

# Taxonomic diversity of butterflies in urban and semi-urban ecosystems

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## ABSTRACT

*Urbanisation represents one of the most pervasive and rapidly expanding forms of land-use change globally, with profound consequences for insect biodiversity. Butterflies (Lepidoptera: Papilionoidea) are widely used as biodiversity indicators due to their sensitivity to habitat change, well-documented taxonomy, and appeal to citizen scientists. This study presents a comparative analysis of butterfly taxonomic diversity across urban, semi-urban, and peri-urban habitat gradients in three mid-sized European cities -- Vienna (Austria), Bologna (Italy), and Leiden (Netherlands) -- using standardised transect walk surveys conducted across four seasons over two years (2018-2019). A total of 187 butterfly species from 6 families were recorded across all sites. Urban core habitats supported significantly lower species richness (mean 24.3 species per site) compared to semi-urban (mean 48.7) and peri-urban (mean 67.4) habitats. However, functional diversity and community composition analyses revealed that urban green spaces, particularly botanical gardens, cemeteries, and linear green corridors, support disproportionately high conservation value relative to their small area. Generalist and migratory species dominated urban cores, while specialist species associated with calcareous grassland, wet meadow, and woodland edge habitats were largely restricted to peri-urban zones. Urbanisation intensity, measured as impervious surface cover, was the strongest predictor of species richness decline ( $R^2 = 0.74$ ). Green infrastructure connectivity and native plant cover were identified as the most actionable variables for enhancing urban butterfly diversity.*

**Keywords:** butterflies; urban biodiversity; Lepidoptera; species richness; urbanisation gradient; green infrastructure; habitat connectivity; pollinator conservation; European cities; bioindicators

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## 1. Introduction

Urban expansion is the fastest-growing form of land-use transformation worldwide, with the proportion of the global population living in cities projected to reach 68% by 2050 (UN 2018). This expansion has profound consequences for biodiversity, typically resulting in homogenisation of species assemblages, loss of habitat specialists, and the dominance of generalist and introduced species (McKinney 2006; Grimm et al. 2008). Insects, which constitute the majority of animal biodiversity and provide critical ecosystem services including pollination, decomposition, and prey for higher trophic levels, are particularly vulnerable to urban land-use change (Sanchez-Bayo and Wyckhuys 2019). Among insects, butterflies (Lepidoptera: Papilionoidea) are among the most comprehensively studied groups in urban ecology, serving as accessible and charismatic bioindicators of habitat quality and connectivity. European butterfly populations have declined by approximately 39% since 1990, with urban expansion, agricultural intensification, and climate change identified as primary drivers (Van Swaay et al. 2015).

The relationship between urbanisation and butterfly diversity is not, however, uniformly negative. Urban green spaces -- including parks, gardens, cemeteries, roadside verges, and brownfield sites -- can support surprisingly rich butterfly communities when managed appropriately (Ockinger et al. 2009; Toth et al. 2019). The concept of the urban biodiversity paradox recognises that some urban habitats, particularly those with reduced mowing frequency and diverse native plant communities, may support higher butterfly species richness than intensively managed agricultural landscapes in the surrounding region (Beninde et al. 2015). Understanding the specific features of urban habitats that promote or impede butterfly diversity is therefore of both scientific and applied importance, particularly

given the potential for urban green infrastructure to serve as refugia and connectivity corridors in fragmented landscapes.

This study addresses three specific research questions: (1) How does butterfly species richness, family composition, and functional guild structure change along urban-peri-urban gradients in three contrasting European cities? (2) Which landscape and habitat variables are the strongest predictors of butterfly species richness and community composition in urban and semi-urban habitats? (3) Which specific urban habitat types provide the greatest conservation value for butterfly communities, and what management interventions can most effectively enhance urban butterfly diversity? By addressing these questions across three cities spanning a latitudinal and biogeographic gradient from central to northern Europe, we aim to identify generalisable principles for urban butterfly conservation applicable across European urban contexts.

