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Electronic Supplementary Material

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Title**: Status and trends of terrestrial arthropod abundance and diversity in the North Atlantic region of the Arctic**

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**Full details on FEC assignment**

To assign individual species to FECs, we used expert knowledge and the biological information in the Greenland Entomofauna (Böcher et al. 2015) and relevant Iceland literature (Lindroth 1957, Gauld and Bolton 1988). Where information was available about different larval and adult feeding preferences or ecological roles, we included the species in more than one FEC. Where species information about larval or adult feeding preferences or their ecological roles were not known or recorded, we searched the scientific literature for more information. We assigned a species to an FEC based on information about species from the same genus or family only where it was clear from the literature that there was no known intra-genus or intra-family variation in food preferences (e.g., the Mycetophilidae family of Diptera are thought to all feed on fungus). When species did not fit any of the five FECs, we created an additional “Other” category, containing species that are mainly predatory, parasitic on other invertebrates, or that have an aquatic larval stage and a terrestrial adult stage with unknown ecological role.

In our classification of FECs for Greenland, we have adopted the subdivision of Greenland into “faunal districts” (*sensu* Böcher (1988); Fig. 1, main text), distinguished by their climate and floristic characteristics. The North district is the most extreme High Arctic zone, with a dry climate and comprising mostly polar desert ecosystem. The North West and North East districts are also within the High Arctic, with a similarly dry climate but with tundra and high mountain vegetation types. The South West and South East districts are in the Low Arctic, with the West experiencing a mild, oceanic coastal climate and warmer, dry summers inland, and the East exhibiting a cool, humid oceanic climate. The South district has more favourable conditions for invertebrate life, with a greater number of habitat types, including inland fiord woodlands containing species such as *Betula pubescens* and *Salix glauca.* Iceland was considered as a single district (Fig. 1, main text). Iceland has a subpolar, oceanic climate. The warm North Atlantic current provides overall warmer annual temperature than in other areas of similar latitude (Einarsson 1976). The highland areas in central Iceland are dominated by tundra heathlands, while in the lowlands some mountain birch (*Betula pubescens* subsp. *czerepanovi*) woodlands still persist (Thórhallsdóttir 1997).

The full classification of species into FEC categories can be found in Table S1. A summary of FECs by species groups (Families or Orders) is given in Tables S2 – 7 below.

**Table S1**: See separate Excel file

**Table S2:** Species richness of the blood-feeding invertebrate families of Iceland, Svalbard, Jan Mayen, Greenland and the Greenland “faunal districts”.



**Table S3**: Species richness of the pollinating invertebrate families of Iceland, Svalbard, Jan Mayen, Greenland and the Greenland “faunal districts”.

**Table S4**: Species richness of the invertebrate decomposer Orders of Iceland, Svalbard, Jan Mayen, Greenland and the Greenland “faunal districts”.



**Table S5**: Species richness of the invertebrate herbivore Orders of Iceland, Svalbard, Jan Mayen, Greenland and the Greenland “faunal districts”.



**Table S6**: Species richness of the prey for vertebrates Orders of Iceland, Svalbard, Jan Mayen, Greenland and the Greenland “faunal districts”.



**Table S7**: Species richness of the predators and parasitoids Orders of Iceland, Svalbard, Jan Mayen, Greenland and the Greenland “faunal districts”.



**Pollinators: Abundance trends in High-Arctic muscid fly species**

In Arctic environments, true flies (Order Diptera) are the most abundant and diverse group of insects (Hodkinson et al. 2013, Coulson et al. 2014) and the Muscidae (house flies and relatives) are one of the most diverse families of Arctic insects. Northern muscids are generally predators of other flies and the adults of many species visit flowers to obtain nectar and/or pollen (Hocking 1968, Kevan 1972, Elberling and Olesen 1999, Tiusanen et al. 2016). Here, we present interannual variation and long-term trends in abundance of individual muscid fly species between 1996 and 2014.

As part of the Greenland Ecosystem Monitoring BioBasis programme at Zackenberg, north-east Greenland (74°28ʹN, 20°34ʹW) (Schmidt et al. 2016), arthropods have been collected with pitfall traps every week during each growing season since 1996. The yellow-colored pitfall traps function like pan traps and catch large numbers of flying insects. Unfortunately, specimens collected in 2010 were lost during transport before sorting. Temporal trends in muscid species abundance were assessed with simple linear models for each assemblage with year as independent variable and adjusted for temporal autocorrelation if detected. Further details on the field and lab work as well as analyses are presented in Loboda et al. (2018).

