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Effects of climate change on alpine arthropods: Possibilities of long-term monitoring in the Finse area, southern Norway

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Norwegian alpine arthropods have been studied for decades in the Finse area, situated in the northern part of the Hardangervidda mountain plateau at about 1200 m a.s.l. This might be a suitable site for monitoring long-term effects of climate change on various arthropod groups. This paper points to several possibilities, using published data as a reference. In the foreland of a retreating glacier, georeferenced locations could be resampled. A common alpine habitat, the so-called snowbed, is sensitive for increased temperatures. Here, snow accumulates during winter, the snow-free season is short, and the vegetation is dominated by the tiny willow *Salix herbacea* L. In the long term, characteristic insects of snowbeds that use *S. herbacea* as food plant may be negatively affected. Examples are certain genera of sawflies (Hymenoptera, Symphyta) and the chrysomelid beetle *Chrysomela collaris* Linnaeus, 1758 (Coleoptera). Furthermore, a gradual elevation of the tree line due to higher temperatures will bring many arthropods to higher altitudes, both ground-living species, as for instance ants (Formicidae), and several arthropods living on birch (*Betula* L.) foliage. A more humid climate will favour hydrophilic subalpine and alpine beetles (Coleoptera). Artificially elevated temperatures in so-called "open top chambers" (OTCs) have given increased herbivory by insects. Norwegian mountains also receive long-transported nitrogen compounds. Experimental fertilisation of a nutrient-poor *Dryas* L. heath rapidly created a grass-dominated vegetation, which changed the soil-living arthropod fauna. Collembola species with a relatively short life cycle took over the dominance among soil microarthropods. With a well-known arthropod fauna, a permanent and modern research station, and easy access by train, Finse may be the best site in Norway to monitor long-time effects of climate change on alpine arthropods.

Key words: Alpine arthropods, climate change, long-term monitoring, Finse, Norway.

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Introduction

The Finse area, situated in the northern part of the Hardangervidda mountain plateau approximately 1200 m a.s.l. (Figure 1), has since the 1960s been a centre for alpine ecological studies. The International Biological Program (IBP) supported various investigations in the 1970s and research activities have proceeded since then (Østbye *et al.* 1975). In a national context, Finse has a moderate oceanic climate and a moderate snow cover. A permanent research station, Finse Alpine Research Centre, belonging to the Universities of Oslo and Bergen, have been practical and easily accessed by train.

Hardangervidda is the largest mountain

FIGURE 1. The Finse study area, with the research station in the foreground, a mosaic of habitat types, and the Hardangerjøkulen glacier. Photo: Erika Leslie.

plateau in Europe, approximately 10000 km^2 in area. The tree line is at approximately 1000 m a.s.l. Altitudes of the plateau vary mostly between 1100 and 1300 m a.s.l., but some peaks even reach 1800 to 1900 m a.s.l. The area contains the sixth largest glacier in Norway, namely Hardangerjøkulen. Fauna and flora have arctic elements such as the wild reindeer *Rangifer tarandus* (Linnaeus, 1758) and the glacier buttercup flower *Ranunculus glacialis* L. Most of the plateau is protected areas, mainly as a national park, but also as a "landscape conservation area".

Over time, climate change may strongly affect alpine flora and fauna. Glaciers all over the world, including Norway, are already shrinking (Oerlemans 2005, Jomelli *et al.* 2011, Malcomb and Wiles 2013). On the Norwegian mainland, a rise in annual temperature by 0.2–0.5°C is expected per decade until 2050 (Hanssen-Bauer & Førland 2001). Furthermore, northwestern Europe, including Norway, receives a constant deposition of long-distance transported atmospheric nitrogen (Hole & Engardt 2008). Alpine habitats with poorly developed soils and low nitrogen content may be sensitive to this fertilisation, resulting in a change in the vegetation.

In Norway, studies have shown that major changes in the vegetation of alpine snowbed-wetlands is rather fast due to changes in the snowcover (Sandvik & Odland 2013). Less snow and longer growing season will facilitate invasion of shrubs, graminoids and herbs.

Referring mainly to studies from the Finse area, we here discuss possible effects of climate change on alpine arthropods. The main purpose is to point at Finse as a possible site for long-term monitoring of climate change on alpine arthropods.

Materials and methods

In this study, the "method" is to build a platform for future monitoring studies. Good knowledge of previous studies is the basis for such monitoring. The "results" part is mainly a review, but some additional results from fieldwork at Finse in 2023 are added (see Olsen & Lønnve 2024 for details). The "discussion" part treats possible consequences of climate change on arthropods, and options for long-term monitoring. For detailed methods, we refer to the original publications. A final part, "conclusion", includes an overview for possible topics dealing with monitoring.

Various questions around climate effects on alpine arthropods are presented below. Results from "open top chamber" experiments with artificially increased temperature are discussed. A characteristic insect fauna in snowbeds is described. This habitat is sensitive to climate change and is now red-listed (Aarrestad et al. 2018). The retreating glacier continuously "produces" new land. What does this virgin ground mean to various arthropods? Can the glacier foreland offer suitable habitats as a compensation for shrinking habitats elsewhere? Would a potentially more humid climate influence the beetle fauna? Would a gradual elevation of the tree line bring quite new insect groups to higher elevations – not only tree-living but also ground-living species?

