SUPPLEMENTARY INFORMATION

# *Arctia menetriesii*: Ecological, phenological, and life history traits of an iconic boreal moth based on over a century-long dataset (Lepidoptera, Erebidae, Arctiinae)

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***Cover image:*** Living female of *Arctia menetriesii* on *Rubus idaeus*, Onokhoy settlement, Uda River valley, Republic of Buryatia, Eastern Siberia, Russia, 11 July 2012 (record ID: AM-035). Photo: Sergey Y. Gordeev.

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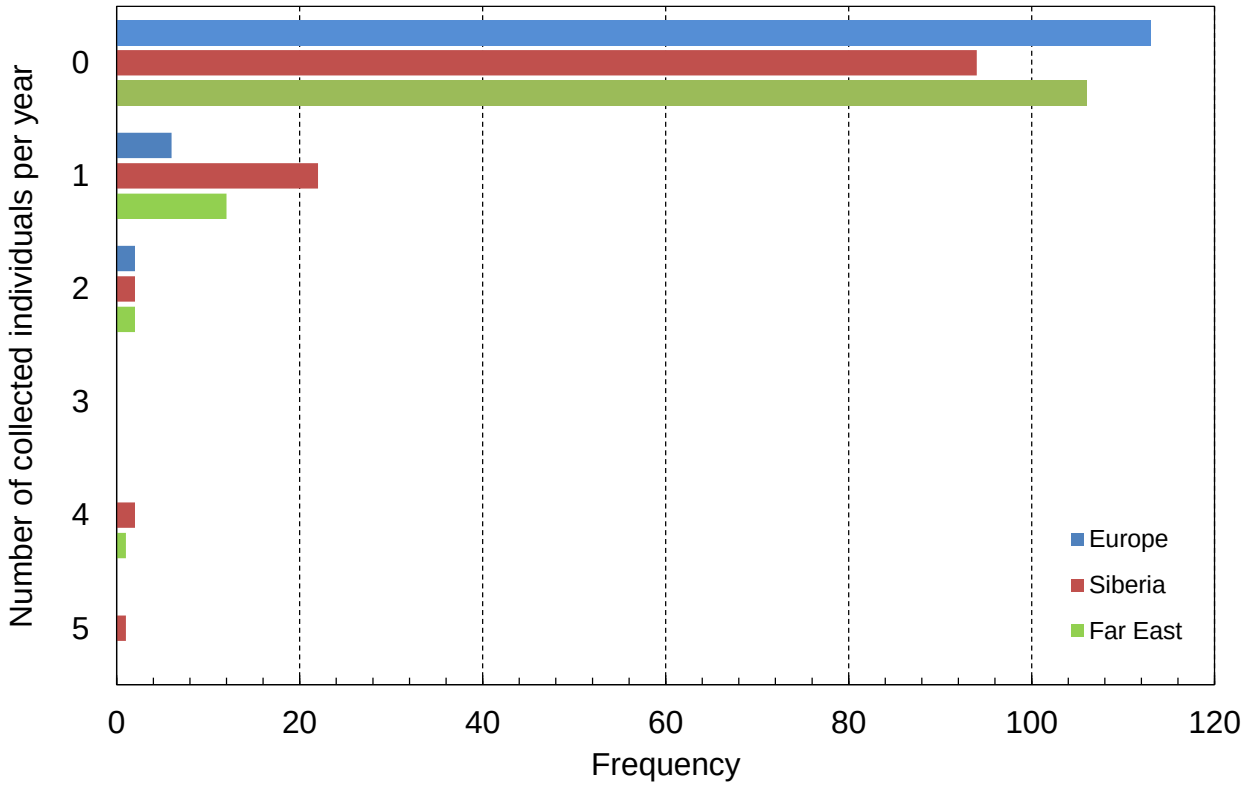
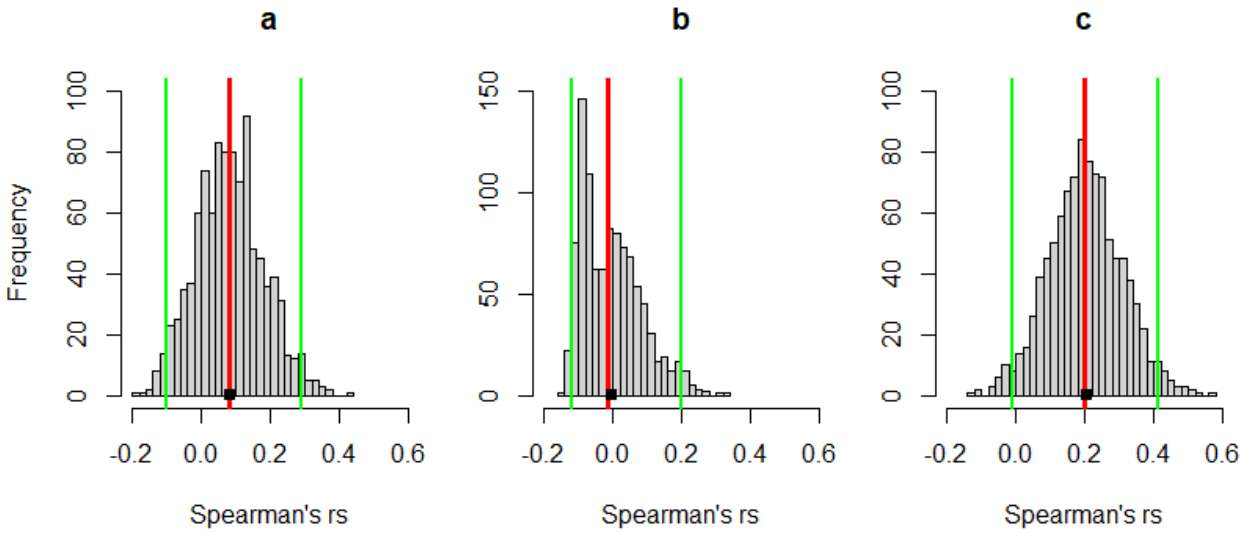
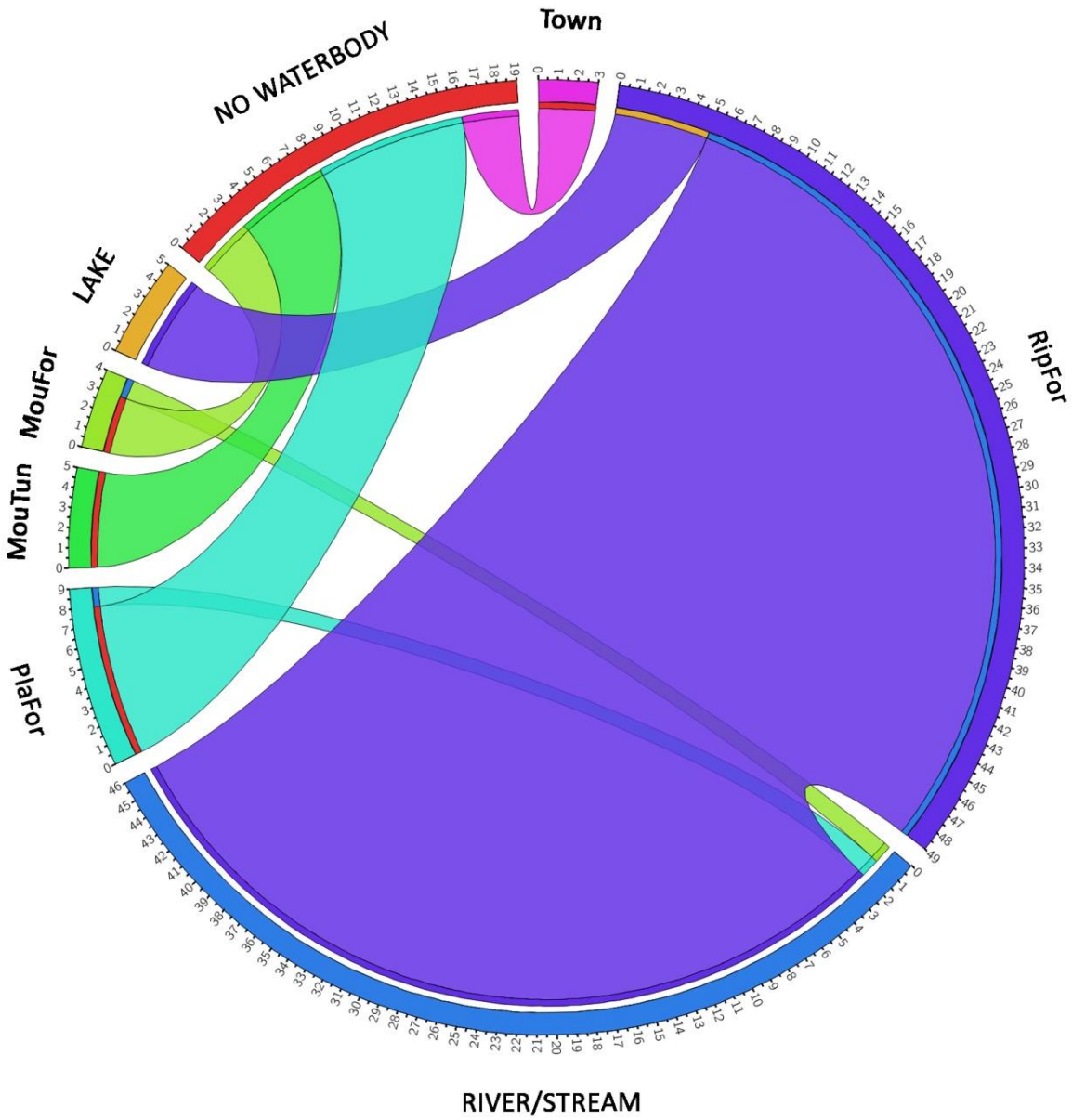



**Supplementary Figure S1.** Frequency histograms of *Arctia menetriesii* annual captures by region (1901-2020).




**Supplementary Figure S2.** Frequency distribution of bootstrapped Spearman's correlation coefficients of *Arctia menetriesii* population dynamics ($B$ = 1000 replications): (**a**) Europe vs Siberia (not significant); (**b**) Europe vs Far East (not significant); (**c**) Siberia vs Far East (Spearman's ρ = 0.205, $N$ = 121, $p$ = 0.024). The distributions of bootstrapped coefficients differ significantly from each other ($\chi^2$ > 74.67; $df$ = 34; $p$ < 0.001). The black square indicates the empirical coefficient value; the red line is the median of the distribution; the green lines are the confidence intervals.




**Supplementary Figure S3.** Habitat breadth of *Arctia menetriesii* categorized by data on the presence of waterbody in a collecting locality. The scales represent the number of collected specimens. Habitats and their groups are represented by broad separate arcs with a length determined by the number of specimens. Their colors refer to the group of habitats in relation to the presence of waterbody: *River/Stream* (dark blue; *N* = 46 specimen records); *Lake* (dark yellow; *N* = 5 specimen records); and *No waterbody* (red; *N* = 19 specimen records). Linking lines between these groups represent shared types of habitats, with the thickness proportional to the number of specimen records for each group. Narrow arcs inserted into linking lines refer to the number of specimen records for each group of habitats in relation to the presence of a waterbody; their color corresponds to those for each group (see above). The line color refers to the type of habitat: *RipFor*, riparian forest (violet); *PlaFor*, plain forest (light blue); *MouFor*, mountain forest (yellowish green); *MouTun*, alpine meadows and tundra (green); and *Town*, urban environment (pink). The plot was created using the online application of Circos (http://mkweb.bcgsc.ca/tableviewer) (Krzywinski et al. 2009).

**Supplementary Table S1.** Brief summary of the breeding experiments on *Arctia menetriesii*

| **Mother female occurrence ID** | **AM-002** | **AM-037** | | **AM-035** | **AM-042** | | **AM-066** |
|---|---|---|---|---|---|---|---|
| **Researcher (team)** | **H. Krogerus** | **O.V. Korsun & N.O. Korsun** | **H. Saarenmaa *et al.*** | **S.Y. Gordeev & T.V. Gordeeva** | **S.Y. Gordeev & T.V. Gordeeva** | **M. Tähtinen *et al.*** | **E. S. Koshkin** |
| Breeding years | 1943–1944 | 2011–2012 | 2011–2012 | 2012-2013 | 2018–2019 | 2018–2019 | 2018 |
| Replications (place of experiment) | Single (Finland) | 1st (Eastern Siberia) | 2nd (Finland) | Single (Eastern Siberia) | 1st (Eastern Siberia) | 2nd (Finland) | Single (Far East) |
| Reference | Krogerus (1944) | Korsun (2016) | This study | This study | This study | This study | Koshkin (2021); this study |
| ***Experimental settings:*** | | | | | | | |
| Usage of *Aconitum* spp. (strongly toxic plant) in larval diet | No | No | No | No | No | No | Yes |
| Usage of *Larix* spp. (weakly toxic plant) in larval diet | No | Yes | Yes | No | No | Yes | Yes |
| Hibernation | Yes | Yes | Partly | Yes | Yes | Partly** | No |
| Hibernation's conditions | Natural | Natural | Mixed | Natural | Natural | Mixed | N/A |
| ***Experimental summary:*** | | | | | | | |
| Number of eggs | 30 | 25 | 80 | 120 | 40 | 110 | 105 |
| Number of 1st instar larvae | 30 | 25 | 80 | 120 | 40 | 90 | 105 |
| Total number of dead larvae (all instars) | 28 | 14 | 72 | 120 | 40 | 57 | 87 |
| Number of larvae dead before hibernation (all instars) | 0 | 12 | 47 | 110 | 0 | 1 | N/A |
| Number of larvae dead during or after hibernation | 28 | 2 | 24 | 10 | 40 | 56 | N/A |
| - including those dead from fungal disease | ≥1 | No data | 24 | N/A | 0 | 8 | N/A |
| Last instar larvae to pupae | 2 | 11 | 8 | N/A | N/A | 33 | 18 |
| - including metamorphosis anomalies (anomalous pupae and larva-pupa intermediates) | 0 | 0 | 0 | N/A | N/A | 0 | 18 |
| - including anomalous larva-pupa intermediates | 0 | 0 | 0 | N/A | N/A | 0 | 4 |
| - including lethal cases of intermediates | 0 | 0 | 0 | N/A | N/A | 0 | 3 |
| Number of pupae with severe anomalies | 0 | 0 | 0 | N/A | N/A | 0 | 10 |
| Number of pupae with insignificant | 0 | 0 | 0 | N/A | N/A | 0 | 4 |

| Mother female occurrence ID | AM-002 | AM-037 | | AM-035 | AM-042 | | AM-066 |
|---|---|---|---|---|---|---|---|
| **Researcher (team)** | **H. Krogerus** | **O.V. Korsun & N.O. Korsun** | **H. Saarenmaa *et al.*** | **S.Y. Gordeev & T.V. Gordeeva** | **S.Y. Gordeev & T.V. Gordeeva** | **M. Tähtinen *et al.*** | **E. S. Koshkin** |
| anomalies | | | | | | | |
| Total number of emerged imago | 2 | 11 | 8 | N/A | N/A | 33 | 14 |
| - including males | 1 | 3 | 7 | N/A | N/A | 17 | 9 |
| - including females | 1 | 8 | 1 | N/A | N/A | 16 | 5 |
| Number of imago with developmental anomalies (brachyptery and wing spreading defects) | 0 | 5 | 1 | N/A | N/A | 2 | 9 |
| - including males | 0 | 0 | 0 | N/A | N/A | 1 | 7 |
| - including females | 0 | 5 | 1 | N/A | N/A | 1 | 3 |
| Total number of fully developed imago | 2 | 6 | 7 | N/A | N/A | 31 | 4 |
| - including males | 1 | 3 | 7 | N/A | N/A | 16 | 2 |
| - including females | 1 | 3 | 0 | N/A | N/A | 15 | 2 |
| ***Survival rates:*** | | | | | | | |
| Total survival rate (eggs to fully developed imago, %) | 6.7 | 24.0 | 8.7 | 0.0* | 0.0* | 28.2 | 3.8 |
| Larval survival rate (eggs to pupated larvae, %) | 6.7 | 44.0 | 10.0 | 0.0* | 0.0* | 30.0 | 17.1 |
| ***Mortality rates:*** | | | | | | | |
| Total mortality rate (%) | 93.3 | 76.0 | 91.3 | 100.0* | 100.0* | 71.8 | 96.2 |
| Larval mortality rate (%) | 93.3 | 56.0 | 90.0 | 100.0* | 100.0* | 70.0 | 82.9 |

