ENTOMOLOGY

Ecological connectivity of bee communities in fragmented areas of Volcano Etna (Sicily, Italy) at different degrees of anthropogenic disturbance (Hymenoptera, Apoidea, Anthophila)

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Abstract

The present study analyses the ecological connectivity of four bee communities in fragmented areas in the foothills of Volcano Etna (Catania province, Sicily, Italy). The surveys were carried out in four sites under different land management regimes from 2007 to 2010. The selected areas include two different urban parks in the city of Catania (Parco Gioeni and Parco degli Ulivi), a Nature Reserve (Complesso Immacolatelle e Micio Conti, San Gregorio di Catania), and an agroecosystem (a citrus orchard, Aci Catena). The well-known bee community of a suburban park (Timpa di Leucatia, north of Catania) was considered as a control site.

The bee communities include 163 species, belonging to the families Colletidae (10 species), Andrenidae (27 spp.), Halictidae (31 spp.), Melittidae (1 sp.), Megachilidae (49 spp.), and Apidae (45 spp.). Comparative zoocenotic analyses have been carried out, by calculating the main diversity indices and different methods of multivariate analysis.

The ecological connectivity was evaluated through cartographic instruments by mapping the level of biopermeability of the foothills of Etna, to highlight how the level of naturality and ecological corridors could affect bee diversity. Furthermore, the degree of environmental fragmentation was evaluated through the biogeographic model of islands under the linear regression species-area, considering the examined sites as "ecological islands". The data obtained highlight that reliable conservation strategies should consider firstly the maintenance of adequate ecological connectivity among environmental patches as well a high degree of local biodiversity, especially a high diversity of flowering plants.

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Introduction

The modification and fragmentation of natural environments due to human activities have obvious but poorly understood consequences on the structure of animal and plant communities (Wilcove *et al.*, 1986; Terayama & Murata, 1990; Dobson *et al.*, 1999; Winfree *et al.*, 2009; Senapathi *et al.*, 2017). In this context, knowledge of pollinating insect populations is fundamental to evaluate the complexity of ecosystems, because their presence, modification, or dramatic decrease could suggest information on the degree of environmental alteration (Porrini *et al.*, 1998; Mazzeo *et al.*, 2001; Henle *et al.*, 2004; Buchholz & Egerer, 2020; Coutinho *et al.*, 2021). The bee fauna is very sensitive to environmental alterations, and the specific components express the degree of quality of the ecosystems of a given territory (Matheson *et al.*, 1996; Goulson *et al.*, 2002; Mazzeo *et al.*, 2007, b; Carré *et al.*, 2009; Seminara *et al.*, 2009). The presence of high specific diversity, in relation also to their bio-ethology, allows us to analyze the degree of environmental complexity (Longo, 2002; Massimino Cocuzza *et al.*, 2016; Turrisi *et al.*, 2021; Villalta *et al.*, 2022).

With regard to Apoidea Anthophila, the effects of habitat fragmentation are insufficiently investigated (Cane, 2001; Steffan-Dewenter & Tscharntke, 1999, 2002; Steffan-Dewenter *et al.*, 2006; Theodorou *et al.*, 2020; Vieli *et al.*, 2021); for instance, a reduction in species diversity is known with the decreasing size of environmental fragments (Aizen & Feisinger, 1994; Ferreira *et al.*, 2019; Hung *et al.*, 2019).

In recent decades, numerous studies have been conducted on the Apoidea of the Volcano Etna (Sicily, Italy) to obtain data on ecology and trophic preferences, also in relation to the sustainable management of agroecosystems (Mazzeo *et al.*, 1999, 2001, 2002, 2004, 2015, 2019; Quaranta *et al.*, 2004; Bella *et al.*, 2020; Turrisi *et al.*, 2021; Las Casas *et al.*, 2022). The southern and eastern slopes of Volcano Etna have a widespread anthropogenic presence, with large territories of widespread naturalness and ongoing processes of fragmentation, especially along the southern and eastern borders, with significant loss of the original biodiversity. This ecological erosion affects, above all, the residual natural environments, marginal areas, and abandoned agroecosystems, with a considerable reduction of the surfaces with spontaneous vegetation with which pollinating insects are associated. This aspect can also drastically affect the pollination of crops and wildflowers (Westrich, 1990; Corbet *et al.*, 1991; Fussel & Corbet, 1992; Hanski, 1999; Ciaccia *et al.*, 2019; Cusser *et al.*, 2019; Theodorou *et al.*, 2020; Villalta *et al.*, 2022).

The present paper is a subsequent contribution after Turrisi *et al.* (2021), focusing on the ecological traits of the bee communities of Etna, especially on habitat fragmentation and ecological connectivity.

Materials and Methods

Study sites

The province of Catania, which covers approximately 3500 km^2, is a mountainous area characterized by the presence of the Volcano Etna and a foothill consisting of an alluvial plain originating from the deposition of sediment from the Simeto River and its tributaries. The territory considered in this study is located on the south-eastern slopes of the foothighs, which have significant urbanization and extensive agricultural areas, especially citrus orchards. Both the natural remnants and the agricultural patches are also strongly fragmented by roads that connect the numerous urban centers, especially near the city of Catania. The selected sites were chosen to consider different habitats, anthropogenic influences, and differentiated management practices (Turrisi *et al.*, 2021). Based on their geographic position, and their land management, the four sites could be considered as fragments of wider areas under low to medium-high anthropogenic pressure. The four sites chosen for this study are characterized by the following aspects: i) an area not less than 8 hectares, ii) located between 100 and 300 m a.s.l., and iii) located within moderately to highly urbanized areas.

