Title**: Circumpolar terrestrial arthropod monitoring: a review of ongoing activities, opportunities and challenges, with a focus on spiders**

**Abstract**

The terrestrial chapter of the Circumpolar Biodiversity Monitoring Programme (CBMP) has the potential to bring international multi-taxon, long-term monitoring together, but detailed fundamental species information for Arctic arthropods lags far behind that for vertebrates and plants. In this paper, we demonstrate this major challenge to the CBMP by focussing on spiders (Order: Araneae) as an example group. We collate available circumpolar data on the distribution of spiders and highlight the current monitoring opportunities and identify the key knowledge gaps to address before monitoring can become efficient. We found spider data to be more complete than data for other taxa, but still variable in quality and availability between Arctic regions, highlighting the need for greater international co-operation for baseline studies and data sharing. There is also a dearth of long-term data sets for spiders and other arthropod groups from which to assess status and trends of biodiversity. Therefore, baseline studies should be conducted at all monitoring stations and we make recommendations for the development of the CBMP in relation to terrestrial arthropods more generally.

**Keywords**: climate change drivers, community composition, surrogates for biodiversity, bioindicators

1. **Introduction**

The pressing need for arthropod monitoring and baseline surveys in the Arctic has been emphasised numerous times, particularly given the likelihood of future widespread and rapid environmental changes (Danks 1992, Hodkinson and Jackson 2005, Christensen et al. 2013, Hodkinson et al. 2013, Coulson et al. 2014). Arthropods are responsible for, and central to, a host of ecological processes in polar habitats at a range of scales, such as pollination, decomposition and soil nutrient cycling (Gillespie et al., 2019). However, insights into temporal changes in the ecosystem services provided by this group of organisms will depend on high quality data gathered over time (Lindenmayer and Likens 2010, Hodkinson et al. 2013). Furthermore, it is argued that connecting and standardising national biodiversity monitoring programmes across the northern circumpolar region would be cost-effective, allow for more timely management, and provide greater power to detect change (Christensen et al. 2013).

The Terrestrial Plan of the Circumpolar Biodiversity Monitoring Programme (CBMP; Christensen et al. 2013) aims to meet these challenges, setting out a framework to harmonise terrestrial species monitoring efforts across the Arctic. In this paper, we reiterate the need for greater support for the establishment of arthropod monitoring programmes within the CBMP due to large gaps in current knowledge. We begin by outlining the status of arthropod monitoring in the Arctic in general, and then use spiders as a model taxonomic group to further illustrate the challenges and opportunities of Arctic biomonitoring. Spiders are an ideal group for this purpose because they are a relatively well-studied, diverse and abundant group of arthropods, occurring in a range of Arctic habitats (Bowden and Buddle 2010a). By focusing on spiders, we can identify data deficiencies and needs that are likely relevant to most major groups of arthropods in the Arctic.

**2. Why are arthropods important to monitor?**

Long-term ecological monitoring is an important part of the commitment to reverse global biodiversity losses, partly because monitoring data help distinguish between diversity and abundance trends and natural fluctuations (Rohr et al. 2007). Yet many monitoring programmes suffer from bias in favour of charismatic and popular species groups such as birds, mammals, and flowering plants (Rohr et al. 2007, Hodkinson et al. 2013). In the Arctic, relatively good monitoring networks and baseline data exist for these groups (e.g., Elrich et al. this issue; Russel et al., this issue; Smith et al., this issue), but we lack similar fundamental information for arthropods (Hodkinson et al. 2013, Gillespie et al. 2019). Paradoxically, arthropods represent one of the most diverse groups, driving many of the ecosystem functions that require safeguarding such as nutrient cycling, decomposition and pollination (Hodkinson and Jackson 2005, Lavelle et al. 2006, Tiusanen et al. 2016, Koltz et al. 2017, Høye and Culler 2018). While the CBMP represents an opportunity to monitor arthropods alongside vertebrates and plants, detailed distribution and biological information is lacking for many species (Hodkinson et al. 2013).

The need for balanced monitoring is increasingly apparent due to the likelihood of strong arthropod responses to climate changes (Høye and Forchhammer 2008a, Høye et al. 2014, Loboda et al. 2018). Being ectothermic organisms with rapid developmental rates, relatively short generation times and often precise habitat requirements (e.g. soil moisture, vegetation cover), arthropods are sensitive to rapid climate change in the Arctic (Høye and Forchhammer 2008a). They can also provide the earliest indication of altered ecological systems (Danks 1992). For example, global temperature changes have already altered the phenology of invertebrates as food for mammals and birds (Tulp and Schekkerman 2008), and earlier snowmelt, and earlier and warmer springs have also affected the sexual dimorphism of the wolf spider *Pardosa glacialis* in Zackenberg, north-east Greenland (Høye et al. 2009).

