health, well-being, thermal comfort, social interactions, or connection to nature (Hunter et al., 2019; Pinto et al., 2022). Indeed, in the context of urban planning policies designed to increase density so as to limit urban sprawl (Idt & Pellegrino, 2021), maintaining green spaces and urban biodiversity remains a critical issue.

Among the different biological groups considered in urban ecosystems, pollinating insects deserve particular attention due to their key role in the production of the fruits and seeds of flowering plants via the pollination function (Smith et al., 2015). But these species are experiencing a critical decline (Biesmeijer et al., 2006; Jacquemin et al., 2020) mainly caused by environmental pollution resulting from agriculture intensification and the use of herbicides and pesticides (LeBuhn & Vargas Luna, 2021; Liang et al., 2023; Muratet & Fontaine, 2015). Consequently, urban areas, in contrast to agroecosystems, could potentially serve as refuges for many of these species (Baldock et al., 2015; Hall et al., 2017; Theodorou et al., 2020) and provide "pollinator habitats" useful for food production (Gren & Andersson, 2018). However, the issue of protecting and maintaining pollinator communities in urban areas is still a challenge because their richness and their abundance remain lower than in semi-natural landscapes (Bates et al., 2011), and their response to urban constraints proves to be largely trait-dependent (Cohen et al., 2022; LeBuhn & Vargas Luna, 2021; Liang et al., 2023). Urban land uses tend to favor generalist species or cavity nesters at the expense of specialists and ground nesting species (Casanelles-Abella et al., 2022; Geslin et al., 2016; Jacquemin et al., 2020; Wenzel et al., 2020) with few threatened species being established (Fauviau et al., 2024).

Despite this variability, several consistent patterns emerge regarding pollinators in urban environments. Locally, many studies highlight the major role of floral diversity, resulting in an increased number of

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successive flowering stages (Anderson et al., 2023; Bates et al., 2011; Cohen et al., 2022; Desaegher et al., 2018; Dylewski et al., 2020; Roguz et al., 2023; Sikora et al., 2020; Wang et al., 2024). The origin of the floral species, weather native or non-native, may impact the response of pollinators (Zaninotto et al., 2023) while the management style of green spaces is a crucial factor (Dylewski et al., 2020; Persson et al., 2020). At a larger scale, pollinator richness and abundance largely depend on the amount of vegetation present in the built fabric, including urban parks, gardens, lawns, meadows, and so on (Wenzel et al., 2020). This explains why, at the urban agglomeration level, a density-dependent pattern is frequently observed along an urbanization gradient, despite some adaptation of feeding regimes according to urban density (Casanelles-Abella et al., 2022). Given this pattern, low human densities (or a low proportion of impervious surfaces) encountered in European urban peripheries promote pollinator richness and abundance compared to the high densities of urban centers (Fortel et al., 2014; Geslin et al., 2016; Lequerica Tamara et al., 2023; Persson et al., 2020).

Nevertheless, when it comes to distinguishing different types of built fabric according to their capacity to host pollinators, few elements are found in the literature (Wenzel et al., 2020). Apart from the previous density-dependent pattern, little is known about the connection between the spatial configuration of built environments and pollinator communities. The usual urban-rural gradient gives prominence to the amount of greenery, but tends to mask the difference in impact due to the variations in composition and spatial configuration of urban settlements. Individual and collective housing, for example, may have similar building densities at the neighborhood scale (Boyko & Cooper, 2011) but may provide to pollinators environments that differ in the layout of their buildings and their plots, and in the layout and the management mode of the herbaceous areas that act as suitable habitats for pollinators.

Beyond the neighborhood scale, another knowledge-gap relates to the potential role of habitat connectivity within the urban landscape via the processes of foraging and dispersal. While many studies address the role of local resources, very few try to include the role of biological corridors interspersed in the built fabric (Vasiliev & Greenwood, 2023), as for other taxonomic groups (Alves d'Acampora et al., 2023; Kang et al., 2012). Distance criteria are sometimes considered (Banaszak-Cibicka et al., 2016; Buchholz et al., 2020), but using Euclidean distances rather than distances considering landscape matrix heterogeneity (Fattorini et al., 2018). Since the connectivity of herbaceous areas involves numerous potential criteria favoring pollinators, it is a factor that should be considered when comparing built fabric patterns, to control for these confounding factors in the analyses.

In this study, we aim to analyze the influence of the built fabric on pollinating insects. Given that the differences among built fabric types may be overly dominated by the density criterion when considering too large a range of building densities (Boyko & Cooper, 2011), we assume that (1) the influence of the built fabric on pollinators can be better detected when focusing on a moderate level of building density, i.e. setting aside the dense urban centers and the suburban areas, (2) the spatial metrics describing the built fabric capture an additional set of information against the other environmental drivers involved such as plant diversity, season, climate, quantity and connectivity of the herbaceous habitat. To test these assumptions on a large set of spatial configurations without site effects, we chose to use an open database from citizen science (Poisson et al., 2020) covering the whole of metropolitan France. Using generic geographical data describing land use and land cover throughout the territory, we characterize the built environment via building typologies and quantify herbaceous connectivity using graph-based modelling (Foltête et al., 2012).

2. Material and methods

2.1. Dataset on pollinators

We used the participatory database SPIPOLL managed by the Muséum National d'Histoire Naturelle and covering the whole of France (https://www.spipoll.org/). This database collates a large series of "collections" compiled using a standardized protocol. Each collection corresponds to a geolocated and dated flowering plant species along with the photographs of all the insect species (including *Coleoptera, Diptera, Hymenoptera*, and *Lepidoptera*) that visited the flower during an observation window of 20 min. These data were harmonized and validated. They have already been used to identify the effect of land-use variations (Deguines et al., 2012), to describe plant-species networks (Desaegher et al., 2018) and their relation to urbanization (Deguines et al., 2016), and to determine the role of domestic gardens (Levé et al., 2019).

In the present study, we use the data for the years 2016 to 2023 located within urban agglomerations. These agglomerations were defined as the catchment area of cities delineated by the French Institute of Statistics and Economic Studies (INSEE) with a minimum population of 100,000 inhabitants. The initial dataset included 26,686 collections distributed in 101 cities and including 896 flowering plant species. The response variable of the statistical analyses was pollinator richness, expressed as the number of insect families because for a substantial number of collections the lower taxonomic levels (genera, species) were not documented or not reliable enough. The data included 44,508 insects distributed in 134 insect families, with *Syrphidae* and *Apidae* as dominant families amounting 20 % and 19 % of the individuals respectively (see Appendix 1 for details).

2.2. Built environment

The built environment of the SPIPOLL collections was characterized using data from BD Topo®, a nationwide geographical database including a layer in which each building is represented by a polygon with a geometric accuracy of 1 m and is documented by a large series of attributes (e.g., type of building, number of floors, year of construction, etc.) (Table 1).

We first defined a "*Plot type*" variable by overlaying this layer on the French cadastral plan (BD Parcellaire®). The aim was to classify the plot in which each collection is located according to the building type present on the plot, leading to five plot types being defined by grouping the building types of Table 1: individual housing (detached or terraced house), collective housing (small, medium, or large collective building), building for professional use (including commercial, industrial, farm, religious and sports buildings), annex building, and no building. The plot type was considered as a rough proxy for the management type, with the assumption that the plots without buildings or with annex buildings are managed in a more extensive way than plots with residential buildings.

The other variables describing the built fabric were based on a circular buffer surrounding each SPIPOLL collection, with a radius related to the distances of foraging movements known for pollinator insects. As this range mainly varies between 100 and 600 m depending on the species (Cant et al., 2005; Hofmann et al., 2020; Peterson et al., 2006; Stevens et al., 2010; Zurbuchen et al., 2010), we chose a value of 500 m to account for most taxa. Considering all buildings within each buffer, we defined two variables: (1) the *Building coverage ratio*, i.e. the ratio of built area to the neighborhood area (Berghauser Pont & Haupt, 2005), and (2) a *Built fabric typology* synthesizing the composition of the built environment from 39 descriptors. These descriptors were the proportion (%) of the 11 building types with regard to the total number of buildings in the neighborhood (Table 1). As the historical dimension is important for a fine description of the built fabric (Moudon, 1997), the most frequent types were separated into four construction periods (before 1945, 1945–1974, 1975–1999, since 2000), plus an "unknown" class when this attribute was not documented, yielding a set of 39 descriptors (Table 1). To generate the *Built fabric typology*, we used a principal component analysis (PCA) followed by a hierarchical ascendant classification (HAC) applied to the main components of the PCA and based on

Table 1
Building types used for the description of the built fabric.

