Integrating Activities for Advanced Communities

D2.5 - Updated 'INTERACT Minimum Monitoring Programme

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CO	Confidential, only for members of the Consortium (including the Commission Services)	

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Publishable Executive Summary

Decision makers rely on robust assessments for taking informed decisions to build resilience and adapt to current and projected climate and ecosystem change. While some variables can be monitored remotely, ground observations are important for understanding ecosystem interactions and obtaining accurate observational data across local gradients. Dispersed observations across the Arctic are important for robust assessments. This task assessed the representation of INTERACT stations compared to the entire arctic domain under current and future climate scenarios. The analysis was made as a comparison between the land areas around all INTERACT stations against the entire arctic domain (to see how representative INTERACT stations are as a whole), and the exclusion of Russian stations was then further investigated to analyse the consequences of the exclusion of Russia from international science cooperation due to the war in Ukraine. The results show that the INTERACT network of stations is already biased for several of the eight assessed variables, and that the removal of Russian stations consistently will increase this bias, sometimes to above the magnitude of expected change towards year 2100. The results were published as open source in a high-ranking international science journal to obtain a proof of concept. This provides the foundation for using the tool to improve observational capacity and provide advice to thematic scientific networks/specialists, research station managers, monitoring programme managers, infrastructure funders, etc.

1. Introduction

The Arctic is still an understudied part of the World, and restricted access or lack of infrastructure makes arctic research more complicated than elsewhere. The first scientific activities in the Arctic were conducted using mobile platforms like ships, dog sledges and more rarely air balloons. Later on aircrafts and vehicles brought scientists deeper into the Arctic. As activities increased, a demand for studying specific locations over time, to also understand variability and change, evolved, and the first research stations were established. In INTERACT, the earliest stations date back to 1906 in the Arctic (Arctic Station, Greenland) and to 1886 in the Alpine area (Sonnblick Observatory, Austria). Over the past few centuries efforts to expand our knowledge of the Arctic has increased and simultaneously, research stations have also grown in number, geographical distribution, size of operations and guest capacity. The 74 INTERACT stations currently host more than 15,000 scientists and students studying the physical environment, ecosystems, societies, etc. every year.

In recent decades we have seen increased international collaboration as an effort to harmonise and standardise measurements and sharing data for wider use and informed decision making, also across the Arctic. Scientists have formed thematic scientific networks in efforts to document the status and trends, and to improve our understanding of climate and ecosystem interactions.

Previous INTERACT reports (INTERACT I and INTERACT II) provide INTERACT stations with recommendations for a minimum monitoring system to contribute to these international efforts, to document current variables being monitored by the stations and to provide information on scientific networks and organisations that gives recommendations for standardisation and harmonisation of measurements.

Research and monitoring activities may be undertaken by the stations themselves, by national programmes or by external scientists. A number of factors determine the monitoring capacity of INTERACT stations, i.e. the operational capacity, facilities, financial and human resources, location attractiveness to scientists and knowledge about the station's existence in national and international science communities. It is a challenging task for station managers to stitch together a patchwork of internal and external science endeavours to maximise the scientific achievement and contributions to societal challenges.

Robust assessments of the arctic region require adequate sampling points to cover climatic and environmental gradients. In this report we examine the geographical representation of INTERACT station in relation to the entire arctic domain. In other words, we try investigate how well the INTERACT stations are located geographically to document current status and trends, and future predictions of arctic climate and environmental change.

In light of the ongoing war in Ukraine and its implication for scientific cooperation in the Arctic, we have chosen to make the analysis for all INTERACT stations and then also to analyse what it means to remove Russian research stations from the analysis.

2. Process and framework

While INTERACT I and II produced reports intended to improve the observational capacity of individual stations by recommending a minimum monitoring system and facilitating linkages to thematic scientific networks, this deliverable will explore whether the INTERACT network of stations is representative for the arctic under current and future climate and ecosystem conditions.

The idea was presented at an INTERACT Station Managers' Forum meeting. Based on discussions, a framework and writing group was established consisting of station managers and scientific experts with knowledge about (i) terrestrial ecosystems, (ii) atmospheric science, and (iii) modelling with linkages to Arctic Council Monitoring programmes and international thematic scientific networks.

2.1. Identification of variables

The group decided to focus on eight key variables (four abiotic and four biotic) for the analysis. The variables were inspired by "*AMAP Arctic Climate Change Update 2021: Key trends and Impacts*" to represent relevant above and below ground climate and ecosystem elements.

Variables selected for analysis:

Abiotic variables:

- Air temperature
- Precipitation
- Snow depth
- Soil moisture

Biotic variables:

- Biomass
- Soil carbon
- Net Primary Production
- