Faculty of Science

Extreme Weather Events in the Terrestrial Arctic

A literature review focusing on the results and consequences of extreme weather events

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Degree of Bachelor of Science
with a major in Earth Sciences
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Abstract

There is a prevailing lack of long-term and short-term research and knowledge about extreme weather events in the terrestrial Arctic region. Because of this, study efforts have been limited in a wide range of subjects relating to the Arctic and extreme weather events. This project is partaking in an ongoing research project at the University of Gothenburg, relating to reviewing existing research and published scientific papers covering extreme weather events in the terrestrial Arctic Region pertaining to occurrences and consequences of these events. Reviews such as this will help to coordinate and focus efforts relating to future investigations in the Arctic region. This study is a literature review, as well as a joint thesis project, aiming to investigate published scientific articles relating to extreme weather events in the terrestrial Arctic region between 1981-2022, with a focus on the occurrences and the consequences of these events. Results from this project will be joined with results from the ongoing research project, aiming for a holistic approach to this subject. After initial cooperation with the university library, assisting in the process of collecting the relevant scientific articles, an introductory screening followed by a first and second full screening of the articles was carried out. The obtained results, produced in Excel and Grapher, show that research during the studied time period has succeeded in including a variety of extreme weather events but lacks a more even distribution among the studied ecosystem types, as well as the perspective of the human aspect. The studied research is also found to a larger degree focus on found consequences of extreme weather events, rather than the occurrences. The distribution among the found consequences is, on the other hand, uneven. Amidst the more researched ecosystems, the studied extreme weather events have been found to have a large impact. Prevailing knowledge about extreme weather events in the terrestrial Arctic region during the studied time period is found to be irregular, based on the type of ecosystem and weather event investigated. There is a need for more research projects focusing on reviewing existing scientific literature in the future.

Sammanfattning

Det är en rådande generell brist på långsiktig och kortsiktig kunskap samt forskning inriktad på extrema väderhändelser i den landbundna arktiska regionen. På grund av kunskapsbristen och det extrema geografiska läget har studier i Arktis begränsats inom ett stort antal områden som rör den arktiska regionen och extrema väderhändelser. Detta projekt är en del av ett pågående forskningsprojekt vid Göteborgs universitet och koncentrerar sig på att granska befintlig forskning och publicerade vetenskapliga artiklar som utforskar extrema väderhändelser i den arktiska regionen på land samt granska förekomsten och konsekvenserna av dessa händelser. Litteraturstudier som denna kommer att bidra till att samordna och fokusera kommande insatser för framtida undersökningar i den arktiska regionen. Denna studie är en litteraturöversikt och ett gemensamt avhandlingsprojekt som syftar till att undersöka publicerade vetenskapliga artiklar om extrema väderhändelser i den arktiska regionen på land mellan 1981-2022, med fokus på förekomsten och konsekvenserna av dessa händelser. Resultaten från detta projekt kommer att kombineras med resultaten från det pågående forskningsprojektet, och syftar till att skapa en helhetssyn på detta ämne. Efter ett inledande samarbete med universitetsbiblioteket, som hjälpte till att samla in relevanta vetenskapliga artiklar, genomfördes en inledande genomgång av artiklarna följt av en första och en andra fullständig genomgång av artiklarna. De erhållna resultaten, som producerats i Excel och Grapher, visar att forskningen under den studerade tidsperioden har lyckats inkludera en mängd olika extrema väderhändelser, men saknar en jämnare fördelning mellan de studerade ekosystemtyperna, liksom perspektivet på den mänskliga aspekten. De studerade artiklarna har också i större utsträckning fokuserat på de konsekvenser som konstaterats till följd av extrema väderhändelser, snarare än på förekomsten av extrema väderhändelser. Fördelningen mellan de konstaterade konsekvenserna är å andra sidan ojämn. Bland de mer undersökta ekosystemen har de studerade extrema väderhändelserna visat sig ha en stor inverkan. Den rådande kunskapen om extrema väderhändelser i det arktiska landområdet under den studerade tidsperioden är oregelbunden, beroende på vilken typ av ekosystem och väderhändelse som undersökts. Det finns ett behov av fler forskningsprojekt med fokus på att granska befintlig vetenskaplig litteratur i framtiden.

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1. Introduction

It is known that there is a prevailing lack of both long-term and short-term observations and studies along with information about extreme events occurring in the Arctic region (AMAP, 2011; Martineau et al., 2022; Revich & Shaposhnikov, 2022). Study efforts have thus been limited in a wide range of subjects relating to the Arctic and extreme events. From insufficient general quality and resolution of available data in the region (AMAP, 2011; Martineau et al., 2022; Revich & Shaposhnikov, 2022) to studying physical properties concerning snow (Martineau et al., 2022), are two examples. Studying weather-related mortality rates affecting the Arctic and subarctic communities has also been proven challenging (Revich & Shaposhnikov, 2022), as well as understanding and collecting knowledge about melt events on ice sheets affected by both intensity and frequency of extreme events (Clarkson et al., 2022). Understanding reindeer herders that are navigating new and uncharted conditions while trying to maintain culturally significant traditions (Axelsson-Linkowski et al., 2020), and investigating traditional diets of indigenous peoples that are being challenged in a changing environment (Andronov et al., 2021) and also understanding the physical abilities and flexibilities in Arctic arthropods facing new extreme environmental conditions (Beet et al., 2022), are further examples of the scope relating to extreme weather events in the Arctic region and current challenges.

This project is partaking in an ongoing, unpublished, research project at University of Gothenburg, focusing on reviewing existing research and published scientific papers covering extreme weather events (EWEs) in the terrestrial Arctic Region pertaining to occurrences and consequences of these events. The types of extreme weather can be related to less or more snow cover, extreme winter warming events, extreme warm or cold temperatures, rain-on-snow events and heatwaves, to name a few (Christensen et al., 2021; Martineau et al., 2022). The consequences of such events can in turn be related to animals, vegetation, energy balances, snow and ice conditions, soil or permafrost changes, livelihoods and impacts affecting culturally significant traditions, to give a few examples (Walsh et al., 2020; Christensen et al., 2021). Habitats affected by the consequences of EWEs in the terrestrial Arctic are ranging from shrub tundra to peatland, barren areas, glaciers, lakes, rivers, coastal regions and tundra, illustrating the variety of environments included and explored in this project (Figure 3, for some examples).

This thesis is a joint project between two students, and as such the subject is shared but specific aims and subsequent results will differ. Combined, these two projects will strive to give a holistic approach to the prevailing knowledge of EWEs in the terrestrial Arctic region.

Relating to the wide and prevailing lack of information, observations and data in the Arctic, reviews such as this will help to coordinate and focus future efforts relating to continued investigations in the Arctic region. It will also serve as a holistic approach to understanding current knowledge and research encompassing Arctic environmental challenges and related challenges faced by Arctic communities. This can thus act as a vital instrument for researchers, local communities and policymakers, further down the line benefitting the ecosystems in themselves and the Arctic populations.

1.1 Aim

This study is a literature review aiming to investigate published scientific articles relating to extreme weather events in the terrestrial Arctic region and focuses on the occurrences, the consequences, the geographical representation as well as on the evolution of published scientific articles over time. The geographical extent of the investigated area is limited to the terrestrial region of the Arctic and includes Norway, Sweden, Finland, Russia, Alaska, Canada, Greenland and Iceland (see Figure 2). This project will investigate articles published between the years 2020-2022, with a focus on compiling the entire data set included in the research project between the years 1981-2022. As a final step, results from this investigation will be joined with results from the ongoing research project pertaining to this subject. The thesis projects together with the ongoing research project will examine scientific articles published between the years 1981-2022. Since this is also a joint thesis project, the research questions below clarify which focus this thesis has.

1.1.1 Research questions

The research questions this project aims to answer:

What are the reported results from the studied scientific articles relating to extreme weather events in the terrestrial Arctic between the years 1981-2022? The results are in relation to:

- What does the distribution look like for the studied extreme weather events addressed in the articles?
- What does the distribution look like for the studied ecosystem types addressed in the articles?
- Is the human aspect included in the articles?

What are the reported consequences from the studied scientific articles relating to extreme weather events in the terrestrial Arctic between the years 1981-2022? The consequences are in relation to:

- To what extent are the articles addressing consequences and occurrences of extreme weather events, and how is this distributed among the articles?

1.2 Extreme weather events

EWEs are unusual and severe weather events mostly related to temperature and precipitation extremes, such as changes in or to the snowpack, extreme temperature conditions, extreme precipitation, and drought (Weladji et al., 2002; Vicente-Serrano et al., 2013). It can also affect different aspects of an area, for example entire ecosystems, the soil, vegetation, animals, and humans (Christensen et al., 2021; Axelsson-Linkowski et al., 2020). Due to weather varying profoundly between regions on a regional, and global scale, what would be classified as an EWE in one place may not be in another. In this study, an EWE will be defined as such if an article describes a weather phenomenon or simulated weather condition as extreme, or directly refer to it as an EWE.

1.3 Study area

The definition of the Arctic used in this study is mainly the Arctic Monitoring and Assessment Programme (AMAP) boundary found in Figure 1 (Arctic Monitoring and Assessment Programme, n.d.). The regions of the Arctic used in this study can be seen in Figure 2, which includes: Sweden, Norway (mainland), Finland, Iceland, Svalbard, East Greenland, West Greenland and Baffin islands, Canadian Arctic Archipelago, Canadian mainland, Alaska, Chukotsky peninsula, Lena/West-mid Siberia, Taymir, Yamal/Novaya Zemlya, Kola peninsula, and Arctic as a whole.

Figure 1. AMAP definition of the Arctic (Arctic Monitoring and Assessment Programme, n.d.).

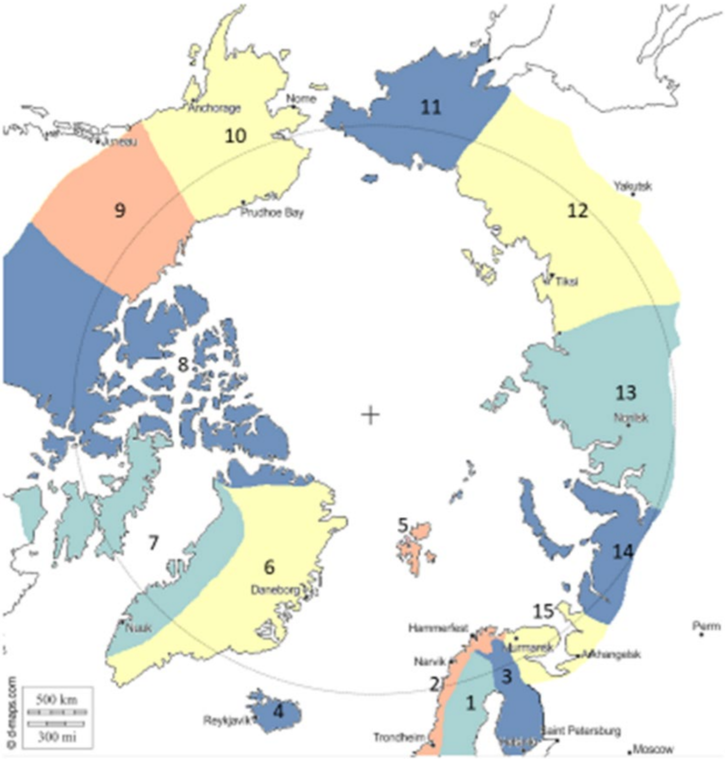

*Figure 2. Map showing the extent of the geographical area of interest. Areas included: 1. Sweden, 2. Norway (mainland), 3. Finland, 4. Iceland, 5. Svalbard, 6. East Greenland, 7. West Greenland & Baffin Islands, 8. Canadian Arctic Archipelago, 9. Canadian mainland, 10. Alaska, 11. Chukotsky Peninsula, 12. Lena/West-mid Siberia, 13. Taymir, 14. Yamal/Novaya Zemlya, 15. Kola peninsula. Also included: Arctic as a whole and non-arctic regions in specific circumstances (*Henni Ylänne, n.d.).

The Circumpolar Arctic Vegetation Map (CAVM) defines the types of Arctic ecosystems as shrub tundra, graminoid tundra, peatland, and barren area/glacier which are the ecosystem types that this study uses. Shrub tundra is a tundra dominated by shrubs, and graminoid tundra is a tundra dominated by low-growing grass-like plants, so-called graminoids (CAVM Team, 2003). Even though the CAVM defines the border of the Arctic as the area above the Arctic tree line, in this study it is used to describe the ecosystem types for the whole Arctic.

According to the CAVM shrub tundra is located in all Arctic regions, but mostly in northern Canada and Russia. Graminoid tundra is also largely in those regions and Alaska. Peatlands can largely be found along the coastline of Alaska, but also some selective areas along the northern Canadian and Russian coasts. Furthermore, barren areas/glaciers can mostly be found in Greenland and other islands close to the pole where the majority consists of glaciers. In addition, this study also uses the CAVMs definition of the tundra-forest boundary, lakes, rivers, and coastal areas, where rivers can be found connected from all over the mainland, but mostly in Russia and Canada, into the Arctic Ocean (CAVM Team, 2003). Some examples of terrestrial Arctic environments can be found in Figure 3.

Figure 3. A selection of various Arctic environments in the terrestrial Arctic region. The top left corner shows a Sámi reindeer herder together with his flock. The top right corner shows Denali National Park and the tundra environment in Alaska. The lower left corner shows an Arctic village in northern Canada. The lower right corner shows the landscape of flat palsas located in the Komi Republic in Arctic Russia (Tromsø Arctic Reindeer, N.d.; Kraig Becker/Getty Images, 2019; Mary Simon, 2012; Hans Joosten, 2019).

There are various animal groups found in the Arctic region. Important terrestrial animals for people living in the various regions are ungulates such as reindeer and muskoxen. Reindeer can be found in all Arctic regions, for example in Svalbard, Alaska, and northern Norway (Hansen et al., 2011; Rattenbury et al., 2009; Risvoll & Hovelsrud, 2016). Muskoxen can mostly be found in Greenland, Canada, and Alaska (Beumer et al., 2020; Mallory et al., 2020;

Berger et al., 2018). But there are also small populations in Siberia, as well as in Sweden and Norway (National Geographic, n.d.; Ytrehus et al., 2008). There are also various coastal and migratory birds as well as invertebrates in the whole Arctic (Martin et al., 2018; Boelman et al., 2017; Machín et al., 2019).

Indigenous people live across the whole Arctic, with the largest populations in Greenland and northern Canada, followed by Alaska and eastern Russia (Wang & Roto, 2019). There is also a much smaller population of indigenous people living in the northern Nordic. The population of the Arctic region consists of around 4 million people (within the AMAP border), of which circa 400,000 are indigenous (World Wildlife Fund [WWF], n.d.).

2. Methods

This project is a literature review investigating published scientific articles relating to extreme weather events in the terrestrial Arctic region. The Gothenburg University Library supported the supervisor in the process of obtaining the relevant articles. The first step, named "Introductory screening", consisted of sorting out the articles based on relevant connections to extreme weather in the terrestrial Arctic region (see Table 1). Thereafter, two thorough screenings were performed with two detailed templates accompanying this process (see Table 2 and 3). In the final steps, the results were compiled into graphs and diagrams to visualize the findings (see Figure 4). This study partakes in an ongoing research project where extreme weather in the terrestrial Arctic region is studied, and the total number of articles included is extended to the year 1981, although the complete search extended to "the beginning of time" and 1981 is when the first article related to this subject was published. It was paramount to match this method with the method of the ongoing research study in order to maintain a consistent methodology.

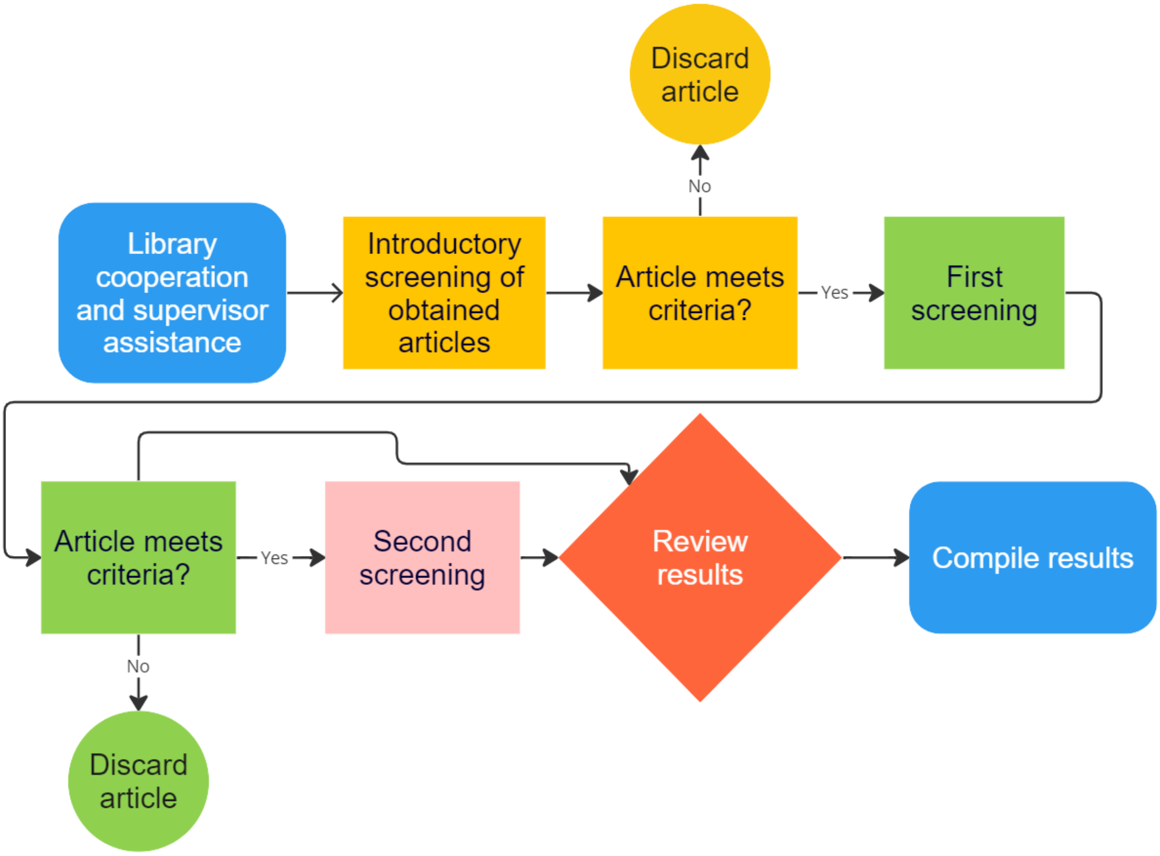

Figure 4. Flowchart showing the general steps in the method of this study.

2.1 Literature search and library cooperation

This study's addition to the dataset was initially to retrieve articles from four different search engines: Scopus, Web of Science (Clarivate), Zoological Records (Clarivate), and Geobase (engineering village). The search was from 2020-01-01 to 2022-12-31, but the articles were reviewed from 2020-04-21. Keywords were searched in specific steps and orders, found in the Appendix. The last step resulted in the final number of articles that would be analysed in the introductory screening. The keywords were related to the Arctic, extreme weather, climate change, specific consequences of extreme weather events etc. The exact keywords searched, what order, and how many articles were found for each step for each of the search engines can be found in the Appendix. After that, all articles from the final searches were put into EndNote where duplicates were removed, after which 2,024 articles remained. As a last step before the introductory screening, the articles were loaded into Rayyan, a webpage for systematic reviews.

2.2 Introductory screening

The initial scope of the first introductory screening of gathered articles was comprised of 2,024 collected articles. The purpose of this second step was to filter out irrelevant scientific articles, which did not meet a set list of predetermined criteria (see Table 1). Articles which did not meet at least one of the requirements were sorted out. All the obtained articles were subjected to a single-blinded test, where both authors of this project inspected and reviewed all 2,024 articles without being aware of the decision of the other. During the process of filtering, the titles, abstracts and keywords of the articles were inspected and thereafter the article was determined suitable or not. If, for example, the article did not match the determined time interval for this study, it was removed. If the article had duplicates, the duplicates were removed. This process was also aided by the extent of the study area (see Figure 2), although an article did not have to take place exclusively in the terrestrial Arctic region which is further explained in Table 1. This procedure took place in the working space Rayyan, where the single-blinded nature of this process was maintained.

As a final step, the single-blinded function was removed, in order to eliminate conflicting opinions of remaining articles. Around 200 conflicting assessments were found and resolved through mutual efforts in dialogue. Out of 2,024 articles, 1,695 were excluded and 329 were included for the first exhaustive screening process, named "First screening of articles".

Table 1. Predetermined including and excluding criteria for the introductory screening.

Including criteria	Articles focusing on the occurrence alternatively the impacts regarding a change and/or increase in the variability and unpredictability of extreme weather events taking place in and experienced by arctic and/or high latitude terrestrial ecosystems.
	Extreme weather events related to the occurrence of for example rain-on-snow, heatwaves and less snow cover.
	Short-term responses of the ecosystem to changed environmental surroundings, meaning 2 years or less.
	Articles reviewing the impacts and/or consequences of atypical weather occurrences.
	Articles reviewing the Arctic and other geographical areas.
	Articles which are reviews, meta-studies and summaries.

	Articles covering anything from biogeochemistry, remote-sensing, archaeology, technology, ecology, polar science, conservation, environment and society, biology, physiology, and more relating to these fields.
	Articles which are exclusively describing the incidents relating to extreme weather events.
	Articles reviewing species adaptation in relation to abnormal temperatures. This can for example relate to laboratory experiments.
	Articles covering lakes, rivers and coastal areas.
	Articles focusing on an experimental study where the beginning of the experiment is included and ≤ 2 years.
	Articles focusing on an experimental study where the impacts and/or consequences of the experiment span more than three years, but the beginning of the manipulations is included.
	Articles focusing on an experimental study and describing the recovery after a short-term experiment relating to aberrant weather events. Can also take place 10 years after the experiment.
Excluding criteria	Articles not related to the terrestrial Arctic ecosystem.
	Articles related to alpine and Antarctic ecosystems.
	Articles exclusively devoted to boreal and coniferous regions and ecosystems. If the study area of an article is in close proximity to the study region of this project, check if it covers any Arctic region.
	Methodological articles, also relating to developing methods.
	Articles reviewing the fundamentals and the structure relating to extreme weather events or a changing climate. This can for example relate to meteorological explanations or teleconnections of weather or climatic patterns stretching over multiple continents.
	Articles relating to marine sciences. This can for example be articles focusing on the marine cryosphere, sea ice or reviewing the oceanic aspect.
	Articles reviewing and explaining the fundamentals of biological, meteorological and/or physiological aspects and mechanisms without direct association with extreme weather and/or climatic events or changes.
	Articles reviewing responses to, for example, freezing or thawing without connection to impacts relating to the increase in frequency.
	Articles describing the impacts of changes in weather conditions where the ecosystem has had time to adapt during a time period of three or more years.
	Articles focusing on an experimental study where the impacts and/or consequences of the experiment span more than three years, and the beginning of the manipulations is not included.
	Articles focusing on trends in weather, weather extremes and/or climate.

2.3 First screening of articles

The first screening consisted of reading 40 out of the 329 included articles from the introductory screening due to time constraints. The 40 articles were selected by being the first 40 in the list of articles, and the list was sorted with the authors in alphabetical order. The articles were evaluated if they should be included, and if so, reviewing them based on a number of questions. The information of the 40 articles was loaded into an Excel template of the first screening. The information included ID, author, date, title, journal, volume, pages, citations, and URL. Thereafter each article was read and evaluated if they should be excluded or included based on the excluding and including criteria in Table 1. If they were to be excluded, the reason would be stated, and if the evaluator was uncertain, it would be stated as well. There were 22 articles included, and they were reviewed based on questions found in Table 2. If the articles only addressed occurrence, only questions 2-7 would be answered.

Table 2. Questions answered for each included article in the first screening. If the articles only addressed occurrence, only questions 2-7 would be answered.

1) Addresses occurrence or the consequence of EWEs?
2) What extreme event is the paper addressing? Alternatives: • winter warming • more snow cover • less snow cover • early snowmelt • late snowmelt • spring frostbites, hail, or snowstorms • extreme cold temperature • extreme warm temperature • heatwave • drought • heavy rainfall • heavy wind/storm • flooding • rain-on-snow • other, list what
3) From what geographical area is the study from? The areas are found in Figure 2.
4) Coordinates (if available)?
5) Closest city and region?
6) How large area is the study encompassing? Alternatives: • 1m - 1 km • 1 km - 1000 km • 1000 km and more
7) What Arctic ecosystem type? It is the main types in the CAFF vegetation map, as well as forest border, coastal, lake, and river. Alternatives: • shrub tundra • graminoid tundra • tundra-forest boundary • peatland • barren area/glacier • lake • river • coastal
8) Study "type"? Alternatives: • observational (qualitative, e.g., questionnaire on observed changes) • observational (quantitative, e.g., time-series of weather records) • experimental (field) • experimental (laboratory) • predictive (e.g., Ecosystem model) • review
9) Field of study?
10) Consequences on what? Alternatives: • snow/ice • vegetation • soil • microorganisms • animals • carbon and nutrient cycles • energy balance/albedo • biodiversity • livelihoods • economics • other, list what
11) Is the human aspect involved? (Answer only if yes) Alternatives:

• yes • yes, also indigenous people involved
12) If the EWE is simulated, how is this done? (e.g., snow fence)?
13) Are other biotic/abiotic factors included in experiments? List which
14) Free comments (e.g., great for review)

2.4 Second screening of articles

The second screening consisted of further investigation of approved articles compiled during the first screening. Again, the articles were reviewed based on a series of inquiries but with a more detailed focus in this step of the process. This work continued in a template in Excel, to which both authors contributed. Information about the current article was loaded in, but this was based on the information from the first screening, and it was possible to refer back instead of repeating the full content. Only the author or authors were necessary to state. The included articles in the second screening were reviewed based on the inquiries found in Table 3. If the article addressed multiple abnormal variables, several entries for the same article were made. If an inquiry was unsuitable, it was ignored.

Table 3. Inquiries included for articles in the second screening.

1) Free notes
2) Article number (if available)
3) Reference (author/authors)
4) Site
5) Vegetation type
6) Time (such as season or more specific if available)
7) Extreme event or increased variability (state which)
8) Abnormal variable (type of EWE or EWEs)
9) Indirect effect
10) Category Alternatives: • Snow, ice and albedo • Soil, microbes and carbon • Vegetation • Animals • Livelihoods • Water • Other

11) Response variable
Alternatives within previous categories:
• Snow, ice and albedo
    ○ Snow layer thickness
    ○ Density
    ○ Ice layer thickness
    ○ Number of ice layers in snow
    ○ Frequency of rain-on-snow events
    ○ Time of snowmelt
    ○ Albedo
    ○ Energy balance

- Soil, microbes and carbon
  - Primary production
  - Respiration
  - Ecosystem CO_2 sink
  - Ecosystem CH_4 release
  - Decomposition
  - Active layer depth
  - Soil temperature
  - Soil water table
  - Soil moisture
  - Microbial biomass
  - Microbial diversity
  - Microbial performance
  - Erosion
  - Leaching (DON, DOC)
- Vegetation
  - Biomass
  - NDVI
  - Amount of bare soil
  - Amount of litter
  - Community composition
  - Diversity
  - Damage on tissues
  - Mortality
  - Greening
  - Flowering
  - Growth
  - Senescence
  - Vegetation C:N ratio
  - Performance
- Animals
  - Population size
  - Loss of species
  - Reproduction success
  - Body condition
  - Forage availability
  - Observed foraging
  - Diversity
  - Range size
  - Calving date
- Livelihoods
  - Monitory gains
  - Health (hospitalization and mental health)
  - Access to natural resources
  - Material damage
  - Vulnerability to further damage
  - Knowledge
- Water
  - Run-off
  - Sediment load
  - Erosion of riverbanks
  - Flooding
- Other
  - Drought

12) Unit (if applicable and/or available)

13) Response

Alternatives:

- Increase
- Decrease
- Stable
- Earlier
- Later

14) Significance (results significant or not)

15) Animal or plant group

16) Species

2.5 Reviewing and compiling the results

The final step in order to collect and present the found results was to produce diagrams and charts relating to the research questions and areas of interest. The majority of the results were produced in Excel, creating charts relating to EWEs, type of studied ecosystems, investigating the human aspect, consequences in the ecosystem and finally studied occurrences and consequences. The results presenting the impact in relation to the number of articles or EWEs and ecosystem types, as well as the results pertaining to the average response and lastly, the results presenting the type of EWEs in relation to the geographical regions, are all produced in the program Grapher 15 (Golden Software).

3. Results

In total efforts, 6,924 published scientific articles have been investigated. 1,030 articles remained after the introductory screening to the first and subsequent second screenings. 422 articles were investigated in the first screening (Figures 5-9 and 14), and 265 articles were reviewed in the second screening (Figures 10-13 and 15). Figures 5 through 8 refer to the research questions about the results found in the studied articles, while figures 9 through 13 are pertaining to the research questions about the consequences found in the studied articles. Lastly, figures 14 and 15 presents a combination of both aspects. All presented pie charts are based on the obtained results from the first screenings, while the bubble charts and the bar charts are based on the results from the second screenings.

3.1 Results obtained from the studied articles

The obtained and assembled results indicate that published scientific articles between the years 1981-2022, relating to EWEs in the terrestrial Arctic region, have succeeded in including a variety of EWEs, as shown in Figures 5 and 6. This relates to both the type of EWE and the type of studied ecosystem. Regarding the studied types of EWEs (Figure 5), the largest shares belong to extreme winter warming events, rain-on-snow and extreme warm T ("temperature"). These types of EWEs have thus been most investigated over the studied time period. Less attention falls on the other hand to spring frostbites, hail or snowstorms as well as to heavy wind/storms and heat waves. In the group "Other", additional extreme events were reported, that did not match the other categories. This could, for example, be "Extreme climate on mortality", "NAO winter" or "Delayed freeze-up, early break-up and storms". For the ecosystem types (Figure 6), there is a possibility to see a slightly poorer distribution among the studied environments, where shrub tundra and graminoid tundra can be seen as having a larger share of the distribution whilst lakes and rivers, for example, are less represented.

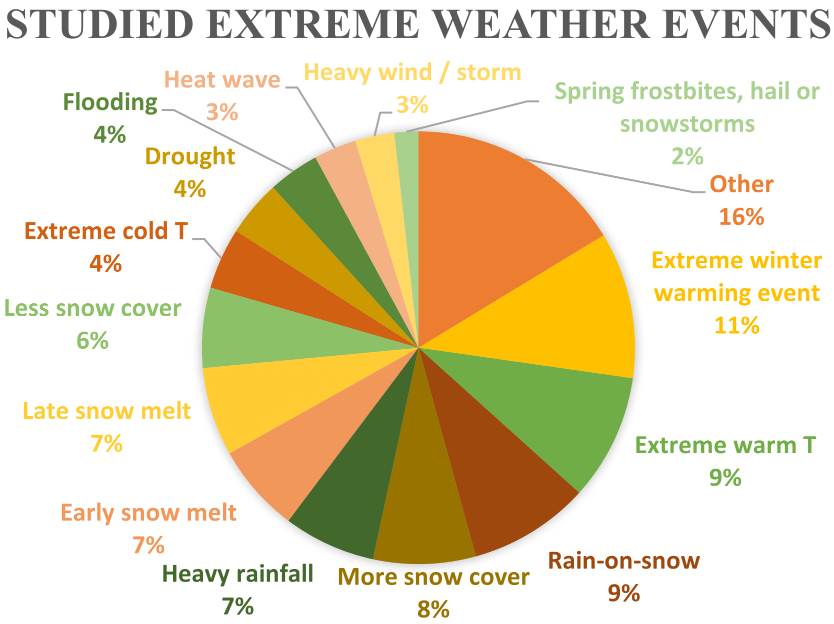

Figure 5. Pie chart showing the distribution of studied extreme weather events between the years 1981-2022, covering 422 studied articles for the terrestrial Arctic region.

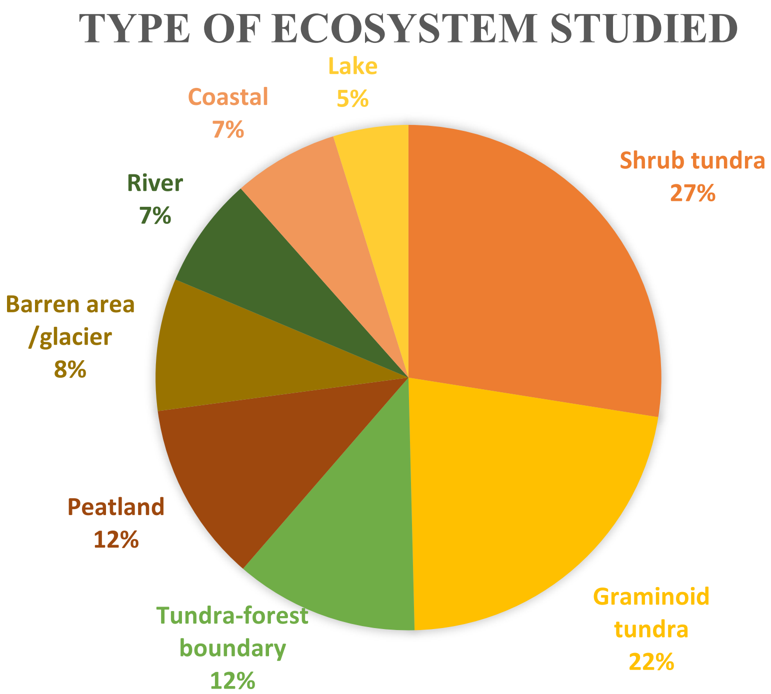

Figure 6. Pie chart showing the distribution of studied ecosystem types between the years 1981-2022, covering 422 studied articles for the terrestrial Arctic region.

The distribution regarding the inclusion of the human aspect is showing a clear division (Figure 7), where 83% of the investigated articles over the study period have not included the human perspective. The distribution regarding the inclusion of the human aspect with or without the perspective of indigenous peoples on the other hand (Figure 8), is found to be more even, where there is slightly more focus on the human aspect without the perspective of indigenous peoples.

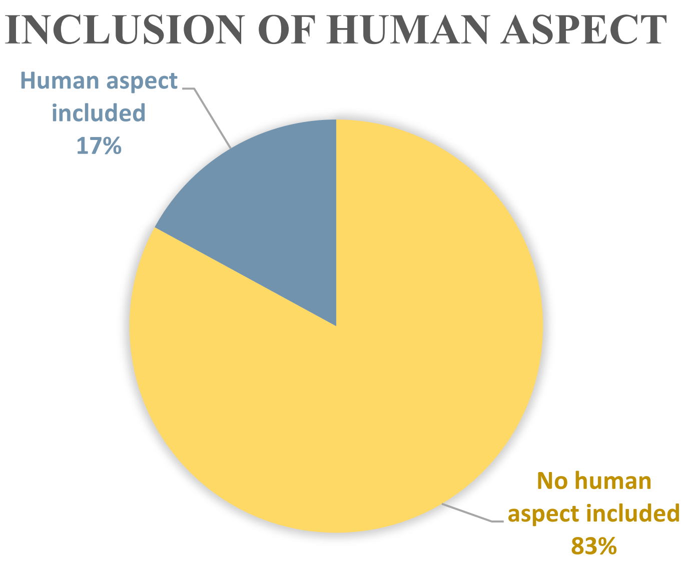

Figure 7. Pie chart showing the distribution of the human aspect between the years 1981-2022, covering 422 studied articles for the terrestrial Arctic region.

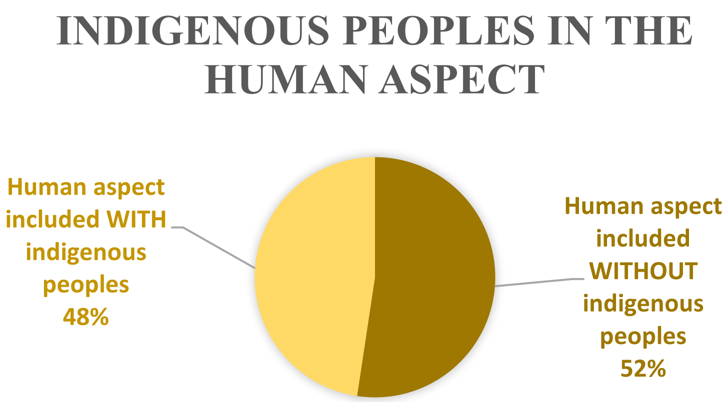

Figure 8. Pie chart showing the distribution of the human aspect with or without the indigenous aspect between the years 1981-2022, covering 422 studied articles for the terrestrial Arctic region.

3.2 Consequences obtained from the studied articles

From the obtained and assembled results, there is a clear indication that published scientific articles between the years 1981-2022 relating to EWEs in the terrestrial Arctic region have also succeeded in including a variety of EWEs in relation to the consequences found in the environment (Figure 9). The distribution, on the other hand, is found to be less even. For example, out of 422 investigated papers, 22% reported consequences on animals and 19% reported consequences on vegetation, but only 1% reported consequences on biodiversity. In the group "Other" (Figure 9), additional consequences were reported, that did not match the other categories. This could, for example, be "Arctic hydrologic cycle" or "Human health".

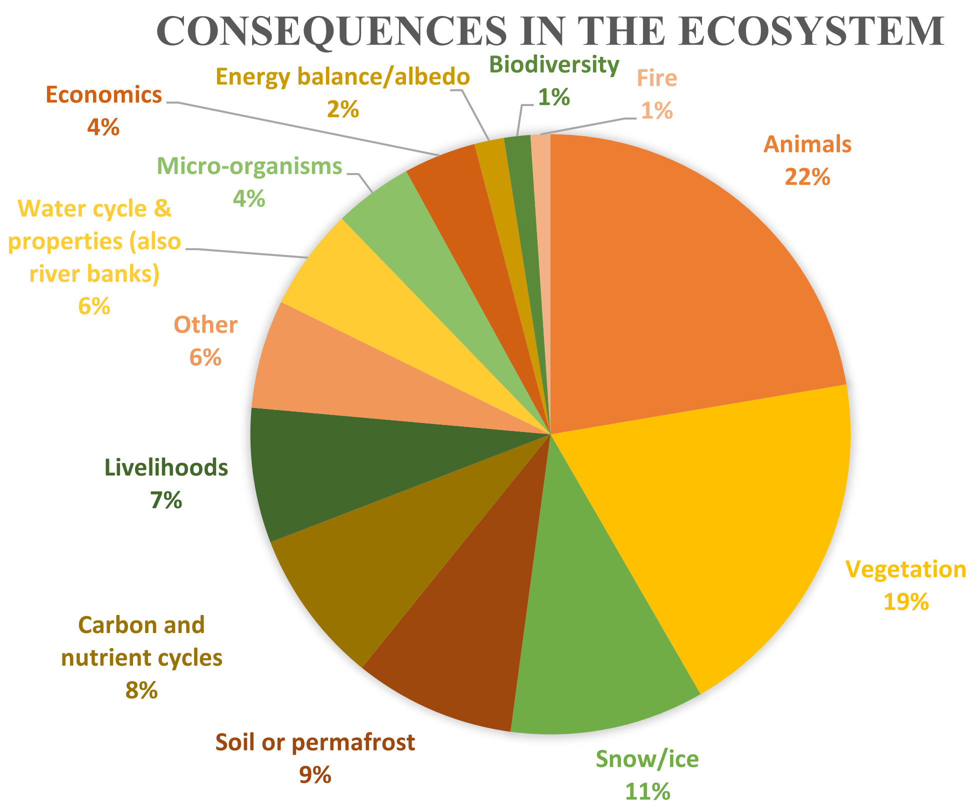

Figure 9. Pie chart showing the distribution of reported consequences in the ecosystem between the years 1981-2022, covering 422 studied articles for the terrestrial Arctic region.

Figures 10 through 12 are showing the distribution of articles in relation to investigated ecosystems combined with found impact. The impact on the x-axis relates to found response reported in the articles, pertaining to an increase, decrease, stable, earlier or later conditions in the studied ecosystem. Figure 10 presents, for example, an outcome where approximately 70% of the studied articles in the category pertaining to "Soil" reported a response ("Impact") relating to EWEs in the terrestrial Arctic. For Figure 10, flora is the most investigated field, while water is the least investigated category. Figure 11 presents the distribution of articles in relation to investigated ecosystems combined with found impact along with the type of EWE. For this result, around 60% of the studied articles reported a response ("Impact") relating to soil conditions regarding the EWE "Icing layers" in the terrestrial Arctic. Figure 12 presents an additional layer of information, where temperature and precipitation are considered as well. For example, around 90% of the studied articles reported a response ("Impact") relating to fauna and precipitation regarding EWEs in the terrestrial Arctic. The size of the bubbles relates to the number of variables investigated for the attached fields (Figures 10-12).

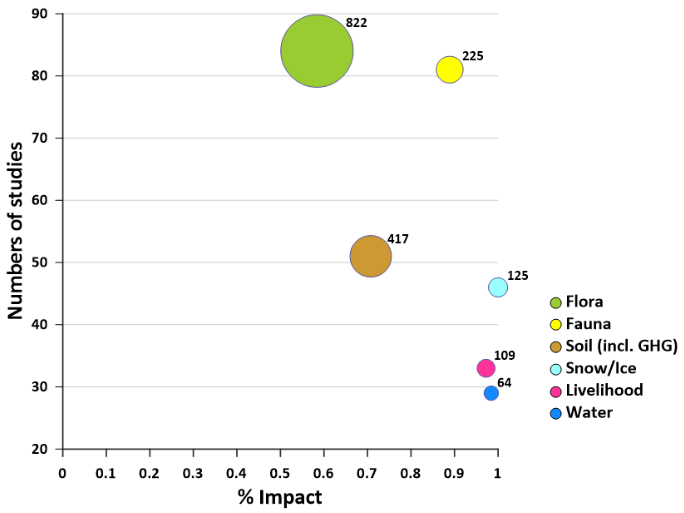

Figure 10. Bubble chart showing the distribution of articles addressing reported impacts, in percent, of EWEs between the years 1981-2022, covering 265 studied articles for the terrestrial Arctic region. The material covers more than the diagram is showing (Mats Björkman, n.d.).

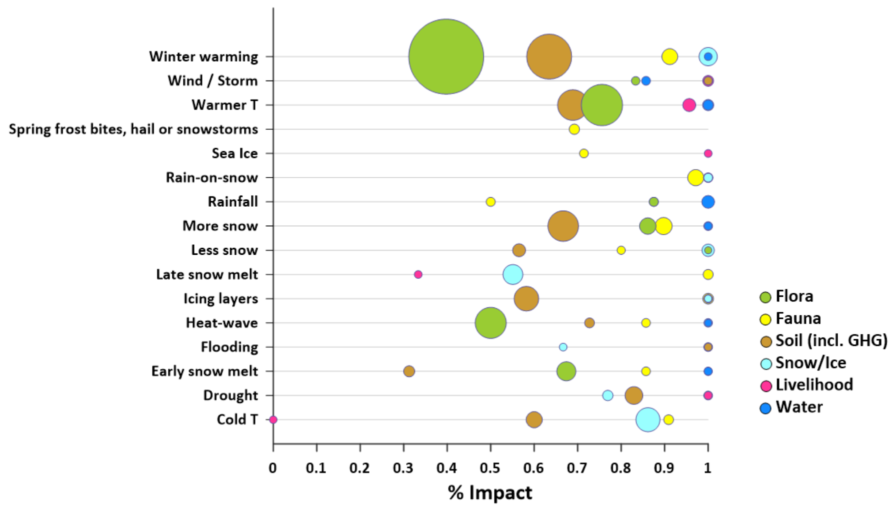

Figure 11. Bubble chart showing the distribution of articles addressing reported EWEs and the relative impact in percent, between the years 1981-2022, covering 265 studied articles for the terrestrial Arctic region. The material covers more than the diagram is showing (Mats Björkman, n.d.).