Building type	Description	For the built fabric typology only	
		Distinction according to the four periods of construction (plus "unknown")	Number of descriptors
Detached house	Detached house for residential use including single-family housing	yes	5
Terraced house	House adjacent to another house, for residential use and including single-family housing	yes	5
Small collective building	Building for residential use with more than one housing unit and up to 3 storeys high	yes	5
Medium collective building	Building for residential use with more than one housing unit and 4 or 5 storeys high	yes	5
Large collective building	Building for residential use with more than one housing unit and at least 6 storeys high	yes	5
Commercial building	Building for commercial and service use	yes	5
Industrial building	Building for industrial use	yes	5
Farm building	Building for agricultural use	no	1
Religious building	Building for religious use	no	1
Sports building	Building for sports use	no	1
Annex building	Garage, veranda, garden shed, etc.	no	1

the Ward criterion. Since we successively tested several selections of SPIPOLL collections to identify the suitable building density range (see Section 2.4), the statistical reduction was applied for each dataset specifically, so as to adapt the *Built fabric typology* resulting from the classification to the statistical variations of the corresponding samples of collections. To make the datasets comparable, we selected in each case the first two components in the PCA. Similarly, we selected approximately the same number of classes from the HAC for each case (4 to 6 classes), by considering the decrease in inter-class dissimilarity.

2.3. Land cover data and landscape variables

We used the OSO land cover map covering the whole of France (https://www.theia-land.fr/en/ceslist/land-cover-sec/) at a spatial resolution of 10 m with 23 thematic classes (version of 2020). A specific land cover map was extracted around each SPIPOLL collection in a 10,000 m-radius circular area. This size was chosen to encompass the environment of the collections at a wide spatial scale so as to consider not only foraging but also dispersal movements.

Within the circular area defined for a given collection, a series of landscape variables were computed. The amount of reachable herbaceous habitat was evaluated by a spatial modelling approach relying on landscape graphs (Galpern et al., 2011; Urban & Keitt, 2001). In these graphs, the nodes are the patches of the optimal habitat for the target species and the links represent the potential fluxes. In our case, the nodes were the herbaceous patches. The links were defined so as to shape a minimal planar graph (Fall et al., 2007) in which each inter-patch link was weighted by the cumulated cost of the least-cost path. The least-cost paths were computed using cost values assigned to the land cover classes, given the general knowledge of the pollinating insect movements in the urban matrix (Rochat et al., 2017) and advices from experts (Table 2). A contrasted scale was applied from the optimal habitat (cost of 1) to the classes least conducive to insect movements (cost of 1000).

The landscape graph built in the neighborhood of each SPIPOLL collection served as the baseline for computing two connectivity metrics: one to approximate the connectivity for daily movements (between foraging habitats) and the other to represent the landscape connectivity for dispersal movements (at a much larger scale). The first metric, named "*Resource*," represents the amount of herbaceous surface areas that can be reached for foraging from the location of the SPIPOLL collection. The herbaceous areas included in this computation may be located inside or outside the urban fabric. The metric gives weight to nearby herbaceous patches by combining their area with the cost-distance between the collection and the patches in the following manner:

$$\boldsymbol{Resource_i} = \sum_j \boldsymbol{a_j e^{-\alpha_r d_{ij}}}$$

with a_j the area of patch j, d_{ij} the cost-distance between the collection i and the patch j, and α_r the parameter controlling the decrease in movement with distance. We chose α_r so that $e^{-\alpha d} = 0.5$ for d corresponding to the median foraging distance of pollinators. Given that this metric implies a conversion between Euclidean and cost-distance units (Appendix 2), the cumulated cost corresponding to 500 m was 1100. It should be noted that because of the medium resolution of the land cover map, some collections are located inside a patch while others are located in the matrix. In the latter case, they were connected by links to the nearby patches in the landscape graph.

The second metric, named "*Flux*", corresponds to the potential dispersal flux occurring from the herbaceous patches located in the neighborhood of the collection.

$$\boldsymbol{Flux_i} = \sum_j \boldsymbol{a_j e^{-\alpha_f d_{ij}}}$$

The formula is the same as for *Resource* but with a specific parameter α_f set so that $e^{-\alpha d} = 0.5$ for d corresponding to the median dispersal distance of 4000 m. It thus represents the same type of computation as *Resource* but for a wider spatial scale. Graphs were built and *Resource* and *Flux* calculated using Graphab 3.0 (Foltête et al., 2021).

As the proximity of crops, orchards, and vineyards is assumed to have a negative influence on pollinators due to the widespread use of pesticides in agricultural areas (LeBuhn & Vargas Luna, 2021), we calculated three additional binary variables assessing the nearby presence (or absence) of crops (including all types of crops in Table 2), orchards, and vineyards.

Table 2
Cost value assigned to land cover classes. The 23 initial land cover classes were grouped into 13 classes.

Land cover class	Cost value
Dense built fabric	1000
Low density built fabric	500
Industrial and commercial area	1000
Road and associated land	1000
Crops of cereals and corn	100
Other crops	10
Grassland and lawn	1
Orchard	10
Vineyard	10
Forest	100
Heathland	10
Mineral area, beach and dune	100
Water body, glacier and snow	1000

2.4. Statistical design

As pollinator richness is a count variable, we fitted a Generalized Linear Mixed Model (GLMM) using a Poisson regression and log link function (Jiang, 2007). We considered as fixed effects the variables corresponding to our main hypotheses (*Built fabric typology, Building coverage ratio, Plot type*, and the two connectivity metrics) plus the three landscape variables (*Crop, Orchard*, and *Vineyard*) (Table 3). Since specialist pollinators depend heavily on specific flowers but this well-known relationship was not within our scope, we considered the identity of the flowering plant species on which pollinators were observed as a random effect. Given the wide geographical and temporal coverage of our data, we also used urban agglomeration, climate type, and date (i.e., combination of month and year) as random effects to avoid spatial and temporal autocorrelation. The climate zones were taken from Joly et al. (2010) (Appendix 3). As our approach was to apply the "traditional null-hypothesis significance testing" (Tredennick et al., 2021) and not to make out-of-sample predictions, we directly included all the fixed and random effects into the model.

To specify the conditions in which the role of urban fabric can be detected, we applied the same GLMM on several data subsets defined according to partitions of the building density variable. Considering its statistical distribution, we initially divided the dataset into six data subsets (Fig. 1).

In the first case, where no restriction of density was applied (case 1), we expected *Building coverage ratio* to be the most important variable among the fixed effects, because the stark contrast of density might give more weight to this variable than to the *Built fabric typology*. Beyond this kind of "null model," we tested several combinations of density thresholds: from 10 % to the maximum value (case 2), from 20 % to the maximum value (case 3), from 10 % to 30 % (case 4), from 10 % to 20 % (case 5), and then from 20 % to 30 % (case 6). In these last five cases, we expected the influence of building density to decrease as the influence of the built fabric became more visible.

Since the data were located in urban agglomerations only, all datasets were sampled so as to minimize spatial autocorrelation. We randomly selected the SPIPOLL collections using a rule of minimum distance of 150 m. In the final statistical model, we checked for the possible presence of spatial autocorrelation in the residuals by applying Moran's test for 50 distance steps with an incrementation of 300 m each (representing a maximum distance of 15 km).

Table 3
Variables included in the GLMM. The continuous variables were all log-transformed because of their highly dissymmetric distribution. The number of classes of the variables *Built fabric typology, Plant, Agglomeration,* and *Date* vary with the size of the selected data subsets (see text for details).