Significant declines were detected in seven of the 14 muscid species, which were found in five or more years (Fig. 4, main text). None of the remaining species were increasing in abundance. The declines in abundance correspond to an overall loss of 80% of individuals between 1996 and 2014. The most abundant species in our data set Spilogona sanctipauli, did not show significant decrease over the study period.

Species-specific patterns of abundance variation may be due to ecological differences among species. Identifying such functional traits is critical in efforts to assess species-specific vulnerability to Arctic climate change. We classified each species according to body size and whether the species is a frequent flower visitor or not. Furthermore, the larvae of some Arctic Spilogona species are known to be aquatic or semi-aquatic predators of other Diptera larvae with adults breeding in damp wet surfaces or in algae along water bodies (Michelsen 2015). Therefore, soil moisture may directly affect the abundance of Spilogona species. We found no consistent pattern of abundance variation across the functional traits examined, but sensitivity to soil moisture may explain why we detected most of the significant declines in Spilogona species. Unfortunately, detailed breeding habits are still undescribed for most arctic insect species, including Muscidae, and we encourage more rigorous assessments of how various functional traits may affect species abundance trends. We reiterate that the incomplete understanding of the ecology of Arctic arthropods constrains our ability to understand and predict how future climate change may affect species interactions and ecosystem functions.

**Decomposers: Collembola from Kobbefjord, Greenland**

Collembola recorded by the Nuuk Basic Climate Change Monitoring Programme at Kobbefjord, Greenland (Aastrup et al. 2015) were collated and analysed for the Decomposers section of the main text. These data cover 27 species found in four different plant communities between 2007 and 2017. The data were originally presented in annual reports of the monitoring programme which are available publicly (<http://g-e-m.dk/gem-localities/nuuk-basic/publications/annual-reports/>). The data are also archived (http://g-e-m.dk/gem-localities/nuuk-basic/ website) and will also be made available on the edaphobase portal (<https://portal.edaphobase.org>).

For analysis in this paper, the data were summarised as mean abundance (expressed as 103 individuals per m2), species richness and diversity (Shannon-Wiener index, H) per sample across three regular sampling seasons (spring, summer and autumn). These data were analysed for trends over time with simple linear regressions, with the three measures above as dependent variables, and year as independent variable. There was no evidence of temporal autocorrelation in the data. As shown in Fig. 4 in the main text and Table S8, there were significant declines in diversity for three of the four communities, stable patterns in species richness for all four communities, and a significant increase in abundance in the *Empetrum* community only.

**Table S8**: Results from linear regression models of Abundance (expressed as 103 individuals per m2), species richness and Diversity (Shannon-Wiener H) of all Collembola against Year for each of the dominant habitats at Kobbefjord, Greenland.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Habitat** |  | **Estimate** | **SE** | **t** | **p** |
| **Abundance** |  |  |  |  |
| *Empetrum* | Intercept | -14743.17 | 3583.43 | -4.11 | 0.009 |
| Year | 7.36 | 1.78 | 4.13 | 0.009 |
| *Salix* | Intercept | -8970.14 | 5096.07 | -1.76 | 0.139 |
| Year | 4.48 | 2.53 | 1.77 | 0.137 |
| *Silene* | Intercept | -909.20 | 11892.14 | -0.08 | 0.942 |
| Year | 0.47 | 5.91 | 0.08 | 0.939 |
| *Loiseleuria* | Intercept | -26093.05 | 9798.92 | -2.66 | 0.056 |
| Year | 12.99 | 4.87 | 2.67 | 0.056 |
| **Species richness** |  |  |  |  |
| *Empetrum*§ | Intercept | 210.65 | 121.59 | 1.73 | 0.158 |
| Year  | -0.10 | 0.06 | 1.69 | 0.166 |
| *Salix\** | Intercept | 233.44 | 88.47 | 2.64 | 0.046 |
| Year | -0.11 | 0.04 | -2.58 | 0.050 |
| *Silene* | Intercept | 387.51 | 204.65 | 1.89 | 0.117 |
| Year | -0.19 | 0.10 | -1.88 | 0.119 |
| *Loiseleuria\** | Intercept | -40.05 | 174.85 | -0.23 | 0.830 |
| Year | 0.02 | 0.09 | 0.25 | 0.817 |
| **Diversity** |  |  |  |  |
| *Empetrum* | Intercept | 262.82 | 39.31 | 6.69 | 0.001 |
| Year  | -0.13 | 0.020 | 6.65 | 0.001 |
| *Salix* | Intercept | 198.85 | 53.34 | 3.73 | 0.014 |
| Year | -0.10 | 0.027 | 3.70 | 0.014 |
| *Silene* | Intercept | 147.79 | 44.64 | 3.31 | 0.021 |
| Year | -0.07 | 0.02 | 3.30 | 0.022 |
| *Loiseleuria\** | Intercept | 128.61 | 83.84 | 1.53 | 0.200 |
| Year | -0.06 | 0.04 | -1.52 | 0.202 |

