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Protocol for the literature review of effects on climate change on insects in Norway

Matthew Grainger, Kyrre Kausrud, Martin Malmstrøm, Anders Nielsen, Irja I. Ratikainen, Paul R. Berg, Anders Bryn, Kjetil Hindar, Johanna Järnegren, Lawrence R. Kirkendall, Erlend Nilsen, Brett K. Sandercock, Eva B. Thorstad and Gaute Velle

Scientific Opinion of the Panel on Biodiversity of the Norwegian Scientific Committee for Food and Environment

Short Abstract: (TBD)

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Protocol for the literature review of effects on climate change on insects in Norway

Preparation of the protocol

The Norwegian Scientific Committee for Food and Environment (Vitenskapskomiteen for mat og miljø, VKM) appointed a project group to draft the protocol. The project group consisted of four VKM members, one external expert and one VKM staff member. The Committee, by the Panel on Biodiversity, will assess and approved the final version.

Authors of the protocol

The authors have contributed to the opinion in a way that fulfils the authorship principles of VKM (VKM, 2023). The principles reflect the collaborative nature of the work, and the authors have contributed as members of the project group and/or the VKM Panel on Biodiversity.

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Competence of VKM experts

Persons working for VKM, either as appointed members of the Committee or as external experts, do this by virtue of their scientific expertise, not as representatives for their employers or third-party interests. The Civil Services Act instructions on legal competence apply for all work prepared by VKM.

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1 Introduction

1.1 Purpose of the protocol

The purpose of this protocol is to describe the approach for a literature-based knowledge synthesis on the effects of climate change on insects in Norway. The protocol defines the scope of the assessment, translates the Terms of Reference into specific review questions, and describes the methods used to identify, screen, assess, and synthesise relevant evidence.

The assessment will cover both long-term effects of anthropogenic climate change and short-term effects of extreme weather and climatic events. It will address direct and indirect effects on insects, including effects on distribution, abundance, genetic diversity, phenology, community composition, species interactions, and ecosystem functions and services. Differences among taxonomic groups, species, regions, ecosystem types, and life stages will be considered where knowledge is available. The assessment also provides the basis for identifying knowledge gaps, assessing uncertainty, and interpreting available evidence in relation to climate projections for Norway, with emphasis on the present, 2050, and 2100.

The protocol is intended to ensure a transparent and structured assessment process, including an opportunity for the public and stakeholders to give feedback in an open consultation.

1.2 Insects

Insects belong to the class *Insecta* within the subphylum *Hexapoda*. They are characterised by a body divided into three main regions — head, thorax, and abdomen — three pairs of legs, one pair of antennae, and external mouthparts. Most adult insects also have one or two pairs of wings, although wings have been reduced or lost in several groups. Insects occur in nearly all terrestrial and freshwater ecosystems and include highly diverse groups such as beetles, flies, moths and butterflies, bees, wasps, ants, true bugs, dragonflies, mayflies, stoneflies, and caddisflies.

Insects are the most species-rich animal group in Norway. Approximately 20 000 insect species have been recorded from Norway, and several thousand additional species are likely to occur but remain undocumented. The known diversity is unevenly distributed among taxonomic groups. For example, Norway has more than 3700 recorded beetle species, 2322 butterfly and moth species, and more than 5000 known species of wasps.[1]

A substantial number of Norwegian insect species are included on the Norwegian Red List for Species 2021. Out of 11014 Norwegian insects that fulfilled the assessment criteria for the

[1] https://artsdatabanken.no/arter/takson/89

2021 Red List by NBIC (the Norwegian Biodiversity Information Center; Artsdatabanken), 1978 were assessed as vulnerable, threatened or extinct. See table 1 below.

Table 1: The number of assessed species in the 2021 NBIC red list (Artsdatabanken 2021) for each insect group. i.e. N= sum of groups RE, CR, EN, VU, NT, LC, not counting NA, NE or DD. The number and percentage of each group that is assessed and found not LC, that means Vulnerable, Threatened or Extinct (VTE) is given as VTE and % VTE. Another 278 species are critically data deficient (category DD), whereas 3141 observed species were not assessed due to being not native to Norway, having poorly resolved taxonomy, large knowledge gaps or other issues (categories NA and NE).

English name	Norwegian name	Order	N	VTE	% VTE
Beetles	Biller	Coleoptera	3417	782	23%
Mayflies	Døgnfluer	Ephemeroptera	48	6	12%
Cockroaches	Kakerlakker	Blattodea	1	0	0%
Snakeflies	Kamelhalsfluer	Raphidioptera	4	1	25%
Alderflies and Dobsonflies	Mudderfluer	Megaloptera	4	0	0%
Scorpionflies	Nebbfluer	Mecoptera	6	0	0%
True Bugs	Nebbmunner	Hemiptera	841	138	16%
Lacewings, Antlions	Nettvinger	Neuroptera	53	4	8%
Dragonflies and Damselflies	Øyenstikkere	Odonata	45	6	13%
Grasshoppers, Crickets, Katydids	Rettvinger	Orthoptera	25	5	20%
Earwigs	Saksedyr	Dermaptera	4	1	25%
Butterflies and Moths	Sommerfugler	Lepidoptera	2190	476	22%
Stoneflies	Steinfluer	Plecoptera	35	2	6%
True Flies	Tovinger	Diptera	2653	285	11%
Caddisflies	Vårfluer	Trichoptera	196	21	11%
Wasps, Bees and Ants	Vepser	Hymenoptera	1492	251	17%
Sum (mean%)			11014	1978	13%

The largest numbers of vulnerable, threatened or extinct species occur among beetles, true bugs, butterflies and moths, true flies, and wasps. These numbers reflect both genuine extinction risk and variation in knowledge among taxonomic groups. For some insect groups, limited taxonomic and ecological knowledge means that several species are placed in the category Data Deficient.

Hexapoda also includes three groups that are not classified as insects: springtails (Collembola), proturans (Protura), and diplurans (Diplura). These non-insect hexapods have six legs but differ from insects in several morphological traits. In this assessment, the main focus is on insects *sensu stricto*. However, evidence on non-insect hexapods may be considered where it is directly relevant to climate-change effects on insects in Norwegian ecosystems, particularly in habitats where these groups may be ecologically important, such as soil and litter.

1.3 Climate change

Climate is essentially the statistical description of weather over time; its mean, median, extreme values, trends and variance on different spatial and temporal scales. We all experience different weather on any given day and location, but the probability of that particular weather that we experience is described by the local climate.

Climate has continuously changed throughout the history of Earth, globally as well as regionally. Some dramatic changes reflect global processes such as orbital forcings, like the repeated glacial/interglacial cycles over millions of years, last seen as the planet emerged from the last ice age into the Holocene interglacial about 11700 years ago. Other changes are shifting regional patterns, like the Medieval Warm Period, named because it was characterized by warm and productive conditions in western and northern Europe, without being part of a synchronized warming of the entire planet (Wang et al. 2023). Many aspects of climate history, such as the much-discussed cold period in the northern hemisphere known as the little ice age that followed the Medieval Warm Period, are a complex mix of shifting global, regional and seasonal patterns that are inconsistently framed in different contexts (Collett et al. 2025, Guo et al. 2024), necessitating care and precision in terminology.

While climate fluctuations are driven by a complex set of interlocking processes (see 1.3.1), increased release of greenhouse gases (e.g. CO_2, CH_4 and N_2O) from a variety of human activities during the last 200 years or so, has strengthened the energy absorption of the atmosphere, re-emitting more energy as heat to Earth's surface. Human-induced changes in atmospheric CO_2 concentrations reached a record annual average of >427 ppm in 2025. This increase is around 50% over its maxima during the 11 previous interglacials over 800.000 years, when it has tended to peak between 260 and 300ppm, like it probably also has over the last four million years (PAGES 2016, Marks-Peterson et al. 2026).

Due to these abrupt atmospheric changes, global mean surface temperature is now also higher than it has been for at least 800.000 years, and it is increasing over ten times faster than it did when emerging from the last ice age (Kaufman & McKay 2022; Lee et al. 2025; Meinshausen et al. 2020; Friedrich et al. 2016; PAGES 2016). In Norway, current growth season temperatures most likely exceed those during the Medieval Warm Period (Björklund et al. 2023). Due to the so-called Arctic amplification and elevation-dependent warming, mainly caused by sea-ice and terrestrial ice-snow reduction respectively, high latitude and alpine regions like Norway experience a more rapid warming compared to the global average (Pepin et al. 2015).

After the last glacial maximum (coldest point in the ice age), the Earth warmed rapidly by natural standards by about 4.5 –7.5 °C over a period of at least 7.000 years (Osman et al. 2021, Kaufman et al. 2020), the exact amount varying between latitudes and estimates. This enforced ecosystem changes and gave rise to new ones in their stead, forcing migration, evolution and extinction on global scales.

Thus, when we discuss the ecological effects of climate change, we are trying to envision change roughly on the scale of between the ice age and our time, arriving ten to fifty times as fast. The rapid onset of change on this magnitude makes time scale important: the 2040s are going to be very different from the 2070s, which will be very different than the 2100s, and climate change does not stop there but goes beyond (Kaufman & McKay. 2022). To say that this makes prediction challenging is an understatement!