Type of variable	Code	Meaning	Detail or transformation
Response variable	*Richness*	Richness in pollinators	Number of families
Nominal variables used as fixed effect	*Built fabric typology*	Class of built fabric	4 –5 classes
	Plot type	Class of plot	5 classes
	Crop	Presence of crop	Binary transformation
	Orchard	Presence of orchard	Binary transformation
	Vineyard	Presence of vineyard	Binary transformation
Continuous variables used as fixed effect	*Building coverage ratio*	Building density	Logarithmic transformation
	Resource	Amount of attainable lawns and grass	Logarithmic transformation
	Flux	Potential dispersal flux in lawns and grass	Logarithmic transformation
Nominal variables used as random effect	*Plant*	Flowering plant species	181–896 classes
	Agglomeration	Urban agglomeration	47–95 classes
	Climate	Type of climate	8 classes
	Date	Month + Year	72–101 classes

Given the imbalance of our sample sizes (ranging from 305 to 4714 collections) due to the six cases of data subset selection, statistical criteria such as pseudo-R2 or AIC could not be used to compare the models fitted for each data subset. Since our main goal was to examine the influence of the built fabric on the richness of pollinators, we started by simply comparing the models according to the effect size of the estimates of the variables and their associated standard errors, with a specific focus on the *Building coverage ratio* and the *Built fabric typology*. This led us to select a specific model suitable for the interpretation of the relationship between pollinator richness and urban fabric.

To supplement this analysis and find possible additional interpretation materials, we also examined the estimates for the random effect variables. This was done for the *Agglomeration* variable by mapping the estimate of each urban agglomeration across France to search for geographical patterns. For the seasonality effect, we used national meteorological data (https://portail-api.meteofrance.fr/web/fr/) to characterize the normal monthly temperatures and the normal monthly rainfall across the entire study area for the period 1952–2022, and compared these data with the *Date* estimates. To align the results with our dataset, these normal values were computed by selecting the data from the 1475 weather stations located within the urban agglomerations under study. We then calculated Pearson's coefficient between the estimate of each date and the deviation between the measured values and the normal values. For the *Plant* variable, we simply listed the 30 flowering plant species with the highest estimates and the 30 species with the lowest estimates, and noted their origin (native/non-native).

3. Results

3.1. Comparison of models by building density

We computed the built fabric typology for the six data subsets. In each case, the first two components of the PCA were selected because inertia plummeted after the second component and remained low for the subsequent ones. Given the dissimilarity decrease of the HAC, five classes were the most relevant choice for designing the urban fabric typology, except for case 3 in which four classes were the best choice. The check for linear correlations between the continuous variables revealed the absence of major collinearities (Pearson's $r < 0.7$) except for case 1 between the variables *Resource* and *Flux* ($r = 0.790$), leading us to remove *Flux* in this instance.

Results for the GLMMs fitted for the six data subsets are presented in Table 4. In all cases, the overdispersion ratio does not significantly exceed 1, meaning that the response variable is not subjected to overdispersion. The marginal R2 is invariably weak (0.017–0.046) compared with the conditional R2 (0.356–0.441), meaning that much of the variance can be ascribed to random effects. Given the ICC values of the random effect variables, the weight of the flowering plant species is far greater, ahead of values for urban agglomeration. *Date* has a moderate influence whereas climate areas have no effect. For all these values, the six cases do not display marked differences.

For the fixed effect variables, marked differences between the cases can be noticed. Overall, the *Built fabric typology* tends not to be significant for cases 1, 3, and 6, while it is almost significant for case 4 and clearly significant for cases 2 and 5. In the detail of the classes, this ranking of cases is found again when considering the number of significant classes. At both extremes, neither of the classes is significant in cases 1 and 6 whereas high significance levels are observed in case 5. The *Plot type* variable is not significant in case 1 only. *Crop* invariably has a negative estimate but never reaches the significance level. The

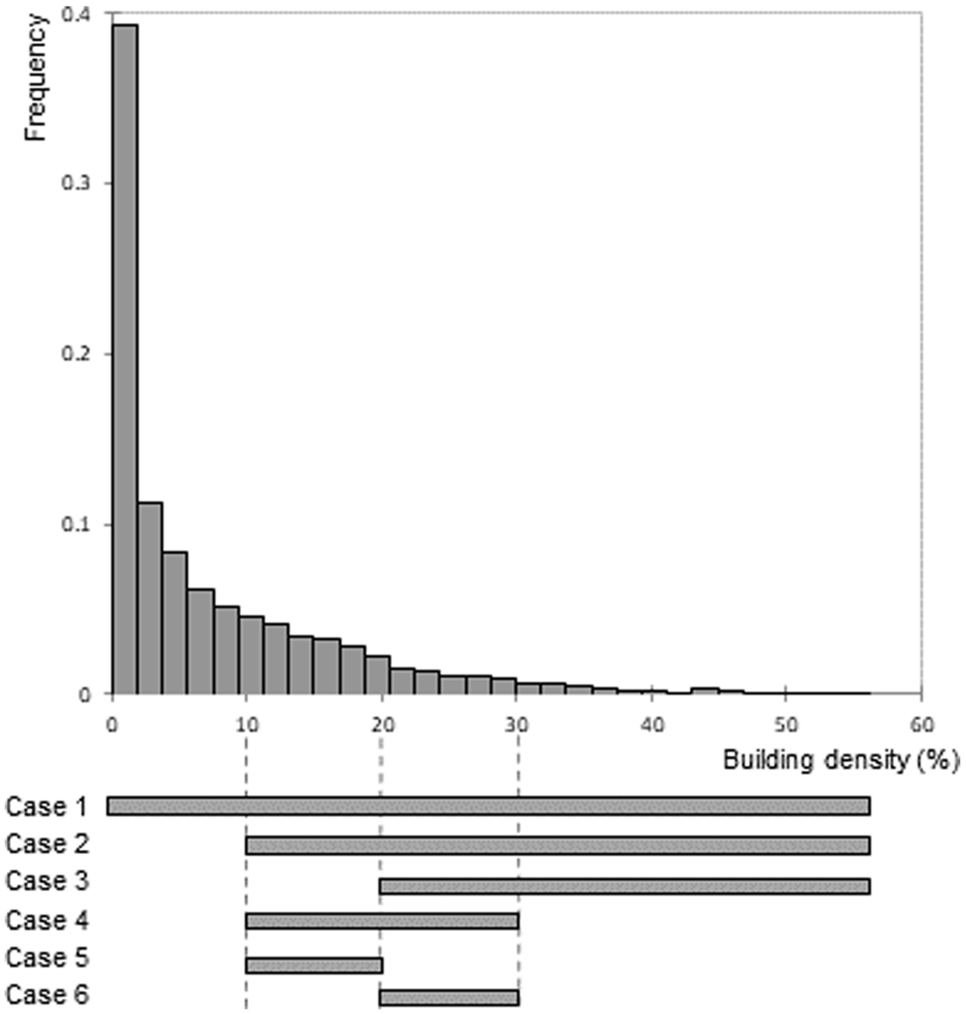


Fig. 1. Statistical distribution of the *Building coverage ratio* around the initial set of SPIPOLL collections. The horizontal bars represent the range of density of six cases of data selection.

influence of *Orchard* and *Vineyard* vary from case to case but exhibit no significant relationship except for the positive influence of *Vineyard* in case 1.

The *Building coverage ratio* has a highly significant negative effect on pollinator richness in cases 1 and 2, it is slightly significant in cases 3 and 4, while it fails to achieve significance in the last two cases. The *Resource* variable has a constantly positive influence, being highly significant in case 1 and more moderately so in all other cases except for case 3 for which it is not statistically significant. Lastly, in all six cases, the *Flux* variable tends to be positive but not significant. Comparison of the six cases suggests that the influence of the built fabric on pollinator richness is greater in the case of medium building coverage ratio (between 10 and 20 %). We focus below on the interpretation of this case.

3.2. Focus on the model built from data with a moderate range of building density

The model resulting from case 5 with building densities ranging between 10 and 20 % is now closely examined. No significant spatial autocorrelation was found in the residual values of the model, regardless of the spatial distance considered (Appendix 4).

First, the *Built fabric typology* is interpreted on the basis of the average percentage of building types in each of the five classes (Appendix 5). These values show that most of the urban areas characterized within the 500 m-radius neighborhoods include a complex combination of building types and construction periods. By simplifying these values, we can describe each class synthetically:

- Class 1 “Old individual housing”: mix of detached and terraced houses, with some small collective buildings, built largely before 1945 and to a lesser extent between 1945 and 1975.
- Class 2 “Post-war individual housing”: residential detached houses mainly built in the post-war period, little collective housing.
- Class 3 “Recent individual housing”: mix of detached and terraced houses with commercial and industrial buildings, mainly built since 1975.
- Class 4 “Mixed buildings”: mix of individual housing including a large proportion of terraced houses, mainly built before 1975, with commercial buildings built after 1975 and some collective buildings.
- Class 5 “Collective housing”: combination of residential collective buildings of various sizes and construction periods.

