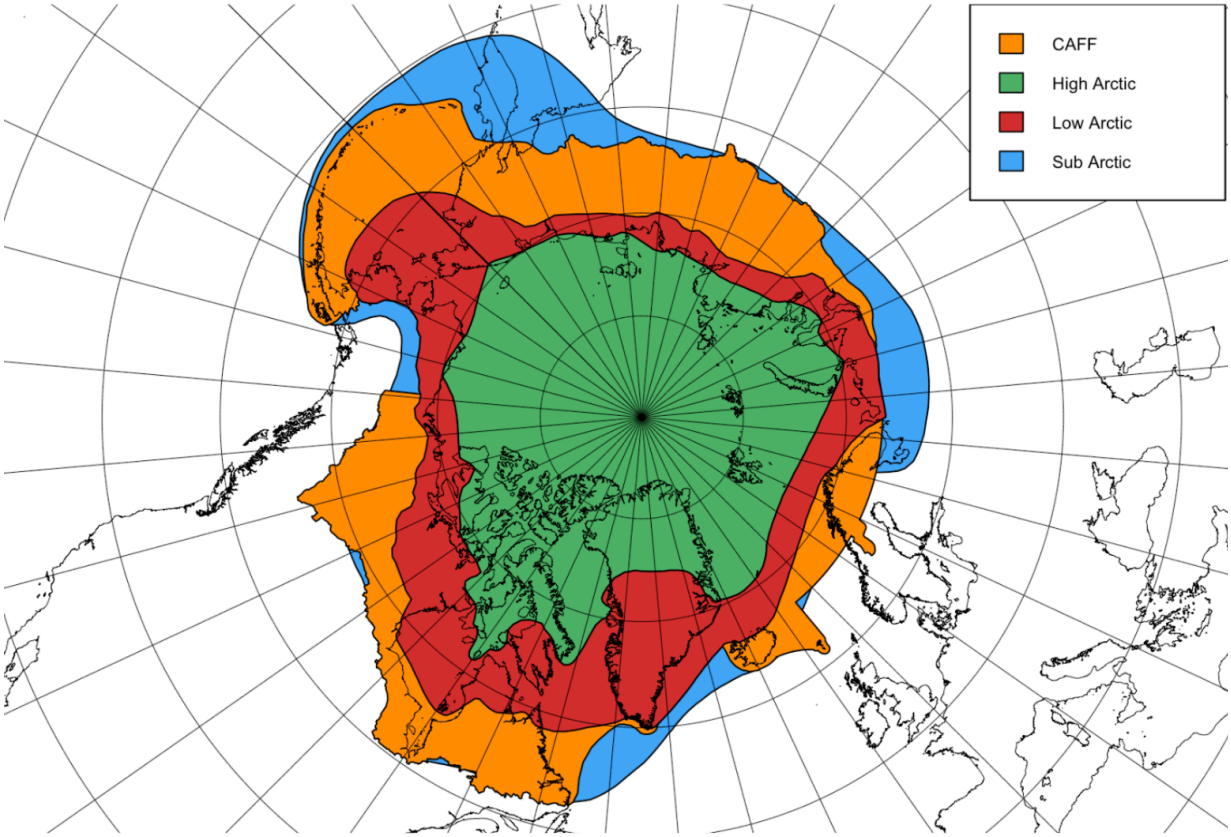
Appendices

All R scripts and data files are available online at: https://doi.org/10.5281/zenodo.15011515

Appendix 1 – The 'Arctic Region'



The Arctic region adapted from Martin *et al.*, (2022), the maximum extent of which has been used to define the Arctic in this study (i.e., the outer contour of all coloured regions). Orange = Conservation of Arctic Flora and Fauna (CAFF) boundary, Green = Arctic Biodiversity Assessment (ABA): High Arctic, Red = ABA: Low Arctic, Blue = ABA: Sub Arctic.