The possibility of re-sampling localities in the glacier foreland, where a primary succession occurs, presupposes exact positions of sampling points. Table 1 gives an overview of previously georeferenced localities. In the field, each locality is marked by a 20 cm high metal bar. Figure 2 illustrates the 25 localities of the glacier foreland, as well as the position of Hardangerjøkulen glacier.

Results: Review of earlier studies

Snowbed: a habitat vulnerable to climate change – and some of its insects. According to The Norwegian Biodiversity Information Centre (Artsdatabanken), the most vulnerable plant community in Norwegian mountains is the snowbed (Aarrestad et al. 2018). This habitat depends on both long-time snow cover and a high soil moisture. It is estimated that increased temperatures may affect 80 % of the snowbeds during the next 50 years and that at least 30 % of snowbed area may change character due to drier conditions. This may locally affect arthropods depending on *Salix herbacea* L. as a food plant. In western mountain areas of Norway, including Finse, increased amounts of snow could theoretically compensate for higher summer temperatures and lead to a limited loss of snowbeds. Until now, however, the receding glacier indicates larger melting than accumulation of snow.

TABLE 1. GPS-coordinates of glacier foreland sampling plots. All 25 plots were used for soil sampling of microarthropods in 2001. Only plots No. 1, 11, 16, 17, and 20 were used for pitfall trapping of macroarthropods in 2007–2008. All sampling plots were in *Salix herbacea* L. vegetation. Details about the plots were given in Hågvar *et al.* (2009).

Plot No.	East	North	Remarks
1	32416118	6716339	Traps 1–20
2	32416118	6716360	
3	32416111	6716368	
4	32416109	6716387	
5	32416112	6716409	
6	32416128	6716441	
7	32416144	6716466	
8	32416096	6716516	
9	32416107	6716632	
10	32416185	6716722	
11	32416202	6716832	Traps 21–40
12	32416281	6716888	
13	32416280	6716996	
14	32416264	6717029	
15	32416266	6717094	
16	32416255	6717142	Traps 41–60
17	32416197	6717270	Traps 61–80
18	32416215	6717347	
19	32416200	6717370	
20	32416204	6717414	Traps 81–100
21	32416226	6717499	
22	32416221	6717557	
23	Not found	Not found	
24	32416219	6717705	
25	32416209	6717794	

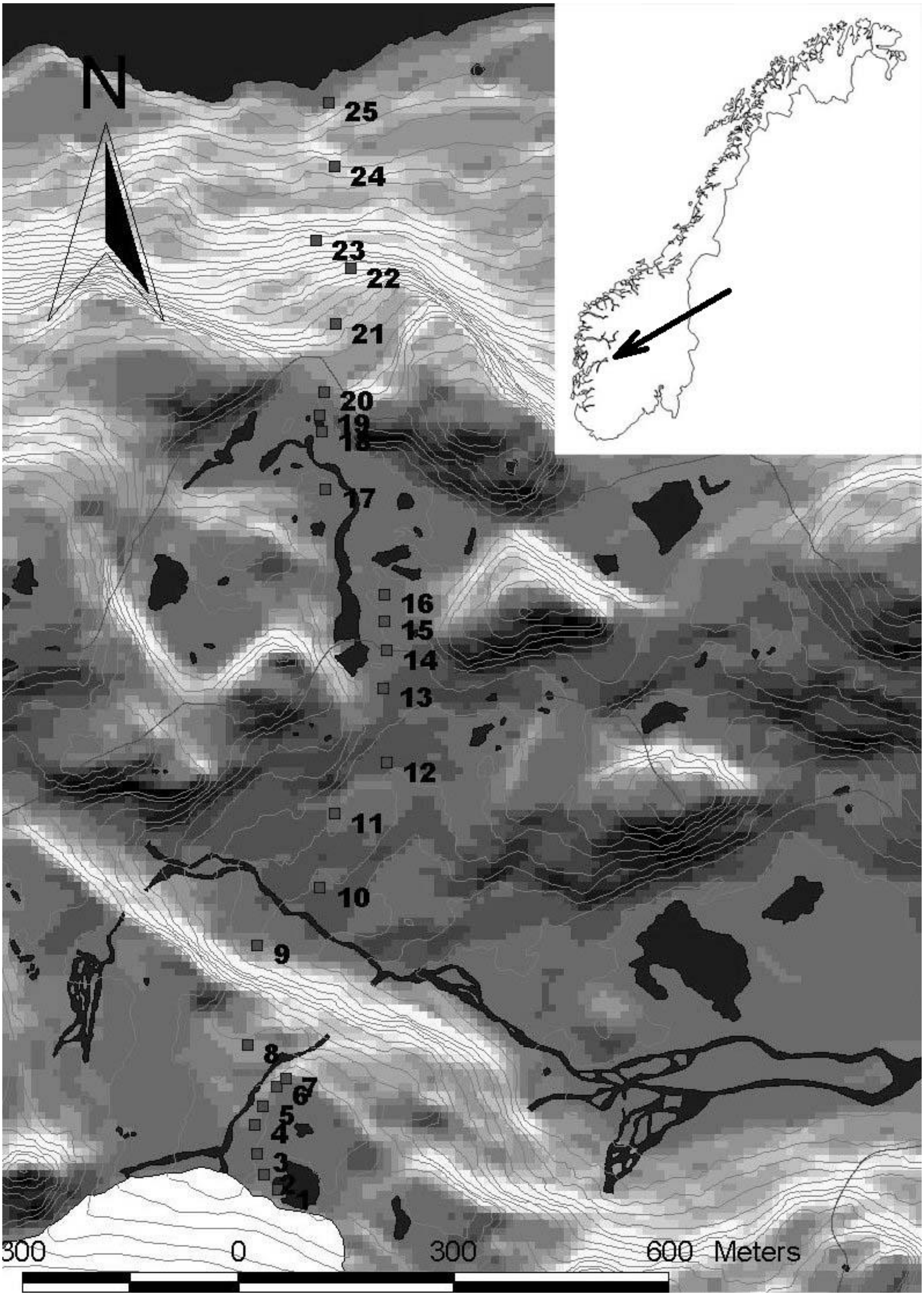

FIGURE 2. Position of 25 sampling points in the glacier foreland terrain, from the glacier snout to the lake Finsevatn in the upper part of the picture. The arrow in the small map shows where the Hardangerjøkulen glacier is situated in southern Norway (60°34´N, 7°28´E). From Hågvar *et al.* (2009).

The host plant and the snowbed community. *Salix herbacea* is only 1–5 cm high and often called "the world´s smallest tree" (Figure 3). It is adapted to arctic and sub-arctic environments and is a common species on Hardangervidda. It can be found in several vegetation types but forms nearly "monocultures" in so-called snowbeds, which are patches in the terrain where the snow melts late (Figure 4). On this mountain plateau, snow covers the ground for more than half the year. Strong winds blow the hill tops more or less bare of snow which accumulates in depressions and slopes where the snow cover may become several meters thick. From year to year, the snow distribution pattern is rather constant, and this pattern is reflected in the different plant communities. Most snowbeds are about 250–500 m^2 in area and this vegetation type covers about one fourth of the ground in the Finse area. In an inner zone of large snow beds, which are melting more than a month later than the outer zone, there are only a few species of mosses and lichens. The outer zone, several meters in width, is totally dominated by *S. herbacea* (Hågvar & Østbye 1975). This continuous "carpet" of *S. herbacea* supports some characteristic insects: the beetle *Chrysomela collaris* Linnaeus, 1758 of the family Chrysomelidae, and certain genera of sawfly wasps (Hymenoptera, Symphyta). *C. collaris* can only use those parts of snowbeds that melt relatively early and have a sufficiently long snow-free period for the beetle to fulfil its life cycle. This means that those parts of snowbeds that melt late and have a very short snow-free period, cannot be used by this beetle.

Besides forming monocultures in snowbeds, *S. herbacea* even belongs to the patchy pioneer plants of newly deglaciated ground. However, *C. collaris* does not colonise the foreland until about 80 years after the ice has retreated (Bråten *et al.* 2012, Hågvar 2023). When vegetation gradually

FIGURE 3. *Salix herbacea* L. may completely dominate the higher flora in snowbeds. Photo: Ole J. Lønnve.

FIGURE 4. A carpet of *Salix herbacea* L. in a late-melting snowbed at Finse. (Three young individuals of rock ptarmigan, *Lagopus muta* (Montin, L. 1781), are also seen in the picture). Photo: Sigmund Hågvar.

closes, *S. herbacea* is mostly outcompeted except for in depressions in the terrain where snow accumulates and melts late. Here, *S. herbacea* outcompetes other plants and can establish the monocultures where the beetle thrives. Therefore, in the glacier foreland, the beetle does not colonise deglaciated ground until patches of snowbed vegetation have been established through a botanical succession.

The beetle *Chrysomela collaris*. The following description of the ecology of *C. collaris* (Figure 5) is based on detailed studies by Hågvar (1975a, b). This is a common beetle of the family Chrysomelidae in the Finse area. Both adults and larvae feed on *S. herbacea* and occur mainly in snowbeds. While many insects adapt to alpine communities by extending their life cycle over two or more years, *C. collaris* has a one-year life cycle. Several factors make this possible. Overwintered adults become active as soon as the snow melts in the outermost part of their snowbed monoculture. Here they feed on unopened buds which have a higher content of calories than fresh leaves. They do not use their fully developed wings for flight but follow by foot the retreating snow edge, often in dense populations while feeding, copulating and laying eggs. Densities around 50 animals per m^2 at the snow boarder are not uncommon but more than 100 per m^2 have been observed (Hågvar 1975a). Later they disperse somewhat, but only a few dm by walking. Flight activity could easily bring animals to non-favourable habitats, especially in this mountain area where weather conditions may change rapidly.