While some species may actually benefit from climatic changes, as they may become less stressed or limited by cold conditions and short seasons, the effects of new interactions arising from range expansions are harder to predict (Convey 2011). The extent to which northward and elevational range shifts are already occurring is unknown due to the lack of research tracking distributional limits of species, but palaeo-ecological work has identified previous rapid shifts of invertebrate faunas in response to climate change (Elias et al. 2006). Poleward invertebrate range expansions will differ in nature for each region of the Arctic due to varying levels of geographical isolation. For example, species on isolated islands such as Greenland, Iceland and Svalbard, have limited dispersal opportunities. Available transport routes and suitable habitats will also limit the arrival of species in these locations (Ingimarsdóttir et al. 2013). Furthermore, certain species are more adept at dispersing than others (Coulson et al. 2002, Coulson et al. 2003) and the ability to survive in a new habitat and disperse further will vary between species (Hodkinson et al. 2013). Colonisation success will depend on factors such as microhabitat structure and temperature, snowmelt and freeze/thaw cycles, the availability of moisture and species interactions (Hodkinson and Bird 1998, Bale and Hayward 2010). These factors themselves are likely to be subject to change, as shrub encroachment is expected to alter habitat structure, and early spring onset will alter phenological cues of some species and the timing of moisture availability (Cooper 2014).

**3. Knowledge gaps in the monitoring of Arctic arthropods**

A review of invertebrate monitoring approaches by Rohr et al. (2007) highlighted the need for structured inventories (i.e., species lists with relative abundances) and the identification of reliable “surrogates of biodiversity”. The diversity of these surrogate groups and how it changes over time may be indicative of broader biodiversity patterns. Identifying such taxa is important, therefore, because complete monitoring of a group as species-rich as the invertebrates is impractical using current, traditional methods. The CBMP adopts these approaches to a certain extent, outlining five large functional species groups of arthropods to target and report on, called Focal Ecosystem Components (FECs: pollinators, decomposers, prey for vertebrates, blood-feeding, and herbivores). However, the FEC approach is difficult to implement for arthropods in practice. Categorisation is challenging for species performing multiple roles or where ecological information is scarce, and the approach underestimates the intensity of labour required to monitor ecological functions and identify sampled species (Gillespie et al. 2019). Furthermore, complete circumpolar inventories do not exist and, where country- or region-level inventories are available (e.g., Coulson et al. 2014, Böcher et al. 2015), the relative importance or abundance of species within communities and their correlations with functional biodiversity are only known for a few key sites (e.g., Cameron and Buddle 2017, Dahl et al. 2018, Koltz et al. 2018, Loboda et al. 2018).

Published work reporting long-term, extensive sampling is also limited in its species level information (Høye and Forchhammer 2008a, Tulp and Schekkerman 2008, Bolduc et al. 2013), taxonomic coverage, or geographic location/extent (Table 1, Fig. 1). Perhaps the most promising current multi-taxon monitoring programme for terrestrial arthropods is in Greenland. The Greenland Ecosystem Monitoring (GEM) Programme has been monitoring arthropods as well as plants, birds and mammals at Zackenberg (74° 28'N, 20° 34'W; Hansen et al. 2017) and Nuuk (64° 08'N, 51° 23'W; Topp-Jørgensen et al. 2017) since 1996 and 2008, respectively. Arthropods are sampled weekly during the growing season using pitfall and flight-intercept traps, and samples are sorted to family-level taxonomic resolution. Further species-level identification and analysis suggest abundance declines for some individual species (Bowden et al. 2018, Loboda et al. 2018) and diversity declines for some functional groups (Gillespie et al., 2019), but the data demonstrate high temporal and spatial (among habitat) variability.

Elsewhere, evidence of long-term trends comes from stand-alone studies, but these typically cover specific taxonomic groups such as moths (unpublished data, see Gillespie et al. 2019) and chironomids in Iceland (Ives et al. 2008), or recent repeats of historic surveys. For example, between 1947 and 1962, the Northern Insect Survey of Canada sampled insect diversity, with an initial focus on biting flies, at over 70 sites in the Canadian and Alaskan Arctic and sub-Arctic (Freeman 1959, Riegert 1999). More recent efforts through individual research programmes aimed to document changes in diversity (Buddle et al. 2008), although the lack of standardised sampling in the earlier surveys prevented the analysis of temporal trends for most species groups (but see Timms et al. 2013). Nevertheless, survey updates carried out in other regions may form the best source of information on “status and trends” of arthropods.