The sites are briefly described below and reported throughout the text using their acronyms (see Turrisi *et al.*, 2021, for further details):

1 – SG, in San Gregorio di Catania, and Acicastello municipalities (37°33’43.52”N, 15°6’53.35”E) (Figure 1A).
Nature Reserve “Complesso Immacolatelle e Micio Conti, Boschi limitrofi”. This natural area is entirely within the Special Conservation Area (ZSC) ITA070008, extending about 68 hectares, at 280 m a.s.l. with relicts of deciduous thermophilous woods with *Quercus* species.

2 – AC, in Aci Catena municipality (37°36’28.49”N, 15°8’22.18”E) (Figure 1B).
Agroecosystem, citrus orchard extending about 10 hectares, at 225 m a.s.l., managed under organic practices. It is very close to the urban context and abandoned cultivated areas with abundant weedy flowering plants.

3 – PG, Parco Gioeni, Catania municipality (37°31’40.06”N, 15°4’52.30”E) (Figure 1C).
Central urban park, entirely in the main centre of Catania city, extending about 75 hectares, at 120 m a.s.l., one of the largest parks of Catania. Thermo-mediterranean vegetation with several allochthonous species (Bella & Musmeci, 2004).

4 – PU, Parco degli Ulivi, Catania municipality (37°31’33.14”N, 15°3’25.98”E) (Figure 1D).
Suburban parks, neighboring Catania municipality, extending about 65 hectares, at 190 m a.s.l. Thermo-Mediterranean vegetation is subsequent to the abandonment of olive orchards (Bella & Musmeci, 2004).

Furthermore, to assess the degree of bee diversity present in the four investigated sites, a comparison was made with the species of a well-investigated site in northern Catania, called Timpa di Leucatia (LE) (37°32’34.56”N, 15°5’8.98”E). This suburban park is located between the municipalities of Catania and Sant’Agata li Battiati, extending about 40 hectares, at an altitude of about 200 m a.s.l. The area is characterized by thermos-Mediterranean vegetation and cultivated areas after the post-cultural abandonment of citrus and olive orchards.

Bee sampling and identification

Faunistic investigations have been carried out with the selected walking-line transects technique, according to Turrisi *et al.* (2021). In the four sites investigated, the observations were carried out for three consecutive years, from February 2007 to February 2010, based on a monthly collection. The transects were 200 m long and 1 m wide and were visited four times per day at 9.00, 12.00, 15.00 and 18.00. During the field surveys, the specimens were counted, registered, and collected when necessary. Further data on the collecting protocol are available from Turrisi *et al.* (2021).

This study also considers the already well-known faunistic data of the site called ‘Leucatia’, obtained by V. Nobile over twenty years. This site was therefore considered as a ‘control site’, and the known data were used for comparison.

The specimens were identified by V. Nobile and are preserved in the collection of the Department of Biological, Geological and Environmental Sciences, Section of Animal Biology “Marcello La Greca”, University of Catania.

Ecological scale adopted

To assess the biopermeability of the territory, a qualitative scale was adopted with three categories that identified areas with low or no, medium, and high ecological connectivity, to estimate the extent of the typology identified and the degree of environmental fragmentation (Table 1). To define the “wide area”, based on bibliographic data relating to the flight width of the various bee species, we considered a concentric neighborhood of 4 km in radius for each site (Figure 1). The “wide area” that included the sites investigated was then correlated with the ‘Sicilian Ecological Network’.

Two different analyses were carried out on the degree of environmental fragmentation: i) comparative subdivision of the three environmental typologies based on their biopermeability, in areas having a radius of 4 km and, ii) spatial distribution of these typologies to define the presence of ecological corridors putatively functional to the bee communities.

Subsequently, the level of biopermeability of the Etnean territory with the sites investigated was represented cartographically to build the territorial network, identifying the areas with the greatest anthropogenic disturbance and those characterized by a higher level of naturalness. Using the constitutive functional categories of ecological networks (nodes, buffer areas, and corridors), we developed a structural hypothesis of the ecological network.

Statistical analysis

PRIMER-E software was used for the statistical processing of faunistic data, starting from a matrix of presence/absence and abundance of species (Clarke & Warwick, 2001). To describe the

Table 1. Criteria for the definition of the environmental biopermeability scale of the investigated sites.

	Areas	Environmental types
		High biopermeability
1	Wet areas and surfacesof relevance	Natural and artificial lakes, artificial basins, rivers and torrential hydrographic networks
2	Forest areas	Wooded areas of artificial and anthropogenic origin
3	Areas with little or no presence of plants	Areas of rocks without vegetation cover,uncultivated areas, geotopes, and abandoned mines
4	Pastures	Meadows and pastures above the tree line
5	Mountain areas	Ridge and watershed lines
		Medium biopermeability
6	Arable crops	Extensive cultivable areas with goodbiological articulation
7	Associated crops anduncultivated, complex cultural mosaics	Woody crops and complex growing systems withgood biological articulation
		Low to no biopermeability
8	Urbanised and infrastructured areas	Urbanised surfaces and urban service systems andindustrial and artisan areas
9	Infrastructured areas with linear distribution	Roads and railway networks