First instar larvae are unable to feed on closed buds. However, at any temperature, buds develop faster than eggs, so newly hatched larvae have fresh leaves available. During three larval stages, larvae feed by making "windows" in the leaves, contrary to adults which eat from the leaf edge.

FIGURE 5. The beetle *Chrysomela collaris* Linnaeus, 1758 eating on a leaf of *Salix herbacea* L. Photo: Tommi Nyman.

Larvae from the same batch tend to keep together and disperse only slowly. They grow quickly and laboratory studies revealed an unusually high assimilation efficiency (Hågvar 1975 b).

Field observations show that both larvae and adults could be active at low temperatures and they survive short-term snow cover or flooding by rain water. Adults may even walk around on the snow surface. Both larvae and adults respond spontaneously to even short periods of favourable weather with increased activity. After hatching in late summer, adults have a feeding period before hibernation (Hågvar 1975a).

Sawflies and snowbeds. At Finse, larvae of sawflies (Hymenoptera, Symphyta) have often been observed on *S. herbacea,* either free-living on leaves (Figure 6) or within galls. Sawflies may swarm as soon as the snow melts, while *S. herbacea* still has buds. In fact, these insects can be found swarming at the retreating snow edge during most of the summer. From an ecological point of view, their use of snowbeds as habitat deserves a closer study. However, the taxonomy of sawflies is difficult.

Sawflies are particularly numerous in the arctic and alpine zones of Palearctic and Nearctic. The majority of the species in such environments belong to the subfamily Nematinae of Tenthredinidae. In Norway, it is estimated that it may be as much as 300–400 species of Nematinae. In Finland, more than 50 % of all sawflies recorded belong to Nematinae (Viitasaari & Vikberg 1985, Taeger *et al.* 2006), and this may also be the case in Norway. The majority of the nematines species in alpine and arctic environments belongs to the genera *Euura* Newman, 1837 and *Pristiphora* Latreille, 1810 (Prous *et al.* 2014). The larvae are either exposed feeders on leaves, or leaf rollers, or miners and gall makers (Viitasaari 2002. Prous *et al.* 2014, Liston *et al.* 2017, Prous *et al.* 2021). In addition, there are some species where the larvae at least partly live inside willow catkins (Zinovjev & Vikberg 1998, Liston *et al.* 2023). The majority of the Nematinae are associated with trees, especially of the families Salicaceae, Betulaceae and Pinaceae. Many Nematinae are phylogenetically poorly

FIGURE 6. A sawfly sitting on a leaf of *Salix herbacea* L. Photo: Ole J. Lønnve.

studied, but the knowledge of the more central-european nematines fauna is better than in the northern and arctic fauna. Within some groups, the species concept is still unclear (Prous *et al.* 2017, Liston *et al.* 2017, Prous *et al.* 2021). Nematinae show a "reversed" latitudinal gradient (Kouki *et al.* 1994): the number of species increases with increased latitude. This can be explained by the fact that many Nematinae use different *Salix* species as host plants, and the diversity of *Salix* is particularly high in alpine and arctic regions. Which *Salix* species different Nematinae species prefer is often unclear, but it is obvious that a number of species can utilise several different *Salix* species (Benson 1955, Schmidt 1997, Prous *et al.* 2017, Liston *et al.* 2017, Prous *et al.* 2021).

Sawflies are generally poorly known from Hardangervidda, but a number of species are recorded from a few localities within Hardangervidda National Park or from localities bordering Hardangervidda (Norwegian Biodiversity and Information Centre 2022).

Particularly gall-inducing *Euura* sawflies are very numerous in alpine and arctic environments in Fennoscandia (in older literature it includes the genera *Euura* Newman, 1837, *Phyllocolpa* Benson, 1960, and *Pontania* Costa, 1852). The gall-inducing *Euura* sawflies are all rather small and mostly dark insects. During field work at Finse in 2023, 13 species of gall-inducing *Euura* sawflies where recorded, some in great numbers (especially species within the *E. mucronate* species group).

Salix herbacea and *S. polaris* are two morphologically and ecologically similar species, both of which occur in snowbeds in the alpine and arctic parts of Fennoscandia. Several sawflies use these two *Salix*-species as host plants. Lacourt (1999) mentions 18 possible European sawflies species feeding on *S. herbacea* and three species on *S. polaris*. At Finse, particularly the gall-inducing *E. herbacaea* is very common on *S. herbacea*. The characteristic and relatively large red galls on its leaves can be seen in late summer and autumn.

Also, some non-gall-inducing *Euura* species (in older literature *Amauronematus* Konow, 1890) use *S. herbacea* as host plant. The species are exposed feeders, and their larvae are usually green and resemble Lepidoptera larvae (Zinovjev & Vikberg 1998, Viitasaari 2002). These are very poorly known from Finse, but several species are recorded from other places on or in adjacent areas to Hardangervidda. In 2023, two specimens of the snowbed specialist *E. abnormis* (Holmgren, 1883) (Figure 6) was recorded at Finse (Figure 7 a,b). One male was netted from *Salix lapponum* at the edge of a snowbed at Finse Alpine Research Centre, while one female was found crawling at a large snow patch south of lake Finsevatn. *E. abnormis* is an arctoalpine species that use *S. herbacea* as host plant (Lacourt 1999, Zinovjev & Vikberg 1998, Liston 2009). The usually brachypterous females only walk around on the ground or on the host plant. Sometimes she can be seen sitting on *S. herbacea* catkins. The males fly around, searching for females. The eggs are deposited as an egg-pocket, which the female inserts under the epidermis of a young leaflet in a developing bud (Zinovjev & Vikberg 1998). A few days after egg-laying, a distinct swelling can be seen on the upper surface of the leaf.