\* These models cannot be considered valid due to high leverage of several points regardless of outlier removal.

§ One outlier removed due to high leverage

**Herbivores: Moth monitoring in Iceland**

Moth monitoring was established in 1995 when Iceland became a participant in the Nordic Moth Monitoring Scheme project, which was initiated in Finland in 1993. The technique of light trapping was adopted for the first time to collect Lepidoptera in the country (Ólafsson and Björnsson 1997). In 1995 four light traps were initially located on two sites, two traps at Tumastaðir in the southern part of Iceland and two at Kvisker in the southeastern part. With the cooperation of The Icelandic Institute of Natural History and Nature Research Centers, traps were gradually located on more sites. Today moth monitoring is active on 19 sites all around Iceland with total of 21 traps (Fig. S1).

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**Figure S1:** Location of moth trapping sites in Iceland. Grey circles indicate trap sites that are no longer in use.

This cooperation makes it possible to compare populations, flight period and habitats between different locations. Most of the traps are active for 30 weeks per year, from April – November, depending on local season. Moths are collected from the traps on the same weekday, every week, and the material is then identified to species and counted. Most data from the Moth Monitoring Scheme in Iceland has not been published nor fully analysed but data from the longest running trap sites are presented here (Fig. 4, main text). Before analysis of species richness and total abundance values, the data were checked for evidence of temporal autocorrelation. Where this was not present, trends over time were tested with simple linear regression. In the case of Abundance at Kvisker B, the response variable was log transformed to reduce the influence of outliers. Where autocorrelation was present, trends were tested with Generalised Least Squares regression with an AR1 correlation structure, using the gls function of the *nlme* package (Pinheiro et al. 2018) in R (R Core Team, 2017). The results are shown in the main text (Fig. 5) and in Table S9 below, revealing a significant positive trend in species richness at two locations, Mógilsá and Tumastaðir, and a significant negative trend in abundance in one trap at Kvisker (not longer active).

The Iceland invertebrate fauna is also subject to unique abiotic factors. In 2000 there was a volcanic eruption in Hekla and 2010 in Eyjafjallajokull. The data from the Moth Monitoring Scheme shows that volcanic eruptions has a major impact on certain moth species, although not at all sites (Mógilsá for example appears unaffected by the 2010 eruption) and has provided unique information on how volcanic ash can affect insect populations and how species recover/not recover from such shock.