Further opportunities for generating long-term data exist through linking arthropod monitoring activities to programmes for other taxonomic groups. For example, throughout Canada and Alaska the Arctic Shorebird Demographics Network has been collecting terrestrial arthropods via pitfall trapping for nearly a decade. However, this programme is currently not linked to arthropod experts and the majority of samples have been dried for biomass sampling (e.g., Bolduc et al. 2013) to generate a gross estimate of food availability for birds. Long-term ecological research stations (e.g. INTERACT 2015) could also be expanded to include more arthropod sampling, by securing the resources to collect samples using standardised methods over long periods and identify them to species level. For example, invertebrates have been studied at the Long-Term Ecological Research Site, Toolik Field Station, located in the Brooks Range, North Slope of Alaska (e.g., Sikes et al. 2013, Koltz et al. 2017), but the station lacks a complete species-level inventory and historic long-term invertebrate monitoring dataset. Nevertheless, Toolik Field Station and the station at Utqiaġvik (Barrow) have recently been included in the U.S. National Ecological Observatory Network (NEON), a large-scale U.S. National Science Foundation project aiming to document ecological changes across the U.S. over the next three decades, incorporating pitfall and CO2 traps for arthropods (Thorpe et al. 2016). It is essential that such projects maintain these commitments and incorporate the standardised protocols of the CBMP in order to create useful baseline summaries. Further, funding to support DNA identification of the high volume of samples from these stations would contribute significantly to the timeliness and efficiency of biodiversity assessments, as well as provide other meaningful information such as improved reference sequences and detection of speciation processes (Porter and Hajibabaei 2018). Scientific engagement with, and productivity from, these types of sites is considered vital to the sustainability of monitoring programmes, because it ensures statistical rigour in sampling designs and facilitates a flow of communication between stakeholders, ensuring continued relevance of the programme (Lindenmayer and Likens 2010). More of these types of collaborations can close some of the enormous geographic gaps in the coverage of monitoring in the Arctic (Fig. 1). The few stations with current monitoring of arthropods found in the literature and on the internet (Table 1) are heavily biased towards insular Arctic, with few monitoring activities of note in continental Europe or Russia. Similarly, there is a latitudinal imbalance, with most monitoring occurring south of 70°N. While this list of stations is not exhaustive, and is not indicative of research or sampling effort (Metcalfe et al. 2018), it illustrates an alarming lack of coordinated efforts in arthropod monitoring.



**Figure 1**: Circumpolar map indicating the locations of research stations with current or expected future arthropod monitoring activities. Details of the stations are in Table 1.

**Table 1:** Summary of the Arctic research stations currently involved in monitoring of arthropods

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Country/ State** | **Location** | **CAVM zone** | **Year started** | **Methods of annual invertebrate sampling** | **Comments** | **Ref** |
| Alaska | Toolik LTER | Low Arctic | 1980 | Pitfall traps, CO2 traps from 2017 | Short term projects only prior to 2017. NEON site status since 2017. Target species are ground beetles and mosquitoes. Other species stored as by-catch. | (Hobbie et al. 2003) |
|  | Utqiaġvik (Barrow) | High Arctic | 2015 | Pitfall traps, CO2 traps | NEON site since 2017. Target species as for Toolik | (Thorpe et al. 2016) |
| Canada | CHARS, Cambridge Bay, Nunavut | High Arctic | Expected 2019 | As CBMP | One of the first CBMP stations | (Government of Canada 2018) |
|  | Bylot Island | High Arctic | 2005 | Modified pitfall traps | As part of broader ecosystem monitoring | http://www.cen.ulaval.ca/bylot/ecomon-anispec-arthropod.htm |
| Greenland | Zackenberg Ecological Research Operations | High Arctic | 1996 | Pitfall traps, flight interception traps | Weekly sampling, family-level identification | (Hansen et al. 2017) |
|  | Nuuk Ecological Research Operations | Low Arctic | 2008 | (Topp-Jørgensen et al. 2017) |
|  | Narsarsuaq | Sub-Arctic | 2014 | Pitfall traps, Malaise traps | Weekly sampling, some species-level identification | (Høye et al. 2018) |
|  | Kangerlussuaq | Low Arctic | 2011 | CO2 traps, Sweep nets, Bug vacs, Pitfall traps | Mosquito monitoring since 2011; Terrestrial studies since 2015 | (Culler et al. 2015) |
| Iceland | Surtsey | Sub-Arctic | 1967 | Pitfall traps (from 2002), Malaise traps (from 2008) |  | (Baldursson and Ingadóttir 2006) |
|  | Mývatn | Sub-Arctic | 1977 | Window traps | Chironomidae and Simuliidae larval studies (Freshwater). See also moth survey sites (section 5). | (Ives et al. 2008) |
|  | Rif | Low-Arctic | 2017 | Pitfall traps, Malaise traps | One of the first CBMP stations | (Jóhannsdóttir et al. 2014) |
| Norway | Varanger | Sub Arctic | 2005 | Survey transects | Annual geometrid moth surveys | (Ims et al. 2013) |
|  |  |  | 2011 | Flight interception traps | Annual Saproxylic insect trapping. Station also located in Svalbard but arthropod monitoring is not conducted |  |
| Sweden | Abisko Scientific Research Station | Sub-Arctic | 2003 | Malaise trap | Extensive study of all species. Short term project to 2005, may be resumed. | (Karlsson et al. 2005) |
| Finland | Kevo Research Station | Sub-Arctic | 1972 | Light traps | Moth monitoring | (Kozlov et al. 2010) |
|  | Kilpisjärvi Biological Station | Sub-Arctic | 1993 | Light traps | Moth monitoring | (Välimäki et al. 2011) |