Some other interesting *Euura* species were found in association to snowbeds at Finse in 2023. Several specimens belonging to *E. variator*-group were recorded. According to Benson (1960), *E. variator* (Ruthe, 1859) is a circumpolar arctic species. In the Alps, reported hostplants are dwarf willow species, such as *S. herbacea* (Benson 1960, Laucourt 1999). One female of *E. nimbus* (Benson, 1960) was collected in association to large snowbeds near Kvannjolnut in the Finse area. The host plant is unknown, but according to Laucourt (2020) it utilizes some dwarf willow species (*Salix* spp.).

Several species of *Pristiphora* were registrated during field work in 2023. In general, the larvae of this genus are exposed feeders, and they overwinter in a cocoon, usually in the litter on the ground. Species within the *Pristiphora carinata* group can be very numerous in alpine and arctic environments. During field work in 2023, at least two very dark species within this group was found in association to snowbeds at Finse. Based on the key given by Benson (1958), they were identified to *P. breadalbanensis* (Cameron, 1882) and *P. lativentris* (Thomson, 1871*)*. According to Lacourt (1999), *P. lativentis* probably uses *S. herbaceae* as host plant. However, according to Liston *et al.* (2022), the identity of *P. breadalbanensis* needs further research to be confirmed, if characters mentioned by Benson (1958) to separate this species from some other species within the *P. carinata* group (*P. borea* (Konow, 1904) and *P. coactula* (Ruthe, 1859)) is reliable.

Within the *P. ruficornis* species group, *P. staudingeri* (Ruthe, 1859) is common at Finse, and was found in numbers during field work in 2023. According to Prous *et al.* (2017) *S. herbaceaea* and *S. phylicifolia* are used as hostplants. *S. phylicifolia* has a limited occurrence in the Finse-area, and *P. staudingeri* was mostly found at localities where *S. herbacea* was present (in addition to *S. lapponum* and *S. glauca*).

Further studies of this interesting group (Figure 8), revealing differences in ecology and host plants, could be rewarding.

Arthropod succession near a melting glacier. An interesting arthropod succession has been described in the foreland of the melting Hardangerjøkulen glacier (Bråten *et al.* 2012, Hågvar 2010, Hågvar 2023, Hågvar *et al.* 2009). The further, and perhaps faster, retreat of the glacier will continuously uncover new areas of pristine ground. This may favour certain species that thrive on pioneer ground: Firstly, cold-adapted species like the carabid beetle *Nebria nivalis* (Paykull, 1790) and the springtail *Agrenia bidenticulata* (T. Tullberg, 1877). Secondly, species that take favour of open ground, like the carabid *Bembidion hastii* C. R. Sahlberg, 1827 and the wolf spider *Pardosa palustris* (Linnaeus, 1758). Thirdly, species that graze on pioneer mosses, as the springtail *Bourletiella hortensis* (A. Fitch, 1863). However, if the glacier over time melts away completely, large areas will

FIGURE 7. The sawfly *Euura abnormis* (Holmgren, 1883) is a snowbed specialist, using *Salix herbacea* L. as host plant. The females usually have reduced wings, and are unable to fly, while the males have very distinctive penile valves, which protrude on the apical part of the abdomen. Upper (**a**): female, lower (**b**): male. Photo: Ole J. Lønnve.

FIGURE 8. Sawflies are both abundant and species-rich at northern latitudes. These specimens were sampled by sweep-netting on small *Salix* L. bushes on the Varanger peninsula in the northernmost part of Norway. Photo: Ole J. Lønnve.

change character and certain pioneer species may disappear. Studies in the Alps have shown that melting glaciers represent a threat to several cold-adapted beetles and microarthropods (e.g., Gobbi *et al*. 2007).

Results from "open top chamber" experiments at Finse with simulated environmental change. Open-top chambers (OTCs) are widely used to study global warming experimentally, and the method is assumed to have few undesired side effects (Hollister & Webber 2000). The chambers at Finse were placed in a nutrient poor *Dryas octopetala* heath at about 1500 m a.s.l. Mean air temperature 5 cm above ground level increased by ca. 1.5˚C and soil temperature by ca. 1.0˚C (Klanderud & Totland 2005, Sandvik & Eide 2009). Experimental plots in the *Dryas octopetala* heath were also used to study effects of fertilisation, both outside and inside the chambers