These classes are illustrated by examples randomly chosen among the 648 neighborhoods defined around the SPIPOLL collections (Fig. 2).

By exponentiating the coefficient estimates of the post-hoc comparisons (Table 5), we can compare these classes according to their influence on the target variable, while fixing the other parameters. The starkest differences occur between class 1 and classes 2 and 3 respectively, showing that the “old individual housing” (class 1) displays a pollinator richness that is 28 % higher than the “recent individual

Table 4

Comparatives results of the GLMM fitted for the six data subsets. *** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$.

	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
Range of building density (%)	[0, max]	[10, max]	[20, max]	[10, 30]	[10, 20]	[20, 30]
Number of SPIPOLL collections	4714	1079	431	918	648	305
Marginal R2	0.020	0.037	0.033	0.030	0.043	0.053
Conditional R2	0.400	0.376	0.245	0.396	0.440	0.361
Overdispersion indicator	1.020	0.761	0.739	0.750	0.697	0.719
Intra-class correlation (ICC) of the random effect variables						
Plant	0.287	0.256	0.149	0.279	0.333	0.204
Date	0.097	0.018	0.015	0.018	0.015	3.44e-14
Agglomeration	0.113	0.153	0.082	0.166	0.163	0.185
Climate	<0.0001	<0.0001	3.16e-15	<0.0001	<0.0001	<0.0001
Estimates of the fixed effect nominal variables						
Built fabric typology (*p* values)	0.559	0.046	0.206	0.066	<0.001	0.261
Built fabric typology class 2/1	0.052	−0.026	0.223*	0.011	−0.247***	−0.075
Built fabric typology class 3/1	0.054	0.122	0.098	−0.153***	−0.321***	0.211
Built fabric typology class 4/1	0.037	0.104	0.093	−0.120*	−0.185*	0.148
Built fabric typology class 5/1	0.030	0.240***	—	0.056	−0.117	−0.041
Plot type (p values)	<0.001	0.070	0.392	0.108	0.095	0.740
Collective housing / Annex	0.049	0.125	0.271	0.089	0.103	0.253
Commercial building / Annex	−0.167***	−0.096	−0.013	−0.113	−0.169	0.041
Individual housing / Annex	−0.011	−0.039	−0.003	−0.086	−0.029	0.111
No building / Annex	0.009	0.071	0.051	0.056	0.084	0.059
Crop	−0.006	−0.067	−0.069	−0.052	−0.075	0.095
Orchard	−0.012	−0.043	−0.057	0.054	0.092	0.009
Vineyard	0.048*	−0.003	0.074	−0.035	−0.075	−0.143
Estimates of the fixed effect continuous variables						
Building coverage ratio	−0.042***	−0.775***	−0.754*	−0.570*	−0.440	0.247
Resource	0.023***	0.036*	0.031	0.037*	0.045*	0.079*
Flux	—	0.005	0.025	0.012	0.001	0.029

housing” (class 2), and almost 38 % higher than the “post-war individual housing” (class 3). Class 1 has a pollinator richness 1.2 times higher than class 4 of “mixed buildings.” Conversely, classes 2 and 3 appear to be less conducive than classes 4 and 5, with a maximum contrast between class 3 (recent individual housing) and class 5 (collective housing), the former harboring 18.5 % fewer pollinator families than the latter. When summarizing all these comparisons, we come to rank the classes by decreasing order of capacity to host pollinators in three groups: most favorable group (class 1), intermediate group (classes 4 and 5), and least favorable group (classes 2 and 3).

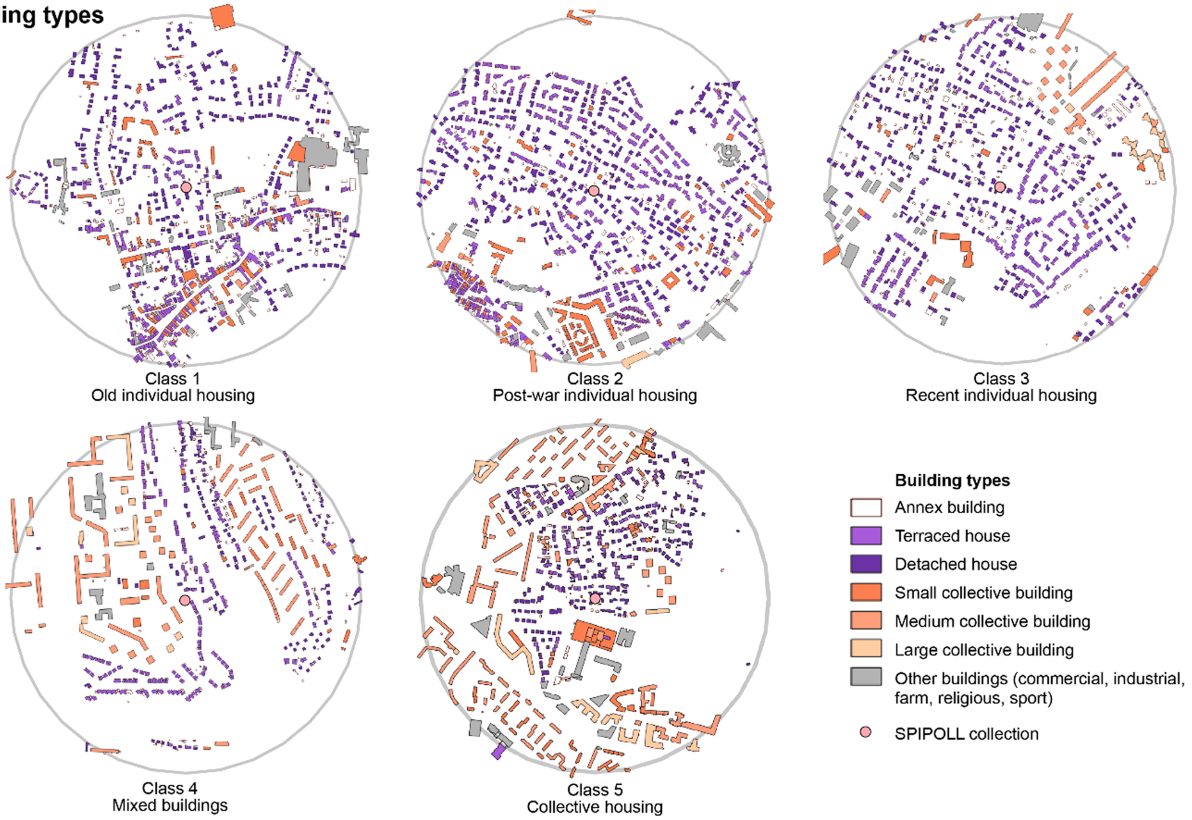
The map of the estimate of each urban agglomeration across metropolitan France does not exhibit any clear spatial distribution, with high and low estimates distributed in all regions and for all agglomeration sizes (Fig. 3), without littoral or Mediterranean effect. The analysis focused on the variable *Date* based on the comparison between the estimates and the deviations from normal meteorological values indicates no correlation with rainfall and a positive and significant correlation with temperatures ($r = 0.27$, $p = 0.02$). Then the comparison between the 30 plant species with the higher estimates with the 30 species with the lowest estimates does not exhibit a difference of origin, with 11 non-native species in both groups, corresponding to 19 % and 20 % of the occurrences respectively.

4. Discussion

The analysis conducted on a large set of urban agglomerations in the whole France provides insights regarding the drivers affecting pollinator richness in urban landscapes. Our approach was designed to explore the influence of urban fabric patterns on pollinators by controlling for the effect of building density, while controlling for other factors assumed to influence the presence of pollinator insects in urban environments. Among these factors, we notice the marked influence of the identity of flowering plant species, urban agglomeration, date, and amount of herbaceous resources. Apart from urban agglomeration, the influence of these factors was rather expected as it had already been observed in previous studies (Wenzel et al., 2020), but it gives credit to the original approach based on massive and participatory data gathered at a national level, while most research in this field usually relies on specific data gathered in a single city with few exceptions (Casanelles-Abella et al., 2022; Deguines et al., 2016; Theodorou et al., 2020). The participatory field data covering large areas are all the more attractive because harmonized and accurate land cover data are now accessible (Gamba & Herold, 2009). Besides allowing us to extend the analysis to numerous urban areas, this approach gives access to a large variety of urban green spaces, including domestic gardens on housing estates (Levé et al., 2019), urban grasslands or informal areas, and not just urban parks as in many studies (e.g. Daniels et al., 2020). In this respect, the value of citizen science data outlined by our study joins the observations of Vereecken et al. (2021) and Desaegher et al. (2018) following their analyses in the large urban agglomerations of Brussels and Paris, and it also confirms general findings about the value of participative or citizen data (Poisson et al., 2020; Reichman et al., 2011). At the same time, these data have limitations relating to their taxonomic resolution and the geographical context in which they are acquired. As an example, our data did not allow us to design plant-insect networks as in local studies based on specific data (e.g., (Jacquemin et al., 2020)) or to perform trait-based analyses as in Gathof et al. (2022).