**4. Case study: Status and trends in Arctic spider diversity and abundance**

Spiders are an excellent candidate group for focused monitoring in the Arctic, not only due to their ubiquity but also because they tend to be relatively easy to collect in a standardised manner (e.g., with pitfall traps, although this can bias the sample towards wandering species), are large enough for non-specialist researchers to separate to “morphotypes”, and unlike many other groups, all life stages perform similar function and occur in the same habitats. In relation to the FEC classification system of the CBMP (Gillespie et al. 2019), spiders represent a large part of one of the FECs (prey for vertebrates). However, spiders are also pivotal in Arctic food webs, serving as the dominant terrestrial arthropod predators with the potential to reflect subtle ecosystem changes (Hodkinson and Coulson 2004, Wirta et al. 2015, Schmidt et al. 2018) and even environmental pollution (Jung and Lee 2012). Recent work has shown that molecular identification of spider prey from gut contents reflects the composition of the local community and prey availability (Schmidt et al. 2018). When DNA metabarcoding methodologies are incorporated within monitoring programmes, groups of organisms such as spiders may be important as “traps within traps”, providing rapid assessments of community composition and trophic cascades of environmental changes. This form of monitoring may be biased, however, as some spider species may prefer certain prey groups (Eitzinger et al. 2019).

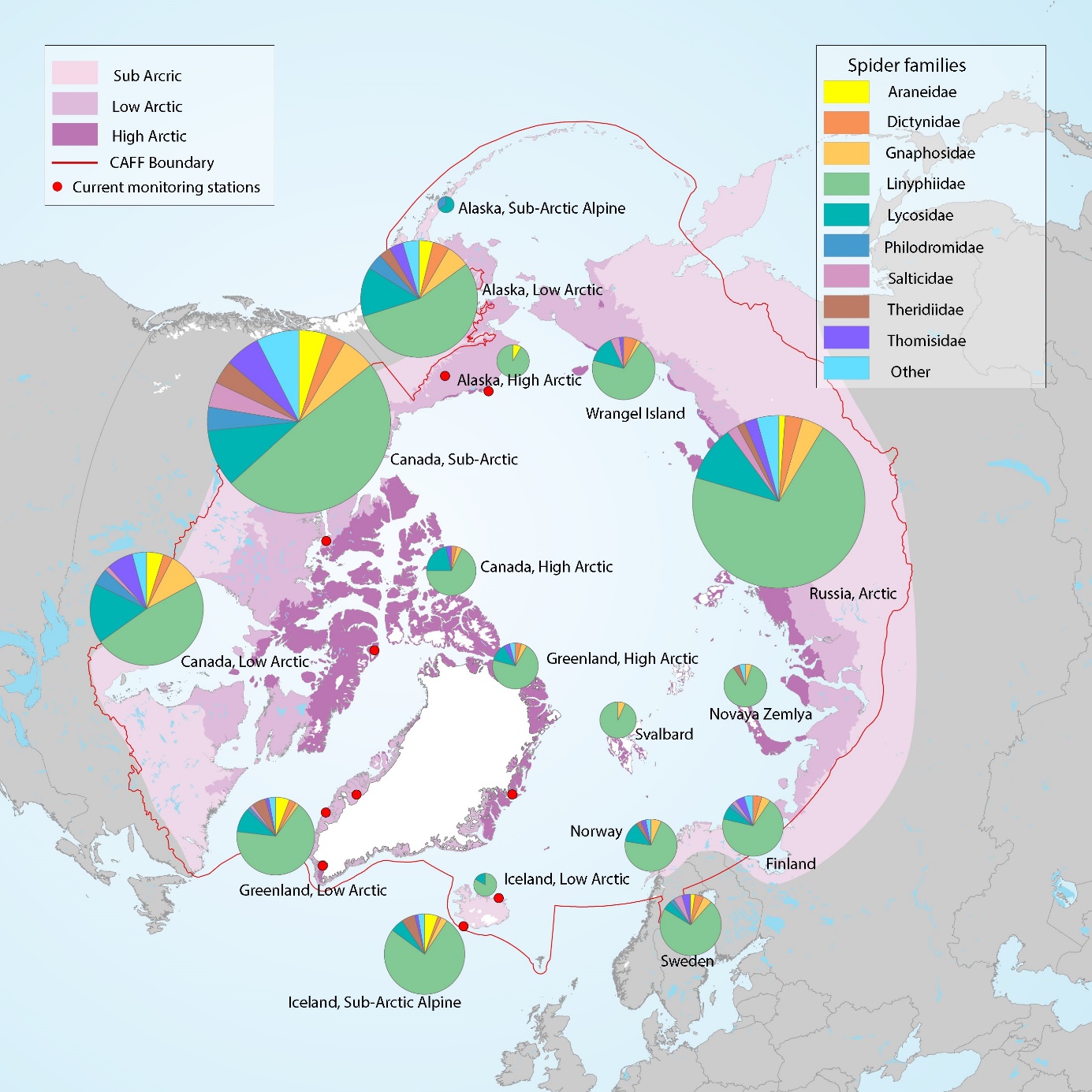
In this case study, we begin by collating spider inventories for each Arctic region. We then summarise the current monitoring programmes that target spiders, and identify opportunities for more extensive sampling, before outlining key trends in, and drivers of, Arctic spider diversity. We conclude with recommendations for addressing important knowledge gaps and developing arthropod monitoring within the CBMP. It is hoped that, through illustrating the amount of work required for a relatively well-known group, this study will alert policy makers, funding agencies and other stakeholders to the need for far greater support for arthropod biodiversity initiatives more generally.