Elevated temperature gave increased herbivory by insects. In a *Dryas*-dominated heath, open-top chambers (Figure 9) were operated at two experimental sites: a "lower" one at 1450 m a.s.l. during nine years, and a "higher" one at 1550 m a.s.l. during twelve years. Feeding marks on leaves were recorded quantitatively and potential herbivore arthropods were recorded (Birkemoe *et al.* 2016). On the higher experimental site, artificial warming gave increased herbivory on two common plants: *Dryas octopetala* L. and *Bistorta vivipara* (L.) Delarbre. It was concluded that two species of Lepidoptera larvae were the actual herbivores: *Sympistis nigrita* Boisduval, 1840 on *D. octopetala*, and *Zygaena exulans* (Hohenwarth, 1792) on *B. vivipara*. On the lower experimental site, temperature increase gave higher herbivory only on *D. octopetala*. It was speculated whether late snow melting and higher temperatures in the lower site was negative for *Z.*

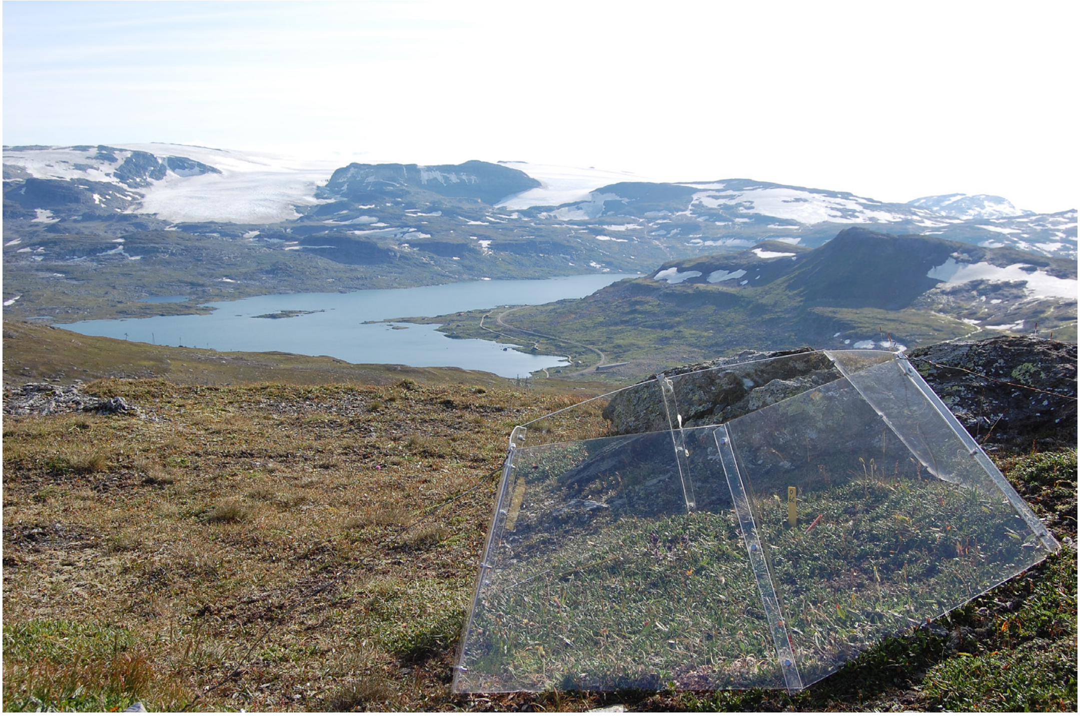

FIGURE 9. Open Top Chamber (OTC) in operation. Two arms of the Hardangerjøkulen glacier are seen in the background. Photo: Kari Klanderud.

exulans larvae (Figure 10).

The ecology of *Sympistis nigrita* has been closer studied at northeastern Greenland (Roslin *et al.* 2013). The larvae are monophagous on *D. octopetala* and was recorded as the most important herbivore on this plant species. The moth overwinters as egg and has a one-year life cycle. While young larvae feed on pistils and stamens within flowers, older larvae feed on leaves. Higher temperatures increase the abundance of *Dryas* flowers, favouring the small larvae (Welker *et al.* 1997; Birkemoe *et al.* 2016). Larva of the other species, *Z. exulans*, are polyphagous, feeding on among other *Salix herbacea* and *Bistoria vivipara* (Hågvar 1976a, Naumann *et al.* 1999). In a no-choice laboratory feeding experiment, Hasle (2013) found that *Z. exulans* larvae were even able to feed on *Dryas*. It could not be excluded that this species, and other generalist herbivores not identified, might be responsible for feeding marks on both plant species. The study concluded that plant-insect interactions may be complicated and difficult to predict as a result of a warmer climate (Birkemoe *et al.* 2016).