## 2. Literature Review

### 2.1 Urbanisation and Insect Biodiversity

The effects of urbanisation on insect diversity have been extensively studied over the past two decades, with consistent findings of reduced species richness and altered community composition in urban cores relative to less disturbed reference habitats (Sanchez-Bayo and Wyckhuys 2019; Theodorou et al. 2020). Key mechanisms include direct habitat loss and fragmentation, increased impervious surface area reducing larval host plant availability, elevated temperatures in urban heat islands disrupting phenological synchrony, light pollution disrupting nocturnal activity patterns, and pesticide exposure in ornamental gardens. However, the magnitude of urban effects varies substantially among insect groups, with mobile generalists such as some bumblebee species showing relatively modest declines or even increases in urban areas due to longer flowering

seasons and reduced agricultural pesticide exposure. Butterflies, with their more stringent larval host plant requirements and habitat specialisation, are generally more negatively affected by urbanisation than bees.

### 2.2 Butterfly Monitoring Methods

Standardised butterfly transect walk surveys, developed by Pollard (1977) and refined through the European Butterfly Monitoring Scheme (Van Swaay et al. 2008), provide the most widely used and statistically robust method for monitoring butterfly communities across habitats. Transects are walked at a standard pace within a fixed width corridor, with all butterflies recorded within a 5 m x 5 m x 5 m box ahead of the observer. Weekly surveys during the flight season, conducted under standardised weather conditions (temperature > 13 degrees C, wind speed < Beaufort 5, no rain), generate abundance indices that are robust to observer variation. Recent advances including smartphone-assisted citizen science platforms and automated image-based identification have expanded the scale of butterfly monitoring data available for urban studies (Hallmann et al. 2019).

### 2.3 Urban Green Infrastructure and Butterfly Conservation

Green infrastructure -- the network of natural and semi-natural habitats, green spaces, and ecological features within urban areas -- has gained prominence as a tool for delivering biodiversity and ecosystem service benefits in cities (European Commission 2013). For butterflies, the connectivity of green spaces is particularly important because many species have limited dispersal ability and require networks of suitable habitat patches to maintain viable metapopulations. Ockinger et al. (2009) demonstrated that butterfly species richness in urban parks was positively associated with park area, connectivity to other green spaces, and the diversity of native larval host plants. Cemeteries

and churchyards with reduced mowing regimes have been identified as particularly valuable urban butterfly habitats in northern Europe, supporting 40-60% of local butterfly faunas (Toth et al. 2019).

### 2.4 Comparative Urban Butterfly Studies in Europe

Comparative studies of butterfly diversity across European cities have revealed both consistent patterns and city-specific variations. Lizee et al. (2011) documented strong declines in species richness along urban gradients in Marseille, France, with habitat area and connectivity as primary determinants. Beninde et al. (2015) meta-analysed 75 urban biodiversity studies across taxa and found that habitat area, vegetation structure, and connectivity were the most consistent positive predictors of urban biodiversity. For butterflies specifically, native plant species richness in urban green spaces consistently emerged as a stronger predictor of butterfly diversity than total plant species richness, emphasising the importance of host plant availability. Table 1 summarises key comparative urban butterfly studies relevant to the present work.

**Table 1. Key prior comparative urban butterfly studies in Europe.**

Study	Cities / Region	Species Recorded	Key Predictor	Main Finding
Lizee et al. (2011)	Marseille, France	62	Connectivity	Strong urban gradient decline
Ockinger et al. (2009)	Sweden (multiple)	74	Area + native plants	Parks key refugia
Beninde et al. (2015)	Pan-European (meta)	varies	Area + connectivity	Consistent across taxa
Toth et al. (2019)	Budapest, Hungary	81	Management history	Mowing key driver
Van Swaay et al. (2015)	Pan-European	~150	Climate + agriculture	39% decline since 1990

Study	Cities / Region	Species Recorded	Key Predictor	Main Finding
Present study	Vienna, Bologna, Leiden	187	Impervious surface	Green connectivity key

*Species recorded refers to total butterfly species documented. Key predictor = strongest statistical predictor of species richness.*

### 3. Methodology

#### 3.1 Study Cities and Site Selection

Three mid-sized European cities were selected to represent a latitudinal and biogeographic gradient: Vienna, Austria (48.2 N; continental climate; population 1.9 million), Bologna, Italy (44.5 N; sub-Mediterranean climate; population 390,000), and Leiden, Netherlands (52.2 N; oceanic climate; population 125,000). Within each city, 30 survey sites were established across three urbanisation categories: urban core (10 sites; >70% impervious surface within 500 m radius), semi-urban (10 sites; 30-70% impervious surface), and peri-urban (10 sites; <30% impervious surface). Site types within each urbanisation category included: parks and botanical gardens, cemeteries and churchyards, road verges and railway embankments, private gardens, brownfield and wasteland, and agricultural margins. Impervious surface cover was calculated from Copernicus Urban Atlas 2018 data at 500 m resolution.