As a first outcome of our analysis, the effect of density was confirmed to be a significant problem when seeking differences caused by the patterns of built fabric. When including all the data from urban centers to the very low density peripheries (case 1 in Table 4), the only effect detected is building density, playing a negative role as expected given the results of previous studies of pollinator diversity along “urbanization gradients” (Fortel et al., 2014; Geslin et al., 2016; Persson et al., 2020; Wenzel et al., 2020). According to the results obtained with data selected by removing the low densities (cases 2, 4, and 5), the classes of built fabric displayed different potentials for hosting pollinators. Conversely, too high a threshold of densities (i.e., a minimum value of 20 % in cases 3 and 6) proved to be irrelevant for achieving a suitable differentiation of the classes of built fabric. In complementary analyses

(a) Building types



(b) Construction periods

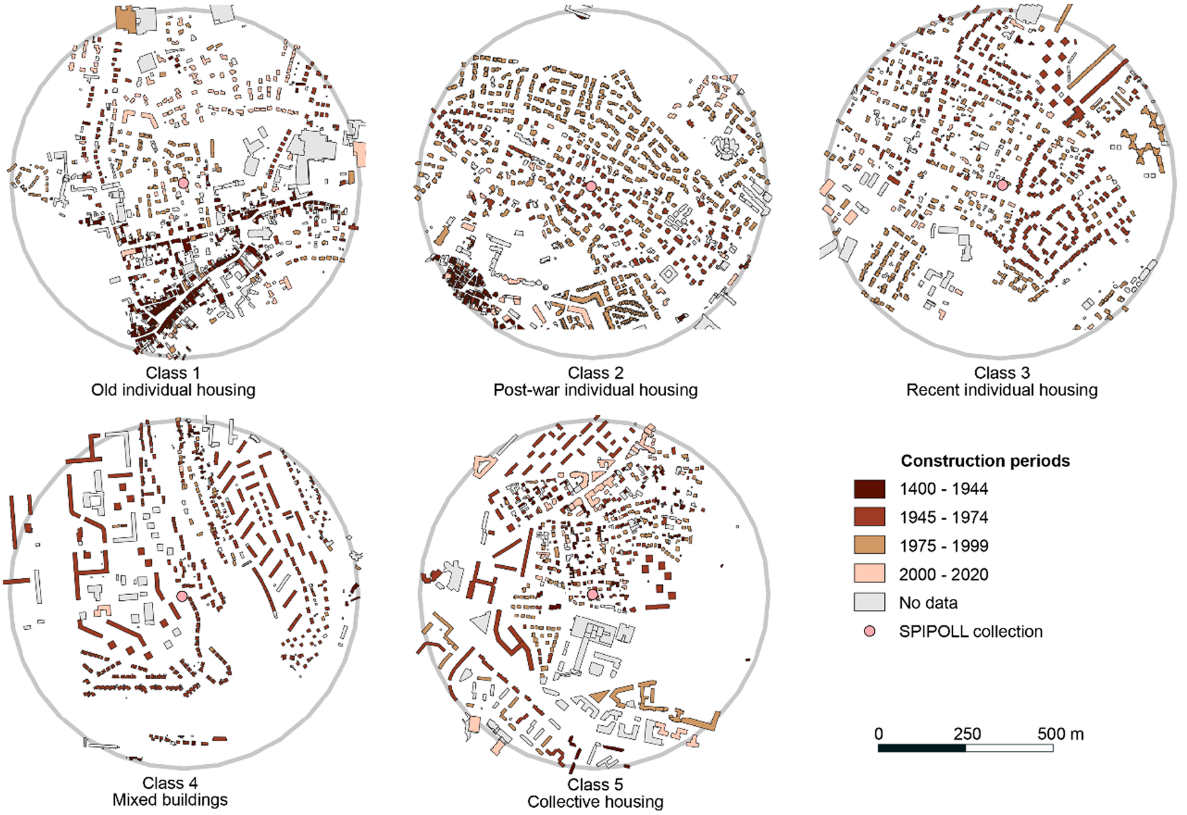


Fig. 2. Examples of the five classes of built fabric typology defined from (a) the buildings types and (b) the construction periods. The example of the class 1 is located in the agglomeration of Rennes, class 2 in Montpellier, class 3 in Bordeaux, class 4 in Le Havre and class 5 in Paris.

Table 5
Post-hoc comparisons between classes of the *Built fabric typology* based on the Poisson GLMM fitted on the data subset of a moderate range of building densities (case 5).

Classes of *Built fabric typology*		exp(β)	SE	*z*	*p*	*p* with Holm correction
1. Old individual housing	2. Post-war individual housing	1.280	0.093	3.380	< .001	0.007
1. Old individual housing	3. Recent individual housing	1.379	0.116	3.828	< .001	0.001
1. Old individual housing	4. Mixed buildings	1.203	0.092	2.404	0.016	0.13
1. Old individual housing	5. Collective housing	1.124	0.100	1.323	0.186	0.929
2. Post-war individual housing	3. Recent individual housing	1.078	0.087	0.932	0.351	1
2. Post-war individual housing	4. Mixed buildings	0.940	0.074	−0.789	0.43	1
2. Post-war individual housing	5. Collective housing	0.879	0.086	−1.32	0.187	0.929
3. Recent individual housing	4. Mixed buildings	0.872	0.074	−1.607	0.108	0.648
3. Recent individual housing	5. Collective housing	0.815	0.084	−1.979	0.048	0.334
4. Mixed buildings	5. Collective housing	0.935	0.088	−0.716	0.474	1

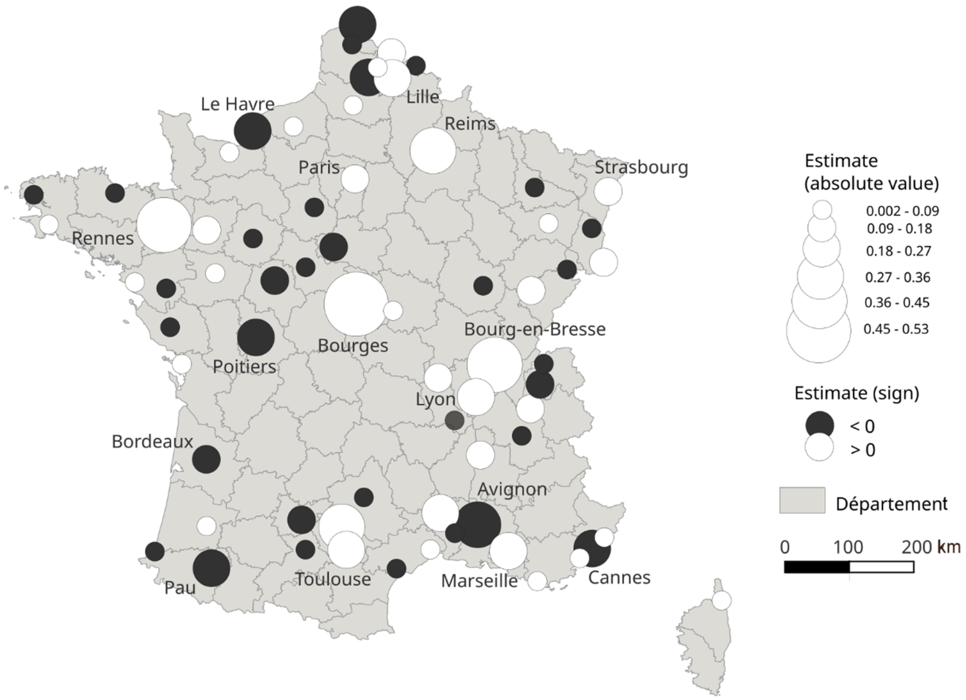


Fig. 3. Estimates of the 69 urban agglomerations in the GLMM. The white dots have positive estimates while black dots have negative ones. The “départements” are French administrative districts.