Climate change affects all aspects of climate, that is, both means, extremes and variances. As global mean temperature increases, Northern Europe in general and Scandinavia in particular, is expected to warm considerably faster than global average (due to polar amplification) and more in winter than in summer. At the same time, climate forecasting predicts increased rainfall, longer growing seasons, less snow cover, greater variability and, paradoxically, probably more summer droughts as well as more frequent lightning and stronger floods, as exemplified by extreme weather events like "Hans" in 2023. However, it is important to keep the different types of extreme weather differentiated and attributed to time period, as for instance spring floods are expected to first vary more dramatically and then decline as less snow means potentially decreased meltwater flow, and that the effects vary with altitude and latitude (Dyrrdal et al. 2025, see also Bakke et al. 2024).

1.3.1 Drivers of climate change

Climate varies due to a mix of solar, orbital, geological and biological "drivers" and the interactions and feedback loops between these.

The fundamental drivers are natural processes over timescales from billions of years to daily cycles, such as variations in incoming solar radiation, the atmospheric gas composition, the earth's albedo[2], volcanic eruptions that inject greenhouse gases, all the photosynthesizing organisms taking CO_2 out of the atmosphere and supplying it with O_2, as well as sunlight-reflecting aerosols into the atmosphere, and long-term orbital cycles (the most known being known as Milankovitch cycles) that alter how solar energy is distributed across Earth. Internal variability within the climate system—especially ocean–atmosphere patterns like El Niño–Southern Oscillation (ENSO) and the North Atlantic Oscillation (NAO)—also causes short-term fluctuations, as well as the interactions between climate and biological/biophysical processes such as albedo changes, evapotranspiration patterns, carbon storage from plants locked in permafrost and wetlands, sediment or other geological formations etc. The processes are too many and too complex to be described in a short introduction.

[2] Albedo is a measure of the proportion of sunlight that a surface reflects away. Fresh snow can have an albedo of up to 0.85, meaning that it reflects 85% of the sunlight that hits it. On the other end of the scale, open ocean can have an albedo lower than 0.1, meaning only 10% of sunlight is reflected, and 90% of the sunlight energy absorbed, heating the earth's surface.

However, over the last century human activities have changed the atmospheric gas composition: burning of fossil fuels, draining of wetlands and deforestation has increased the atmospheric CO_2 concentration, industrial processes and agriculture has added other greenhouse gasses (GHGs) such as methane and nitrous oxide, and land-use changes alter Earth's albedo and carbon storage. Aerosols can temporarily cool the climate by reflecting sunlight, partially offsetting warming but also disrupting rainfall patterns. Because of the large ocean volume and high heat-capacity of water, about 90% of the excess heat energy retained by GHGs are stored in the oceans, affecting currents, vertical structure, evaporation, ocean chemistry and interactions with the atmosphere. All the human-induced changes interact with the natural processes both as negative (regulatory) and positive (destabilizing) feedback loops.

1.3.2 Direct effects of climate change

First, most directly, the concentrations of GHGs in themselves have biochemical effects. As current biota has evolved under lower concentrations, recent worrisome findings suggest that human **blood chemistry will be outside of accepted healthy ranges even in outdoor air** around 2085 if the CO_2 concentrations keep rising (Larcombe & Bierwirth 2026), and we are probably not unusual among mammals and many other animals in this respect. Also, as atmospheric CO_2 is in a dynamic equilibrium with carbonic acid in water, introducing more **CO_2 lowers aquatic pH**, negatively affecting several major groups of marine life as well as the oceanic carbon cycle itself. Although this report does not concern marine life, we still note that perturbations in oceanic carbon cycle over evolutionary time scales have been associated with periods of biodiversity loss also on land (Trudgill et al. 2025). Lastly, the **CO_2 fertilisation of plants** seem to, up to a point, increase plant growth but at the cost of nutrient densities and other physiological alterations, the interplay of which seem to have implications for plant-eating animals, especially plant-eating insects (AbuELELa et al 2025, Bede & Blande 2025). In addition, the CO_2 fertilization is now probably counteracted by increased vapour pressure deficit (Yuan et al. 2019), potentially leading to decreased plant growth.

Secondly, the direct effects of extreme weather, including prolonged events like drought, unseasonal frost, heat waves and floods may exceed the **physiological tolerance levels** of species not adapted to those conditions. As insects utilize a wide range of physiological and behavioural adaptations to create or use local microclimates to insulate themselves from extreme events as well as normal seasonal and diurnal fluctuations, physiological tolerances observed in laboratory settings must be interpreted in the light of the insect's mitigation strategies such as the availability of shelter and other microhabitat in the wild. Furthermore, insects may even accumulate damage at sub-lethal temperatures, and prolonged periods of such sub-lethal temperatures may result in cumulative thermal injury that impairs performance and reduces fitness even in the absence of acute lethal events (Jørgensen et al. 2021, Arnold et al. 2025).

The long term mean shifts may have more direct effects on ectotherm insects than on mammalian groups, as they integrate the number of **degree days through development** and activity over a longer time even when they buffer against short extreme events. So, while not necessarily outside physiological tolerances, temperatures interacting with humidity and day length may determine development time, activity and voltinism, and hence reproductive success, population persistence and eventually phenology and competitive relationships.

More subtly but no less importantly, the pattern shifts are often very important to small, animals whose lives are greatly affected by ambient temperature, wind and humidity, both as extreme values and short-term (diurnal) variability (Stoks et al. 2017). During 2001–2020, night temperature increased at a rate 2.7 times the day rate, considerably reducing the **diurnal temperature range** (Wang et al. 2023), which interacts with insect metabolism (accumulation of degree days), activity patterns, phenology and ultimately survival, ecological interactions and distributions (Chan and Shen 2025, Chen et al. 2015, Vangansbeke et al. 2015).

1.3.3 Indirect effects of climate change

The indirect effects of climate change on insects are more complex and harder to predict on longer time scales. However, they may be governing much of the expected change in insect communities. We may divide them into:

Antagonistic effects, where climate effect is mediated through antagonisms, including predation or competition. If one species can better handle a change in disturbance regime, extreme events or just better utilize a change in degree days, it may become a stronger competitor for a shared resource or exert a larger predation pressure on a species that is otherwise little directly affected by climate. Alternatively, if a species distribution is limited by the presence of antagonists such as predators or competitors, it can experience release into a new range because of negative climate effects on the antagonist. Likewise, a climate effect that is unproblematic in itself for a population may allow an antagonist to expand its range and into areas formerly functioning as refugia for the focal species.

Temporal effects, where the climate effect is mediated through seasonality or the ability to match the seasonality of a key resource/avoid an antagonist. Essentially a version of the **match-mismatch** framework (Stenseth and Mysterud 2002, Hegland et al. 2010) where for instance two species may be perfectly capable of dealing with direct climate effects, but where a climate- induced lack of synchrony is detrimental (or beneficial) for at least one of them. Often reproductive success is affected by how well the phenology of the prey overlaps with key periods of predator demand or pollinator activity with plant flowering. On a larger time scale, we can also consider a time effect when a suitable “climate envelope” for the species keeps existing nearby, but it cannot **migrate fast enough to stay within it**. Or, if it can, it is dependent on a key resource that cannot itself migrate fast enough to keep up with its climate zones as they keep moving. To assess the latter effects, it is important to consider not just how fast single species can migrate compared to its climate zone but how long the succession process takes before the habitat is ready to receive migration of said species.

Scarcity effects, where the climate effect is mediated through a limiting resource becoming less abundant, like habitat, a food resource or a key mutualist etc. This includes changing **disturbance regimes such as more frequent forest fires and droughts** destroying habitat-building species. The most well-known effects may be ones that are limiting, for instance we will not observe insects inhabiting old dead trees in a landscape without old dead trees of a suitable species, a parasitoid outside the range of a suitable host, or obligate mutualist pollinators outside the range of its plant etc.

Context and cascades: We note that these categories overlap and are not mutually exclusive. Any single species is likely to experience several direct and/or indirect effects of climate change at once, and it is the **net effect** on the species that determine the outcome. Including non-climate effects, as pollution from pesticides, organic compounds and heavy metals may add to the physiological stress of pathogens or temperatures, and habitat loss and fragmentation by human activity may not allow free migration to follow climate zones – particularly relevant in the context of communities migrating at the speed of its slowest necessary member. While other human impacts are not the subject of this report, we must assume human-impacted landscapes on at least the current level interacting with the effects of further climate change. To avoid an infinite regress or an overwhelming amount of ecological detail, we approach assemblages and associations statistically, through interpolation from historical data and models (see section 3 Conceptual approach).

While often mentioned in media, we suspect that ocean level rise will be of minimal ecological importance, as even the most dramatic scenarios predict <80cm rise in mean sea level along the Norwegian coast until 2100 (Simpson et al. 2026). While this may threaten some coastal infrastructure and some coastal habitats, Norwegian topography means the affected areas will be limited compared to the tidal cycle and storm waves that the impacted species assemblages already are adapted to, so that the species should have time to migrate the short distances required to keep track with the rising mean sea water level.

1.3.4 Effects on ecosystem functions and services

We will treat ecosystem functions and services together in context of each other for better readability and saving space. A broad and ecologically fundamental group as insects can influence a huge range of ecosystem functions and services, but some aspects to include would be:

Biodiversity in other groups: Whereas the species composition in most areas will change over time, the net effects of climate on diversity at different spatial scales is far from trivial. Insect diversity may be important for the biodiversity in other groups. More diverse ecosystems are both more resistant to emergent diseases and have more genetic resources. Contributing factors include **specialist pollinators** and **as food for non-insect predators**.

Nutrient transport: Insects may consume food one place and defecate or become food sources for animals somewhere else and thereby contribute to **nutrient circulation** even between ecosystems. Insects can also move nutrients vertically in the soil as part of nest building, and distribute nutrients from plants and from nutrient hotspots like carcases and dung. Other insects can have large defoliating outbreaks or attack crops as **pests** when climate conditions and other factors let an herbivorous species escape predation.

<u>Vector capacity:</u> Insects vector **microorganisms** with many different functions, from pathogens causing human and animal disease to fungi and nematodes that infect trees and shape forest dynamics. Usually disease vectoring is considered a “negative service”, but it may also contribute to biodiversity or population control.

<u>Population control:</u> Some insects predate or parasitize other species that otherwise would have detrimental effects on other parts of the ecosystem, as disease vectors on wildlife, domestic animals or humans, or as pests on agriculture or forestry. A species that escapes predation may also out-compete populations for a shared limiting resource, thus reducing biodiversity. Thus, a negative effect on another species may be **providing population contro**l, an ecosystem function as well as service.

<u>Ecological management:</u> Some insects have unique complex strategies for **managing their own habitat and resources**, such as the anthill-building forest ants, and European red forest ants actively protecting conifer seedlings from pine weevils (*Hylobius abietis*) by harassing them (Maňák et al. 2013).

<u>Network complexity:</u> Complex networks such as diverse ecosystems with many interacting species and populations contributing complementary ecosystem functions are often considered more resilient and stable, or faster at recovering from perturbations, although this discussion is unresolved and highly dependent on what definition of robustness or resilience is used (Landi et al. 2018, Stouffer and Bascompte 2010, Tylianakis et al. 2010). Research on general effects of ecological network complexity on ecosystem services has likewise not reached consensus but shows promise (Casali et al 2025, Barnes et al. 2018).

For more on the conceptual and analytical framework see below and section 3.

1.4 Scope and delimitations to the assessment

This assessment is a literature-based knowledge synthesis of the effects of climate change on insects in Norway. The primary focus is on identifying, evaluating, and synthesising existing scientific evidence regarding how climate change, including climatic extremes, affect insect species, populations, communities, and the ecosystem functions and services they provide.

The assessment covers both the immediate and the more cumulative, longer-term, effects of anthropogenic climate change on insects. Furthermore, the assessment will cover both these immediate and the cumulative effects in both the near future (until mid-century) and the longer term (end of the century or beyond).

Both direct effects of weather and climate conditions on the survival, reproduction and life histories of the insects themselves as well as indirect effects on insects from how weather and climate change ecological interactions, habitat change, resource availability, and other environmental drivers will be considered. Thus, all known aspects of climate change, not just increased mean temperatures, but also changed frequencies and magnitudes of heatwaves, droughts, flooding, frost events and fire regimes etc., as well as overall bioclimatic parameters such as altered snow conditions, growing season length, phenology etc. are within scope.

The assessment focuses primarily on native insect species occurring in Norway. However, evidence relating to non-native species, expanding species ("doorknocker species") (e.g. VKM 2022), and species expected to colonise Norway under future climatic conditions may be included where relevant for understanding future ecological impacts. Evidence from Norway will be prioritised, but studies from climatically, ecologically, or biogeographically comparable regions may also be included when Norwegian evidence is limited.

The assessment will consider evidence from a range of study types, including field observations, monitoring programmes, experiments, ecological modelling studies, species distribution models, and previous evidence syntheses. Where available, evidence will be interpreted in relation to climate projections relevant to Norway, with particular emphasis on current conditions, 2050, and 2100.

Limitations

This assessment is not intended to provide an exhaustive species-by-species vulnerability assessment for all Norwegian insects (about 15000 insect species currently having been recorded out of an estimated total diversity of around 23000 species in Norway). The availability of evidence varies substantially among taxonomic groups, habitats, geographic regions, and impact pathways, and conclusions will therefore reflect the distribution of available knowledge rather than the full diversity of Norwegian insects.

The assessment does not generate new empirical data and will not conduct original monitoring, experimentation, or population modelling beyond the synthesis of existing evidence. While species distribution modelling may be used to illustrate potential future changes for selected species or species groups, such models should be interpreted as projections under specified assumptions rather than predictions of future outcomes.

Climate change is only one of several drivers affecting insect populations. In practice, climate effects frequently interact with land-use change, habitat fragmentation, pollution, invasive species, forestry, agriculture, hydrological alteration, and other anthropogenic pressures. It is often difficult to attribute observed changes exclusively to climate change, and the assessment will therefore emphasise interactions among drivers where evidence is available.

The assessment will not attempt a formal quantitative risk assessment of extinction risk, population viability, or ecosystem service loss for individual species. Similarly, because the evidence base is expected to be highly heterogeneous, no formal meta-analysis or quantitative evidence synthesis is planned across the full assessment. Instead, evidence must be synthesised narratively and interpreted in the context of its strengths, limitations, and associated uncertainties.

Finally, projections of future impacts are inherently uncertain because they depend on future greenhouse-gas emissions, climate-system responses, ecological interactions, evolutionary adaptation, dispersal processes, and management actions. All conclusions regarding future impacts should therefore be interpreted as conditional on current scientific understanding and the assumptions underlying the available evidence.

1.4.1 Conceptual framework

The assessment is structured around a conceptual framework that links climate change and other anthropogenic drivers to their effects on insects, species interactions, and the ecosystem functions and services they support. The framework provides the overarching structure for synthesising evidence and organising findings throughout the final assessment.

Climate change can influence insects directly through changes in temperature, precipitation, and extreme climatic events, affecting physiological processes such as survival, development, and reproduction. These physiological responses can subsequently influence individual-level characteristics such as phenology, behaviour, and dispersal, which may then scale up to affect population abundance, distribution, and genetic diversity. Changes at the population level can alter community composition, species interactions, and trophic relationships, ultimately affecting ecosystem functions and services such as pollination, decomposition, and food-web dynamics.

At the same time, climate change does not act in isolation. Other anthropogenic drivers, including land-use change, habitat loss, pesticide use, and invasive species, may influence insects directly or interact with climatic drivers to amplify, mitigate, or modify ecological responses. The assessment therefore considers both direct and indirect pathways, recognising that multiple drivers frequently act simultaneously.

The conceptual framework shown in Figure 1 will be used to organise evidence throughout the report and to identify linkages between climatic drivers, biological responses, ecological interactions, and ecosystem-level consequences.

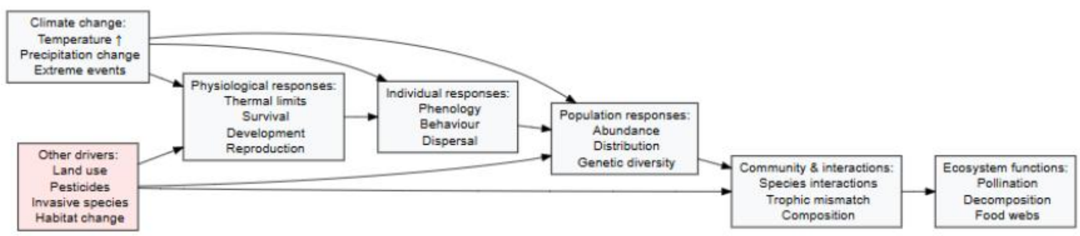

Figure 1: Conceptual framework illustrating the pathways through which climate change and other anthropogenic drivers influence insects, from physiological responses at the individual level through population and community changes to impacts on ecosystem functions and services. Arrows indicate potential direct and indirect pathways, recognising that effects may occur across multiple levels of biological organisation simultaneously.

1.5 Terms of reference (ToR)

The purpose of the assignment is to provide an overview of the current state of knowledge regarding the climate change vulnerability of native insect species in Norway, as well as the effects of an increasingly extreme climate and how these effects are expected to develop in the future. The work shall be based on a literature review and follow the approach described in the IUCN guidelines (IUCN 2016; Foden et al. 2019).

VKM is requested to prepare a knowledge synthesis. Based on the literature, VKM is asked to review and summarize how climatic factors and interactions with other drivers are expected to directly and indirectly affect native insects. The assessment should distinguish between long term and short-term effects and include examples of impacts on individual species.

We ask that the factors formulated as the following Terms of reference (ToR) are included.

1.5.1 ToR 1 – Effects of long-term anthropogenic climate change on insects

1.1 Species distributions, abundance (population size), and genetic diversity

1.2 Phenology

1.3 Community composition and species interactions

1.5.2 ToR 2- Effects of short-term, unpredictable extreme climate events on insects

2.1 Heatwaves and extreme temperatures

2.2 Seasonal and context-dependent effects of extreme climate events (e.g. frost, snowfall,

rain-on-snow events) in interaction with other anthropogenic drivers

2.3 Drought

2.4 Extreme precipitation and flooding

2.5 Fire

1.5.3 ToR 3 – Additional Assessments and Analyses

a) To the extent that knowledge is available, differences in impacts among taxonomic groups, species, geographic regions, or ecosystem types should be highlighted. Furthermore, the synthesis should address how extreme temperatures not only directly affect survival, but also how climatic extremes may influence critical life-history stages (e.g. Parratt et al. 2021). Interactions between climate change and other drivers should be assessed.

b) Where possible, an overarching assessment should be made of the potential implications of the anticipated effects for ecosystem functions and services provided by insects. This should include a brief discussion of impacts on threatened species, nationally prioritized responsibility species, wild pollinating insects, and habitat types that are important for insects (see Sydenham et al. 2023).

c) The synthesis should include a compilation of risk-reducing measures that can enhance resilience and robustness to climate change and improve living conditions for the taxonomic group (cf. IUCN 2016; Foden et al. 2019).

d) A review of knowledge gaps and uncertainties relevant to Norway should be provided.

e) The assessment shall be based on climate projections from the Norwegian Climate Service Center, drawing on IPCC emission scenarios. Results should be interpreted in relation to these projections, with main emphasis on SSP3-7.0 in line with the precautionary principle, while also including RCP2.6. The temporal scope shall include the present, 2050, and 2100. Where information is available on threshold values or tipping points at which climate change may trigger changes in insects or their living conditions, these should be described.

1.6 From terms of reference to sub-questions

To operationalise the Terms of Reference, the project group translated each ToR into a set of specific review questions. These questions will guide the literature search, screening, synthesis, and interpretation of evidence across taxonomic groups, geographic regions, ecosystem types, climate scenarios, and time horizons. These are listen in Table 2.

Table 2: Interpretation of terms of reference into sub-questions to be targeted in this assessment and additional questions that needs to be addressed.

Terms of reference - operationalized	Specific questions based on ToR that need to be addressed
1.1 Effects of long-term anthropogenic climate change on the spatial distribution, abundance, and genetic diversity of insects in Norway	**Distribution:** How is the spatial distribution of native insects in Norway expected to change under long-term climate change? How is the spatial distribution of doorknocker species of insects in Norway expected to change under long-term climate change? Which species or species groups are projected to expand, contract, shift northwards, shift upwards in elevation, or lose climatically suitable habitat? To what extent are observed or projected distributional changes attributable to climate change rather than land-use change, habitat fragmentation, pollution, invasive species, or other drivers?

	Abundance: What evidence exists that long-term climate change affects insect abundance, biomass, or population trends in Norway or in climatically comparable regions? Are population responses expected to be negative, positive, or context-dependent across taxonomic groups, habitats, and regions? **Genetic diversity:** What is known about the effects of climate change on the genetic diversity, population structure, adaptive potential, and gene flow of insects relevant to Norway? Are small, isolated, alpine, Arctic, coastal, or habitat-specialist populations particularly vulnerable to loss of genetic diversity or reduced adaptive capacity?
1.2 Effects of long-term anthropogenic climate change on insect phenology	How has climate change affected the timing of insect emergence, flight periods, reproduction, diapause, migration, and voltinism? Are phenological changes expected to differ among taxonomic groups, life stages, habitats, or regions in Norway? To what extent may climate-driven phenological shifts cause mismatches between insects and host plants, prey, predators, parasitoids, competitors, pollination partners, or other interacting species? Are there examples of earlier emergence, extended activity periods, additional generations per year, or disrupted diapause in insects relevant to Norway?
1.3 Effects of long-term anthropogenic climate change on community composition and species interactions	How is long-term climate change expected to alter insect community composition, including species richness, beta diversity, turnover, dominance structure, and functional composition? Which species groups are expected to increase or decrease in relative importance under projected climate change? How may climate change alter interspecific interactions, including competition, predation, parasitism, herbivory, host–parasitoid dynamics, mutualisms, and pollination networks? How may climate change affect intraspecific processes, such as density dependence, dispersal, mating success, local adaptation, and population connectivity?

	Are there indications that novel species assemblages or disrupted interaction networks may occur in Norwegian ecosystems?
2.1 Short-term effects of heatwaves and extreme temperatures on insects	What are the direct effects of heatwaves and extreme high temperatures on insect survival, behaviour, physiology, reproduction, development, and activity? Which life-stages are most sensitive to extreme heat (eggs, larvae, pupae, adults, overwintering stages, or reproductive phases)? How do heatwaves affect insects indirectly through host plants, prey availability, predators, parasitoids, pathogens, soil moisture, or habitat quality? Are species adapted to cold, alpine, Arctic, boreal, or humid habitats especially vulnerable to extreme heat?
2.2 Short-term effects of frost, snowfall, snow-cover change, rain-on-snow events, ice encasement, and freeze–thaw events	What are the effects of extreme frost, reduced snow insulation, heavy snowfall, rain-on-snow events, ice encasement, and freeze–thaw cycles on insect survival and population dynamics? How do winter and spring extremes affect overwintering success, diapause, emergence timing, and reproductive success? How do ice events on frozen ground affect terrestrial insects in soils, litter, vegetation, and under snow? How does ice encasement, anchor ice, or altered ice conditions affect aquatic insects in rivers, streams, lakes, ponds, and wetlands? What is known about freezing tolerance and cold tolerance among insect taxa relevant to Norway, and how does tolerance differ among species groups and life stages?
2.3 Short-term effects of drought on insects	What are the direct effects of drought on insect survival, desiccation risk, development, reproduction, behaviour, and dispersal? How does drought affect insects indirectly through changes in host plants, nectar availability, vegetation quality, soil moisture, dead wood, aquatic habitats, prey, predators, parasitoids, or pathogens? Are aquatic insects, wetland insects, soil-dwelling insects, pollinators, or herbivorous insects particularly sensitive to drought? How do drought effects vary among regions, ecosystem types, and life stages?

2.4 Short-term effects of extreme precipitation and flooding on insects	What are the effects of extreme rainfall, high-flow events, and flooding on insect mortality, drift, displacement, emergence, reproduction, and habitat availability? How do flooding events affect terrestrial, riparian, wetland, and aquatic insects differently? Are effects mainly negative, or can flooding also create or maintain important habitats for some insect groups? How do flood timing, duration, frequency, magnitude, and seasonality influence insect responses?
2.5 Short-term effects of fire on insects	What are the immediate and short-term effects of wildfire or climate-driven fire events on insect mortality, habitat loss, habitat creation, colonisation, and community composition? Which insect groups are negatively affected by fire, and which groups may benefit (e.g. from burned wood, open habitats, or early successional conditions)? How do fire intensity, frequency, season, spatial extent, and post-fire management influence insect responses? How relevant are fire effects on insects in Norway under projected climate change?
3a Variation in responses among taxa, species, regions, ecosystems, life stages, and interacting drivers	Which insect taxa, functional groups, species traits, and life-history strategies are associated with high vulnerability or resilience to climate change? Do climate-change responses differ among major Norwegian regions, including southern, western, eastern, northern, alpine, boreal, Arctic, coastal, freshwater, wetland, forest, semi-natural, and agricultural landscapes? How do climate extremes affect critical life-history stages beyond immediate survival, including reproduction, diapause, host use, dispersal, larval development, and overwintering? How do climate change and climatic extremes interact with other drivers (e.g., (land-use change, habitat fragmentation, pollution, pesticides, eutrophication, hydropower regulation, forestry, agriculture, urbanisation, invasive species, and pathogens)?
3.b Implications for ecosystem functions, ecosystem services,	How may climate-driven changes in insect populations affect ecosystem functions, such as pollination, herbivory, decomposition,

threatened species, responsibility species, wild pollinators, and important insect habitats	nutrient cycling, food-web support, predation, parasitism, pest regulation, and disease vectoring? How may climate change affect ecosystem services and disservices mediated by insects, such as crop pollination, forestry, biological control, pest outbreaks, and vector-borne disease risk? How may climate change affect threatened insect species in Norway? How may climate change affect Norwegian responsibility species, including species where Norway holds a large share of the European or global population? How may climate change affect wild pollinating insects and pollination networks in Norway? How may climate change affect habitat types and areas that are especially important for insects?
3.c Risk-reducing measures	Which measures can reduce climate-related risks to insects in Norway by increasing habitat quality, connectivity, population resilience, microclimatic buffering, and adaptive capacity? Which measures are relevant across ecosystems, and which are specific to forests, wetlands, freshwater systems, agricultural landscapes, semi-natural grasslands, alpine areas, coastal areas, or urban landscapes? How can conservation, restoration, land-use planning, monitoring, and management reduce the combined effects of climate change and other anthropogenic pressures? What is the strength of evidence for proposed risk-reducing measures?
3.d Knowledge gaps and uncertainties	What are the main knowledge gaps in the literature on climate-change effects on insects relevant to Norway? Which taxa, regions, ecosystems, climate drivers, life stages, and response variables are less well or poorly studied? What are the main sources of uncertainty, including climate projections, species occurrence data, taxonomic bias, monitoring bias, short time series, limited experimental evidence, model uncertainty, and difficulties in separating climate effects from other drivers? Which knowledge gaps are most important for management decisions and future monitoring?
3.e	How are insect distributions, abundance, phenology, genetic diversity, community composition, and ecosystem functions expected to change

Climate scenarios, time horizons, thresholds, and tipping points	under relevant climate scenarios, with emphasis on the present, 2050, and 2100? How do projected impacts differ between low-emission and high-emission scenarios, including RCP2.6 and SSP3-7.0? What is known about climatic thresholds, ecological thresholds, or tipping points beyond which negative effects on insects or their habitats may increase sharply? Which species, habitats, regions, or ecosystem functions are most likely to approach such thresholds in Norway?

2 Methods

2.1 Literature search

A structured literature search will be conducted to identify peer-reviewed studies and relevant grey literature addressing the effects of climate change on insects relevant to Norway. The search strategy will be developed to capture both long-term anthropogenic climate change and short-term extreme climate events, including interactions with other environmental drivers.

The literature search will be informed by the Terms of Reference and the conceptual framework described in Chapter 1, particularly the distinction between direct and indirect climate effects, ecological interactions, and ecosystem-level consequences. The search strategy will follow principles commonly used in systematic evidence synthesis, including transparency, reproducibility, and structured documentation of search components.

Searches will be conducted in Web of Science Core Collection, lens.org and Scopus. Additional targeted searches will be conducted using Google Scholar and citation chasing (using the citation chaser tool, Haddaway et al. 2022) of key review papers to identify potentially relevant studies not captured through database searches. Searches will primarily focus on literature published in English, although Nordic studies identified through reference lists or expert knowledge may also be considered where relevant.

The searches will use combinations of terms relating to:

1. the target organism group (e.g. insects, pollinators, etc.),
2. climate-related exposures (e.g. climate change, warming, drought, flooding, frost, wildfire),
3. ecological responses and impacts (e.g. abundance, phenology, species interactions, distribution shifts, resilience, ecosystem function).

Where necessary, searches will be adapted to database-specific syntax while retaining the same conceptual structure.

2.1.1 Components of the research question (PECO)

The search strategy will be structured using a modified PECO framework (Population, Exposure, Comparator, Outcome). Given the broad and largely observational nature of the evidence base, explicit comparators and standardised outcomes are expected to be absent or highly variable across studies.

2.1.1.1 Population

The population component will target insects and related groups potentially relevant to Norwegian ecosystems.

Example search string:

TS=(insect* OR hexapod* OR lepidopter* OR coleopter* OR dipter* OR hymenopter* OR hemipter* OR orthopter* OR odonat* OR ephemeropter* OR plecopter* OR trichopter*)

2.1.1.2 Exposure

The exposure component will target both long-term climatic changes and short-term extreme climatic events, including associated ecological disturbances.

TS=("climate change" OR climatic change* OR global warming OR temperature change* OR warming OR heatwave* OR extreme temperature* OR drought* OR flood* OR flooding OR extreme precipitation OR rainfall OR snow* OR frost* OR "rain on snow" OR fire* OR wildfire* OR phenolog* OR season* OR hydrolog* OR disturbance* OR vegetation change* OR habitat change*)

2.1.1.3 Comparators

No explicit comparator term will be included in the search strategy. Many ecological climate-change studies are observational, correlative, or modelling-based and do not use formal experimental comparators. Relevant studies may therefore include comparisons across spatial gradients, temporal trends, experimental warming treatments, or before–after designs.

2.1.1.4 Outcomes

Outcome terms will not be explicitly included in the search strategy because ecological responses to climate change are highly diverse and inconsistently described across the literature. Restricting searches using predefined outcome terminology may exclude relevant studies. Outcomes considered during screening will include changes in:

- species distribution,
- abundance,
- biomass,
- phenology,
- physiology,
- survival,
- species interactions,
- community composition,

- ecosystem functions,
- resilience and vulnerability.

2.1.2 Testing the search

The search strategy will be iteratively tested and refined to ensure retrieval of a set of known relevant studies identified *a priori* by the project group. Benchmark articles will include major reviews and empirical studies addressing insect responses to climate change, biodiversity trends, ecological interactions, and climate vulnerability.

The final search strategy will aim to retrieve the key benchmark papers in Table 3.

Table 3. Benchmark publications used to test the search strategy

Benchmark article	Indexed in WoS?	In search results?	Reason for absence
Projected decline in European bumblebee populations in the twenty-first century | Nature	Yes	Yes	
Scientists' warning on climate change and insects - Harvey - 2023 - Ecological Monographs - Wiley Online Library	Yes	Yes	
Insects and recent climate change | PNAS	Yes	Yes	
Agriculture and climate change are reshaping insect biodiversity worldwide | Nature	Yes	Yes	
The contribution of insects to global forest deadwood decomposition | Nature	Yes	Yes	
The recovery of European freshwater biodiversity has come to a halt	Yes	Yes	
Multiple stressors on biotic interactions: how climate change and alien species interact to affect pollination - Schweiger -	Yes	No	Non-natives are not explicitly named in the search but adding this term increases the search results 3-fold.

2010 - Biological Reviews - Wiley Online Library			
Assessing species vulnerability to climate change, and implementing practical solutions	Yes	Yes	
Patterns of beta diversity in Europe: the role of climate, land cover and distance across scales	Yes	No	Beta-diversity is not in the search terms but adding it increases the results because many macro-ecological papers do not focus on climate change
Compounded effects of climate change and habitat alteration shift patterns of butterfly diversity	Yes	Yes	
The fingerprints of global climate change on insect populations	Yes	Yes	
Phylogenetic constraints in key functional traits behind species' climate niches: patterns of desiccation and cold resistance across 95 drosophila species	Yes	No	Cold tolerance is missing from the search
Tougeron, K., Brodeur, J., Le Lann, C. and van Baaren, J. (2020), How climate change affects the seasonal ecology of insect parasitoids. Ecol Entomol, 45: 167-181.	Yes	Yes	
Midges below zero: A review of hibernal emergence of Chironomidae in temperate regions	No	No	Not indexed on WoS (but it is indexed on lens.org and GoogleScholar)

Search sensitivity will be prioritised over specificity due to the broad scope of the assessment and the substantial variability in terminology used within ecological climate-change research.

2.1.3 Inclusion and exclusion criteria

Studies will be included if they:

- address insects or related arthropods,
- examine observed or projected effects of climate change or climatic extremes,
- address ecological, physiological, population-level, community-level, or ecosystem-level responses,
- are relevant to boreal, temperate, alpine, arctic, or otherwise ecologically comparable systems relevant to Norway,
- include empirical, modelling, experimental, or synthesis-based evidence.

Studies will be excluded if they:

- focus exclusively on marine systems,
- address agricultural production without ecological relevance,
- lack a climate-related exposure,
- are purely methodological without ecological application,
- consist solely of opinion pieces without supporting evidence.

Given the limited Norway-specific literature for some topics, studies from climatically or ecologically comparable regions may also be considered where relevant.

2.2 Screening

All records identified through the literature searches will be imported into Rayyan (Ouzzani et al. 2016) for screening and management. Duplicate records will be identified and removed prior to screening.

Screening will be conducted in two stages:

1. Title and abstract screening.
2. Full-text screening.

Eligibility will be assessed against the predefined inclusion and exclusion criteria described in Section 2.1.3.

Prior to formal screening, reviewers will undertake a calibration exercise using a sample of records to ensure a consistent interpretation of the eligibility criteria. Disagreements will be discussed and the screening guidance refined where necessary. To assess screening consistency, a subset of records will be independently screened by two reviewers during both title-and-abstract and full-text screening. Agreement rates and reasons for disagreement will be reviewed periodically throughout the screening process. Where disagreements cannot be resolved through discussion, decisions will be made by consensus within the project group.

The project will use the artificial intelligence (AI) prioritisation functionality available within Rayyan to support screening efficiency. AI-assisted screening will be used solely to prioritise the order in which records are presented to reviewers and to identify potentially relevant studies earlier in the screening process. AI will not be used to make final inclusion or exclusion decisions. All eligibility decisions will be made by human reviewers based on the predefined inclusion and exclusion criteria.

The purpose of AI-assisted prioritisation is to improve screening efficiency while maintaining transparency and human oversight. The project group will monitor the performance of the prioritisation process and periodically evaluate whether newly screened records continue to contribute substantial new evidence. Screening may be concluded once the project group determines that additional screening is unlikely to materially alter the conclusions of the assessment. The rationale for any such decision will be documented transparently in the final report.

A flow diagram describing the number of records identified, screened, excluded, and included will be reported in the final assessment.

2.3 Data extraction

Information from all included studies will be extracted using a standardised data-extraction form developed for this assessment (Appendix 1). The purpose of data extraction is to ensure consistent recording of information relevant to the Terms of Reference, facilitate transparent synthesis of evidence, identify knowledge gaps, and support assessment of uncertainties and confidence in the evidence.

Data extraction will focus on study characteristics, climate-related drivers, ecological responses, and the relevance of findings to Norwegian ecosystems. Information recorded will include bibliographic details, geographic location, ecosystem type, taxonomic group, study design, climate variables considered, response variables measured, and the main findings reported by the authors. Where available, information on projected future impacts, climate scenarios, ecological mechanisms, interactions with other environmental drivers, and proposed adaptation or management measures will also be extracted.

Particular attention will be given to recording the type of climate effect investigated (e.g. long-term warming, drought, flooding, altered snow conditions, heatwaves, or fire), the ecological level of response (e.g. physiology, phenology, population dynamics, community composition, species interactions, or ecosystem functions), and whether effects are reported as positive, negative, mixed, or uncertain. Studies addressing ecosystem services and ecosystem functions provided by insects, including pollination, decomposition, nutrient cycling, biological control, and food-web support, will be identified to support the broader ecosystem-level assessment.

Because the assessment encompasses a wide range of evidence types, including observational studies, experiments, monitoring programmes, ecological modelling studies, and previous evidence syntheses, the extracted information will primarily be used for narrative synthesis. Quantitative results will be recorded where available, but the primary objective is to identify patterns, consistencies, and sources of variation across taxonomic groups, ecosystems, geographic regions, and climate drivers.

2.3.1 Assessing bias

A formal risk-of-bias tool will not be applied because the evidence base is expected to consist primarily of heterogeneous ecological observational studies, experiments, monitoring data, and modelling approaches for which no universally accepted bias-assessment framework currently exists.

Instead, findings will be interpreted in light of key sources of uncertainty and limitations within the available evidence base (see Appendix 2), including:

- geographical biases in study location and coverage;
- taxonomic biases in the groups of insects studied;
- uneven evidence availability across regions, taxa, or impact pathways;
- short temporal baselines that may limit detection of long-term trends;
- inconsistencies in monitoring methods and study designs;
- uncertainty associated with future climate projections;
- limitations in causal inference from correlational studies.

Particular attention will be given to whether findings are supported across multiple independent studies, regions, taxa, or methodological approaches. Evidence gaps and areas where conclusions are based on limited or geographically restricted evidence will be explicitly highlighted.

2.3.2 Confidence in evidence

Confidence in the evidence will be assessed narratively rather than through formal evidence grading systems developed for medical research. Ecological evidence relating to climate change is often heterogeneous, context-dependent, and based on multiple complementary lines of evidence rather than standardised experimental designs.

Confidence assessments will therefore consider:

- consistency of findings across studies,
- agreement between observational and experimental evidence,

- ecological plausibility,
- strength of mechanistic understanding,
- relevance to Norwegian conditions,
- and the degree of uncertainty associated with future projections.

Where evidence is limited, inconsistent, or strongly context-dependent, this will be explicitly highlighted in the assessment.

3 Conceptual framework for the final assessment report

3.1 Rapid climate change and shifting ecosystem dynamics

Changes in ecosystems and their functions are driven by extremely abrupt climate changes of previously unobserved magnitudes. This assessment is based on the understanding that the changes to Norwegian insect fauna due to climate change is likely to be driven by larger-scale changes in ecosystem extent and function. A baseline expectation may be that shifts in insect populations are likely to follow the expected large-scale shifts in their habitats. (See fig 2 below.)

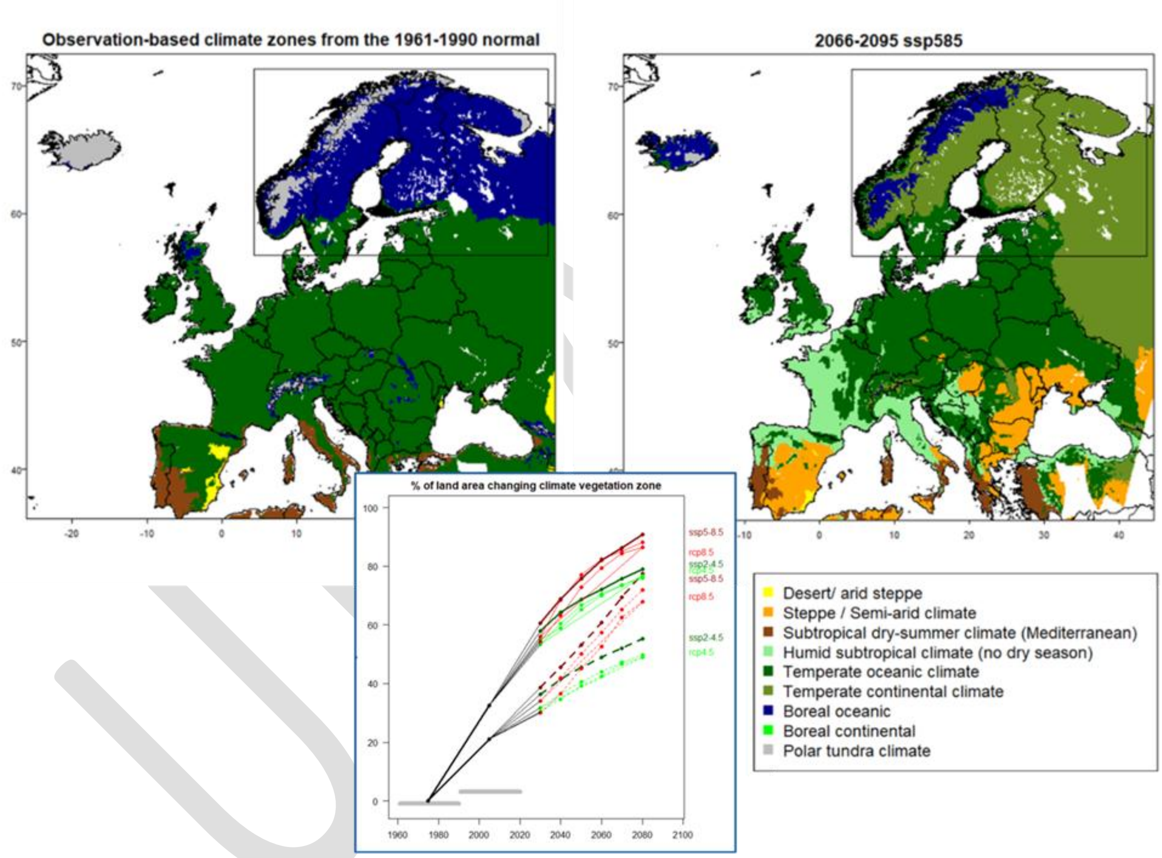

Figure 2: Illustrating the race between climate change, ecosystem succession and species migration. Upper left figure shows the distribution of Köppen-Trewartha vegetation climate zones in Europe from the meteorological Normal period 1961-1990 (defined in the Norwegian Nature Index as climatic normal period), the upper right figure shows the climate zone distribution expected 2066-2095 under ssp585 which for that period has overlapping confidence intervals with ssp370. The lower middle graph shows the percentage of land area data that changes to a new climate zone over the period. The cutout rectangles in the map figures highlights the Nordic region, where changes are more rapid than for Europe as a whole. We see that for Europe as a whole, about 50% of the land area will be in a different vegetation ecological zone by the latter part of the century than it was when it started, and for the Nordic region this is more on the order of 80%. Made from data provided by Holtanová et al. (2025).

However, we cannot assume that the insect fauna simply moves with the climate zone. One important reason for this is that ecological communities do not migrate as a whole, but as individuals and populations, many of which are dependent on other species already existing there. For example, insects inhabiting old oaks cannot establish in freshly established brush but must wait for forest succession to allow maturation of oaks to the appropriate stage, a process that takes at best decades, often centuries. (See Figure 3). Similar arguments will hold for insect species linked to other old growth forests.

While insects as a group is found across climate zones in every major biome, many insects are highly specialized towards temperature regimes for development or depend on hosts, prey or habitat-building species which are often much slower to migrate and may have narrower temperature ranges or other needs. I.e. Even when the new climate will allow forest to grow on the Hardanger plateau, mature forests will take centuries to appear there (as was demonstrated by the slow succession dynamics after the last ice age), and suitable habitat for insects that prefer old forest will be scarce.

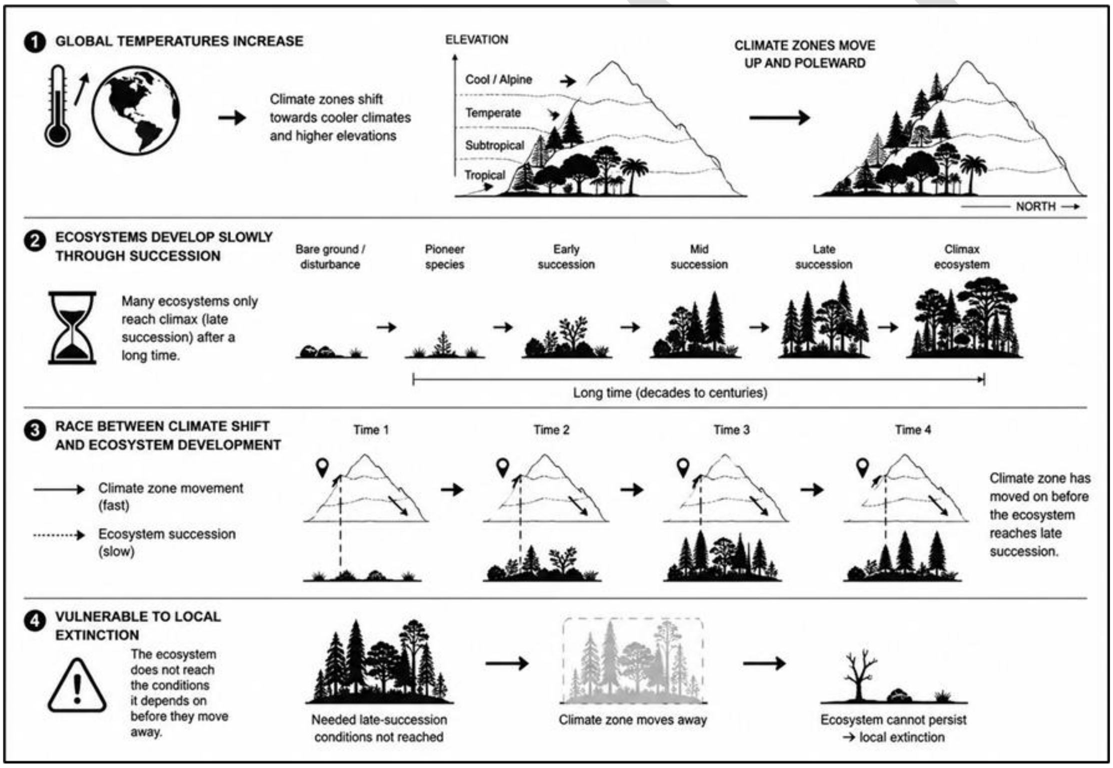

Figure 3: Illustrating the race between climate change, ecosystem succession and species migration. As climate zones shift generally polewards and to higher elevations as global mean temperature increases, species often must migrate to persist. However, they cannot simply follow their climate zone but are at each step limited by whether the new habitat having reached a succession stage where they can establish. Thus, not only species with poor spreading ability but also late-succession species are at a considerable disadvantage when climate shifts rapidly, and at a heightened risk of extinction and extirpation.