**4.1 An inventory of circumpolar Araneae**

The main aim of this section is to summarise the species richness of spiders for each country with land in the High-, Low-, and/or Sub-Arctic zones as defined by the Circumpolar Arctic Vegetation Map (CAVM; CAVM Team 2003), but with Sub-Arctic restricted to alpine habitats (i.e., those occurring above the treeline). Subsequently, we aim to highlight aspects of data quality and availability that will need to be addressed in future monitoring efforts. Full details of data sources and geographic classification can be found in the supplementary material. Species lists are given in Table S1.

We encountered two key issues in producing our summaries of species richness of Arctic spider families (Fig. 2, Table 2). First, much of the available information on species distribution is organised according to definitions other than the CAVM zones. For example, Marusik and Eskov (2009) provide a comprehensive list of species occurring in the Russian tundra, but the study reports on surveys across the CAVM High/Low Arctic boundary. Records in this and other studies are not digitised with geographic coordinates, preventing a classification of species by CAVM zones without direct examination of the specimens’ labels. The Russian richness value is therefore an underestimate, with significant regions such as Siberia largely omitted from consideration, and the figure representing the “Russian Arctic” as a whole. Second, species records are not always accompanied by elevation information, causing difficulties with classifying species as “alpine” (See supplementary material). It was not possible to distinguish between alpine and non-alpine species in Canada at all, resulting in an inflated final richness value. Conversely, the species richness of the sub-Arctic alpine region of Alaska was estimated as only three species, based on assumptions of timberline elevation. This is clearly an underestimate and highlights the need for more alpine sampling and future recording of sampling elevations. Such information would particularly help to monitor species’ elevational range shifts.

Due to the above issues, we are restricted to broad inferences about diversity patterns. As expected, larger territories of the Arctic accommodate a richer fauna, and as with many other arthropod groups, the species richness and number of families decrease with increasing latitude (Hodkinson et al. 2013). An additional clear pattern from the data is that the spider family Linyphiidae dominates the Arctic fauna, probably reflecting a combination of their effective dispersal and colonisation ability and their cold-hardiness (Kumschick et al. 2009, Convey et al. 2015, Loboda and Buddle 2018). The Lycosidae are also well represented in the Arctic, absent only from some High Arctic islands, and species within this family tend to be collected in high abundance in open areas such as the tundra (Bowden and Buddle 2010a, Loboda and Buddle 2018) or forest gaps (e.g., Buddle et al. 2000). The species richness of this group also tends to make up between 7 and 10% of spider communities in most Arctic habitats, making it a consistent indicator of overall diversity (Y. Marusik, pers. obs.). Conversely, the Salticidae is the most species-rich spider family globally but is not well represented in the Arctic. The reason for this is not clear, but phylogeographic work indicates that the family radiated mainly in the tropics (Hill and Richman 2009).



**Figure 2:** The diversity of the main spider families in the circumpolar region (those present in seven or more regions; the *Other* category consists of 10 families – see Table 2; note Franz Josef Land with only two Linyphiidae species is omitted for clarity). The size of the pie charts corresponds to the total richness of each area (see Table 2). Note that species richness for sub-Arctic regions consists only of alpine species, except for Canada, which includes both alpine and non-alpine species. The red dots indicate monitoring stations that target arthropods (Fig. 1, Table 1), but with those not using techniques to capture spiders removed.