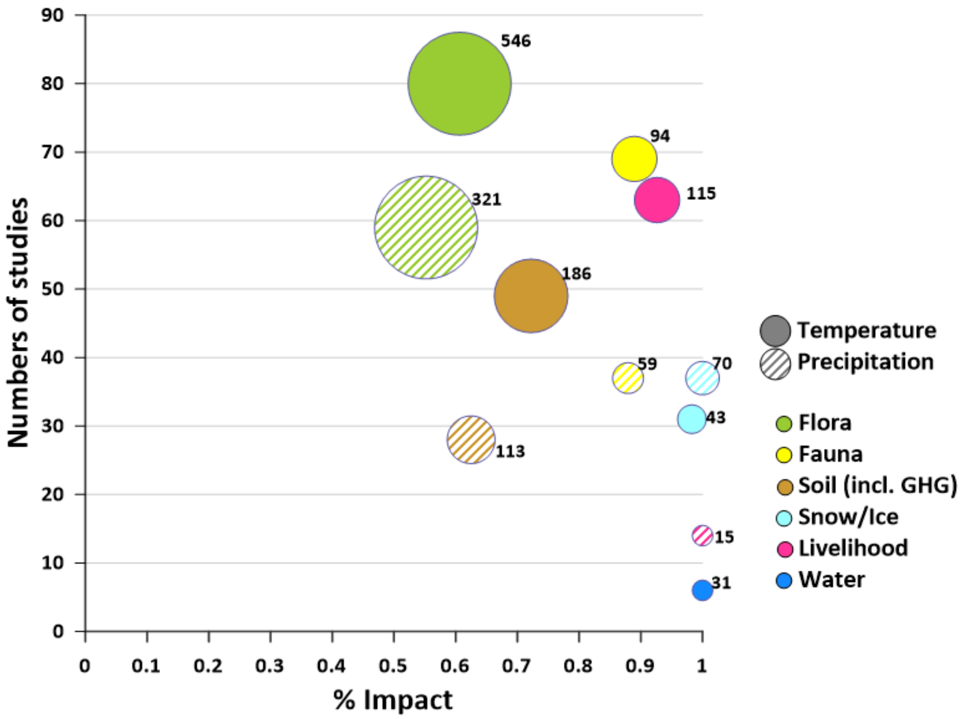

Figure 12. Bubble chart showing the distribution of articles addressing reported impacts, in percent, of EWEs between the years 1981-2022, covering 265 studied articles for the terrestrial Arctic region. Extreme events relating to temperature and precipitation are presented with the studied categories, found on the right.

Figure 13 is showing the average response distribution of the studied ecosystem variables related to investigated EWEs. This bar chart is displaying the response distribution within each category. Relating to the distribution amongst categories, there is an overall more negative response within the categories “Animals” and “Livelihoods” at the top, while the following categories overall have a more positive impact. For example, the variable “Body condition” has around 50% average negative response in connection to EWEs which means that on average, 50% negative response has been seen regarding body condition in connection to EWEs in the terrestrial Arctic. This can for example pertain to a loss of body mass in connection to an EWE.

Figure 13. Bar chart showing the average response distribution of the studied ecosystem variables within categories related to investigated EWEs between the years 1981-2022, covering 265 studied articles for the terrestrial Arctic region. The striped bars indicate a statistically significant result. The different groups of colour relate to variables within categories in connection to EWEs. Yellow presents "Animals", pink presents "Livelihoods", turquoise presents "Snow, ice and albedo", brown presents "Soil, microbes and carbon", green presents "Vegetation" and blue presents "Water".

3.3 Obtained results and consequences combined
Figures 14 and 15 are showing the distribution of investigated articles focusing on occurrence and/or consequence, where Figure 15 is also presenting an additional layer of information pertaining to the geographical area and the type of EWE as well as the number of papers investigated (n_{papers}). In Figure 14, there is a clear division between the distribution of papers investigating consequence or occurrence. Only 32% of investigated articles are focusing on the occurrence of EWEs. Figure 15 is showing how the distribution is different between the geographical regions and investigated EWEs, where it is apparent that, for example, "Extreme cold T" has been the most prominent in the area of Iceland, as reported in the studied articles. In other words, approximately 30% of the articles about Iceland investigate "Extreme cold T".

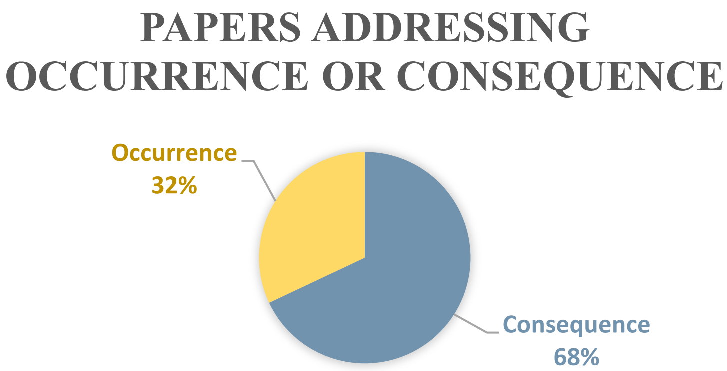

Figure 14. Pie chart showing the distribution of articles addressing reported occurrences or consequences of EWEs between the years 1981-2022, covering 422 studied articles for the terrestrial Arctic region.

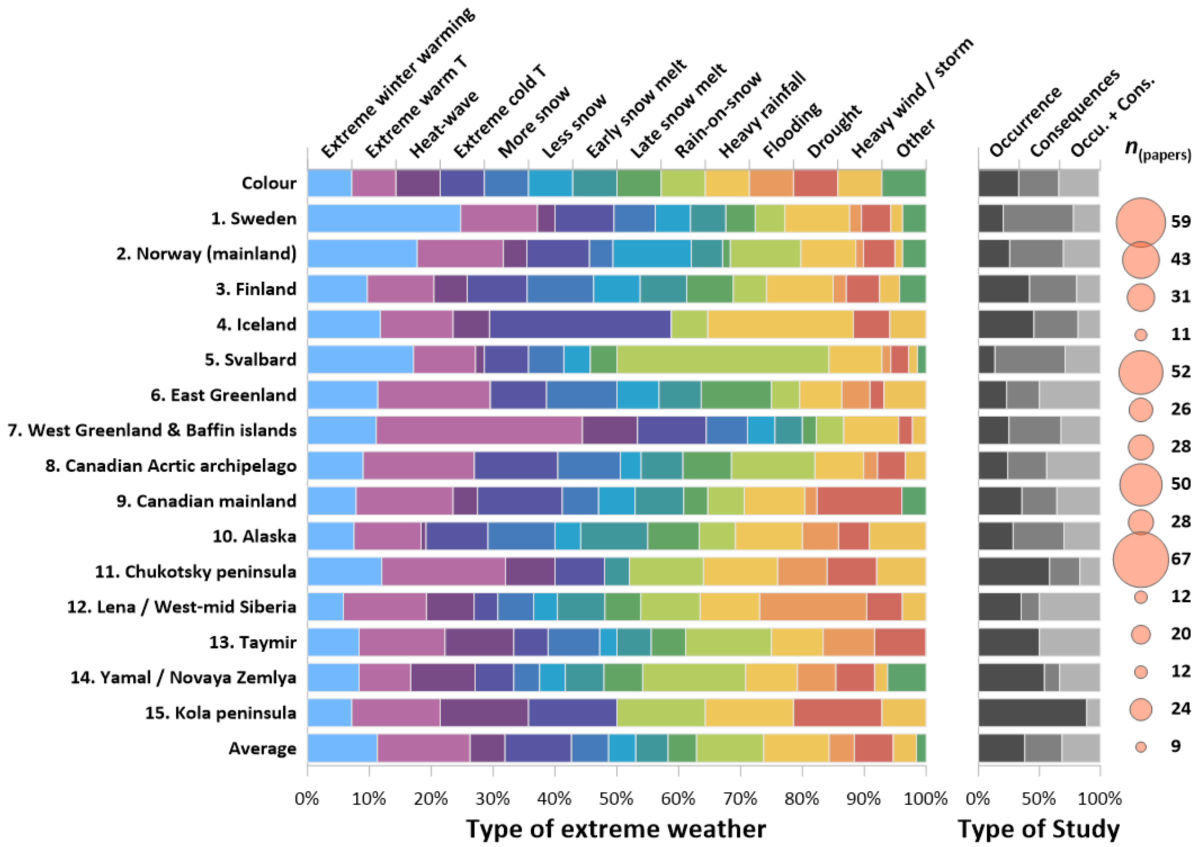

Figure 15. Bar chart showing the type and amount of extreme weather in relation to the geographical areas between the years 1981-2022, covering 265 studied articles for the terrestrial Arctic region. Additionally, a relation to papers addressing occurrence and/or consequence of EWEs can be found on the right side, as well as the number of papers (n_{papers}). The legend of the colours can be found at the top of the bars, relating to the type of EWE. The x-axis on the bottom sums up to 100%.

