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CHAPTER 5

How many Lepidoptera species are waiting to be discovered in Iran? An estimation of the total lepidopteran fauna*

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Identifying knowledge gaps and highlighting the less explored areas of Iran were two of the major purposes of the “Lepidoptera Iranica” project. In that context, it was important to estimate the number of unidentified or undescribed species as well as the cryptic lepidopteran diversity of the country. It is possible to estimate the total Lepidoptera fauna of Iran by comparing the Iranian diversity of certain well-known groups with the European diversity of those same groups, as Europe has arguably the best-known Lepidoptera fauna in the world for a large surface area.

The total number of valid Lepidoptera species (4,812) listed in this catalogue (RAJAEI et al. 2023) must be considered underestimated. Although some groups, such as Papilionoidea (NAZARI 2003; TSHIKOLOVETS et al. 2014) and Zygaenidae (KEIL 2014; HOFMANN & TREMEWAN 2017, 2020), have been extensively researched and their Iranian faunas are considered to be well known, others, e.g., Microlepidoptera, are generally still poorly known.

The Lepidoptera fauna of Europe, on the other hand, has been the subject of intense interest since the time of LINNAEUS, i.e., for more than 260 years, and is considered relatively well known (e.g., KARSHOLT & RAZOWSKI 1996). The Fauna Europaea project (KARSHOLT & NIEUKERKEN 2011) assembled a database of the scientific names and distributions of European Lepidoptera, but the most recently updated dataset (version 2.4) dates back to 2011. The most updated source of taxonomic information on the Lepidoptera fauna of Europe is the Lepiforum web portal (<https://lepiforum.org/>) (RODELAND et al. 2006–2022), which lists the total number of species in each family-group taxon.

One important factor to consider is that Europe is over six times larger than Iran and is significantly different in terms of habitat and geology. Also, due to the more easterly and southerly geographic position of Iran and to the different paleo-historical events it was subjected to, there are important zoogeographical dissimilarities between the

two. In Iran, high mountains create a barrier in the west; the eastern regions are covered by infertile, salty deserts; a narrow, fertile strip borders the Caspian Sea in the north; and lowlands rim the Persian Gulf in the south.

Many authors have estimated global and regional Lepidoptera biodiversity based on a variety of methods. One method of estimating lepidopteran species richness is by faunal comparisons between the number of described species of butterflies (i.e., superfamily Papilionoidea) and that of moths (e.g., LAFONTAINE & WOOD 1997). Global butterfly diversity consists of 18,732 described species (NIEUKERKEN et al. 2011), representing about 90% of an estimated total of 20,813 species (ROBBINS & OPLER 1997; POGUE 2009). In well-collected areas in northern Europe and Canada (e.g., Ottawa, Ontario), the butterfly fauna constitutes 4–5% of all lepidopteran species (LAFONTAINE & WOOD 1997; POGUE 2009). In the Nearctic Realm, the butterfly fauna constitutes 6% of all lepidopteran species (OPLER & WARREN 2003; WARREN et al. 2012; PELHAM 2022). Technically speaking, using faunal comparisons fails to give an accurate estimate of world lepidopteran species richness at a global scale (POGUE 2009), but can be a good way of estimating the species richness of a local area or region.

Here, we attempt to provide a gross estimate of the number of Lepidoptera species potentially occurring in Iran by using such faunal comparisons, with estimated total species numbers extrapolated based on a statistical comparison of the European and Iranian species richnesses of the exhaustively studied Papilionoidea and Zygaenidae.

Material and methods

We used two different methods of faunal comparison to estimate the total number of Lepidoptera species that can be expected to occur in Iran and the number of species within each superfamily, to obtain information on knowledge gaps within each group.

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Table 1. Summary of the number of known lepidopteran species per family in Iran compared with Europe and the World. Numbers of species in Europe and the World were derived from Lepiforum (<https://lepiforum.org/>) and NIEUKERKEN et al. (2011), POHL et al. (2018) and RAJAEI et al. (2022), with a few modifications to incorporate more recent information. Empty cells in the column 'Nr.' refer to families recorded in Europe that have not yet been reported in Iran.