(not presented in the paper), we tested the sensitivity of the statistical models to the number of classes of built fabric, with the idea that a more precise typology (i.e., with a higher number of classes) could make relationships visible without restricting the dataset in terms of building density. But this did not result in any improvement in the statistical relationships between urban morphology and pollinators. Selecting the data using what we called a “moderate range of building density” proves thus to be the simplest approach for going beyond the classical effect of urban density (Fig. 4). The results obtained from this explanatory analysis of the density range may be explained by the link between density (i.e., building coverage ratio) and the description of the built fabric based on a statistical reduction. In all cases, without limiting the maximal building density, i.e. including the urban centers, the first factorial axes derived from the 39 building variables are strongly correlated with the building coverage ratio (r^2 from 0.4 to 0.7 in regression models fitting this variable). Only the restriction of building coverage ratio between a minimum and a maximum value makes the built fabric typology independent of density (here $r^2 < 0.18$). In this case, the range 10–20 %, identified as the most relevant, results from a compromise between the removal of extreme density values and the size of the remaining sample.

The interpretation and the ranking of the classes of built fabric according to their capacity to host pollinators, all other factors being equal, led us to identify old individual housing as the most favorable built fabric pattern, in contrast to other patterns dominated by individual housing built in the post-war period and the late twentieth century. The classes of collective housing or exhibiting a great mix of types of building and construction periods are characterized by a median position against the previous ones. The observed variation between the built fabric classes raises concerns about the “functional” causes of such a difference. First, as the ranking of the classes stresses the contrast in construction periods, we may wonder whether the age of the green spaces interspersed in the built fabric is the key factor. Without any additional data about this factor, and considering that most green spaces were designed in the same period as their surrounding buildings, we tried to elude the question by conducting two complementary analyses with built fabric typologies (1) based on the construction period only, and (2) based on the type of building only. Applying the same model as in Section 3.2 to these alternative typologies, we found that it was unsuitable to consider the construction periods alone ($p = 0.121$ for building typology), whereas considering building types alone yielded significant results ($p = 0.001$) even though it led to distinguishing one class only in the post-hoc comparisons. In short, what makes built fabric classes different in terms of pollinator hosting is more the type of building than the construction period, but the combination of both factors makes for a more suitable typology.

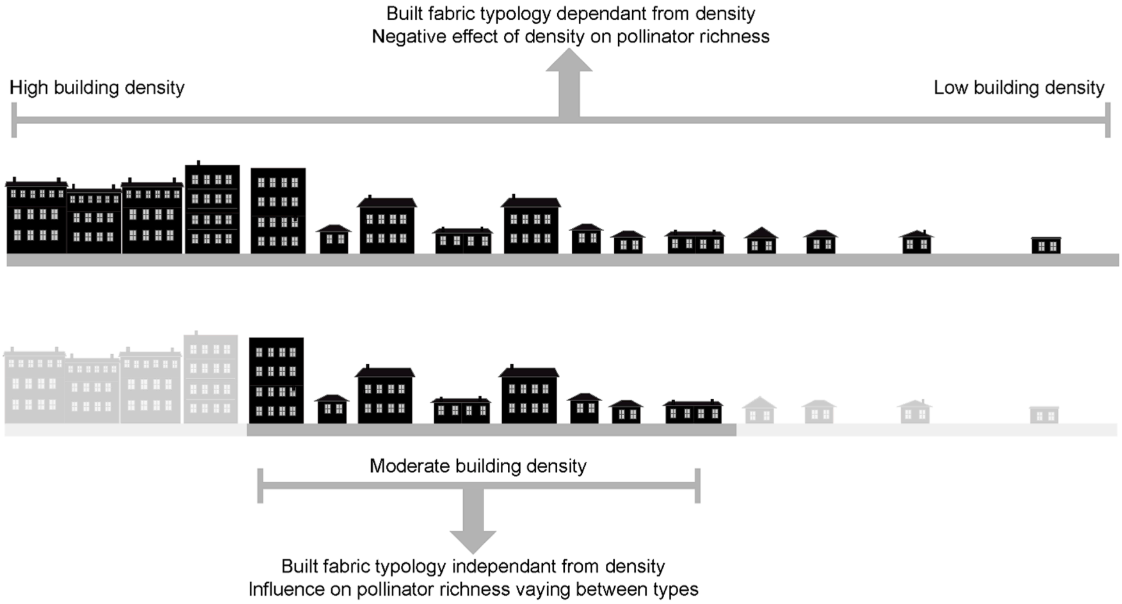


Fig. 4. Graphical abstract of the link between building density and built fabric typology in relation with pollinator richness.

The second way to understand the “functional” difference between the classes of built fabric requires us to focus on the resource availability for pollinators. In this respect, we included a variable that directly represents this aspect with the graph-based metric *Resource* expressing the amount of herbaceous resources and their connectivity. This variable was conducive to pollinator richness regardless of the data selection scenario, and was not statistically linked to the *Built fabric typology* ($p = 0.116$ in an ANOVA run between these variables). Another aspect that may cause differences between the classes of built fabric is the functional characteristics of the plant species they host. To test this, we used the database BiolFlor (Kühn et al., 2004) in combination with SPIPOLL to list the distribution of functional traits within the four classes. Among these traits, we investigated flower shape and size, floral color, the flowering season and duration, the life form (perennial, therophyte, geophyte) and finally the optimal habitat and its diversity. However, this complementary analysis was restricted to the native species and did not show a clear link between the classes of built fabric and these traits, except for a greater presence of large flowers ($p = 0.064$) and a slightly higher diversity of optimal habitats in old individual housing. As these differences were not marked, we assume that the contrasts between the built fabric classes may indirectly express other aspects characterizing the herbaceous areas they encompass, possibly pertaining to their management and usage frequencies, especially since these criteria have already been emphasized in numerous studies (Dylewski et al., 2020; LeBuhn & Vargas Luna, 2021; Muratet & Fontaine, 2015; Persson et al., 2020). In the present case, we also sought to include this effect by identifying five plot types, but this variable was too coarse. Consequently, we may assume that the green spaces included in the “old individual housing” are on average subject to lighter management than the other urban fabric classes, and specifically the most recent housing estates combining both detached and terraced houses. Further analyses focused on cases for which the mode and intensity of management are precisely described and would be required to validate this interpretation. Finally, it should be pointed out that all these ecological variations caused by the built fabric patterns have to be relativized because they occur within a subsection of urban agglomerations as a result of our focus on moderate building densities. Overall, the urbanization gradient remains the major driver of pollinator richness.

It should also be noted that our description of the built fabric at the neighborhood level was based on the coupling between building types and construction periods, but that it did not extend beyond the composition of the building elements. It could thus be worthwhile including descriptors capable of capturing the differences in spatial configuration, from the localization of the buildings and more globally from the street network to describe the urban fabric. Another issue about the description of built fabric is the shape and the size of the neighborhood used to characterize the built environment of the collections. Here we have chosen a circular shape with a 500 m radius to be in line with the maximal distance of foraging of most pollinators. However, such a circular neighborhood led to include a large diversity of buildings (what is visible in the examples of the Fig. 1) making difficult the interpretation of built fabric classes, while another rationale would be to use a ‘urban planning-oriented’ neighborhood as for example based on blocks (Araújo De Oliveira, 2022; Fleischmann et al., 2020). This would yield more uniform built fabric classes and more easily in connection with urban strategies relying on neighborhood projects (Blanco et al., 2022), but would be further away from the perceived environment of pollinators.

Apart from the influence of urban patterns, the analysis—applied to data spanning eight years and a geographical extent of 69 urban agglomerations—showed the sensitivity of the results to the spatio-temporal context. Variations due to the seasonality of the observations did not appear to carry much weight in our results, although the results do seem to be related to meteorological conditions, especially temperatures. In contrast, variations between agglomerations are marked. Surprisingly, we did not find a spatial distribution suggesting a geographical explanation, nor was the climate factor significant. This supports the claim that multiple factors influence urban pollinator diversity to varying extents, making it difficult to reach general conclusions (Liang et al., 2023). However, several ideas could be proposed to explain these variations that could be subject to further analyses, starting with their regional context (agricultural, forested, etc.), which could induce variations in the local pool of insect species or differences in greening policies among agglomerations potentially leading to discrepancies in the diversity of flowering plant species.