Thus, we suspect a landscape-level shift towards more disturbance –prone, shorter-lived ecological communities that can migrate fast and establish early, as they are better able to persist and be favoured by the rapidly changing unstable conditions created by a rapidly warming global climate. For instance, predictive species distribution models must be reality checked against the poorest migrants and succession time required for the slowest habitat building members of a community. This informs our approaches for impacts on the potentially cascading interactions between insects and ecosystem services and functions.

3.2 ToR aswered for each main ecosystem

Following the general introduction on how climate change is expected to have an over-arching effect on climatic zones and ecosystems in Norway, up until year 2100, VKM aim to answer the Terms of reference, as detailed as possible for each of the main ecosystems that are included in the mandate.

If possible (depending on the outcome of the literature search), VKM will use example species, or species groups that are typical for these ecosystems, as models for each system. Suggested species/groups for each of the main ecosystems are:

- Mountain - Apollo-butterflies
- Wetland - Dragonflies
- Forest - Bark beetles and birch moths
- Freshwater - Non-biting midges + EPT (mayflies and stoneflies) or caddisflies
- Open lowlands and cultural landscapes - Bumblebees
- Urban areas - Mosquitoes (and biting midges)
- Polar regions – Blowflies

3.3 Effects on important ecosystem functions across scales

Insects are an evolutionary very old and highly diverse group that is found in every major ecosystem on the planet. While individually small, their great abundance means that they as a group make up a biomass of about the same magnitude as all of humanity and our domestic animals together (Rosenberg et al. 2023). It is therefore not surprising that they perform central ecosystem functions and are parts of major energy and nutrient cycles (see figure 4 and table 3). It is in fact hard to imagine any major ecosystem persisting in a recognizable form if insects were to disappear. Thus, the recent declines in arthropod diversity, abundance and biomass are grounds for considerable concern and likely central to the global biodiversity crisis (Wildermuth et al. 2025).

Synthesizing knowledge on its magnitude and how the insect decline interacts with, and the degree to which it is caused by, climate change is therefore central to our assessment of how ecosystem functions performed by insects are affected under climate change. Reasons are under investigation, but potential factors include climate stress (Müller et al. 2023), phenology disruption/mismatch (Fang et al. 2026), habitat destruction and other land use changes (Méndez-Rojas et al. 2021), pervasive pollution of pesticides or other persistent compounds like microplastics (Shen et al. 2023), or lower performance under elevated CO_2 levels (Xie et al. 2015). Most likely it is a combination of these factors (Blütghen et al. 2022; Gebremariam 2024; Vidal et al. 2026).

To get a systematic overview of the myriads of ecosystem functions carried out by insects, we have divided them into three categories in six broad classes (Figure 4 and Table 3):

Energy and nutrient fluxes

Insects process a substantial part of the global terrestrial energy and nutrient cycles

Downwards in the food web: Insects take up immense amounts of nutrients and energy from a wide range of organism groups through herbivory, predation, parasitism and detritivory. This biomass is then distributed across the ecosystem.

Upwards in the food web: Insects are themselves food to a myriad of other species, from microbes and fungi to other arthropods and larger vertebrates like bats, birds and rodents.

Ecosystem structures

Insects shape the biochemical and physical structure of their habitat and surrounding ecosystems

Nutrient cycling: Insects contribute to habitat structure by breaking down dead organisms of every size, from plant litter to dead animals, shaping space and freeing nutrients otherwise locked in dead organisms.

Habitat engineering: Insects shape habitats both by moving nutrients around, such as between land, freshwater and soil, but also physically by burrowing, mound building, killing trees or otherwise shaping plant community structure.

Life cycle interactions

Insects are part of the life history strategies of many other organisms, shaping community interactions, population structures and the resulting biodiversity

Pollination and spread: Maybe the most well-known ecosystem function of insects is being essential to the reproduction, spread and genetic structure of many plants for whom they carry pollen. Less is known about their roles in spreading fungi and other microbes.

Disease vectoring: Among the microorganisms spread by insects are bacteria, viruses, fungi and parasites that are spread to new hosts. From the forest-killing blue-stain fungi vectored by bark beetles to the malaria parasites and myriad of arboviruses that affect vertebrates.

In sum this means that insects shape the population dynamics and competitive relationships, genetic diversity, spread and resilience of ecosystems.

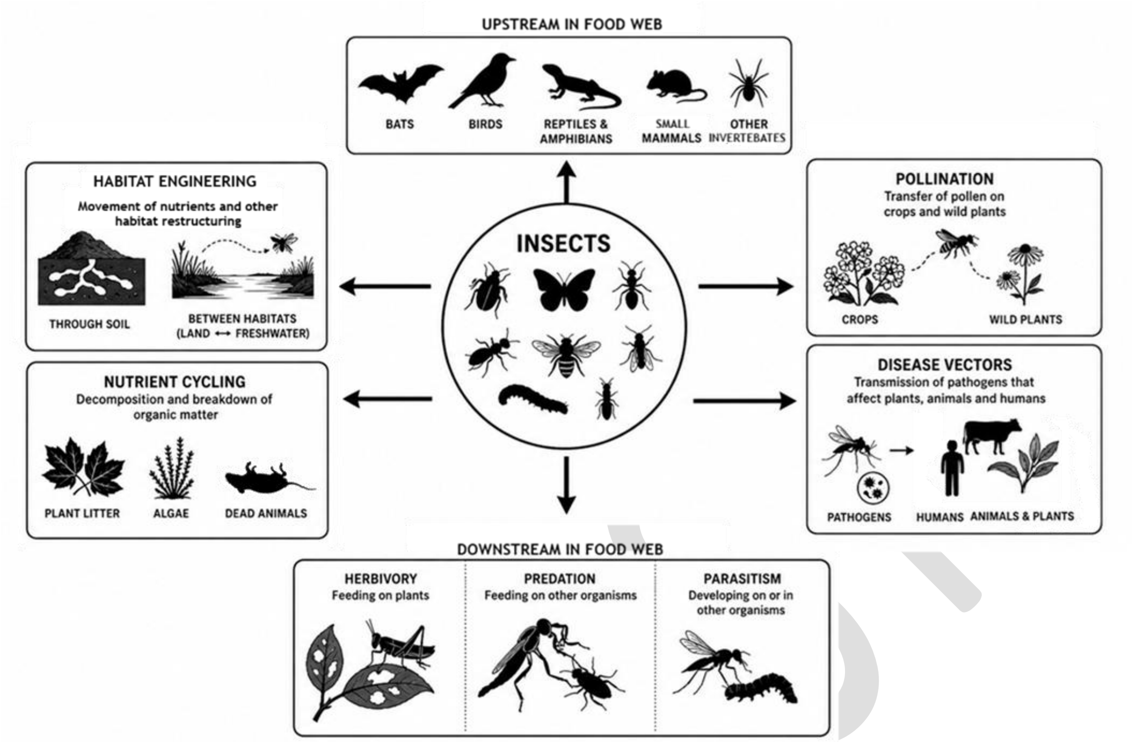

Figure 4: Schematic overview of central ecosystem functions in which insects play a major role. The ecosystem functions are fundamental to the ecosystem services. See also Table 4 and Figure 3.

3.4 Overarching effects on ecosystem services

The main overarching ecosystem service provided by insects could be seen as maintaining ecosystem functions, as they are fundamental to all human needs (see 3.3. above). Specific types of ecosystem services performed by insects are even more difficult to sort into any sort of natural taxonomy, but we identify some broad classes (figure 5, table 4) that give an overview of main types of services, and the fact that these sometimes come with a negative sign with regards to human wishes. *An important aspect of our work will therefore be to assess whether climate change affects the balance between positive and negative services*.

Negative contexts: Pest outbreaks, such as tree-killing bark beetles and crop pests, parasitism by insects on humans or animals and plants valued by humans, and insects vectoring parasites and pathogens that in turn infect humans, animals or plants are a major source of mortality, suffering, ecological disruption and economic loss.

Positive contexts: On the flip side, the impact of some insects is often seen as fundamental to biological control of other potential pests and diseases (insect-mediated or otherwise) which would otherwise have a negative impact. At the same time, the impact of insects in ecosystem maintenance through nutrient cycling and habitat creation is fundamental to human bioeconomies from animal pasture to forestry as well as maintaining other species that in turn perform positive ecosystem services like being targets for hunting, fishing, recreation or providing pest control.