**Table S9:** Results of linear regression and generalised least squares regression models of total moth abundance and species richness at six of the longest running trapping sites in Iceland. Abundances were divided by 1000 before analysis to reduce the magnitude of estimates.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Trap location** | **Variable** |  | **Estimate** | **SE** | **t** | **p** |
| **Kvisker A** | Abundance | Intercept | 77.3 | 104.18 | 0.74 | 0.472 |
|  | Year | -0.04 | 0.05 | -0.71 | 0.492 |
| Species richness | Intercept | 242.1 | 526.33 | 0.46 | 0.654 |
|  | Year | -0.10 | 0.26 | -0.39 | 0.701 |
| **Kvisker B** | Abundance | Intercept | 81.88 | 26.96 | 3.04 | 0.010 |
|  | Year | -0.04 | 0.01 | -2.98 | 0.011 |
| Species richness | Intercept | 797.08 | 433.46 | 1.84 | 0.091 |
|  | Year | -0.38 | 0.22 | 1.76 | 0.105 |
| **Mógilsá** | Abundance\* | Intercept | -148.09 | 72.70 | -2.04 | 0.069 |
|  | Year | 0.07 | 0.04 | 2.06 | 0.066 |
| Species richness | Intercept | -1627.18 | 426.3 | -3.82 | 0.004 |
|  | Year | 0.83 | 0.21 | 3.89 | 0.003 |
| **Rauðafell** | Abundance§ | Intercept | 445.80 | 670.41 | 0.66 | 0.521 |
|  | Year | -0.22 | 0.33 | -0.67 | 0.519 |
| Species richness | Intercept | 320.58 | 968.13 | 0.33 | 0.747 |
|  | Year | -0.15 | 0.48 | 0.31 | 0.767 |
| **Tumastaðir A** | Abundance | Intercept | -307.78 | 165.15 | -1.86 | 0.077 |
|  | Year | 0.16 | 0.08 | 1.89 | 0.074 |
| Species richness§ | Intercept | -586.21 | 420.01 | -1.40 | 0.178 |
|  | Year | 0.31 | 0.21 | 1.46 | 0.159 |
| **Tumastaðir B** | Abundance | Intercept | -215.91 | 158.36 | -1.36 | 0.188 |
|  | Year | 0.11 | 0.08 | 1.39 | 0.180 |
| Species richness | Intercept | -577.80 | 225.38 | -2.56 | 0.019 |
|  | Year | 0.30 | 0.11 | 2.68 | 0.015 |

\* These variables were log transformed to reduce the influence of outliers

§ These variables were modelled with Generalised Least Squares regression with an AR1 correlation structure to account for temperal autocorrelation.

**Prey for Vertebrates: Analyses of abundance trends in High-Arctic arthropod families of potential vertebrate prey**

We used data provided by the BioBasis programme at Zackenberg, Greenland (74°28ʹN, 20°34ʹW) (Schmidt et al. 2016) between 1996-2016 (excluding 2010, see information on Muscidae analysis above) to investigate long-term trends in abundances of arthropod families that are potential prey to vertebrates. There is limited data on which arthropod species actually contribute to vertebrate diets; thus, we used information from recently published studies by Bolduc et al. (2013) and Wirta et al. (2015) to compile a list of arthropod families from Zackenberg that are likely to be prey for Arctic birds (Table S10). For each study year and sampling plot, we calculated the total number of individuals from these families that were caught during the months of June, July, and August. Total summertime abundances were then corrected by the number of trapping days within a given plot (see Koltz et al. 2018). We fit linear mixed effects models to test for habitat-specific changes in the total abundances across all families (Table S10) and for each order individually (i.e., Araneae, Diptera, Hymenoptera, Lepidoptera) using the packages *nlme* (Pinheiro et al. 2018) and *lmerTest* (Kuznetsova et al. 2013, Bates et al. 2014) in R (R Core Team 2017). The interaction between study year and the habitat type from which samples were collected (mesic heath, arid heath, or wet fen) was included as a fixed predictor in the models; sampling plot was included as a random effect. Abundance data (total individuals corrected by trapping days) were log transformed prior to analyses. To account for temporal autocorrelation in the abundance data, we also specified the correlation structure using the corARMA function and designated p and q (the autoregressive order and moving average order, respectively) based upon visual inspection of the correlograms of the normalized residuals from the models. Models were reduced by eliminating non-significant interactions, followed by non-significant main effects one by one.

**Table S10:** Arthropod families present at Zackenberg that were classified as potential prey to Arctic birds according to information in Bolduc et al. (2013) and Wirta et al. (2015).

|  |  |
| --- | --- |
| **Family** | **Order** |
| Anthomyiidae | Diptera |
| Braconidae | Hymenoptera |
| Cecidomyiidae | Diptera |
| Ceratopogonidae | Diptera |
| Chironomidae | Diptera |
| Collembola | Collembola |
| Culicidae | Diptera |
| Dictynidae | Araneae |
| Empididae | Diptera |
| Geometridae | Lepidoptera |
| Ichneumonidae | Hymenoptera |
| Linyphiidae | Araneae |
| Lycosidae | Araneae |
| Muscidae | Diptera |
| Mycetophilidae | Diptera |
| Noctuidae | Lepidoptera |
| Nymphalidae | Lepidoptera |
| Pieridae | Lepidoptera |
| Scathophagidae | Diptera |
| Sciaridae | Diptera |
| Syrphidae | Diptera |
| Tachinidae | Diptera |
| Thomisidae | Araneae |
| Tipulidae | Diptera |