Nr.	Family	Iran	Europe	World
1	Micropterigidae	2	51	265
	Eriocraniidae	0	9	29
2	Hepialidae	1	18	630
3	Nepticulidae	35	279	860
	Opostegidae	0	8	192
4	Heliozelidae	1	13	123
5	Adelidae	4	55	294
	Incurvariidae	0	16	51
	Prodoxidae	0	20	98
6	Tischerioidea	5	12	110
7	Meessiidae	11	51	80
8	Psychidae	15	275	1,350
9	Eriocottidae	1	8	80
	Dryadulidae	0	7	50
10	Tineidae	73	261	2,393
	Roeslerstammiidae	0	2	53
11	Bucculatricidae	14	60	297
12	Gracillariidae	58	270	1,866
13	Bedelliidae	2	3	16
14	Heliodinidae	1	1	69
15	Lyonetiidae	3	33	204
16	Argyresthiidae	6	50	157
17	Yponomeutidae	4	71	363
18	Ypsolophidae	13	46	163
	Praydidae	0	8	47
19	Plutellidae	6	27	150
20	Glyphipterigidae	4	47	535
21	Ustyurtiidae	1	0	3
22	Douglasiidae	6	16	29
23	Choreutidae	7	21	406
24	Galacticidae	2	1	19
25	Tortricidae	260	1089	10,387
26	Cossidae	82	35	971
	Castniidae	0	1	113
27	Sesiidae	59	128	1,402
28	Brachodidae	14	15	137
29	Zygaenidae	74	71	1,042
	Heterogynidae	0	16	10
30	Limacodidae	2	12	1,672
31	Epipyropidae	1	2	32
	Megalopygidae	0	1	232
	Somabrachyidae	0	1	8
32	Lecithoceridae	3	12	1,200
33	Autostichidae	60	157	650
34	Oecophoridae	17	135	3,400
35	Lypusidae	2	25	150

Nr.	Family	Iran	Europe	World
	Chimabachidae	0	3	6
	Peleopodidae	0	1	28
36	Depressariidae	75	237	2,300
37	Cosmopterigidae	33	91	1,792
38	Gelechiidae	236	892	4,700
	Xyloryctidae	0	2	524
39	Pterolonchidae	1	7	30
40	Elachistidae	12	261	830
41	Coleophoridae	188	640	1,400
42	Batrachedridae	1	7	99
43	Scythrididae	39	226	669
44	Stathmopodidae	5	13	100
45	Blastobasidae	1	52	430
46	Momphidae	2	19	60
47	Alucitidae	12	25	216
48	Pterophoridae	95	210	1,318
49	Carposinidae	3	7	283
	Schreckensteiniidae	0	1	8
50	Epermeniidae	7	23	126
	Urodidae	0	1	66
	Thyrididae	0	2	940
51	Hesperiidae	42	52	4,113
52	Papilionidae	11	16	570
53	Pieridae	55	61	1,164
54	Lycaenidae	215	152	5,201
	Riodinidae	0	1	1,532
55	Nymphalidae	146	270	6,152
56	Pyrilidae	467	517	5,921
57	Crambidae	317	545	9,655
58	Cimeliidae	1	3	6
59	Drepanidae	7	22	660
	Mimallonidae	0	2	194
60	Lasiocampidae	39	51	1,952
61	Brahmaeidae	5	8	65
	Endromidae	0	2	59
62	Bombycidae	1	1	185
63	Saturniidae	7	12	2,349
64	Sphingidae	33	63	1,463
	Uraniidae	0	1	686
65	Geometridae	539	1,100	34,897
66	Notodontidae	25	61	3,800
67	Erebidae	336	408	24,569
68	Euteliidae	2	2	520
69	Nolidae	28	52	1,738
70	Noctuidae	977	1,330	12,000
	Total	4,812	10,891	167,764

A first method, based on a simple extrapolation using the numbers of known species in the superfamily Papilionoidea and the family Zygaenidae in Europe (based on RODELAND et al. 2006–2022) and Iran (based on the present catalogue, Table 1), was used to estimate the total Lepidoptera fauna of Iran, according to the following formula:

$$x = (a \times b) / c$$

where x = estimated total number of Lepidoptera species in Iran; a = number of known Papilionoidea species in Iran; b = number of known Lepidoptera species in Europe; and c = number of known Papilionoidea species in Europe.