Direct services: Pollination of crop plants, provisioning and being part of valued cultural activities are important ecosystem services even though they may look peripheral to the fundamental services of supporting biodiversity and ecosystem functioning.

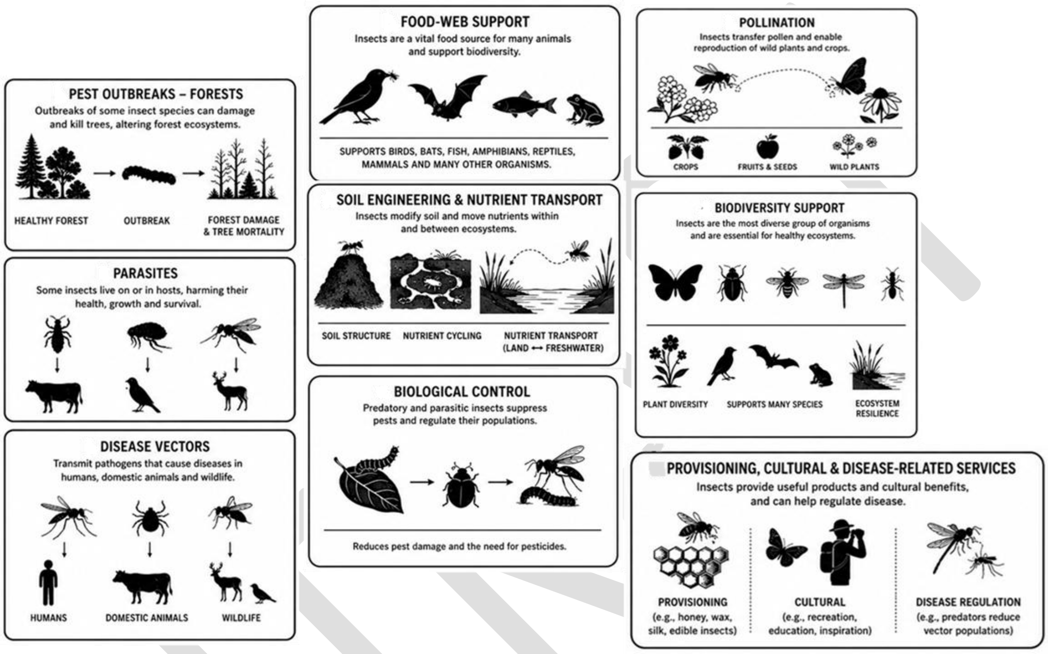

Figure 5: Schematic overview of ecosystem services in which insects play a major role, both of positive and negative value from a human perspective.

Table 4: Major classes of ecosystem functions and services (with examples of positive and negative values to humans) sketching out some main impact types of insects. See also figures 3, 4 and 5.

Ecosystem function	Description	Ecosystem services (+/-)
Foodweb upstream	Insects provide major food sources for many organism groups, both vertebrates and other invertebrates as well as microorganisms	+ Biodiversity maintenance + Food for ecologically and commercially valuable wildlife + Provisioning from honey and other products
Foodweb downstream	Insect herbivores, predators and parasites use a host of plants, fungi, other invertebrates and even vertebrates as food, prey and hosts	+ Population control - Pest outbreaks
Transport of pollen	Insects spread pollen, contributing to the reproduction of wild plants and crops	+ Wild plant reproduction + Crop reproduction - Weed and invasive reproduction
Transport of organisms	Insects transport microorganisms that may be fee-living but also vector diseases by viruses, bacteria, parasites and fungi	- Diseases in crops, livestock, wildlife, wild plants and humans - Population control and biodiversity maintenance
Cycling nutrients	Insects eat litter, detritus and carcasses, as well as living plant and animal matter and microorganisms, making nutrients available for other parts of the food web	+ Removal of dead matter + Nutrient cycling - Breaking down structures
Cycling habitats	Insects shape habitats through digging, tunnelling and transport of matter and nutrients between and within habitats	+ Diversyifying habitats + Making nutrients available in more areas - Breaking down habitats and removing nutrients

4 Uncertainties

The conclusions to be drawn in the final report will be associated with uncertainties related to different types of information used. We will address uncertainty related to particular datatypes, described below, and summarize uncertainty related to our conclusions.

4.1 Uncertainties related to climate projections

Climate models predict future climate conditions depending on greenhouse gas emission scenarios and are in themselves associated with uncertainties, increasing the longer into the future they are asked to predict. Four fundamentally distinct sources of uncertainty exists: (1) Emission trajectory (how much greenhouse gases do we actually end up emitting), (2) Concentration trajectory (as our emissions interact with biogeochemical processes, what concentrations do we end up with in the atmosphere), (3) Global climate forcing trajectory (how sensitive is the climate system, when all feedbacks are taken into account, to the atmospheric changes), and, finally, (4) Downscaling from the global forcing to regional and local effects, for our purpose centred on Scandinavia and exactly how our climate changes under specific global conditions. We will discuss the choice of climate scenario(s) and how the different uncertainties pertain to the timeframes we are assessing.

4.2 Uncertainties related to direct impact on insect species

Limited knowledge exists on climate tolerance of most insect species. Different aspects of climate conditions affect different insects in contrasting ways, but for most species none or only limited information is available on how they will react to changes in temperatures, precipitation patterns, air humidity or extreme events.

4.3 Uncertainties related to the ability of insect species to find favorable climate conditions through migration

Insects vary in their ability to move through the landscape, and migration and spreading patterns for most insects are not known. It is therefore uncertainties related to whether particular species will be able to change their distribution to favourable climate conditions at higher latitudes or elevations.

4.4 Uncertainties related to how insect species assemblages shift with changes in habitat and other biotic interactions

Insect species have habitat requirements that themselves might be affected by climate change in subtle ways. Food plants and prey or plants providing nectar and pollen for pollinators might change their distribution or go extinct because of altered climate conditions. Many insects have nesting habitats in dead wood or hollow oaks, landscape elements that will use centuries to establish in new areas, as climate change force the species out of their current range. Uncertainties will be associated with how such species and habitat interactions insects participate in will be affected by climate change. When taking interactions with a whole complex ecosystem into account, we must look for historical examples and theory grounded in empirical evidence. To make general robust assessments we must simultaneously assess how wrong we are likely to be.

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Appendix 1. Data extraction table

Variable	**Description / Notes**
Study ID	Unique identifier assigned during screening
Citation	Full reference
Document type	Journal article, report, book chapter, thesis, review, evidence synthesis, modelling study, etc.
Country/Region	Study location
Norwegian relevance	Norway / Fennoscandia / Arctic / Boreal / Temperate Europe / Other
Ecosystem	Forest, freshwater, wetland, alpine, coastal, agricultural, urban, Arctic, multiple
Taxonomic group	Order (e.g. Coleoptera, Lepidoptera, Diptera, Hymenoptera)
Species	Species name where available
Functional group	Pollinator, herbivore, predator, parasitoid, decomposer, aquatic insect, pest, vector, etc.
Native status	Native, non-native, expanding ("doorknocker"), unclear
Study design	Monitoring, observational, experimental, laboratory, field experiment, modelling, review
Climate driver	Long-term warming, precipitation change, drought, flooding, heatwave, frost, snow-cover change, fire, multiple
Climate variable	Temperature, precipitation, snow depth, humidity, growing season length, degree-days, etc.
Climate scenario	Observed climate change, SSP, RCP, climate projection used
Time horizon	Present, near future (~2050), late century (~2100), historical trend

Variable	**Description / Notes**
Direct or indirect effect	Direct physiological effect, indirect ecological effect, both
Response variable	Distribution, abundance, biomass, survival, reproduction, phenology, genetic diversity, community composition, ecosystem function, etc.
Direction of effect	Positive, negative, mixed, no clear effect
Magnitude reported	Quantitative estimate if available
Mechanism proposed	Brief description of hypothesised mechanism
Life stage affected	Egg, larva, pupa, adult, overwintering stage, multiple
Other drivers considered	Land-use change, forestry, agriculture, pollution, invasive species, etc.
Ecosystem function/service	Pollination, decomposition, pest regulation, food-web support, nutrient cycling, etc.
Management implications	Any adaptation or mitigation measures suggested
Key findings	Brief summary (1–3 sentences)
Key uncertainties identified by authors	As reported by study authors
Extractor comments	Notes from reviewer

Appendix 2. Assessing bias

Domain	**Assessment**	**Notes**
Geographic relevance	High / Medium / Low	How relevant is the study system to Norwegian conditions?
Taxonomic relevance	High / Medium / Low	Focal species/taxa likely to represent Norwegian insects?
Study design strength	High / Medium / Low	Experimental > long-term monitoring > short-term observational > expert opinion
Temporal coverage	High / Medium / Low	Long enough to detect climate effects?
Climate attribution	High / Medium / Low	Ability to separate climate effects from other drivers
Data quality	High / Medium / Low	Adequate sampling design and reporting?
Projection uncertainty	High / Medium / Low	For modelling studies only
Consistency with wider evidence	High / Medium / Low	Do findings align with broader literature?
Applicability to Norway	High / Medium / Low	Directly transferable to Norwegian ecosystems?
Major limitations	Free text	Main caveats identified by reviewer