**Table 2:** The number of spider species within each family and region of the circumpolar Arctic.

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  |  |  | **Family** | | | | | | | | | | | | | | | | | | |  | |
| **Country** | **Zone** | **Agelenidae** | **Amaurobiidae** | **Araneidae** | **Clubionidae** | **Cybaeidae** | **Dictynidae** | **Gnaphosidae** | **Hahniidae** | **Linyphiidae** | **Liocranidae** | **Lycosidae** | **Miturgidae** | **Philodromidae** | **Pisauridae** | **Salticidae** | **Tetragnathidae** | **Theridiidae** | **Thomisidae** | **Titanoecidae** | **Total** | |
| Norway | Sub-Arctic alpine | - | - | - | 1 | - | - | 2 | - | 22 | - | 4 | - | - | - | - | - | 1 | 1 | - | 31 | |
| Svalbard | High Arctic | - | - | - | - | - | - | 1 | - | 14 | - | - | - | - | - | - | - | - | - | - | 15 | |
| Sweden | Sub-Arctic alpine | - | - | 1 | - | - | 2 | 2 | - | 31 | - | 2 | - | 1 | - | 2 | - | - | 2 | - | 43 | |
| Finland | Sub-Arctic alpine | - | - | - | - | - | 2 | 2 | - | 29 | - | 3 | 1 | 1 | - | 1 | - | - | 2 | 1\* | 42 | |
| Russia (mainland) | Arctic | - | 1 | 4 | 7 | 1 | 11 | 14 | 2 | 239 | - | 35 | - | 3 | - | 7 | 3 | 5 | 8 | - | 340 | |
| Alaska | High Arctic | - | - | 1 | - | - | - | - | - | 11 | - | - | - | - | - | - | - | - | - | - | 12 | |
|  | Low Arctic | - | - | 6 | 4 | - | 7 | 10 | 2 | 85 | - | 21 | - | 7 | - | 1 | 1 | 5 | 6 | - | 156 | |
|  | Sub-Arctic alpine | - | - | - | - | - | - | - | - | - | - | 2 | - | 1 | - | - | - | - | - | - | 3 | |
| Canada | High Arctic | - | - | - | - | - | 1 | 1 | - | 19 | - | 6 | - | - | - | - | - | - | 1 | - | 28 | |
|  | Low Arctic | - | - | 7 | 3 | - | 4 | 14 | - | 70 | - | 25 | - | 7 | - | 2 | 3 | 1 | 11 | - | 147 | |
|  | Sub-Arctic alpine | 1 | 2 | 19 | 9 | - | 13 | 23 | 6 | 188 | 1 | 39 | - | 16 | 2 | 17 | 7 | 16 | 24 | 1\* | 384 | |
| Greenland | High Arctic | - | - | - | - | - | 1 | 1 | 1 | 17 | - | 3 | - | - | - | - | - | - | 1 | - | 24 | |
|  | Low Arctic | - | - | 4 | - | - | 2 | 1 | 1 | 46 | - | 7 | - | 1 | - | 1 | 1 | 4 | 1 | - | 69 | |
| Iceland | Low Arctic | - | - | - | - | - | - | - | - | 5 | - | 1 | - | - | - | - | - | - | - | - | 6 | |
|  | Sub-Arctic alpine | - | - | 4 | - | - | 1 | 2 | - | 56 | - | 4 | - | - | - | - | 2 | 4 | 1 | - | 74 | |
| Novaya Zemlya | High Arctic | 1 | - | - | - | - | - | 1 | - | 18 | - | - | - | - | - | - | - | 1 | - | - | 21 | |
| Wrangel Island | High Arctic | - | - | - | - | - | 3 | 1 | - | 30 | - | 6 | - | - | - | 2 | - | - | 1 | - | 45 | |
| Franz Josef Land | High Arctic | - | - | - | - | - | - | - | - | 2 | - | - | - | - | - | - | - | - | - | - | 2 | |

\*This record refers to *Titanoeca nivalis*, found in the Oglivie mountains, Yukon (Bowden & Buddle 2010), and northern Finland (Koponen et al 2013)

**4.2 Current monitoring of Arctic spiders**

Ideally, a complete account of circumpolar spider diversity would include recent trends of diversity or abundance, as this would enable identification of those species, habitats, or regions most at risk from future environmental changes. Such evaluations have not been completed previously: there are no red data list records for Arctic spiders due to a lack of data, and remarkably, the only dataset with more than 10 years of standardised observations is that from the Zackenberg monitoring programme. Spiders from these samples have recently been identified to species level and analyses have revealed that some species have declined significantly in abundance between 1996 and 2014 at Zackenberg (Figure 3). Specifically, some habitat specialists (*Collinsia thulensis* and *Erigone psychrophila*, both Linyphiidae) have significantly declined in the region in response to warming and earlier spring onset over the 18 year period (Bowden et al. 2018). *Erigone psychrophila,* in particular, is associated with a fen habitat at Zackenberg that is undergoing rapid reductions in cover through altered snow dynamics and increased evapotranspiration (Schmidt et al. 2012). This species also appears to have declined in Svalbard (M. Dahl, pers obs). Many other species demonstrate highly variable patterns in abundance, particularly *Erigone arctica*, which appeared to be declining until 2010, after which the population seems to increase, highlighting the need for continuous and uninterrupted long-term species monitoring across multiple habitats.



**Figure 3**: Abundance of individuals per trap across the snow-free season and for all habitats combined, from 1996 to 2014 at Zackenberg Research Station, North-East Greenland, separated by key spider species. Abundances have been calculated to control for trapping effort by calculating abundance per trap-day for each trap, and then multiplying this value by the total number of trap days for the site (85). Solid lines are linear regression lines, significant at the p < 0.05 level. (Redrawn with permission from Bowden et al. 2018).