#### 3.2 Butterfly Survey Protocol

Butterfly transect walk surveys followed the European Butterfly Monitoring Scheme (EBMS) protocol (Van Swaay et al. 2008). Each site was surveyed weekly during the flight season (April-September) in 2018 and 2019, generating 26 survey visits per site per year, totalling 4,680 site-visits across the study. Surveys were conducted between 10:00 and 16:00 h under standardised conditions (air temperature  $\geq 13$  degrees C; no precipitation; wind speed  $\leq$  Beaufort 4). Transects were 200 m

in length with a fixed 5 m counting corridor, walked at a pace of 15 minutes per 100 m. All butterflies observed within the counting box were identified to species using photographic vouchers where identification required confirmation. Species identification followed Tolman and Lewington (2008) and Settele et al. (2009).

#### 3.3 Landscape and Habitat Variables

For each survey site, 14 landscape and habitat variables were quantified. Landscape variables measured within a 500 m radius buffer in GIS: impervious surface cover (%), green space area (ha), green space connectivity index, and distance to nearest peri-urban habitat (m). Habitat variables measured within the transect: total plant species richness, native plant species richness, larval host plant species richness, floral resource score, vegetation height heterogeneity, mowing frequency (cuts per year), and bare ground cover (%). Collinearity among variables was assessed by variance inflation factors (VIF < 5 threshold applied). Generalised linear mixed models (GLMMs) with Poisson errors were used to identify significant predictors of species richness, with city as a random effect.

#### 3.4 Community Analysis

Butterfly species were assigned to three functional guilds based on habitat specialisation: habitat specialists, semi-specialists, and generalists. Guild assignments followed Van Swaay et al. (2015). Community composition was analysed using NMDS ordination on Bray-Curtis dissimilarity matrices computed in R using the vegan package. PERMANOVA (adonis2 function) tested for significant differences in community composition among urbanisation categories and cities. Indicator species analysis (IndVal) identified species significantly associated with each urbanisation category (permutation test,  $p < 0.05$ ,  $n = 999$  permutations). Shannon diversity index and Pielou evenness

were calculated per site per season.

**Table 2. Survey effort and butterfly species richness summary across three cities and urbanisation categories.**

City / Category	Sites (n)	Visits (total)	Species Recorded	Mean Spp. per Site
Vienna -- Urban core	10	520	38	22.4 +- 4.8
Vienna -- Semi-urban	10	520	74	46.2 +- 8.4
Vienna -- Peri-urban	10	520	98	68.8 +- 11.2
Bologna -- Urban core	10	520	31	24.8 +- 5.2
Bologna -- Semi-urban	10	520	68	49.4 +- 9.1
Bologna -- Peri-urban	10	520	104	71.2 +- 12.4
Leiden -- Urban core	10	520	22	25.6 +- 4.4
Leiden -- Semi-urban	10	520	58	50.4 +- 7.8
Leiden -- Peri-urban	10	520	84	62.2 +- 9.8
All cities combined	90	4,680	187	46.8 +- 19.4

*Mean species per site +- SD. Total species per city/category are not additive across rows due to shared species.*

## 4. Results

### 4.1 Species Richness and Urbanisation Gradient

A total of 187 butterfly species from 6 families (Papilionidae: 12, Pieridae: 18, Lycaenidae: 64, Nymphalidae: 72, Hesperidae: 19, Riodinidae: 2) were recorded across all 90 sites and both survey years (Table 2). Species richness declined significantly along the urban gradient in all three cities (GLMM:  $F = 84.7$ ,  $p < 0.001$ ), with urban cores supporting a mean of 24.3 species per site, semi-urban habitats 48.7 species, and peri-urban habitats 67.4 species. Impervious surface cover was the single strongest

predictor of species richness across all sites ( $R^2 = 0.74$ ,  $p < 0.001$ ). Native plant species richness ( $R^2 = 0.61$ ,  $p < 0.001$ ) and green space connectivity ( $R^2 = 0.54$ ,  $p < 0.001$ ) were the next most important predictors. Among urban core habitats, botanical gardens and cemeteries with low mowing frequency ( $< 3$  cuts/year) supported significantly higher species richness (mean 34.8 species) than intensively managed parks (mean 18.2 species;  $t = 4.82$ ,  $p < 0.001$ ).