Reactions among soil arthropods to increased temperature and/or fertilisation. Norwegian mountains are subject to both increased temperature and atmospheric nitrogen deposition. In the nutrient poor *Dryas* heath, soil arthropods were studied after four years of artificial warming and/or fertilisation. Increased temperature alone had little effect on vegetation except for decreasing the abundance of some *Carex* and bryophyte species, and microarthropods were practically unaffected. However, nutrient addition with or without increased temperature, strongly altered the vegetation by favouring tall grasses and certain forbs (Klanderud 2008). This change in vegetation greatly affected both the abundance and the dominance hierarchy of the soil microarthropod community (Hågvar & Klanderud 2009). Interestingly, a strong increase in microarthropod density in fertilised plots was due to a rapid response in certain Collembola species with a short (one year) life cycle. Microarthropods with a longer life cycle, such

FIGURE 10. The larva of the moth *Zygaena exulans* (Hohenwarth, 1792) is easy to recognize. Photo: Ole J. Lønnve.

as oribatid mites and certain Collembola species, would need longer time to respond. Increased litter production from graminoids and forbs might have triggered the population increase in Collembola. Predatory Gamasina mites responded positively to the increased prey availability. The decline of *Dryas* plants in fertilised plots led to reduced populations of a ground-living, sucking Coccoidea species (Homoptera) which has *Dryas* as host plant.

In summary, we observed increased biomass of microarthropods, contrasting responses of closely related species, that species with short life cycle may rapidly take over dominance, and that predators responded to increased prey availability. Long-term effects of such multiple reactions may be difficult to foresee.

Although fertilisation was much stronger than could be expected under natural conditions, increased atmospheric deposition of nitrogen represents a long-term threat to nutrient poor habitats. Alpine regions in Norway have a tolerance limit for increased atmospheric deposition of nitrogen between 5 and 15 kg per hectare per year. These limits have already been crossed several places in south Norwegian mountains (Austnes *et al.* 2018). Like the actual *Dryas* heath, snowbeds are nitrogen poor sites and sensitive to atmospheric deposition (Woolgrove & Woodin 1996). Nutrient poor vegetation types may in general develop higher dominance of herbs and grasses (Tamm 1991).

International studies on floral responses to climate change in arctic-alpine environments. The Finse OTC experiments are part of a larger international cooperation on the possible long-term effects of climate change on plant communities. A review paper based on repeated plant surveys from 302 mountain summits across Europe documented increased floral diversity in many cases due to temperature increase. A continent-wide acceleration in this change was strikingly synchronized with accelerated global warming (Steinbauer *et al.* 2018).

A global assessment of experimental climate warming on tundra vegetation stressed that this vegetation type exhibits strong regional variation in response to increased temperatures. In vulnerable regions, cumulative effects may become much greater than observed untill the present (Elmendorf *et al.* 2012).

Another global review pointed to changed phenological patterns in flowering time of tundra plants. Certain species shifted phenology more than others. On average, plants at colder sites were more phenologically sensitive to increased temperatures, and late-flowering species more than early-flowering species (Prevey *et al.* 2019).

Discussion: Possible consequences of climate change for plant-arthropod relations, and options for long-term monitoring

Phenological mismatch and life cycles. The above-mentioned floristic observations and predictions from arctic and alpine environments indicate several potential effects on plant-arthropod relations. Any floral changes, both in species composition and phenology have potential to affect natural arthropod communities. It may for instance be a loss of host plant, or a phenological mismatch between arthropod and plant. The latter may affect vital functions as pollination and seed dispersal.

Life cycle patterns and reproduction success may be affected by climate change. If the snow-free season becomes longer, the beetle *C. collaris* could theoretically try to start a second and unsuccessful generation in the autumn. In that case, the species may go extinct in this area because it is the adult beetles that are adapted to survive the winter. The moth *Zygaena exulans* (Figure 11), which is a common species in the area, has

FIGURE 11. *Zygaena exulans* (Hohenwarth, 1792) resting in a flower of *Dryas octopetala* L. Photo: Erika Leslie.

S. herbacea as one of several possible host plants for larvae. However, this species has an ecology quite different from *C. collaris* (Hågvar 1976a). *Z. exulans* would probably tackle a longer snow-free season better since the larvae seem to be able to hibernate in any larval stage. Life cycle length is at least two years. Larvae of quite different sizes can be found together in spring, and they cannot be grouped into cohorts. The number of larval stages is unknown. Both field and laboratory studies indicate very slow growth.

Z. exulans larvae pupate close to the ground, often attaching the surrounding cocoon to a straw near the soil surface. In mid or late summer, hatching occurs rather synchronised in warm, sunny weather and is probably triggered by heating of the ground. Adults typically seek to *Hieracium* L., 1753 flowers for nectar. The swarming activity is vulnerable to bad weather. Heavy rain, which may come suddenly at Finse, can kill a high portion of the adult generation, resulting in low reproduction success in that year. However, the presence of larvae of different developmental stage is probably an assurance for the species survival since some of the remaining larvae will hatch the next summer. Negative effects of climate change could be increased rain showers in the swarming period and a possible mismatch between hatching time and flowering time of the *Hieracium* plant. The ability to hibernate in different larval stages indicates that the species would be able to survive under new climatic conditions.