Appendix 2 – Table of most frequently used words

Word	Frequency	Word	Frequency	Word	Frequency
arctic	1628	studi	876	condit	665
chang	1542	plot	869	model	633
event	1268	snow	812	differ	624
climat	1249	**popul**	766	growth	619
temperatur	1249	**extrem**	758	**ecolog**	609
winter	1175	veget	748	season	608
speci	1120	high	719	respons	599
warm	1107	**tundra**	713	summer	591
year	1094	site	696	time	573
use	990	may	695	**ecosystem**	559
plant	973	data	694	caribou	552
effect	963	ice	689	observ	527
soil	941	area	677	**weather**	525
increas	883	fig	671	cover	522

The 42 most frequent words used in the 10 relevant papers identified in the scoping search to identify words for inclusion in the search string of our meta-analysis. Pertinent words were used to produce a comprehensive search string with words in bold being selected for inclusion in the finalised search string.

Appendix 3 – Fine-tuning and final search strings

Fine-tuning of the search string led to the addition of “NOT (human OR energy OR infrastructure)” to each search string due to the high number of human health, infrastructure, and energy-related papers not relevant to our research questions.

The final search string for Scopus was:
TITLE-ABS-KEY (("extreme event" OR "extreme climat* event" OR "extreme weather" OR "extreme heat" OR "extreme temperature" OR "extreme precipitation" OR "rain on snow" OR "extreme winter warming") AND (tundra OR arctic) AND (ecosystem OR ecology OR species OR populations) AND NOT (human OR energy OR infrastructure)).

The final search string for Web of Science was:
TI = (("extreme event" OR "extreme climat* event" OR "extreme weather" OR "extreme heat" OR "extreme temperature" OR "extreme precipitation" OR "rain on snow" OR "extreme winter warming") AND (tundra OR arctic)) OR AB = (("extreme event" OR "extreme climat* event" OR "extreme weather" OR "extreme heat" OR "extreme temperature" OR "extreme precipitation" OR "rain on snow" OR "extreme winter warming") AND (tundra OR arctic) AND (ecosystem OR ecology OR species OR populations) NOT (human OR energy OR infrastructure)).

Appendix 4 - List of 17 papers included in meta-analysis (data sources)

1. Bjerke, J. W. *et al.* Persistent Reduction of Segment Growth and Photosynthesis in a Widespread and Important Sub-Arctic Moss Species After Cessation of Three Years of Experimental Winter Warming. *Functional Ecology* **31**, 127–134 (2017). https://doi.org/10.1111/1365-2435.12703

2. Bokhorst, S. *et al.* Impacts of Extreme Winter Warming in the Sub-Arctic: Growing Season Responses of Dwarf Shrub Heathland. *Global Change Biology* **14**, 2603–2612 (2008). https://doi.org/10.1111/j.1365-2486.2008.01689.x

3. Bokhorst, S. *et al.* Warming Events Damage Sub-Arctic Vegetation: Consistent Evidence From an Experimental Manipulation and a Natural Event. *Journal of Ecology* **97**, 1408–1415 (2009). https://doi.org/10.1111/j.1365-2745.2009.01554.x

4. Bokhorst, S. *et al.* Impacts of Extreme Winter Warming Events on Litter Decomposition in a Sub-Arctic Heathland. *Soil Biology and Biochemistry* **42**, 611–617 (2010a). https://doi.org/10.1016/j.soilbio.2009.12.011

5. Bokhorst, S. *et al.* Impacts of Multiple Extreme Winter Warming Events on Sub-Arctic Heathland: Phenology, Reproduction, Growth, and CO2 Flux Responses. *Global Change Biology* **17**, 2817–2830 (2011). https://doi.org/10.1111/j.1365-2486.2011.02424.x

6. Bokhorst, S. *et al.* Extreme Winter Warming Events More Negatively Impact Small Rather Than Large Soil Fauna: Shift in Community Composition Explained by Traits Not Taxa. *Global Change Biology* **18**, 1152–1162 (2012a). https://doi.org/10.1111/j.1365-2486.2011.02565.x

7. Bokhorst, S. *et al.* Vegetation Recovery Following Extreme Winter Warming Events in the Sub-Arctic Estimated Using NDVI From Remote Sensing and Handheld Passive Proximal Sensors. *Environmental and Experimental Botany* **81**, 18–25 (2012b). https://doi.org/10.1016/j.envexpbot.2012.02.011

8. Bokhorst, S. *et al.* Climatic and Biotic Extreme Events Moderate Long-Term Responses of Above- and Belowground Sub-Arctic Heathland Communities to Climate Change. *Global Change Biology* **21**, 4063–4075 (2015). https://doi.org/10.1111/gcb.13007

9. Bokhorst, S. *et al.* Contrasting Survival and Physiological Responses of Sub-Arctic Plant Types to Extreme Winter Warming and Nitrogen. *Planta* **247**, 635–648 (2018). https://doi.org/10.1007/s00425-017-2813-6

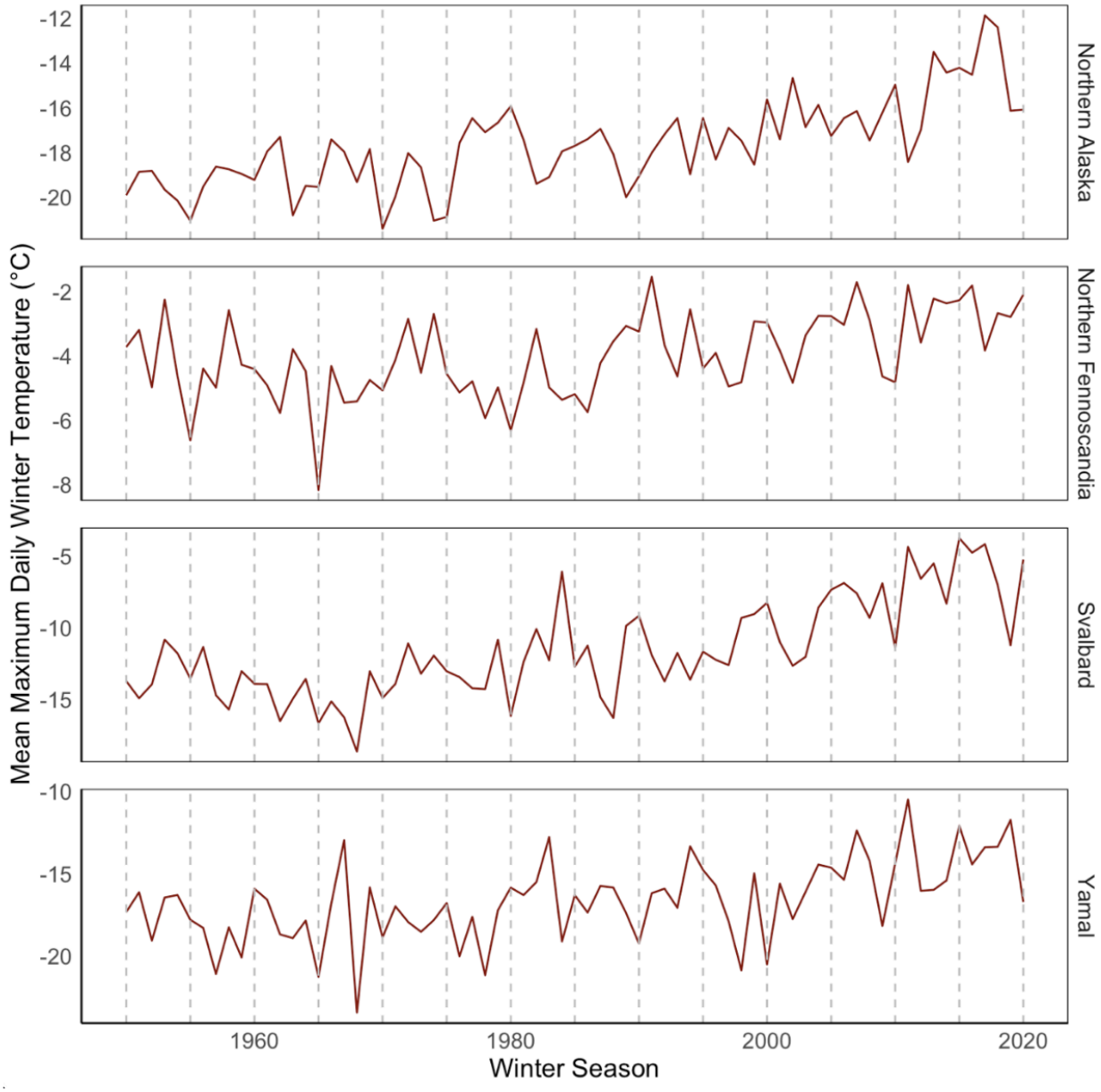
410. Bokhorst, S. *et al.* Sub-Arctic Mosses and Lichens Show Idiosyncratic Responses to Combinations of Winter Heatwaves, Freezing and Nitrogen Deposition. *Physiologia Plantarum* **175**, (2023). https://doi.org/10.1111/ppl.13882
11. Hansen, B. B. *et al.* Climate Events Synchronize the Dynamics of a Resident Vertebrate Community in the High Arctic. *Science* **339**, 313–315 (2013). https://doi.org/10.1126/science.1226766
12. Loe, L. E. *et al.* Behavioral Buffering of Extreme Weather Events in a High-Arctic Herbivore. *Ecosphere* **7**, (2016). https://doi.org/10.1002/ecs2.1374
13. Milner, J. M. *et al.* Experimental Icing Affects Growth, Mortality, and Flowering in a High Arctic Dwarf Shrub. *Ecology and Evolution* **6**, 2139–2148 (2016). https://doi.org/10.1002/ece3.2023
14. Poirier, M. *et al.* Snow Hardness Impacts Intranivean Locomotion of Arctic Small Mammals. *Ecosphere* **12**, (2021). https://doi.org/10.1002/ecs2.3835
15. Semenchuk, P. R. *et al.* Snow Cover and Extreme Winter Warming Events Control Flower Abundance of Some, but Not All Species in High Arctic Svalbard. *Ecology and Evolution* **3**, 2586–2599 (2013). https://doi.org/10.1002/ece3.648
16. Stien, A. *et al.* Congruent Responses to Weather Variability in High Arctic Herbivores. *Biology Letters* **8**, 1002–1005 (2012). https://doi.org/10.1098/rsbl.2012.0764
17. Treharne, R. *et al.* Arctic Browning: Impacts of Extreme Climatic Events on Heathland Ecosystem CO2 Fluxes. *Global Change Biology* **25**, 489–503 (2019). https://doi.org/10.1111/gcb.14500