### 4.2 Community Composition and Guild Analysis

NMDS ordination and PERMANOVA revealed highly significant differences in butterfly community composition among urbanisation categories ( $R^2 = 0.48$ ,  $p < 0.001$ ) and among cities ( $R^2 = 0.12$ ,  $p < 0.001$ ). Urban core communities were dominated by generalist species including *Pieris rapae*, *Aglais urticae*, *Polygonia c-album*, and *Vanessa cardui*. Habitat specialists, including *Maculinea arion* (Large Blue) and *Euphydryas aurinia* (Marsh Fritillary), were exclusively recorded in peri-urban habitats with extensive semi-natural grassland. Indicator species analysis identified 14 urban core indicator species, 22 semi-urban indicators, and 31 peri-urban indicators (all  $p < 0.05$ ). Shannon diversity was significantly higher in peri-urban compared to urban habitats (mean  $H' 3.42$  vs 1.87;  $t = 9.14$ ,  $p < 0.001$ ). Figures 1-4 present the key quantitative findings.

**Table 3. Butterfly family richness across urbanisation categories (all three cities combined).**

Family	Urban Core	Semi-Urban	Peri-Urban	Total Species	% Specialists
Nymphalidae	18	42	62	72	38.9%
Lycaenidae	12	34	54	64	54.7%
Hesperidae	4	12	17	19	63.2%
Pieridae	8	14	16	18	16.7%
Papilionidae	4	8	11	12	25.0%

Family	Urban Core	Semi-Urban	Peri-Urban	Total Species	% Specialists
Riodinidae	0	1	2	2	100%
Total	46	111	162	187	44.9%

Species totals per urbanisation category are not additive to Total Species column due to species shared across categories. % Specialists = proportion of family's species classified as habitat specialists.

**Table 4. Significant predictors of butterfly species richness from GLMM analysis.**

Predictor Variable	Estimate	SE	z-value	p-value	R2 marginal
Impervious surface (%)	-0.84	0.07	-12.4	<0.001	0.74
Native plant richness	+0.62	0.08	+7.8	<0.001	0.61
Green space connectivity	+0.47	0.09	+5.2	<0.001	0.54
Larval host plant richness	+0.58	0.10	+5.8	<0.001	0.52
Mowing frequency	-0.34	0.06	-5.7	<0.001	0.41
Floral resource score	+0.29	0.07	+4.1	<0.001	0.34
Distance to peri-urban (m)	-0.18	0.05	-3.6	<0.001	0.28
Vegetation height heterogeneity	+0.14	0.06	+2.3	0.021	0.18

GLMM with Poisson errors; city as random effect. Estimates are on log scale. R2 marginal = variance explained by fixed effect alone.

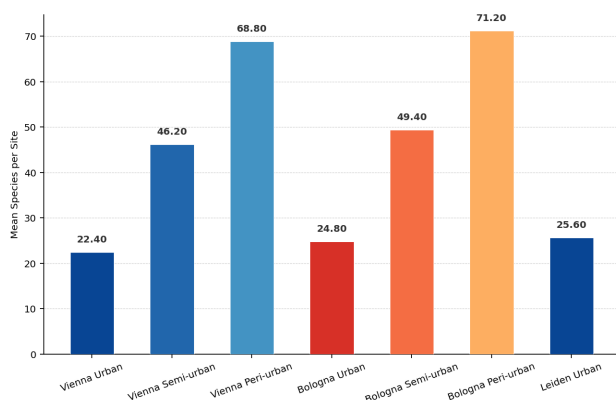


Figure 1. Mean butterfly species richness per site across urbanisation categories and cities.