4. Discussion

4.1 Results and consequences found in the studied articles

From the obtained and assembled results, it is apparent that published scientific articles between the years 1981-2022 relating to EWEs in the terrestrial Arctic region have succeeded in including a variety of EWEs; in relation to the type of EWE and the type of ecosystem as well as the consequences found in the environment (Figures 5, 6 and 9). On a general level, this could mean that scientific research has been able to include necessary aspects relating to EWEs and the Arctic region. However, when considering the details, it is evident that different regions will have different opportunities and challenges which will lead to varying focal points depending on, for example, geographical location. Not all consequences, for example, can be examined everywhere, which is evident in the results. This can explain the results to a degree or is at least one aspect of the outcomes.

When considering the human aspect versus no human aspect included, not taking into account whether the human perspective is considering indigenous peoples or not, there is a clear division (Figure 7). 83% of all studied articles do not include the perspective of humans. Relating this to the results presented in the bubble charts, there is a greater focus on flora, soil and fauna among the scientific articles (Figures 10, 11 and 12). It is not so alien then, to deduce that the human perspective would be less represented among these types of studies where it may be both unsuitable and difficult to include an anthropological perspective. It is, however, important to note the value of the perspective of local communities, and not forget their part in the ecosystem, both traditional as well as more modern cultures. Considering the human perspective with or without the aspect of indigenous peoples (Figure 8), the research can be considered to have succeeded in including both aspects, which can reflect back to the amount of indigenous versus non-indigenous peoples available to include in research projects in the Arctic region. Regarding the consequences in the ecosystem, where animals, vegetation and snow/ice have the largest share whilst biodiversity and energy balance/albedo, for example, have a smaller share may be a result of research interests (funding, trending topics), accessible ecosystems or manageable projects (Figure 9). For all papers investigated in this study, the major share focus on the perspective of consequences, rather than on the occurrences (Figure 14), which may also be a result of possible research projects. It may be a much more difficult task to be able to study an ongoing EWE. The difficulties of capturing an EWE in the act, together with the remoteness of the study areas further complicate the possible studies and experiments.

A deeper understanding of both impacts and consequences is possible from the bar charts (Figures 13 and 15). In Figure 13, it is possible to discern that the average response for each variable varies both within and among the studied categories. It is important to bear in mind that not all positive average responses pertain to a positive result or consequence for the ecosystem. For example, if an article reported an increase in the melting rate of snow during early spring, this would be reported in this study as an increase (of the melting) while it at the same time has a likely negative impact on the ecosystem. The same can be applied to the case of material damage, which is increasing during an EWE. This could be called a negative positive, and vice versa in the opposite cases. This is important to keep in mind when interpreting these results. In Figure 15, the geographical areas of interest relate to the different types of EWEs along with the focus on occurrence and/or consequences found in the studied articles. Yamal/Novaya Zemlya, Finland, Norway and Sweden, for example, have been more successful in, over the studied time period, including a greater variety of EWEs compared to the other studied geographical areas. Iceland and the Kola peninsula on the other hand have included the least amount of different EWEs. It should be noted that overall, the studied geographical areas have succeeded in including most studied variables related to EWEs. From another point of view, the articles covering the Chukotsky peninsula, the Yamal/Novaya Zemlya region and the Kola peninsula have a higher proportion of occurrence reported in the studied articles. These results could relate to specific conditions in those regions, or to another variable unknown in this study. As a last note to the results in this figure, it is of value to mark the number of studied articles in relation to the geographical areas. This will influence the reliability of the results.

4.2 Relation to previous studies

As previously noted, the remoteness and the oftentimes unpredictable weather and nature of the Arctic region create the conditions regarding opportunities and difficulties that fieldwork and studies will face in this part of the globe. Many of the studied articles mentioned a lack of long-term and short-term in situ observations and a general lack of sufficient and available data with reliable quality and desired resolution from the Arctic region, along with large knowledge gaps (AMAP, 2011; Martineau et al., 2022; Revich & Shaposhnikov, 2022). One of the foundational challenges of the region relates to the remoteness of the Arctic, which has and is continuing to hinder fieldwork, observational studies and long-term as well as short-term experiments and gathering of information, to name a few examples of the implications. The possibly harsh nature in itself can be a challenge and a threat for both humans and equipment during scientific expeditions, where rescue may be far away making much-needed expeditions elusive at times. Another aspect of the challenges in this region relates to the number of countries and states that have a claim on the Arctic. As such, many religions, countries, philosophies, policymakers, politicians, peoples and councils need to cooperate and create agreements in the region (Arctic Council, 2023). This may shape, delay or halt the development of vital research. But despite these extreme difficulties, the Arctic proves an important part of our lives, for example in contributing natural resources that are internationally interesting (Vaguet et al., 2021).

Considering traditional and historical practices in the Arctic region, the example of the Sámi people in northern Europe and the practice of reindeer herding highlight new challenges well. The reindeer herders unanimously express concerns with new challenges regarding unprecedented weather and climate extremes (Axelsson-Linkowski et al., 2020). Generational knowledge is usually a vital tool in order to navigate the landscape and manage the reindeer and at the same time educate younger herders, but with new conditions in the landscape, the older herders can contribute less and less with their knowledge as there is simply no previous memory of these conditions for the benefit of the younger herders (Axelsson-Linkowski et al., 2020). Both the traditional way of managing the reindeer herds, such as striving to keep a rotational grazing scheme, as well as the new phenomena of locked pastures, which is when the pasture is locked due to ground icing oftentimes making food inaccessible for the reindeer, are a few examples of the challenges for the tradition of reindeer husbandry in relation to EWEs in the terrestrial Arctic region (Axelsson-Linkowski et al., 2020). One illustrative aspect showcasing these new difficulties is revolving around the fact that the Sámi do not have any words to describe what is happening in the landscape (Axelsson-Linkowski et al., 2020). This emphasizes just how alien these experiences are. This situation is somewhat of a paradox, where the indigenous peoples (again) are among the worst affected by both extreme environmental conditions as well as the adjustments in society for more sustainable energy sources, affecting the landscape used by the reindeer husbandry (Axelsson-Linkowski et al., 2020). This development and trend in societal management combined with new weather and climate conditions, are likely one that will widely affect people around the Arctic, not only communities in northern Europe.

4.3 Methodology

The method of this project was intended to mimic the ongoing research project in order to maintain a consistent methodology. This was chosen with care as this project partakes in an ongoing research project and the fact that it in later steps of the process would create a more reliable foundation to compare the findings. The concept of reviewing literature and published scientific articles in the search of understanding the current knowledge situation in relation to extreme environmental conditions in the Arctic region is an approach that has been investigated in multiple locations over the last few years (Walsh et al., 2020; Markkula et al., 2019; Callaghan et al., 2021). Walsh et al. (2020), investigate the northern areas as a whole in relation to extreme events, also including non-Arctic regions, while Markkula et al. (2019) examine the view of the Sámi people in Finland and Callaghan et al. (2021) explore the Siberian conditions in a changing context. There is a consensus that there currently is a great need to synthesize knowledge in relation to extreme events in the Arctic and nearby regions (Walsh et al., 2020). In the case of the study made by Callaghan et al. (2021), they synthesize Russian research, making research from Russia more available. This aspect is vital in our case as well, since it in some cases was necessary to ignore Russian scientific articles due to language barriers. Overall, these aspects make review studies such as the project of this thesis, valuable for future efforts regarding extreme environmental conditions in the Arctic region.

4.4 Future improvements and opportunities

The focus and boundaries of this project were to investigate published scientific articles relating to the terrestrial Arctic region between the years 1981-2022. As such, all articles which did not meet these foundational criteria were ignored. As mentioned earlier, language barriers also hindered the investigation of potential articles, such as Russian articles. Another potential limiting aspect is related to the selection of keywords used in the literature search, which will shape the outcome and the amount of obtained articles for investigation, which could also be seen as a language barrier. This would most likely continue to be a limiting factor in a similar future study, but it is important to remain vigilant and aware of these limitations. Another central limitation of this project pertains to the very definition of "extreme" relating to EWEs. To solve this issue, the definition of each article had to act as the determining body. Otherwise, the risk of losing a number of potential papers due to a specific definition determined by the authors, would most likely have been very high. In this way, the possibility of capturing as many angles and articles as possible increases.