N/A – not applicable. *All the larvae dead during natural (outdoor) hibernation in Eastern Siberia due to the extremely low winter temperatures. **Nine larvae developed to imago without hibernation.

**Supplementary Table S2.** Confusion matrix of linear discriminant analysis of *Arctia menetriesii* localities with possible odd- and every-year appearance of imago based on monthly mean climate characteristics. Numbers of confused placements are bold.

| Life cycle | Biennial (two-year development) | Annual (one-year development) | Total |
|---|---|---|---|
| Biennial (two-year development) | 15 | **2*** | 17 |
| Annual (one-year development) | **1**** | 38 | 39 |
| Total | 16 | 40 | 56 |

*AM-011 (North Urals) and AM-037 (Transbaikalia, Eastern Siberia); *AM-013 (Khanty-Mansi Region, Western Siberia).

**Supplementary Table S3.** Confusion matrix of linear discriminant analysis of *Arctia menetriesii* localities based on monthly mean climate characteristics. Number of confused placements is bold.

| Regions | Europe | Siberia | Far East | Total |
|---|---|---|---|---|
| Europe | 9 | **1*** | 0 | 10 |
| Siberia | 0 | 34 | 0 | 34 |
| Far East | 0 | 0 | 16 | 16 |
| Total | 9 | 35 | 16 | 60 |

*AM-011 (North Urals).

**Supplementary Table S4.** List of potential factors and causes that may contribute to the 'extreme rarity' of *Arctia menetriesii*

| Category | Factor/Cause | Affected stage | Population-level effects | Scale | Assessment of impact | Evidence | References |
|---|---|---|---|---|---|---|---|
| Research artifact | Low detectability | All stages | None | Global | None | Preference to hard-to-reach, unpopulated areas, short flying period of imago, and, probably, reduced daily activity | This study |
| Natural hazard | Climate fluctuations (lower air temperatures) | Imago | Decreasing offspring abundance | Global | Quantitative | Non-parametric correlation analyses | This study |
| Natural hazard | Extreme weather events such as periods with extremely low temperatures in winter and summer frosts | Imago | Decreasing offspring abundance | Regional | Qualitative | Field observations and direct experimental data | This study (E. S. Koshkin, pers. comm.; S. S. Sleptsov, pers. obs.; S. Y. Gordeev, pers. obs.) |
| Natural enemy | Fungal infections | Larva | Decreasing adult abundance | Global | Quantitative | Direct experimental data on larval hibernation (breeding experiments) | Krogerus (1944); this study (H. Saarenmaa's experiments) |
| Biological trade-off | Tendency to feed (at least in part) on toxic host plants, probably, as a source of biochemical precursors (alkaloids and other secondary plant metabolites) | Larva, pupa, and imago | High mortality rate in last instar larvae, frequent metamorphosis anomalies and wing spreading defects | Global | Quantitative | Field observations (including a wild female AM-011 with undeveloped wings); direct experimental data (breeding experiments); indirect experimental data on other Arctiinae species | Saarenmaa (2021); Berlov & Bolotov (2015); Koshkin (2021); Ermakov (2006); Nupponen & Fibiger (2012); von Nickisch-Rosenegk & Wink (1993); Schulz (1998); Martins & Trigo (2016); Dickel (2018); Wink (2018) |
| Natural hazard | Floods | Larva | Decreasing adult abundance | Regional | Qualitative | Indirect evidence: significant preference to riparian habitats, especially in river and stream valleys could indicate that floods may influence the species abundance | This study |
| Natural enemy | Parasitoids | Larva | Decreasing adult abundance | Unknown | Qualitative | Indirect evidence: experimental data on *Arctia* spp. and other Erebidae species (e.g., | Shilenkov & Richter (1998); Bolotov *et al.* (2015); Koshkin (2021); Stireman III & Shaw (2022); |