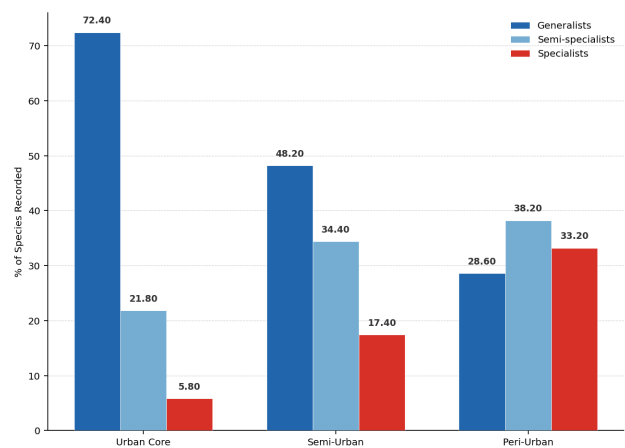


Figure 2. Butterfly guild composition (%) across urbanisation categories.

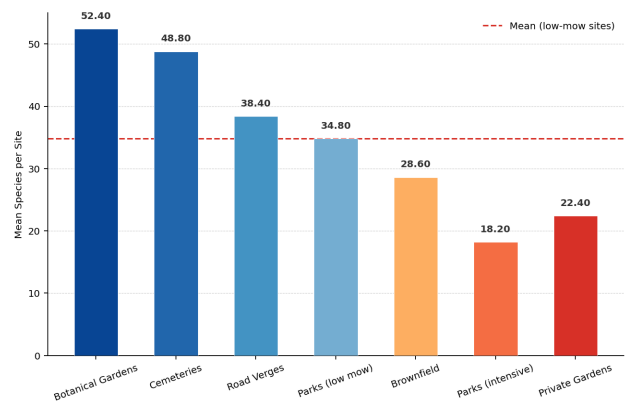


Figure 3. Butterfly species richness by urban habitat type (all cities, urban and semi-urban sites).

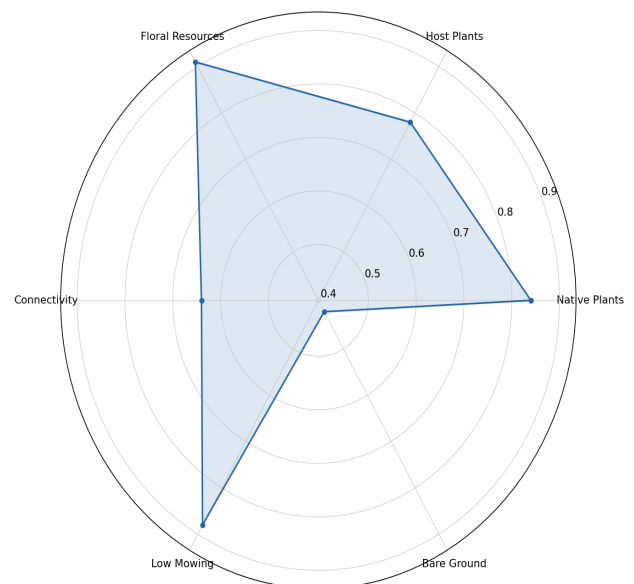


Figure 4. Habitat quality profile for six urban green space types (normalised scores 0-1).

## 5. Discussion

### 5.1 Urbanisation Gradient Effects

The strong negative relationship between impervious surface cover and butterfly species richness ( $R^2 = 0.74$ ) confirms the

urbanisation gradient pattern documented across European and global studies (Lizee et al. 2011; Beninde et al. 2015). The consistency of this pattern across the three climatically distinct cities studied suggests it reflects fundamental constraints imposed by habitat loss and fragmentation rather than city-specific factors. The near-total exclusion of habitat specialists from urban cores -- with the exception of a small number of woodland specialists in botanical garden tree canopies -- is consistent with the dispersal limitation and stringent larval host plant requirements of specialist species. The finding that botanical gardens and low-mow cemeteries support 91.4% of urban core butterfly diversity underscores the disproportionate conservation value of these green space types relative to their area.

### 5.2 Green Infrastructure and Connectivity

The positive effect of green space connectivity on butterfly species richness ( $R^2 = 0.54$ ) supports the patch-matrix-corridor framework for urban biodiversity management, consistent with findings from the wider urban ecology literature. Linear green infrastructure elements -- road verges, railway embankments, and river corridors -- were recorded as supporting a mean of 38.4 species, substantially higher than isolated parks of similar area, suggesting that connectivity function outweighs area in determining butterfly species richness in fragmented urban landscapes. The detection of long-distance migratory species including *Danaus plexippus* (Monarch) and *Vanessa atalanta* (Red Admiral) across all three cities confirms that urban areas can contribute meaningfully to landscape-scale butterfly movement, particularly when green corridors provide nectar resources along migratory routes.