Since the study encompasses a large number of sites, we might wonder if the results obtained from French cities could be generalized to other regions in the world. This question is all the more topical because the higher ratios of urban growth are currently observed in tropical regions (Sun et al., 2020). However, following the review of Wenzel et al. (2020), most of the studies dealing with pollinators in urban environment are located in temperate regions. Understanding of the pollinator response to urbanization in tropical regions is thus insufficient to make strong hypotheses about the role of building fabric in these areas. In Asian megacities, the link between urban density and biological responses as pollinator diversity and abundance seems to be similar to the outcomes found in temperate regions (Sing et al., 2016; Stewart et al., 2018). But the urban configurations may be quite different from those of European cities, where suburbs of several levels of density include old villas with domestic gardens (identified here as the most favorable built pattern). The analysis of tropical urban patterns in relation to pollinators could thus be a promising avenue for future research.

Finally, the outcomes of this study provide some elements that could have practical implications. The first one is the consequence of the dominant role of floral diversity and the building density on pollinator richness when considering the whole urban area. Since floral diversity partially depends on the surface area of the green spaces, urban management has little scope for improvement when only focusing on the way green spaces are managed or used, without maintaining or even increasing the herbaceous surface areas and their connectivity. In urban neighborhoods of high building density, adding a small green space may contribute to improve the well-being of residents (Halecki et al., 2023; Verma et al., 2020) but will not provide a significant improvement in pollinator richness if this patch remains small or isolated. Conversely, the urban peripheries including larger herbaceous areas of diverse functions will provide more resources even if their interest for pollinators may strongly vary according to the usage and the management of these areas. With this in mind, the current policy of urban densification of European countries is a threat for some communities like pollinator insects. This is more specifically the case at the intermediate level of building density around urban centers, where connectivity and spatial configuration of herbaceous areas are important criteria in offsetting the smaller extent of these areas compared to those in urban peripheries.

Inside the urban fabric of intermediate density, the richness difference observed between individual housing built before 1945 and postwar individual housing raises new questions. This leads us to consider further studies to better compare these built patterns by characterizing the size and geometry of the land parcels, their management modes, and the spatial configuration of buildings. This would require to enrich the analysis, e.g. with cadastral data and multidate satellite imagery to assess for mowing frequency during spring and summer. Such an extension of the study would benefit from a focus on 'urban planning-oriented' neighborhoods mentioned above, rather than on circular neighborhoods, to provide results that are easier to interpret in urbanistic terms.

5. Conclusion

From a large set of participatory data on pollinator insects and land cover data covering urban agglomerations throughout France, we have focused on the influence of the urban fabric on pollinator richness while considering other possible drivers. We found that the effect of urban fabric patterns on pollinators emerges only when the analysis is confined to a range of moderate building density (i.e., between 10 % and 20 % in 500 m-radius neighborhoods), otherwise the effect of the urbanization gradient tends to mask these variations or they simply do not exist at the two ends of the density gradient. For this intermediate range of building density, putting aside the variations due to the other drivers, comparison of the built fabric classes reveals that the oldest housing estates prove to be more conducive to pollinators, specifically when contrasted with the most recent individual housing.

CRediT authorship contribution statement

Jean-Christophe Foltête: Writing – original draft, Methodology, Funding acquisition, Formal analysis, Conceptualization. **François-Marie Martin:** Writing – review & editing, Methodology, Formal analysis. **Gilles Vuidel:** Writing – review & editing, Software, Methodology, Data curation. **Lise Ropars:** Writing – review & editing, Methodology, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix 1. Distribution of the families of insect species

Order of insect species	Family of insect species	Number of indivduals	Percentage of individuals
Diptera	Syrphidae	9055	20.345
Hymenoptera	Apidae	8756	19.673
Lepidoptera	Nymphalidae	1859	4.177
Diptera	Tachinidae	1852	4.161
Hymenoptera	Andrenidae	1752	3.936
Hymenoptera	Halictidae	1367	3.071
Coleoptera	Coccinellidae	1246	2.799
Coleoptera	Oedemeridae	1235	2.775
Coleoptera	Nitidulidae	1143	2.568
Hymenoptera	Colletidae	1133	2.546
Hymenoptera	Ichneumonidae	1106	2.485
Lepidoptera	Pieridae	912	2.049
Coleoptera	Scarabaeidae	890	2.000
Hymenoptera	Megachilidae	801	1.800
Hymenoptera	Vespidae	794	1.784
Diptera	Sarcophagidae	769	1.728
Diptera	Empididae	718	1.613
Coleoptera	Cantharidae	567	1.274
Diptera	Bombyliidae	540	1.213
Hymenoptera	Crabronidae	492	1.105
Coleoptera	Mordellidae	491	1.103

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Order of insect species	Family of insect species	Number of indivduals	Percentage of individuals
Coleoptera	Cerambycidae	441	0.991
Lepidoptera	Lycaenidae	433	0.973
Diptera	Sepsidae	425	0.955
Diptera	Rhiniidae	422	0.948
Diptera	Conopidae	310	0.697
Hymenoptera	Tenthredinidae	290	0.652
Coleoptera	Dermestidae	286	0.643
Hymenoptera	Philanthidae	230	0.517
Diptera	Bibionidae	219	0.492
Lepidoptera	Sphingidae	210	0.472
Coleoptera	Scraptiidae	202	0.454
Diptera	Chloropidae	196	0.440
Coleoptera	Chrysomelidae	191	0.429
Diptera	Muscidae	187	0.420
Hymenoptera	Formicidae	183	0.411
Lepidoptera	Noctuidae	154	0.346
Coleoptera	Cleridae	137	0.308
Hymenoptera	Sphecidae	137	0.308
Hymenoptera	Gasteruptiidae	135	0.303
Hymenoptera	Chrysididae	130	0.292
Lepidoptera	Zygaenidae	130	0.292
Diptera	Ulidiidae	128	0.288
Hymenoptera	Pompilidae	126	0.283
Diptera	Stratiomyidae	124	0.279
Diptera	Anthomyiidae	108	0.243
Lepidoptera	Papilionidae	108	0.243
Diptera	Scatopsidae	100	0.225
Lepidoptera	Erebidae	97	0.218
Diptera	Sciaridae	93	0.209
Lepidoptera	Adelidae	76	0.171
Lepidoptera	Crambidae	60	0.135
Hymenoptera	Melittidae	58	0.130
Hymenoptera	Tiphiidae	57	0.128
Lepidoptera	Geometridae	54	0.121
Hymenoptera	Bembicidae	50	0.112
Lepidoptera	Hesperiidae	50	0.112
Hymenoptera	Scoliidae	45	0.101
Diptera	Calliphoridae	41	0.092
Coleoptera	Elateridae	41	0.092
Hymenoptera	Cephidae	40	0.090
Lepidoptera	Sesiidae	38	0.085
Coleoptera	Melyridae	37	0.083
Diptera	Asilidae	31	0.070
Coleoptera	Tenebrionidae	31	0.070
Diptera	Platystomatidae	29	0.065
Diptera	Scathophagidae	29	0.065
Coleoptera	Byturidae	27	0.061
Coleoptera	Buprestidae	26	0.058
Hymenoptera	Sapygidae	20	0.045
Hymenoptera	Braconidae	18	0.040
Diptera	Tabanidae	16	0.036
Coleoptera	Meloidae	16	0.036
Hymenoptera	Cimbicidae	13	0.029
Diptera	Cecidomyiidae	12	0.027
Diptera	Chironomidae	12	0.027
Diptera	Tephritidae	11	0.025
Coleoptera	Lycidae	11	0.025
Lepidoptera	Pterophoridae	10	0.022
Lepidoptera	Micropterigidae	10	0.022
Coleoptera	Curculionidae	9	0.020
Lepidoptera	Thyrididae	9	0.020
Diptera	Tipulidae	7	0.016
Coleoptera	Phalacridae	6	0.013
Coleoptera	Pyrochroidae	6	0.013
Coleoptera	Staphylinidae	5	0.011
Coleoptera	Mycteridae	5	0.011
Coleoptera	Carabidae	5	0.011
Hymenoptera	Mutillidae	4	0.009
Hymenoptera	Argidae	4	0.009
Hymenoptera	Chalcididae	4	0.009
Lepidoptera	Tortricidae	3	0.007
Diptera	Dolichopodidae	3	0.007
Hymenoptera	Torymidae	3	0.007
Lepidoptera	Choreutidae	3	0.007
Hymenoptera	Perilampidae	3	0.007
Hymenoptera	Eurytomidae	2	0.004