As seen from the obtained results, there is a need for research projects with a focus on reviewing existing literature and scientific articles in the future. For example, there is a need for further exploration of the human aspect, as well as expanding the research done in less examined ecosystem types, such as lakes, coastal areas and barren areas/glaciers. The same can be said for the consequences found in the ecosystems, where there is a need in the future to further investigate the currently less researched variables, such as biodiversity, energy balance/albedo and economics. Currently, these are the areas that need to be expanded upon in future research projects.

With the anticipation of climate change and the likely increase of human activity in the Arctic region, the need for a deeper understanding of extreme environmental conditions in the Arctic region will increase as well. From increased forecast qualities to equipment well adapted to the future environment including extremes and to well-prepared rescue possibilities as well as to improved housing, to name a few examples of both current and coming challenges. In order to develop multiple layers of societies, we need a wide variety of well-researched subjects. Again, review and meta-studies can help to both fill that gap and most importantly create a foundation for future research opportunities.

5. Conclusions

Based on the attained results from the studied scientific articles relating to extreme weather events in the terrestrial Arctic between the years 1981-2022, the outcome is presented in relation to the research questions:

From the studied articles, it is evident that scientific research has succeeded in covering a wide variety of extreme weather events during the study period. The distribution among the studied extreme weather events is relatively evenly distributed. The distribution among the studied ecosystem types is less evenly divided, where shrub tundra and graminoid tundra are amidst the most well-researched types of ecosystems. Lakes, rivers and coastal ecosystems are, on the other end, among the less well-researched ecosystem types during the study period. Our knowledge about extreme weather events in the terrestrial Arctic region thus concludes as irregular, based on the type of ecosystem and weather event investigated. Furthermore, the aspect of the human perspective has not been well represented in the scientific literature during the study period. On the other hand, when the human aspect has been included in the research, the distribution between indigenous peoples included versus no inclusion of indigenous peoples is relatively even.

Lastly, the studied research has been found to focus on consequences of extreme weather events, rather than occurrences of the same during the study period in the terrestrial Arctic region. This uneven distribution can also be seen among the types of studied consequences, where biodiversity, fire and energy balance/albedo are among the least researched. On the other hand, animals, vegetation, snow/ice, soil and livelihoods are among the more well-researched ecosystems in relation to found consequences of extreme weather events. The studied extreme weather events have been found to have a large impact relating to these ecosystems.

5.1 Future research possibilities

As seen from the obtained results, there is a need for research projects with a focus on reviewing and synthesizing existing literature and scientific articles in the future. For example, there is a need for further exploration of the human aspect in relation to extreme weather events. There is also a need for expanding the research done on less examined ecosystem types, such as lakes, rivers and coastal areas. In the same way, more research focusing on the occurrence of extreme weather events is also necessary, as well as aiming for more evenly distributed research among the different types of consequences studied.

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Appendix A

The following tables include the keywords searched in the search engines Scopus, Web of Science (Clarivate), Zoological Records (Clarivate), and Geobase (engineering village).

Table A1. Scopus search from 2020-01-01 to 2022-12-31 (searched 2023-03-28). Green marks the final number of articles.

		2020-2022
#1	TITLE-ABS-KEY (extreme* AND (snow* OR hail* OR sleet* OR frost* OR flooding OR rainfall OR "rain fall"))	10,233
#2	TITLE-ABS-KEY ((earl* OR late* OR delay*) W/2 (snow* OR frost*))	805
#3	TITLE-ABS-KEY (extreme* W/3 (weather OR event* OR storm* OR wind* OR temperature*))	26,068
#4	TITLE-ABS-KEY ("rain-on-snow" OR "winter warming" OR "winter thaw" OR "heat wave*" OR heatwave* OR drought* OR "ice-crust*" OR "ice crust*" OR (snow W/3 crust*))	41,208
#5	#1 OR #2 OR #3 OR #4	67,322
#6	TITLE-ABS-KEY (arctic OR sub-arctic OR "sub arctic" OR high-arctic OR "high arctic" OR polar OR tundra OR lapland OR lappland)	59,642
#7	#5 AND #6	1,389
#8	TITLE-ABS-KEY ("climat* change" OR "climat* event*" OR "climat* warming" OR "global warming" OR "global change" OR "arctic amplification" OR "chang* climate")	152,505
#9	#5 OR #8	198,590
#10	TITLE-ABS-KEY (reindeer* OR caribou OR "Rangifer tarandus")	1,034
#11	#9 AND #10	198
#12	#7 OR #11	1,565

Table A2. Web of Science search from 2020-01-01 to 2022-12-31 (searched 2023-03-28). Green marks the final number of articles.

		2020-2022
#1	TS=(extreme* NEAR/3 (weather OR event* OR storm* OR wind* OR temperature*))	19,495
#2	TS=(extreme* AND (snow* OR hail* OR sleet* OR frost* OR flooding OR rainfall OR "rain fall"))	11,997
#3	TS=((earl* OR late* OR delay*) NEAR/2 (snow* OR frost*))	696
#4	TS=("rain-on-snow" OR "winter warming" OR "winter thaw" OR "heat wave*" OR heatwave* OR drought* OR "ice-crust*" OR "ice crust*")	42,082
#5	TS=(snow NEAR/3 crust*)	8
#6	#1 OR #2 OR #3 OR #4 OR #5	63,387
#7	TS=(arctic OR sub-arctic OR "sub arctic" OR high-arctic OR "high arctic" OR polar OR tundra OR Lapland OR Lappland)	48,135
#8	#6 AND #7	1,282
#9	TS= ("climat* change" OR "climat* event*" OR "climat* warming" OR "global warming" OR "global change" OR "arctic amplification" OR "chang* climate")	131,598
#10	#6 OR #9	173,383
#11	TS=(reindeer* OR caribou OR "Rangifer tarandus")	1,054
#12	#10 AND #11	225

#13	#8 OR #12	1,484

Table A3. Zoological records (Clarivate) search from 2020-01-01 to 2022-12-31 (searched 2023-03-28). Green marks the final number of articles.

		2020-2022
#1	TS=(extreme* NEAR/3 (weather OR event* OR storm* OR wind* OR temperature*))	1,025
#2	TS=(extreme* AND (snow* OR hail* OR sleet* OR frost* OR flooding OR rainfall OR "rain fall"))	347
#3	TS=((earl* OR late* OR delay*) NEAR/2 (snow* OR frost*))	62
#4	TS=("rain-on-snow" OR "winter warming" OR "winter thaw" OR "heat wave*" OR heatwave* OR drought* OR "ice-crust*" OR "ice crust*")	1,463
#5	TS=(snow NEAR/3 crust*)	3
#6	#1 OR #2 OR #3 OR #4 OR #5	2,474
#7	TS=(arctic OR sub-arctic OR "sub arctic" OR high-arctic OR "high arctic" OR polar OR tundra OR Lapland OR Lappland)	3,748
#8	#6 AND #7	83
#9	TS= ("climat* change" OR "climat* event*" OR "climat* warming" OR "global warming" OR "global change" OR "arctic amplification" OR "chang* climate")	10,513
#10	#6 OR #9	11,900
#11	TS=(reindeer* OR caribou OR "Rangifer tarandus")	354
#12	#10 AND #11	70
#13	#8 OR #12	141

Table A4. Geobase (Engineering Village) search from 2020-01-01 to 2022-12-31 (searched 2023-03-28). Green marks the final number of articles.

		2020-2022
#1	((($extreme NEAR/3 $weather) OR ($extreme NEAR/3 $event) OR ($extreme NEAR/3 $storm) OR ($extreme NEAR/3 $wind) OR ($extreme NEAR/3 $temperature)) WN KY)	10,958
#2	(($extreme AND ($snow OR $hail OR $sleet OR $frost OR $flooding OR $rainfall OR {rain fall OR {rain falling})) WN KY)	6,308
#3	((($early NEAR/2 $snow) OR ($early NEAR/2 $frost) OR ($late NEAR/2 $snow) OR ($late NEAR/2 $frost) OR ($delay NEAR/2 $snow) OR ($delay NEAR/2 $frost) OR {rain-on-snow} OR {winter warming} OR {winter thaw} OR {heat wave} OR $heatwave OR $drought OR {ice-crust} OR {ice crust} OR ($snow NEAR/3 $crust)) WN KY)	15,029
#4	#1 OR #2 OR #3	25,522
#5	(($arctic OR $sub-arctic OR {sub arctic} OR $high-arctic OR {high arctic} OR $polar OR $tundra OR $Lapland OR $Lappland) WN KY)	17,198
#6	#4 AND #5	725
#7	((($climate NEAR/0 $change) OR ($climate NEAR/0 $event) OR ($climate NEAR/0 $warming) OR ($global NEAR/0 $warming) OR ($global NEAR/0 $change) OR {arctic amplification}) WN KY)	58,641
#8	#4 OR #7	74,274
#9	(($reindeer OR $caribou OR {Rangifer tarandus}) WN KY)	430
#10	#8 AND #9	88
#11	#6 OR #10	805