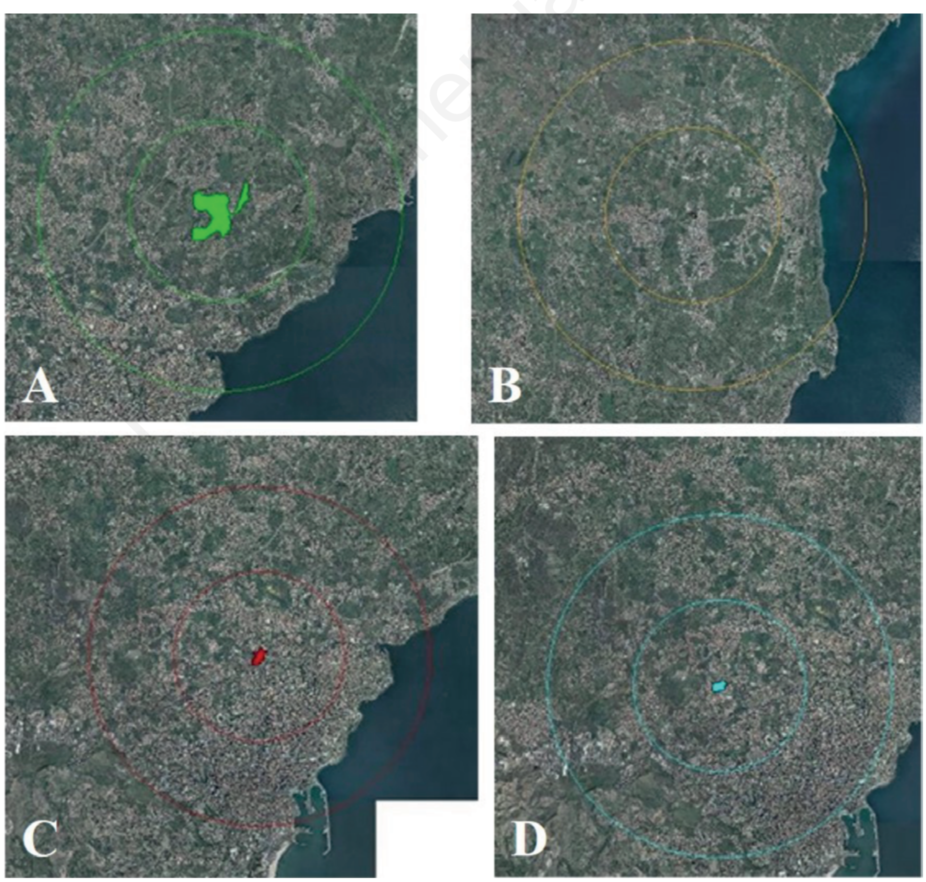

Figure 1. Satellite map of the eastern foothills of Volcano Etna, with the definition of the broad areas (buffers) for the investigated sites: (A) nature reserve (SG), (B) agroecosystem (AC), (C) central urban park (PG), and (D) peripheral urban park (PU).

composition, structure, and dynamics of the bee communities, the Shannon-Weaver index, the Pielou equipartition index, and the Simpson index were also calculated. In addition, the average value of each index was calculated for each site using an analysis of variance. A multivariate analysis was carried out to elucidate different ecological traits. Using Non-Metric Multidimensional (nMDS) methodology, were compared and graphed the populations of the different sites, based on the species composition and the specimen number. An nMDS plot was constructed through the similarity matrices, which graphically grouped the samples, and an ANOSIM-test was also conducted, useful for verifying the hypothesis of a lack of differences between the sites. Subsequent analyses were carried out at a higher level of aggregation, also considering the genera. Principal Component Analyses (PCAs) were implied to highlight the taxa having the greatest impact on species/sample variability. For the species with the greatest variability on the first three main components, bubble-plots were created to evaluate the number of specimens collected for each sample.

Furthermore, to compare the bee communities, we conducted a Correspondence Analysis (CA) (Digby & Kempton, 1987; James & McCulloch, 1990) by analysing the relationships between the four sampled sites and the families or species. The specific relationships (correspondences) between the examined taxa (*s*) and the sampling sites (*p*) were also identified. The calculations were carried out using the program Statistica 6.0.

For the Aci Catena (AC) site, a specific analysis was carried out to highlight any changes in the structure of the bee community caused by an unexpected change in agricultural practices (mechanical weeding) in the second year of the survey. The principal component analysis (PCA) method was also used for creating a graph of the principal components, with the samples inserted as a function of the species/sample matrix. The species with the greatest variability were highlighted by plotting their vectors on the main component graph, and bubble plots were produced for each of them to evaluate the number of specimens in each sample.

For the cartographic processing, a GIS system was used through the ArcView program to expand the observations to the investigated site and the surrounding area, through soil maps and the degree of urbanization; the latter was assessed through the photointerpretation of digital orthographic projections. This analytical approach highlighted the areas potentially suitable for bees.

Results

Structure of the bee communities

Overall, 1140 specimens of Apoidea were collected during the surveys in the four sites investigated, belonging to 104 species (*Supplementary Table S1*): Andrenidae (20 species), Halictidae (15 species), Megachilidae (31 species) and Apidae (38 species). Also, adding the species of the control site of Leucatia (LE), the species number of bees is 163. The bee communities of the sites are composed as follows: 46 species in the agroecosystem (AC), with 246 specimens (21%); 63 species in the Nature Reserve (SG), with 314 specimens (30%); 54 species in the central urban park (PG), with 354 specimens (25%); 53 species in the peripheral urban park (PU), with 226 specimens (24%); and 102 species were observed in the control site of Leucatia (LE).

The most represented families were Apidae, with 566 specimens (49.7%); Megachilidae, with 404 specimens (35.4%); followed by Andrenidae with 103 (9%) specimens and Halictidae, with 67 (5.4%) specimens. Further data on the qualitative and quantitative aspects of the bee populations of the sites investigated are reported by Turrisi *et al.* (2021). Considering the species collected in the three years of research in the four sites and those relating to the site of Leucatia, the presence/absence matrix of the species were constructed (*Supplementary Table S1*, *Figure S1*).

Statistical analysis of bee communities

The results for the nMDS plots and the hierarchical aggregation obtained considering all the samples of the four sites investigated are presented in *Supplementary Figures S2-S4*. In contrast, the results obtained from nMDS plots refer to all the samplings carried out in the different months of the three years of the study are shown in *Supplementary Figure S5*.

With a similarity gradient from 0 to 100, the hierarchical grouping of clusters was also considered, which highlighted how much the collections for each month in one site could be compared with that of another one (*Supplementary Figure S6*). The results for the nMDS plots refer to all the samplings carried out in the different months of the three years of the study presented in *Supplementary Figures S7* and *S8*, which considered the phenology of the species in the three years of investigation grouped in a single year. The results of the PCA are shown in *Supplementary Figures S9-S13*, which highlight the species that most characterize each sample and identify those with the greatest variability on the first three main components. The vectors of the principal components and the product of the bubble plots are presented in *Supplementary Figures S10-S13* to evaluate the number of specimens in each sample.

The agroecosystem of Aci Catena, which in 2009 was subjected to a drastic change in agricultural techniques due to mechanical weeding, as shown in *Supplementary Figure S14* shows the consequences. In this analysis, each sample was numbered in ascending order according to the capture date; the broken line joins the points that identify the monthly samples. The variations of the bee population in the Aci Catena site were also analyzed through the nMDS and cluster analysis (*Supplementary Figure S15*).

Correspondence analysis of species-sites

In addition to the number of species, some ecological indices were calculated (Tables 2-5) to evaluate the richness of the bee populations of each site. The results of the differences between the means were evaluated by ANOVA (P=0.01). The results of the correspondence analysis of species/site (*Supplementary Tables S2-S6*) are shown in *Supplementary Figures S16-S18*, in which the total inertia expressed by the data matrix was 0.81250 (χ^2= 925.44, df= 312, P=0,0000), with the first axis representing approximately 45.5% (eigenvalue 0.369), the second axis representing approximately 31.9% (eigenvalue 0.259) and the third axis representing approximately 22.8% (eigenvalue 0.185).

Environmental matrix and ecological connectivity

The analysis of the territorial matrix in which the studied sites were located allowed us to evaluate the degree of anthropization and the degree of ecological-functional isolation, as well as to identify the main ecological corridors. On the basis of the environmental characteristics of the wide area, defined by 4 km buffers, we identified in the network the degree of potential ecological connectivity of the individual sites, as shown in Figure 2. The degree of biopermeability is represented with the following colors: green (high absence), yellow (medium absence), and red (low absence) (*Supplementary Figure S19*). The low absence biopermeability component, corresponding to the urbanized territory, was predominant in all the sites investigated, ranging from 35% in Aci Catena to 70% in Parco Gioeni of the buffer considered; the other sites had values of 45% for San Gregorio, 62% for Leucatia, and 65% for Parco degli Ulivi. The average biopermeability areas were of limited extension, varying from 10% to 20% of the total, with similar values. Finally, the matrix with high biopermeability was variable from 18% of Parco Gioeni to 50% of Aci Catena, followed by Parco degli Ulivi at 20%, San Gregorio at 35%, and Leucatia at 23% (*Supplementary Figure S19*). Furthermore, as shown in the graph in *Supplementary Figure S20*, the linear regression analysis of the number of species on the surface width of the investigated sites showed good congruence with the insular biogeographical models (MacArthur & Wilson, 1967).

Discussion

Population analysis

Analyzing the number of species of the investigated sites, a remarkable richness and diversification of bee populations were revealed, even for those strongly altered by human activities. This confirms the role of 'biodiversity reservoir' assumed by the fragments of territory in the Etna foothills.

The multivariate analyses of the presence/absence data of the species in the sites (*Supplementary Table S1*) showed substantial congruence, confirmed by the two aggregation dendrograms with the same hierarchical arrangement of the bee populations in the

Table 2. Values of ecological indices for the bee population of the agroecosystem (AC).

Diversity indices for site AC						
Sample	S	N	d	J'	H'(loge)	1-Lambda
0308AC	6	16	1.80	0.95	1.70	0.80
0309AlC	5	5	2.49	1.00	1.61	0.80
0310AC	11	21	3.28	0.90	2.15	0.85
0408AC	14	69	3.07	0.89	2.34	0.88
0409AC	18	38	4.67	0.95	2.74	0.93
0410AC	11	25	3.11	0.86	2.07	0.83
0508AC	11	18	3.46	0.91	2.18	0.86
0509AC	14	26	3.99	0.91	2.41	0.89
0510AC	12	27	3.34	0.87	2.16	0.84
0610AC	1	3	0.00	N/A	0.00	0.00
0610AC	1	1	N/A	N/A	0.00	0.00
N/A	N/A	N/A	N/A	N/A	N/A	N/A
N/A	N/A	N/A	N/A	N/A	N/A	N/A
MEANS	9.45	22.64	2.92	0.91	1.76	0.70
SD	5.50	19.12	1.28	0.04	0.92	0.35
Tot.	104	249				

Table 3. Values of ecological indices for the bee population of the nature reserve (SG).