Higher altitude limits for plants and arthropods: A gradual transformation of the whole ecosystem. Increased temperatures will induce a gradual rise of the tree line. If the tree line over time increases with about 200 m, the Finse area will become covered by birch forest. That would lead to a complete change in both vegetation types and the arthropod fauna. Many arthropod species, especially herbivores, live on birch trees close to the tree line (Hågvar 1972; 1976 b). Moreover, a fauna of ground arthropods will follow. Among them are certain species of ants (Hågvar 2005). These may affect other arthropods, both as predators and by tending and protecting plant-sucking aphids. As shown by Ottesen (1996) the different beetle species in the subalpine and alpine region have specific upper altitudinal limits today. Any increase in mean temperature will collectively rise these altitudinal limits, contributing to new arthropod communities in the Finse area. A general limitation for altitudinal "climbing" of species and vegetation types will, however, be the upper height of the actual terrain itself, as well as the more sparce soil cover at higher altitudes. Certain cryophilic species bound to high altitudes can be lost.

Possible effects of increased precipitation: Who takes favour of wetter conditions? In an extensive study in the Finse area, based on pitfall trapping in different habitats, Ottesen (1996) showed that many subalpine and alpine beetles were favoured by high moisture conditions. If precipitation gradually increases at Hardangervidda, this may favour more hydrophilic beetle communities, in combination with wetter vegetation types. However, if climate change in this area implies extreme variations, for instance with occasional drought, this could disfavour hydrophilic beetles.

Conclusions: Finse as a future reference area?

Long-term effects of climate change can only be documented by comparing data over decades. For instance, in studies of long-term effects of acid rain, previous data about water chemistry have been crucial to document both acidification and the following recovery of surface waters in Norway after artificial liming (Larssen 2005). Thanks to old data from museum collections and field studies, changes in the distribution of European carabid beetles have been documented (Brandmayr & Pizzolotto 2016). However, there is often a problem to disentangle effects of climate change from effects of human activity and land use. Therefore, effects of climate changes should preferably be studied in sites with minimum human influence. The high altitude area of Finse in southern Norway is such a site.

The melting Hardangerjøkulen glacier near Finse clearly demonstrates an ongoing climate change. During the last decades, various studies in this area have accumulated considerable

TABLE 2. Examples on possible monitoring programs on climate change effects on arthropods in the Fines area.

Arthropod group	Topic for monitoring	Basic publications	Remarks
Microarthropods: Collembola and Acari	Effect of climate change on colonization rate near melting glacier	Hågvar *et al.* 2009, Hågvar 2010, 2023.	Soil samples in 2001. Sites have GPS-coordinates, see the present publication
Macroarthropods: Coleoptera and Aranea	Effect of climate change on colonization rate near melting glacier	Bråten *et al.* 2012.	Pitfall traps in 2007–2008. Sites have GPS-coordinates, see the present publication
Macroarthropods: Coleoptera and Aranea	Long-term change in species composition and community structure in five different plant communities	Østbye *et al.* 1978, Hauge *et al.* 1978, Østbye & Hågvar 1996.	A three-year pitfall study during 1969–1971.
Chrysomela collaris L. (Coleoptera) and *Zygaena exulans* (Hohenwarth, 1792) (Lepidoptera)	Will their life cycle be influenced by climate change?	Hågvar 1975 ab, 1976a	
Arthropods on birch	Will they follow the birch to higher altitudes?	Hågvar 1976 b	This study is from the Sogndal area in the Sognefjord, but is relevant by describing altitudinal zonation of arthropods on birch
Formicidae	Will they expand to higher altitudes?	Hågvar 2005	This study is from the Sogndal area in the Sognefjord, but is relevant by describing altitudinal zonation of Formicidae
Coleoptera	Effect of climate change on altitudinal distribution and habitat choice	Ottesen 1996	The study also covers a larger area outside Finse
Hymenoptera Symphyta, Tenthredinidae.	Will the characteristic fauna of sawflies in snowbeds be affected by climate change?	This paper	
Microarthropods: Collembola and Acari	Effect of artificial warming in Open Top Chambers in the field	Hågvar & Klanderud 2009	Such studies could be repeated, using different techniques

documentation about the arthropod fauna and its dependence on various habitat types. These data, from specific sites and years, may serve as a basic reference for possible re-samplings later, in order to reveal long-term effects of climate change. One example is the three-year pitfall study during 1969–1971 of species composition and phenology of beetles and spiders in five different habitat types (Østbye *et al.* 1978, Hauge *et al.* 1978, Østbye & Hågvar 1996). Other examples are studies within the glacier foreland itself, where georeferenced localities (Table 1) were sampled within a succession gradient (for microarthropods by soil samples in 2001, and for surface active arthropods by pitfall traps in 2007–2008). The actual collection sites can be re-sampled at any time. Other questions could be how the beetle *Chrysomela collaris* and the moth

Zygaena exulans, with different life cycles, will respond to a longer snow-free period and higher mean temperatures. Will the latter manage best due to a more flexible life cycle (Hågvar 1976a)? Furthermore, will the rich fauna of sawflies (Hymenoptera, Symphyta) in today´s snowbeds, change if their red-listed habitat shrinks of changes character? Table 2 lists a number of possible topics for long-term monitoring of arthropods.

Finse may be the best site in Norway for monitoring effects of climate change on alpine arthropods. The fauna is rather well known through studies over several decades, the human influence on nature is minimal, the area has easy access by train, and there is a permanent and well-equipped on-site research station.

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