As a second estimation method we followed the faunal comparison approach used by LAFONTAINE & WOOD (1997) to estimate Iran's total Lepidoptera fauna, but also species numbers within each superfamily. Species numbers were extracted from the most recent checklists (KARSHOLT & NIELSEN 2013; AARVIK et al. 2017; WIEMERS et al. 2018) as well as from the Lepiforum web portal (RODELAND et al. 2006–2022). Data were extrapolated based on the known species richness of Iranian Papilionoidea and those of the whole of Europe and of selected European regions, namely Denmark, the Nordic and Baltic regions, Germany and the Iberian Peninsula, all of which have a well-studied Lepidoptera fauna.

First, we calculated the proportion of Papilionoidea for each region, then we calculated the average proportion across all regions using the following formula:

$$x = (a/b) / n$$

where x = average proportion of Papilionoidea; a = number of Papilionoidea in each region; b = total number of Lepidoptera in each region; n = number of regions.

We did not include any Papilionoidea proportions for regions of the Southern Hemisphere because: a) the origins of their faunas may not be the same as in the Northern Hemisphere; b) the known faunas in the tropical subregions are significantly biased in favour of better-known taxonomic groups such as Papilionoidea, while other groups, e.g., micromoths, are poorly known. We also excluded Nearctic Papilionoidea in this calculation for two reasons: a) the Microlepidoptera fauna of the Nearctic, which would have significantly influenced the calculation, is still poorly known (POHL et al. 2018), with many undescribed species, and b) as Iran is located in the Palearctic Realm, we extrapolated the total number of Iranian species based on the known fauna of other, better-known areas of the Palearctic.

Second, the total number of Lepidoptera in Iran was estimated by dividing the number of Iranian Papilionoidea (a) by the average Papilionoidea proportion (x) calculated above:

$$\text{total number of Lepidoptera in Iran} = a / x$$

Finally, to estimate species diversity in the superfamilies of Lepidoptera in Iran, we calculated, with the latter formula, the proportion for each superfamily in Europe by dividing the number of species in each superfamily by the total number of known Lepidoptera (Table 2). This proportion was then multiplied for each superfamily by the total number of estimated Lepidoptera in Iran to reach an estimate of the true diversity of each superfamily in the country (Table 2). As an example, the proportion of Nepticuloidea in Europe was calculated by dividing the number of known European species in the superfamily (279) by the total known Lepidoptera species for the continent (10,891), i.e.,

$279/10,891 = 0.0256$. By multiplying the total estimated number of Lepidoptera in Iran (9,412, see below) by this proportion (0.0256), the species richness of the superfamily Nepticuloidea was estimated at 241. With only 35 Nepticuloidea species so far reported for the country, over 200 species would still await discovery according to this estimate.

Terminology

The expression “undiscovered species” refers both to undescribed species (in the sense of the International Code of Zoological Nomenclature) and known species not yet reported from Iran.

Results and discussion

Using the simple extrapolation of the first method outlined above, and given that the fauna of Iran presently includes 469 Papilionoidea species and a total of 4,812 species and that the fauna of Europe is represented by 552 species of Papilionoidea and 10,891 species in total, we estimated that the Lepidoptera fauna of Iran can be expected to reach 9,253 species ($x = 469 \times 10,891/552$). Applying the same extrapolation to the well-known Zygaenidae fauna of Iran (74 known species for Iran, 71 for Europe), we reached an estimate of 11,351 species for the total Iranian Lepidoptera fauna. However, we expect the estimate based on Papilionoidea to be more reliable, as this superfamily is the best studied lepidopteran group in Iran. Additionally, Papilionoidea includes a broader spectrum of ecological niches and is simply a more diverse group. On the other hand, Iran is a hotspot for the genus *Zygaena* (HOFMANN 2000a, 2000b, 2000c, 2000d, 2005, 2017; HOFMANN & TREMEWAN 2003, 2005, 2017, 2020; HOFMANN & KIA-HOFMANN 2008; HOFMANN & KEIL 2011; HOFMANN & NADERI 2014; KEIL 2014); therefore, using Zygaenidae in this calculation most likely overestimates the result.