Diversity indices for site SG						
Sample	S	N	d	J'	H'(loge)	1-Lambda
0309SG	3	3	1.82	1.00	1.10	0.67
0310SG	10	17	3.18	0.93	2.15	0.87
0408SG	14	39	3.55	0.89	2.35	0.88
0409SG	13	25	3.73	0.93	2.38	0.89
0410SG	17	38	4.40	0.90	2.55	0.89
0508SG	9	18	2.77	0.81	1.78	0.75
0509SG	11	19	3.40	0.96	2.31	0.89
0510SG	22	50	5.37	0.87	2.70	0.90
0608SG	12	23	3.51	0.93	2.32	0.88
0609SG	9	19	2.72	0.92	2.03	0.85
0610SG	8	15	2.58	0.94	1.96	0.84
0708SG	13	32	3.46	0.85	2.17	0.84
0709SG	8	16	2.52	0.94	1.96	0.84
MEANS	11.46	24.15	3.31	0.91	2.14	0.85
SD	4.68	12.53	0.90	0.05	0.40	0.07
Tot.	149	314				

different sites. The bee population of the control site, Leucatia (LE), had a well-differentiated faunistic composition and a low index of similarity with the other four sites, thus constituting a distinct group, as pointed out by Turrisi *et al.* (2021, *Supplementary Figure S1*); the other four sites constituted a wide group within which there were three different subgroups, consistent with the prediction of similarity based on the type of environment and the relationships of micro-geographic proximity.

The analysis of the populations using nMDS based on the presence/absence in the different sites (*Supplementary Figure S1*) highlighted the presence of two groups, one represented by the two urban parks with an affinity of about 50%, the other by the two sites of Aci Catena and San Gregorio.

In a further analysis, the data from the three years of the survey were grouped into a single sample, adding the number of specimens per species observed in each month of the year. In the nMDS analysis, this data set showed the similarity of the bee populations of the different sites in all months. Only the population of the agroecosystem of Aci Catena was different in May 2009 due to the cultivation practices (mechanical weeding) applied in April, which significantly changed the structure of the bee population (*Supplementary Figures S5-S6*) compared to the previous and next year. The graph in *Supplementary Figure S15* shows the affinity of the populations in April, grouped in a single cluster with 40% similarity, while the lowest values in the other months of the year represent the changes in the bee population of

Table 4. Values of the ecological indices for the bee population of central urban park (PG).

Diversity indices for site PG						
Sample	**S**	**N**	**d**	**J'**	**H'(loge)**	**1-Lambda**
0209PG	2	2	1.44	1.00	0.69	0.50
0308PG	4	9	1.37	0.88	1.21	0.67
0309PG	7	13	2.34	0.95	1.84	0.83
0310PG	10	21	2.96	0.96	2.20	0.88
0408PG	11	47	2.60	0.99	2.37	0.90
0409PG	15	40	3.80	0.90	2.43	0.89
0410PG	23	57	5.44	0.83	2.60	0.88
0508PG	19	54	4.51	0.90	2.76	0.93
0509PG	17	66	3.82	0.96	2.72	0.93
0510PG	19	34	5.10	0.91	2.66	0.90
0708PG	2	6	0.56	0.65	0.45	0.28
0709PG	1.00	1.00	N/A	N/A	0.00	0.00
N/A	N/A	N/A	N/A	N/A	N/A	N/A
MEANS	10.83	29.17	3.08	0.90	1.83	0.72
SD	7.70	23.37	1.60	0.10	0.98	0.30
Tot.	130	350				

Table 5. Values of the ecological indices for the bee population of the peripheral urban park (PU).

Diversity indices for site PU						
Sample	**S**	**N**	**d**	**J'**	**H'(loge)**	**1-Lambda**
0308PU	9	15	2.95	0.94	2.06	0.85
0309PU	11	17	3.53	0.94	2.26	0.88
0310PU	11	25	3.11	0.78	1.87	0.77
0408PU	3	4	1.44	0.95	1.04	0.63
0409PU	17	34	4.54	0.91	2.57	0.90
0410PU	15	21	4.60	0.94	2.56	0.91
0508PU	12	24	3.46	0.95	2.37	0.90
0509PU	10	39	2.46	0.98	2.25	0.89
0510PU	16	27	4.55	0.89	2.45	0.87
0610PU	13	21	3.94	0.96	2.47	0.91
0310PU	1	3	0.00	N/A	0.00	0.00
N/A	N/A	N/A	N/A	N/A	N/A	N/A
N/A	N/A	N/A	N/A	N/A	N/A	N/A
MEANS	10.73	20.91	3.14	0.92	1.99	0.77
SD	5.00	11.04	1.42	0.06	0.79	0.27
Tot.	118	230				

the agroecosystem (*Supplementary Figure S14*). The PCA carried out on all samples of the four sites per month, highlighted the four species characterizing the different sites in terms of abundance (*Supplementary Figures S9-S13*): *Andrena agilissima italica*, *Anthophora crinipes*, *Habropoda tarsata*, and *Osmia aurulenta*. They were dominant in the months of March-May, with a peak in April, and with *A. agilissima italica* more abundant in the peripheral urban park (PU) (*Supplementary Figure S10*), *A. crinipes* more abundant in the agroecosystem (AC) (*Supplementary Figure S11*), *H. tarsata* more abundant in the nature reserve (SG) (*Supplementary Figure S12*) and *O. aurulenta* more abundant in the central urban park (PG) (*Supplementary Figure S13*).