**Table S11:** Results of linear mixed effects models of summertime abundances of potential vertebrate prey at Zackenberg, as predicted by study year and habitat type. Separate models were fitted for the total abundance of all families identified as potential vertebrate prey (Table S10) and for each individual arthropod order (Araneae, Lepidoptera, Diptera, and Hymenoptera). Values for p and q represent the autoregressive order and moving average order for year, respectively. Arid heath is the reference category for habitat type.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Fixed effects terms** | **Coeff.** | **SE** | **df** | **t** | **p-value** | **p** | **q** |
| **Total FEC prey** |  |  |  |  |   | 2 | 1 |
| Intercept | 57.364 | 13.447 | 91 | 4.266 | 0.000 |   |   |
| Year | -0.028 | 0.007 | 91 | -4.178 | 0.000 |   |   |
| Habitat type (reference category: arid heath) |   |   |   |
|  Mesic heath | 0.233 | 0.090 | 2 | 2.571 | 0.124 |   |   |
|  Wet fen | 1.002 | 0.110 | 2 | 9.110 | 0.012 |   |   |
| Year x Habitat (reference category: arid heath) |  |   |   |   |
|  Mesic heath |  |  |  |  | n.s. |   |   |
|  Wet fen |  |  |  |  | n.s. |   |   |
| **Araneae** |   |   |   |   |   | 3 | 3 |
| Intercept | 42.490 | 9.329 | 91 | 4.554 | 0.000 |   |   |
| Year | -0.021 | 0.005 | 91 | -4.483 | 0.000 |   |   |
| Habitat type (reference category: arid heath) |   |   |   |
|  Mesic heath | 0.086 | 0.051 | 2 | 1.683 | 0.235 |   |   |
|  Wet fen | 0.316 | 0.062 | 2 | 5.099 | 0.036 |   |   |
| Year x Habitat (reference category: arid heath) |  |   |   |   |
|  Mesic heath |  |  |  |  | n.s. |   |   |
|  Wet fen |  |  |  |  | n.s. |   |   |
| **Diptera** |   |   |   |   |   | 1 | 1 |
| Intercept | 37.652 | 16.741 | 91 | 2.249 | 0.027 |   |   |
| Year | -0.018 | 0.008 | 91 | -2.192 | 0.031 |   |   |
| Habitat type (reference category: arid heath) |   |   |   |
|  Mesic heath | 0.183 | 0.114 | 2 | 1.611 | 0.249 |   |   |
|  Wet fen | 1.017 | 0.138 | 2 | 7.348 | 0.018 |   |   |
| Year x Habitat (reference category: arid heath) |  |   |   |   |
|  Mesic heath |  |  |  |  | n.s. |   |   |
|  Wet fen |  |  |  |  | n.s. |   |   |
| **Hymenoptera** |   |   |   |   |   | 4 | 1 |
| Intercept | 8.409 | 1.591 | 91 | 5.285 | 0.000 |   |   |
| Year | -0.004 | 0.001 | 91 | -5.197 | 0.000 |   |   |
| Habitat type (reference category: arid heath) |   |   |   |
|  Mesic heath | -0.016 | 0.007 | 2 | -2.150 | 0.165 |   |   |
|  Wet fen | 0.111 | 0.009 | 2 | 12.356 | 0.007 |  |   |
| Year x Habitat (reference category: arid heath) |  |   |   |   |
|  Mesic heath |  |  |  |  | n.s. |   |   |
|  Wet fen |  |  |  |  | n.s. |   |   |
| **Lepidoptera** |   |   |   |   |   | 2 | 1 |
| Intercept | 0.482 | 3.608 | 89 | 0.134 | 0.894 |   |   |
| Year | 0.000 | 0.002 | 89 | -0.100 | 0.920 |   |   |
| Habitat type (reference category: arid heath) |   |   |   |
|  Mesic heath | 14.036 | 4.832 | 2 | 2.905 | 0.101 |   |   |
|  Wet fen | -0.424 | 5.804 | 2 | -0.073 | 0.948 |   |   |
| Year x Habitat (reference category: arid heath) |  |   |   |   |
|  Mesic heath | -0.007 | 0.002 | 89 | -2.900 | 0.005 |   |   |
|  Wet fen | 0.000 | 0.003 | 89 | 0.064 | 0.949 |   |   |

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