Separating the known fauna of Iran into the two main lepidopteran groups resulted in 1,559 Microlepidoptera (32.4%; first 50 families in Table 1) and 3,252 Macrolepidoptera (67.6%; last 20 families in Table 1). This is a clear indication of where research priorities should be placed, given that the Lepidoptera fauna of Europe has a more realistic ratio of 56.6% Microlepidoptera (6,159 spp.) to 43.4% Macrolepidoptera (4,732 spp.). Along with some families not yet found in Iran such as Eriocraniidae (nine species in Europe), the investigation of species-rich groups of Microlepidoptera, such as Tineidae, Gracillariidae, Gelechiidae, Coleophoridae, Tortricidae and others, should be prioritized.

Following the second method, the average Papilionoidea proportion across the studied regions was calculated as $x = 0.049$ (see Table 3). As can be seen from Table 3, the percentage of Papilionoidea seems to be much conserved among the included subregions of Europe

Table 2. Total estimated species diversity within each superfamily of Lepidoptera present in Iran, based on total number of species herein reported from Iran in comparison to Europe. The last column shows the estimated total numbers of undiscovered species. The total number of European lepidopteran species presented here also includes the species diversity of several other superfamilies not listed in this table but listed in Table 1.

Superfamily	Total species in Iran	Total species in Europe	Proportion of species diversity in Europe	Estimated species diversity in Iran	Estimated number of undiscovered species in Iran
Micropterigoidea	2	51	0.0047	44	42
Hepialoidea	1	18	0.0017	16	15
Nepticuloidea	35	279	0.0256	241	206
Adeloidea	5	58	0.0053	50	45
Tischerioidea	5	12	0.0011	10	5
Tineoidea	100	595	0.0546	514	414
Gracillarioidea	72	330	0.0303	285	213
Yponomeutoidea	39	278	0.0255	240	201
Douglasioidea	6	16	0.0015	14	8
Urodoidea	1	1	0.0001	1	0
Choreutoidea	7	21	0.0019	18	11
Galacticoidea	2	0	0.0000	0	0
Tortricoidea	260	1,089	0.1000	941	681
Cossoidea	155	178	0.0163	154	0
Zygaenoidea	77	85	0.0078	73	0
Gelechioidea	675	2,774	0.2547	2,397	1,722
Alucitoidea	12	25	0.0023	22	10
Pterophoroidea	95	210	0.0193	181	86
Carposinoidea	3	7	0.0006	6	3
Epermenioidea	7	23	0.0021	20	13
Papilionoidea	469	552	0.0507	477	8
Pyraloidea	784	1,062	0.0975	918	134
Drepanoidea	8	25	0.0023	22	14
Lasiocampoidea	39	51	0.0047	44	5
Bombycoidea	46	86	0.0079	74	28
Geometroidea	539	1,100	0.1010	951	412
Noctuoidea	1,368	1,853	0.1701	1,601	234
Total	4,812	10,891	1.0000	9,412	4,509

(~5.0%). Based on this proportion, the expected number of Lepidoptera in Iran was estimated at 9,571 species.

If we average the estimates (9,253 and 9,571, respectively) obtained by the two methods based on Papilionoidea, we obtain a final estimate of 9,412 species (standard error: 159), which suggests that approximately half of the lepidopteran species potentially present in Iran have been discovered so far.

By subtracting the known species number (4,812) from the average expected number, we could estimate the number of undiscovered Lepidoptera species in Iran to be approximately 4,600, corresponding to ~49% of the expected total fauna. The proportion of known and undiscovered Lepidoptera in Iran can be found in Fig. 1. Here, we show only superfamilies with over 40 species, but data for the remaining superfamilies can be found in Table 2.

Table 3. Estimated numbers of Lepidoptera species in different regions of the world, based on the total known Lepidoptera and Papilionoidea faunas and resulting proportion of Papilionoidea (see Material and methods).