Affinity among populations and correspondence analysis of species/site

The correspondence analysis of species/site led to a reduced set of correlated variables capable of analyzing the associations of the sites based on the species composition (*Supplementary Figures S16-S18*). From the analysis of the graph of the first two axes (*Supplementary Figure S16*), which overall expressed 77.2% of the total inertia, it was possible to identify a group of sites consisting of the two urban parks, which showed a greater affinity, and the isolated positions of the agroecosystem (AC) and the nature reserve (SG). The faunistic affinity of the two urban parks was probably due to their vegetational affinity and a similar extension. The third axis, on the other hand, separated the two urban parks (*Supplementary Figure S17*). Data presented in *Supplementary Tables S3-S6* show, for each axis, the species that most determined the affinities and differences between the sites with inertial values >1.5%. The bee species that discriminated the two urban parks from the other two sites were mainly *Amegilla albigena*, *Osmia aurulenta*, *O. kohli*, *O. latreillei iberoafricana*, *Rhodanthidium sticticum*, *Megachile sicula*, *Hoplitis anthocopoides*, and *Andrena agilissima italica*, which, although not exclusive to these sites, were present here with greater frequency and abundance (*Supplementary Table S3*). In the correspondence analysis (*Supplementary Figure S18*) obtained by simultaneously considering the species with inertial values >1.5%, the distribution of the abundances of the species is shown considering the affinities between the populations. In particular, the groups of species represented by *Anthophora crassipes*, *Eucera algira*, *Nomioides facilis* (present only in the central urban park, PG), *Lasioglossum laeve*, *Osmia notata* and *Andrena fumida* (present only in the peripheral urban park, PU), *Amegilla albigena*, *Osmia aurulenta*, *Megachile sicula*, *Hoplitis anthocopoides*, *Andrena agilissima italica*, *Rhodanthidium sticticum*, *Osmia latreillei iberoafricana*, *O. kohli* and *Xylocopa iris*, are those that most characterised the two urban parks (*Supplementary Table S6*).

Environmental fragmentation and ecological corridors

The fragmentation of the territory linked to the expansion of urban and suburban areas in the foothills of Volcano Etna creates isolated areas, often of limited extension, to support significant bee communities. A small population was obviously exposed to significant erosion and not capable of adequate resilience. These small bee communities, lacking significant ecological-functional con-

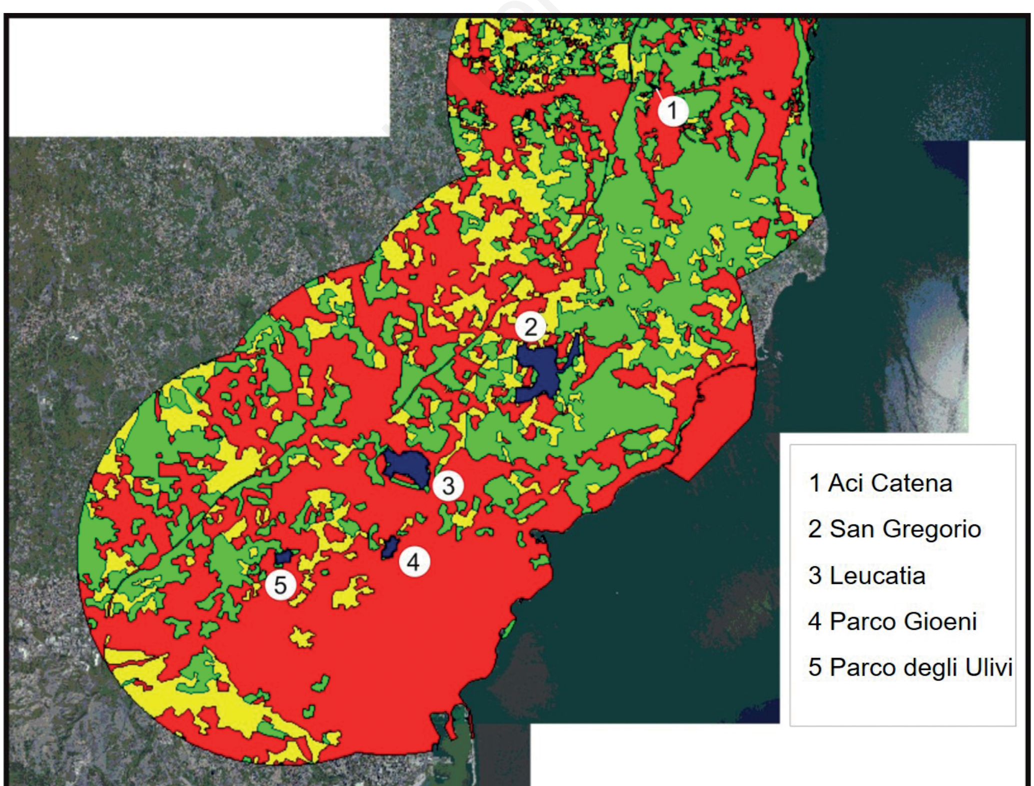

Figure 2. Representation of the biopermeability of the medium and broad area (buffer zone of 4 km) of the studied sites; green: high, yellow: medium, red: low to absent.

nectivity due to the erosion of the environmental matrix, could be affected by local disappearance, with the consequent modification of trophic networks (La Point *et al.*, 2015; Buchholz & Egerer, 2020; Coutinho *et al.*, 2021).