There is excellent potential elsewhere for long-term data generation (Table 1). Monitoring programmes have recently been launched elsewhere in Greenland, including an ambitious dedicated arthropod monitoring program launched in 2014 at Narsarsuaq, South Greenland, building on the GEM arthropod sampling manual, with additional spatial replication also covering elevational variation (Høye et al. 2018). Also, in Kangerlussuaq in western Greenland, arthropod monitoring with pitfall traps began in 2016 with plans to continue through to at least 2021. Traps in Kangerlussuaq are in operation for three weeks in July and cover a range of habitat types (wind-eroded areas, shrub, grass) at sites near (<1-2.5 km) and far (25 km) from the Greenland Ice Sheet. However, these relatively new endeavours must be assured of continuous funding to ensure that a) sampling is conducted over long and uninterrupted time scales, and b) trap catches are continually identified and counted to generate the data in a timely manner. DNA barcoding techniques are now widely available to help with the second requirement (Porter and Hajibabaei 2018). Furthermore, such efforts need to be expanded to cover more areas of the Arctic, as the locations that currently use trapping techniques to capture spiders (pitfall traps and sweep netting) on a regular basis are mainly restricted to the insular and Low or Sub-Arctic zones (Fig. 2). For spiders, and other terrestrial arthropods, information on trends over time are insufficient to extrapolate findings to other habitats, species groups, and regions of the Arctic.

**4.3** **Drivers of spider diversity and community composition**

Under future warmer conditions, spider diversity and community composition may be expected to change in many areas through changing snowmelt dynamics and moisture availability (Bowden et al. 2018). Shrub encroachment into alpine and Low Arctic habitats is also likely to lead to changes in spider community composition (Rich et al. 2013, Høye et al. 2018). For example, many ground dwelling wolf spider (Lycosidae) species are found in high densities on the Arctic tundra, preferring high solar irradiation for basking, thermoregulation and incubating their eggs (Bowden and Buddle 2012, Loboda and Buddle 2018), and such conditions may become fragmented or limited with the encroachment of shrubs. Other bottom-up processes via factors such as changing plant health and diversity, vegetation structure (Bowden and Buddle 2010b, Hansen et al. 2016), moisture availability and their effects on herbivore prey, will likely combine with direct impacts on physiology and activity in ways that are as yet unclear (e.g. Barrio et al. 2016, Koltz et al. 2018).

In addition, species may have distinct responses to changing temperatures and moisture regimes (e.g. Danks 1992, Hodkinson et al. 1998, Dahl et al. 2018). Differential responses between trophic levels (e.g., spiders and prey) have the potential to disrupt species interactions with consequences for diversity and community composition (Høye and Forchhammer 2008b, Høye et al. 2014, Gillespie et al. 2016). Most of these impacts are understood in relation to spring and summer temperatures, but changing winter temperatures may also influence responses of arthropods such as winter-active spiders (Koltz et al. 2018). Thus, future studies are needed that specifically focus on the impact of changing winter conditions on arthropod abundance and diversity (Bale and Hayward 2010). There is also a paucity of studies recording biological microclimates over long timescales, which are necessary both in terms of understanding the stresses faced by organisms, and in identifying even large-scale changes in active season length (see discussion in Convey et al. 2018). At least for biological responses in body size, phenology and abundance, it is fairly clear that these are likely linked to snowmelt timing and temperature (Høye and Forchhammer 2008b, Høye et al. 2009, Bowden et al. 2015, Loboda et al. 2018).

**5. Recommendations for circumpolar arthropod monitoring**

In general, the species lists and isolated long-term datasets of our illustrative example are insufficient to assess the status of, or recent changes in, spider diversity (Christensen et al. 2013, Gillespie et al. 2019). However, this data collation has highlighted key knowledge gaps and requirements that will inform the initial stages of spider monitoring, as well as more general arthropod sampling. First, we lack structured inventories of the vast majority of arthropod groups in many regions of the Arctic (Hodkinson et al. 2013, Gillespie et al. 2019). Second, the geographical coverage of monitoring and potential for long-term data generation is clearly unbalanced across much of the Arctic and, even where there is good coverage, more habitat types and ecosystems require study. Third, these imbalances inevitably result in a dearth of long-term trend information for even the best-known species groups. Without more structure and organization in our information about terrestrial Arctic arthropods, we cannot confidently establish which taxa should be the targets of monitoring and how they should be most efficiently collected.

Spiders are a good candidate biodiversity “surrogate”, particularly the Lycosidae. This family is well represented in easily implemented pitfall trapping due to a wandering predatory habit increasing the probability of capture compared to the sit-and-wait behavior of the Linyphiidae. The consistent diversity representation of this family across habitats and zones would also enable early detection of changes in community composition, especially if captures are combined with DNA metabarcoding. However, we advise against relying on a) one taxonomic group as a biodiversity surrogate, b) only one trapping technique, and c) catches from one or a few locations and habitats. The CBMP aims to avoid points a) and b), but we recommend that monitoring plans are expanded to address point c). For example, monitoring at any particular station should involve trapping in multiple locations at small physical scales to account for subtle variations in variables such as soil moisture (Cameron and Buddle 2017, Høye et al. 2018), habitat (Wyant et al. 2011, Ernst et al. 2016) and vegetation structure (Bowden and Buddle 2010a, Hansen et al. 2016, Høye et al. 2018). Similarly, trapping should be conducted at multiple time points to include seasonal variation (Bowden et al. 2018). Given the degree of habitat/structural specialisation among Arctic spiders, for example, it may also be prudent to monitor changes in habitat conditions, particularly as air temperatures taken at research stations may not accurately reflect conditions experienced by surface-dwelling and soil invertebrates (Convey et al. 2018).