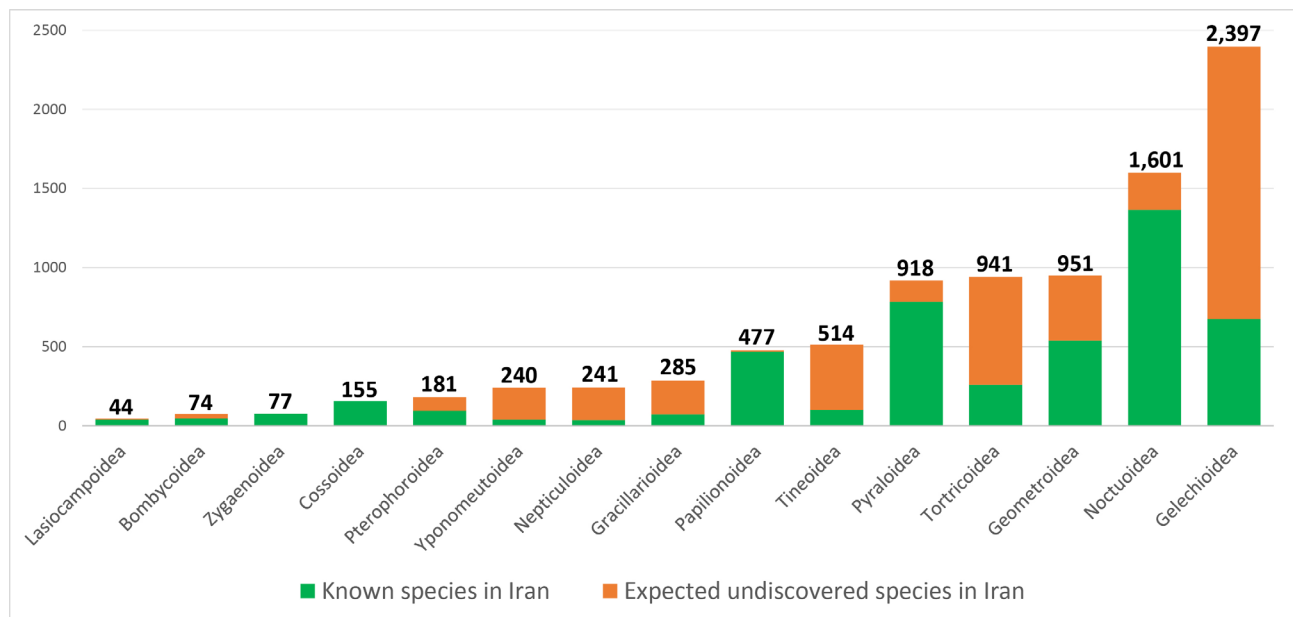
Nr.	Regions/ Country	Total known Lepidoptera species	Nr. of known Papilionoidea species	Papilionoidea proportion*	Estimated nr. of Lepidoptera species based on Papilionoidea proportion in each region/country
1	Iran	4,812	469	10%	9,412
2	Europe	10,891	552	5.0%	11,265
3	Denmark	2,620	113	4.26%	2,306
4	Nordic and Baltic regions	3,259	166	5.1%	3,388
5	Germany	3,700	187	5.0%	3,816
6	Iberian Peninsula	4,684	230	5.0%	4,693
7	World	157,424	18,768	12%	383,020

To estimate the number of species in each superfamily we applied the above average total estimate (9,412 species) to the superfamilies listed in Table 2. Our results highlight several fascinating aspects of Iran's lepidopteran diversity (Fig. 1), as follows.

Tineoidea (80%), followed by Tortricioidea (72.4%) and Gelechioidea (72%) showed high percentages of estimated undiscovered species, Gelechioidea being recognized as the most speciose lineage within the order in Iran with over 1,700 undiscovered species according to our estimate. These megadiverse superfamilies were largely neglected

during recent sampling activities and nearly all knowledge dates to the 1960s and 1970s, when microlepidopterists such as H. G. AMSEL and F. KASY participated in collecting expeditions in the country.