The two urban parks, inserted in extremely urbanized territorial contexts, were the sites with the highest degree of isolation in an ecological-functional sense (Figure 2); the control site (LE) is moderately isolated, whereas the two sites with a lower degree of isolation were the nature reserve (SG) and the agroecosystem (AC), as they are bordered by areas with medium to high biopermeability (*Supplementary Figures S*1, *S2*, *S19* and Figure 2). Obviously, the overall degree of biopermeability was closely correlated with the distance of the sites from urban centers and with the increase of their surface. The degree of functional ecological fragmentation based on the biopermeability highlights how the greatest degree of ecological connectivity occurs in the northern area of Catania, due to the presence of an extensive network of ecological corridors; on the other hand, the north-west area highlights the preponderance of territories with low ecological connectivity (*Supplementary Figure S20*). From the examination of the different sites, it is clear that the two urban parks, despite being characterized by significant geographical isolation, host relatively rich bee populations (Table 1), with a preponderance, however, of widely distributed species. On the basis of the biopermeability represented in Figure 2, the characters of ecological connectivity have been identified, considering the spatial contiguity or continuity of the network represented by the areas with medium and high values. The site of the site control (LE) and that of the two urban parks (PG, PU) is characterized by the almost absence of ecological corridors in the area to the south-east, while to the northwest the ecological corridors show a moderately broader development.

The metropolitan area of Catania will be the main threat to current levels of biodiversity, as it limits or prevents the possibility of exchange between bee populations. The site of the nature reserve (SG) highlights the greatest presence of ecological corridors, with high biopermeability in the broad areas located to the north-east and south-west. The agroecosystem (AC) has a significant environmental matrix with good ecological connectivity in all directions and a good development of linear connection systems. Many of these ecological-functional connection areas are represented by citrus orchards (D'Urso *et al.*, 2001). The fragmentation processes are currently increasing in the broad area where the sites investigated are, leading to the coexistence of complex environmental patches with large, urbanized areas, cultivated areas, others in post-cultural abandonment, as well as public parks and private gardens. This environmental mosaic, characterized by a medium-high degree of fragmentation (Figure 2 and *Supplementary Figure S19*), is the primary cause of the drastic reduction in the exchange of individuals between populations, where the disappearance of some species is accompanied by the prevalence of other species with a wider ecological adaptivity. The rather rich and differentiated bee communities in the two urban parks are certainly linked to the disjunction between the nesting site and the foraging sites, an aspect that allows these insects to be present even in areas with high anthropogenic disturbance (Turrisi *et al.*, 2021). The colonization processes of a site also depend on the dispersion capacity and, therefore, on the vagility of the species, and this aspect is significantly variable in the different species, from a few hundred meters to several kilometers (Gathmann & Tscharntke, 2002; Greenleaf *et al.*, 2007). Precisely on this aspect, the choice of the buffer size around the site to be investigated was made to estimate the area of ecological influence in the processes of dispersal of the species and to subsequently be able to correlate them with the state of fragmentation of the environmental matrix (Figure 2).

Regarding the Sicilian Ecological Network, among the five sites studied, currently, only the nature reserve (SG) is currently included, as it represents a nodal area SIC (ITA070008) of the Natura 2000 Network. Numerous other areas with different degrees of protection in the foothills of Etna, some also close to the sites studied, certainly have a functional role as nodal areas in the definition of ecological corridors, but unfortunately, the environmental matrix in which they occur has low biopermeability, and therefore their ecological connectivity with the sites studied will decrease in the short-medium timescale.

Evaluation of environmental fragmentation using the biogeographical model of the islands