Overall, extensive initial work will be required at each monitoring station of the CBMP to determine the appropriate sampling design given local habitat conditions, establish structured species inventories and evaluate the extent to which the station represents the diversity of species in the region. Subsequent work should also investigate how sampled species groups meet the requirements of bioindicators or surrogate species (e.g., ease of identification, locally abundant, representative of the community or FEC, indicative of environmental changes, Hodkinson and Jackson 2005). To these ends, it will be important to foster partnerships between researchers (particularly taxonomists) and local communities, ensure strong leadership at monitoring stations and secure continued funding. These aspects are key in ensuring that preserved samples of arthropods are not left to accumulate in storage or be discarded. Rather, they should be identified in a timely manner to the appropriate taxonomic level, curated in suitable repositories, and their data shared (e.g., via the Global Biodiversity Information Facility; gbif.org) to enable future re-examination and use to generate both monitoring and research outputs (Rohr et al. 2007, Lindenmayer and Likens 2010).

Future species inventories should also be digitised to give accessible reference databases of circumpolar invertebrate species, along with their morphological and functional traits and habitat requirements. Existing trait databases for invertebrates, such as SoilBioStore (soilbiostore.au.dk) and BETSI (betsi.cesab.org), could be used to derive FECs and other functional groupings more easily. Where the ecosystem role of a species is poorly known, the level of current knowledge will be indicated by missing trait information and FEC assignment. Monitoring efforts should also be accompanied by the production of DNA barcode data which, given funding for environmental DNA studies and considerable improvements in sequence database coverage, will help make monitoring easier for such a diverse and challenging species group (Porter and Hajibabaei 2018). For example, Alaska has begun production of a DNA Barcode library of Alaskan arthropods, which has so far resulted in DNA barcodes for 1,748 species (Sikes et al. 2017). This online library has already been used in a number of studies, including diet analyses of birds (McDermott 2017) and a study using high-throughput sequencing methods to inventory terrestrial arthropods (Bowser et al. 2017). A similar co-ordination project for barcodes of polar invertebrates generally, PolarBOL (<http://www.polarbarcoding.ca/>), also promises to provide an efficient mapping and monitoring tool for biodiversity on a large scale. The extension of barcode libraries of this kind to more species groups would be invaluable to the science of ecology and to broad monitoring programmes like the CBMP, particularly if samples cannot be identified by traditional means within reasonable time limits, or if sampling is incidental to monitoring of other groups such as mammals and birds. However, it should be noted that DNA-based methods should not replace traditional specimen-vouchering methods which support taxonomic research, particularly as some taxa cannot yet be identified by DNA barcodes (Rix et al. 2018), and as intact specimens provide important information for other valuable areas of study, such as intraspecific trait variation (Bowden et al. 2015).

**6. Conclusion**

In this review, we have demonstrated that the CBMP faces a huge challenge in making its arthropod monitoring efficient. We have identified the following recommendations for arthropod monitoring within the CBMP:

1. On a pan-Arctic scale, there is a need to address the geographical imbalance in knowledge and monitoring of Arctic arthropods by prioritising the development of new monitoring stations in High Arctic locations, and maintaining existing stations.
2. At local scales, initial studies are required at each station to create “structured inventories” (species lists with relative abundances), and to identify key surrogates for biodiversity in order to place monitoring data into context.
3. The above initial studies should also provide local information on the habitat types to include in monitoring, and the specifics of the sampling regime (i.e, the timing and the types of methodologies used), to ensure target taxa are collected appropriately.
4. Sampling programmes should be planned with rigorous statistical design and appropriate environmental monitoring (e.g. micro-habitat soil moisture and temperature) in order to link biological trends with environmental changes at biologically-relevant scales (Convey et al. 2018).
5. A detailed plan of continuous specimen identification and vouchering is required for each station, together with sustainable sources of funding set aside for taxonomic work and DNA barcoding, to ensure that samples are converted to usable, high resolution, globally shared, and open-access data.

The CBMP represents an unprecedented opportunity to bring knowledge of Arctic arthropods in line with that of their temperate counterparts, and ideally with that of vertebrates and flowering plants. It also has the potential to meet the pressing need for greater international collaboration, as is currently facilitated by the Network for Arthropods of the Tundra (Høye and Culler 2018) and the online sharing of open-access data. Much work and financial backing is required, however, if the programme is to come close to meeting its potential for arthropods.

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