Appendix 5 - Categorisation of response variables into two broader categories

Quantity	Energetic requirements
Abundance	Tunnel length (burrowing depth)
Peak flower abundance	Time to layer B (burrowing depth)
Alive:dead shoots ratio	Time to layer C (burrowing depth)
Biomass (above ground density)	Displacement (migration)
Shoot growth	PSII activity
Calf at heel (proportion of females with calf)	Photosynthetic rate
Winter mortality (standardised)	
April body mass (biomass)	
Berry production	
Survival	
Shoot alive	
Greenness	
Segment length	
Segment width	
Length:width ratio	

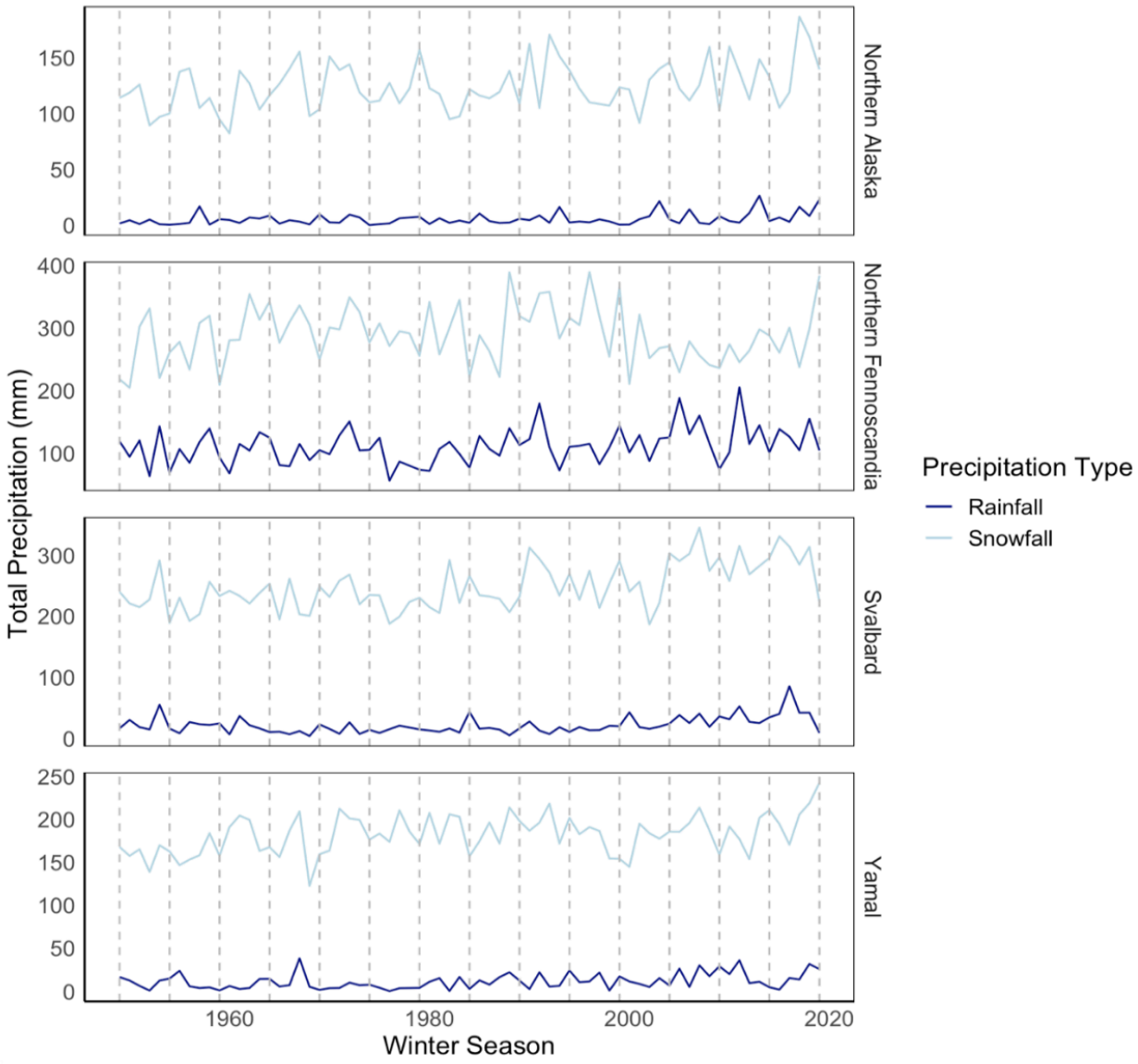
Response variables used in our meta-analysis to determine whether rain-on-snow and extreme winter warming events in the Arctic have a significant negative effect on the fitness of native biota, categorised into two broader categories to allow for comparisons across the 17 studies examined. Quantity-related variables assess changes in population and individual traits, while energetic requirements examine physiological and metabolic adjustments resulting from the consequences of extreme winter events.

Appendix 6 – Arctic regions have experienced a significant increase in average maximum daily winter temperature



Mean maximum daily winter temperatures (°C) averaged across different Arctic areas of special interest (see Methods) across winter seasons (October to March). Grey dotted lines represent 5-year intervals. Areas of special interest are ordered alphabetically from top to bottom: Northern Alaska, Northern Fennoscandia, Svalbard, and Yamal (North-western Siberia).

Appendix 7 – Most Arctic regions have experienced an increase in annual precipitation since 1940



Total snowfall in millimetres water equivalent (light blue) and rainfall in millimetres (dark blue)in each winter season (October to March) for the Arctic areas of special interest (see Methods) from 1950-2020. Grey dotted lines represent 5-year intervals. Regions are ordered alphabetically from top to bottom: Northern Alaska, Northern Fennoscandia, Svalbard, and Yamal (North-western Siberia).

Appendix 8 – Heterogeneity explained in the models with different moderators

Model	$R^2(\%)$
Full	6.66
Experimental Y/N	1.27
Event Type	3.41
Kingdom	1.87
Phylum	7.23
Taxonomic class	6.76
Broad Category	0.02