The linear regression analysis of the number of species in the analysed sites shows good congruence with the models of the island biogeography (*Supplementary Figure S20*). All the sites studied can be approximated to islands in an ecological-functional sense and is to be attributed to the environmental matrix in which they are inserted, affected by more or less pronounced fragmentation processes. The dispersion points relating to the central urban park (PG), the peripheral urban park (PU), and the agroecosystem (AC) sites are very close to the 'best straight line' identified by the model. In contrast, those sites of the control site (LE) and nature reserve (SG) are marginally placed at the fiducial limits of 95% calculated for the same line (*Supplementary Figure S20*). In detail, the control site (LE) shows a greater species-surface ratio and, therefore, a greater diversity of its bee population. The site of the nature reserve (SG), on the other hand, has a species-surface ratio lower than the expected value and, therefore, a certain insularity in an ecological sense. The process of environmental fragmentation leads to establishing areas, often with a high degree of naturalness with a reduced extension, to an increase in the distance between them, and therefore to a reduction of their surface within the territorial context. There are positive correlations between the size of the fragments of the territory with species richness and the abundance of their populations, identifying such interrelations as the correlation number of species-area and abundance of species-area (Terayama & Murata, 1990; Rosenzweig, 1995; Connor *et al.*, 2000; Gibb & Hochuli, 2002; Ferreira *et al.*, 2015). An important aspect, even if poorly investigated, is relating the composition of the landscape matrix with the areas surrounding the fragments (Ricketts, 2001). Pollinator species that are more or less selective in the choice of nesting site and foraging habitat, especially those with limited dispersal capacity and depending on obligatory mutualistic relationships, are obviously the most sensitive to habitat fragmentation (Holt *et al.*, 1999; Steffan-Dewenter & Tscharntke, 1999, 2002; Davies *et al.*, 2000; Tscharntke *et al.*, 2002; Steffan-Dewenter, 2003; Steffan-Dewenter *et al.*, 2006). In general, bee species that nest on the ground in urbanized areas due to soil inaccessibility are those whose populations are most at risk (Hernandez *et al.*, 2009; Danforth *et al*., 2019). Consequently, urban habitat is more suitable for generalist and cavity-nesting bee species. The effects of urbanization on other categories of bee species, such as cleptoparasitc and parasitic social bees, need to be further investigated in the future. However, some results of this study, reported by Turrisi *et al*. (2021), showed a higher percentage of hypogeic (ground-nesting) bee species (50%, 52 species) compared to hypergeic (cavity-nesting) species (40.38%, 42 species) the remaining component are parasitic species.

Conclusions

The aim of the present research was to conduct a census of the bee communities of five sites on Volcano Etna close to the metropolitan area of Catania at different degrees of anthropogenic disturbance placed in a complex environmental matrix with more or less pronounced fragmentation. The data obtained shed light on the composition and dynamics of the bee communities in the Etnean foothills to: i) assess the degree of environmental alteration of the territory; ii) identify the most ecologically significant areas; iii) evaluate the ecological role of marginal areas; iv) provide useful tools in the territorial planning and management phases; v) define more precisely the nodes of the Ecological Network. The examination of the data on the phenology of the bee populations showed that the peak of activity and the greatest number of species and specimens occurred in the months of March-May. This suggests that agronomic management methods should be adapted or even avoided to prevent strong modifications during this peak of activity and highest diversity, thus avoiding negative ecological impacts. The linear regression analysis of the number of species compared with the surface of the sites studied highlights how these territories are similar to islands in an ecological-functional sense, a condition to be correlated with the environmental matrix in which they fall, characterized by extensive anthropisation processes and considerable fragmentation of the territory. Thus, the data obtained confirm the ecological role of the environmental fragments, including urban parks, agroecosystems, and natural remnants, as a reservoir of biodiversity and their significant role as nodal areas for protecting the biodiversity within the urban and periurban context of the metropolitan city of Catania.

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Online supplementary material:

Figure S1. Dendrogram with the presence-absence matrix of the species in the four studied sites and the Leucatia site with the "neighbour-joining" method, and the Horn algorithm.

Figure S2. nMDS obtained from the presence-absence matrix of the species reported in the four studied sites and the reference site, Leucatia.

Figure S3. nMDS plot of the samples based on the presence-absence in the four investigated sites in the three years of the study.

Figure S4. Hierarchical grouping that includes all the samples of the four investigated sites.

Figure S5. nMDS plot for all the samplings of the four investigated sites in the different months.

Figure S6. Hierarchical grouping achieved through the similarity gradient (0-100).

Figure S7. nMDS plot of the phenology of the species in the three years of investigation grouped in a single year.

Figure S8. Hierarchical grouping of the phenology of the species in the three years of investigation grouped in a single year.

Figure S9. PCA plot of sites in relation to months and vector species of the main components.

Figure S10. PCA plot of sites in relation to months for Andrena agilissima italica.

Figure S11. PCA plot of sites in relation to months for Anthophora crinipes.

Figure S12. PCA plot of sites in relation to months for Habropoda tarsata.

Figure S13. PCA plot of sites in relation to months for Osmia aurulenta.

Figure S14. PCA of the specimens sampling in the agroecosystem (AC) site in ascending order per month.

Figure S15. nMDS and hierarchical grouping of the variations of the populations in the agroecosystem (AC) site in relation to the different months in the years of the surveys.

Figure S16. Analysis of species-sites correspondence, considering axes I and II as references.

Figure S17. Analysis of species-sites correspondence, considering axes I and III as references.

Figure S18. Analysis of species-sites correspondences, with details of the characterising species.

Figure S19. Biopermeability of the large area (4 km buffer) with the survey sites. Low to absent biopermeability (green), medium (red), high (blue).

Figure S20. Linear regression for the correlation between the number of species and the sizes of the sites.

Table S1. Presence/absence matrix of the species recorded in the five sites studied: Aci Catena (AC), San Gregorio (SG), Parco Gioeni (PG), Parco degli Ulivi (PU), and Leucatia (LE).

Table S2. Contingency table with the number of specimens of the species, the value of the abundance ranks (^{r}), and the average number of specimens collected in the four sites investigated.

Table S3. Distribution of the number of specimens for the selected species with inertial values greater than 1.5% for axis I.

Table S4. Distribution of the number of specimens for the selected species with inertial values greater than 1.5% for axis II.

Table S5. Distribution of the number of specimens for the selected species with inertial values greater than 1.5% for axis III.

Table S6. Distribution of the number of specimens for the selected species in the sites investigated with an inertial value greater than 1.5%.