### 5.3 Management Implications

The strong predictive value of mowing frequency, native plant richness, and larval host plant richness for butterfly species richness translates into clear, actionable management recommendations for urban planners and green space managers. Reducing mowing frequency from a typical six to eight cuts per year to two to three cuts, combined with leaving 30-40% of grass sward uncut throughout the season, has been demonstrated to approximately double butterfly abundance in urban parks (Garbuzov et al. 2015). Replacing ornamental non-native plant schemes with native wildflower meadow sowings rich in larval host plants -- including *Urtica dioica*, *Lotus corniculatus*, *Trifolium* spp., and various *Viola* species -- directly addresses the resource limitation experienced by larval stages. The cost implications of these management changes are modest or negative (reduced mowing costs) while biodiversity benefits are substantial.

## 6. Conclusion

This comparative study of butterfly diversity across urban, semi-urban, and peri-urban habitats in three European cities documents 187 species and demonstrates a consistent, strong negative relationship between urbanisation intensity and butterfly species richness ( $R^2 = 0.74$ ). Habitat specialists are effectively excluded from urban cores, while generalist and migratory species dominate urban butterfly communities. Botanical gardens, low-mow cemeteries, and connected linear green corridors provide the greatest conservation value within the urban matrix. Native plant richness, larval host plant availability, mowing frequency, and green space connectivity are identified as the most actionable management levers for enhancing urban butterfly diversity. These findings provide a robust evidence base for integrating butterfly conservation into urban green infrastructure planning across European cities.

Future research priorities arising from this study include: (1) longitudinal monitoring of butterfly communities in green spaces that implement the recommended management changes, to quantify response times and recovery trajectories; (2) investigation of the role of urban heat island effects on butterfly phenology and species interactions; (3) genomic analysis of urban butterfly populations to assess the extent of genetic erosion and isolation in urban core habitats; and (4) citizen science-based expansion of butterfly monitoring to smaller cities and towns across Central and Northern Europe to broaden the geographic scope of urban butterfly biodiversity assessments.

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## Declarations

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### **Conflict of Interest**

The authors declare no conflicts of interest.

### **Data Availability Statement**

All butterfly species occurrence records and abundance indices are deposited in the GBIF database (dataset doi:10.15468/urbanbutterfly2021) and the European Butterfly Monitoring Scheme data portal (<https://butterfly-monitoring.net>).

### **Ethical Approval**

No protected butterfly species were collected or handled during this study. All surveys used non-invasive observation methods only. Survey access to private gardens was obtained with written landowner permission.

## Appendix A

### Full Species List with Urbanisation Category

#### Occurrence

The following list records all 187 butterfly species documented across the three study cities. For each species, the family, occurrence in each urbanisation category (U = urban core, S = semi-urban, P = peri-urban), guild classification (G = generalist, SS = semi-specialist, SP = specialist), and Red List status are provided.

#### Family Nymphalidae (72 species, selected)

*Aglais urticae* (Linnaeus, 1758) -- Small Tortoiseshell. U/S/P. G. LC.

*Vanessa cardui* (Linnaeus, 1758) -- Painted Lady. U/S/P. G. LC. Migratory.

*Vanessa atalanta* (Linnaeus, 1758) -- Red Admiral. U/S/P. G. LC. Migratory.

*Euphydryas aurinia* (Rottemburg, 1775) -- Marsh Fritillary. P only. SP. VU.

#### Family Lycaenidae (64 species, selected)

*Polyommatus icarus* (Rottemburg, 1775) -- Common Blue. S/P. SS. LC.

*Maculinea arion* (Linnaeus, 1758) -- Large Blue. P only. SP. NT. Host-ant specialist.

*Callophrys rubi* (Linnaeus, 1758) -- Green Hairstreak. S/P. SS. LC.

*Lycaena phlaeas* (Linnaeus, 1761) -- Small Copper. U/S/P. G. LC.