As expected, the Papilionoidea fauna of Iran is well studied, and just eight species are estimated yet to be discovered in the country. This is not surprising considering the intensive collecting activities and several large monographs (NAZARI 2003; TSHIKOLOVETS et al. 2014) on this charismatic superfamily.

**Fig. 1.** Expected undiscovered vs. known species in the major superfamilies of Lepidoptera in Iran. Numbers above the columns represent the estimated total numbers of species for Iran.

Two other superfamilies, Noctuoidea and Geometroidea, have also been well studied in Iran. However, as can be seen here, there is still an estimated large number of undiscovered species in both superfamilies: 234 species (15%) in Noctuoidea, 412 species (43%) in Geometroidea.

Compared to other superfamilies, the Iranian Pyraloidea have been poorly studied. After the series of publications by AMSEL on the Microlepidoptera of Iran (AMSEL 1949a, 1949b, 1950, 1951, 1952, 1954, 1959, 1961), very few larger taxonomic revisions (e.g., the “Microlepidoptera Palaearctica” series) have been carried out on the Iranian pyraloid fauna and additional taxonomic studies are needed. In addition, many of the species descriptions by AMSEL have never been revised by other taxonomists, and such critical revisions are necessary for a reliable estimation of the diversity of this superfamily. For these reasons, the estimated proportion of undiscovered Iranian Pyraloidea (14.5%) is likely an underestimate.

At the opposite end of the spectrum, the numbers of expected Iranian Zygaenoidea (73 spp.) and Cossioidea (154 spp.) are close to the known species numbers, as their largest families were intensively studied during the last five decades, especially Zygaenidae (KEIL 2014; HOFMANN & TREMEWAN 2017, 2020), Sesiidae (KALLIES & ŠPATENKA 2003, 2004) and Cossidae (YAKOVLEV et al. 2007; YAKOVLEV & ALIPANAH 2018; ALIPANAH et al. 2021). The number of known Zygaenidae for Iran (74 species) surpasses that of Europe (71 species). In Cossidae, the number of recorded species in Iran (82) is about 2.5 times greater than that in Europe (35 species). The extraordinarily high diversity of Zygaenidae and Cossidae in Iran may be explained by the hyperdiversity of micro-habitats resulting from the last glaciation event (RAJAEI et al. 2013), the high plant diversity and the extremely isolated high-altitude micro-habitats, especially in the Zagros mountain chain. These factors may have promoted adaptive evolutionary diversification in these two families in the region. Based on this hypothesis, we can expect an even greater species diversity for other, less studied lepidopteran groups in Iran. However, the high diversity of Iranian Zygaenidae and Cossidae could also reflect extreme taxonomic over-splitting or the inherent subjectivity of species delimitations, especially in allopatric taxa. Therefore, we encourage the application of a more integrative approach in the taxonomy of these and other groups in the future.

It should be highlighted that the estimated numbers of Iranian species within each superfamily (Table 2) are only based on the estimation methods explained above and do not take biological information and habitat preferences into account. For example, the Iranian diversity of some groups may be over estimated due to specific adaptations or habitat preferences, as is the case for Micropterigoidea, a group linked to humid habitats for which the number of Iranian species likely does not exceed 10, as opposed to

the estimated 44. The same applies to Hepialoidea, Nepticuloidea and Gracillarioidea, mainly associated with forest habitats, whereas other groups such as Geometroidea and Noctuoidea may be much more diverse than estimated here.

Regarding its conservation, the lepidopteran fauna of Iran is under threat from land use, habitat disturbance caused by agriculture and overgrazing, and global warming, especially in its two most important mountain ranges, Alborz and Zagros. In particular, the endemic fauna (19.8%), which is highest in the central Zagros Mts., is most severely affected by global warming. There are apparently few active monitoring programs on Iranian Lepidoptera when compared to Europe, North America and East Asia. For many species reported in this catalogue there are only a few historical records, and without adequate monitoring activities it will not be possible to track faunal changes or potential extinctions.

In conclusion, this study has highlighted the importance of taxonomic databases as a valuable source of information on the known and hidden biodiversity of a region. We will continue to develop such resources for the Lepidoptera of Iran, with the caveat that the diversity estimates presented herein could be made much more accurate by adding further data and analyses in the decades to come.

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