| Category | Factor/Cause | Affected stage | Population-level effects | Scale | Assessment of impact | Evidence | References |
|---|---|---|---|---|---|---|---|
| | | | | | | *Arctia ornata*, *A. tundrana*, and *Orgyia trigotephras*) indicate that *A. menetriesii* may also be pressed by parasitoids | Hammami *et al.* (2023) |
| Natural enemy | Predators | Larva | Decreasing adult abundance | Unknown | Qualitative | Indirect evidence: experimental data on other Arctiinae taxa (e.g., *Grammia* spp.) indicate that *A. menetriesii* may also be affected by predators | Mason *et al.* (2014) |

**Supplementary Note S1.** Additional observations from M. Tähtinen *et al.*'s breeding experiment of 2018-2019 in Finland

A brief preliminary summary of this breeding experiment is presented in Table S1, while a more detailed description will be published elsewhere (Tähtinen et al., in prep.). Over 150 eggs were obtained from the wild mated female AM-042 that was collected in the Chikoy National Park (50.1598°N, 109.2483°E, altitude 1450 m; Transbaikalia, Eastern Siberia, Russia) on 14 July 2018 by Pekka Alestalo (Bolotov et al. 2022). 110 eggs were bred in Finland during the period of 2018-2019. Our main goals in this breeding were to rear females to lure males in summer 2019 and to breed the next generation of the species. The larvae were divided to six Finnish lepidopterologists for breeding.

Summer months during the larvae rearing in July-September were hot and dry. The larvae were reared in house at room temperature (22-25°C). A good care of larval hygiene was taken, cleaning and changing food plants at least once a day after the first larval stage. Dandelion (*Taraxum* sp.), red currant (*Ribes rubrum*), and willow (*Salix* sp.) were used as the main host plant sources. Larvae did not consume *Aconitum* but a small part of larvae partly feed on larch (*Larix* sp.). Before winter hibernation, the level of larval morality was very low (<5%). This pattern is different from that of Koshkin's experiment, showing the high level of larval mortality even at earlier instars (Koshkin 2021). A possible explanation is that the larval diet in our case did not contain strongly toxic plants (*Aconitum*). Dry hot weather during the larvae rearing may also contribute to a lower larval mortality rate at the earlier stages discovered by us.

Nine adults emerged without hibernation from two breeders. They were partly developed under natural light, supplementing artificial lighting. Nearly half of the remaining larvae overwintered under two variants of in-vitro temperature conditions: at approximately +2°C (larger part of the larvae) and at approximately -5°C (smaller part of the larvae). The success rate for these larvae was rather high (~50%). Two of these larvae looked dehydrated already before the artificial diapause. Generally, desiccation of the body was the main reason for larval mortality during hibernation, while a smaller part of the larvae were found dead due to fungal disease. Moreover, many healthy-looking larvae did not manage to form pupa after artificial hibernation. Problems at this stage were at least partly similar to those in Koshkin's (2021) experiment. The larvae succeeded to pupate did not have any problem to develop to imago. The in-vitro adults emerged during the period of 20-30 June 2019.

It should be noted that long-term overwintering period under the above-zero temperature (approximately +2°C) requires keeping suitable humidity to avoid both desiccation and fungal disease but, as our experience shows for the first time for *Arctia menetriesii*, it is possible with a high success rate. In contrast, only ~15% of the larvae that overwintered under natural conditions have developed to adults. This value is comparable with the results that were obtained from H. Saarenmaa *et al.*'s breeding experiment of 2011-2012 (mother female ID: AM-037) in Finland (Saarenmaa 2021).

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