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Order of insect species	Family of insect species	Number of indivduals	Percentage of individuals
Lepidoptera	Plutellidae	2	0.004
Diptera	Ceratopogonidae	2	0.004
Hymenoptera	Psenidae	2	0.004
Lepidoptera	Glyphipterigidae	2	0.004
Lepidoptera	Pyralidae	2	0.004
Diptera	Therevidae	2	0.004
Diptera	Sciomyzidae	2	0.004
Diptera	Asteiidae	2	0.004
Coleoptera	Brentidae	2	0.004
Diptera	Culicidae	2	0.004
Diptera	Rhagionidae	2	0.004
Hymenoptera	Diapriidae	1	0.002
Hymenoptera	Siricidae	1	0.002
Diptera	Mycetophilidae	1	0.002
Hymenoptera	Figitidae	1	0.002
Diptera	Phoridae	1	0.002
Diptera	Pipunculidae	1	0.002
Hymenoptera	Eulophidae	1	0.002
Diptera	Lonchopteridae	1	0.002
Diptera	Lauxaniidae	1	0.002
Diptera	Hybotidae	1	0.002
Coleoptera	Hydrophilidae	1	0.002
Diptera	Nemestrinidae	1	0.002
Hymenoptera	Xiphydriidae	1	0.002
Diptera	Acroceridae	1	0.002
Hymenoptera	Platygastridae	1	0.002
Lepidoptera	Schreckensteiniidae	1	0.002
Diptera	Rhinophoridae	1	0.002
Diptera	Lonchaeidae	1	0.002
Hymenoptera	Evaniidae	1	0.002
Diptera	Agromyzidae	1	0.002
Diptera	Ephydridae	1	0.002
Lepidoptera	Depressariidae	1	0.002
Diptera	Simuliidae	1	0.002
Lepidoptera	Scythrididae	1	0.002
Lepidoptera	Coleophoridae	1	0.002
Diptera	Opomyzidae	1	0.002

Appendix 2. Conversion procedure from metric units to cost units

We created a large sample of about 145 million least-cost paths between herbaceous patches within all the neighborhoods of the SPIPOLL collections. To make this sample representative of the landscapes in which empirical studies of insect movements are conducted (e.g., (Hofmann et al., 2020)), the least-cost paths including a strong barrier (i.e., a cost value of 1000) were omitted. From the selected set of links, we fitted the cost distance from the metric distance using a log-log regression with an intercept value set to zero. Although no perfect fit could be expected for the two distances, the regression coefficients allowed us to assess the order of magnitude of the cost distance according to a given metric distance.

Appendix 3. Climate zones defined in (Joly et al., 2010) for metropolitan France

Type 1: Mountain climates
Type 2: Semi-continental climate and climate of mountain fringes
Type 3: Degraded oceanic climate of central and Northern France
Type 4: Modified oceanic climate
Type 5: Oceanic climate
Type 6: Modified Mediterranean climate
Type 7: Climate of the South-West basin
Type 8: Mediterranean climate

Appendix 4. Spatial autocorrelation coefficients of residuals of the GLMM applied with building densities between 10 % and 20 %

Note: none of the coefficients were significant with $p < 0.05$.

Min distance	Max distance	Number of pairs	Moran's coefficient
0	300	183	0.0353148
300	600	324	−0.0335404
600	900	243	−0.0304282
900	1200	185	−0.152737

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Min distance	Max distance	Number of pairs	Moran's coefficient
1200	1500	162	0.037431
1500	1800	155	0.0531764
1800	2100	155	0.10011
2100	2400	190	0.0622713
2400	2700	180	0.0559287
2700	3000	142	0.00345335
3000	3300	184	0.0673337
3300	3600	156	0.153724
3600	3900	185	0.0868958
3900	4200	220	0.0399748
4200	4500	214	0.0291518
4500	4800	218	−0.0697619
4800	5100	189	0.0366306
5100	5400	205	0.0731734
5400	5700	199	0.012888
5700	6000	194	0.181385
6000	6300	204	−0.0226368
6300	6600	226	−0.00839109
6600	6900	249	0.0240842
6900	7200	299	−0.0845789
7200	7500	288	−0.0721257
7500	7800	241	−0.110049
7800	8100	209	−0.0432281
8100	8400	192	−0.0616438
8400	8700	210	−0.0359729
8700	9000	187	0.0399537
9000	9300	199	−0.0494736
9300	9600	190	−0.0436069
9600	9900	210	0.0498106
9900	10,200	206	0.0619803
10,200	10,500	233	−0.0582632
10,500	10,800	219	−0.00520815
10,800	11,100	217	−0.08136
11,100	11,400	258	0.025698
11,400	11,700	243	−0.0314401
11,700	12,000	227	0.0338561
12,000	12,300	193	−0.0913067
12,300	12,600	262	−0.051774
12,600	12,900	223	0.10961
12,900	13,200	228	−0.0900185
13,200	13,500	220	0.0215159
13,500	13,800	223	−0.0443629
13,800	14,100	225	0.0204086
14,100	14,400	228	−0.00318779
14,400	14,700	210	0.0156365
14,700	15,000	186	−0.0066194

Appendix 5. Average percentage of building types in the five classes of the built fabric

Type of building	Building period	Class 1	Class 2	Class 3	Class 4	Class 5
Detached house	Before 1945	6.522	4.053	0.905	3.255	4.914
	1945–1974	6.477	8.551	6.057	5.083	3.580
	1975–1999	4.187	10.392	13.576	4.373	1.613
	From 2000	1.637	4.906	4.678	1.374	0.670
	Unknown	3.821	3.117	2.117	2.483	2.625
Terraced house	Before 1945	9.749	5.196	0.670	3.733	7.170
	1945–1974	4.051	3.935	3.862	7.260	3.272
	1975–1999	3.068	6.177	9.216	5.501	1.410
	From 2000	1.301	1.719	1.878	0.767	0.696
	Unknown	3.611	2.239	1.032	1.671	2.548
Small collective building	Before 1945	3.150	1.066	0.193	0.773	3.869
	1945–1974	1.285	0.667	0.331	1.005	1.543
	1975–1999	1.029	1.027	0.741	1.080	0.809
	From 2000	0.924	0.861	0.702	0.736	0.694
	Unknown	2.178	1.900	1.972	2.474	2.650
Medium collective building	Before 1945	0.528	0.021	0.001	0.042	2.183
	1945–1974	1.148	0.186	0.070	0.805	2.303
	1975–1999	0.558	0.107	0.242	0.922	1.172
	From 2000	0.342	0.255	0.198	0.510	1.057
	Unknown	1.326	0.497	0.513	1.485	2.297
Large collective building	Before 1945	0.021	0.000	0.000	0.011	2.059
	1945–1974	0.346	0.023	0.013	0.378	1.812

(*continued on next page*)

(*continued*)

Type of building	Building period	Class 1	Class 2	Class 3	Class 4	Class 5
	1975–1999	0.237	0.012	0.018	0.455	1.104
	From 2000	0.077	0.000	0.022	0.274	0.881
	Unknown	0.378	0.050	0.132	0.696	2.233
Commercial building	Before 1945	0.364	0.146	0.049	0.168	0.527
	1945–1974	0.193	0.076	0.086	0.202	0.360
	1975–1999	0.276	0.154	0.580	0.690	0.562
	From 2000	0.441	0.398	1.251	1.606	0.866
	Unknown	2.899	1.420	4.641	6.603	5.155
Industrial building	Before 1945	0.008	0.001	0.001	0.001	0.006
	1945–1974	0.006	0.000	0.000	0.021	0.021
	1975–1999	0.011	0.003	0.053	0.032	0.026
	From 2000	0.006	0.001	0.019	0.022	0.015
	Unknown	0.340	0.104	1.394	1.041	0.601
Farm building		0.000	0.131	0.052	0.201	0.138
Religious building		0.118	0.066	0.019	0.051	0.149
Sports building		0.186	0.151	0.222	0.320	0.383
Annex building		37.132	40.395	42.498	41.896	36.023

Data availability

Data will be made available on request.

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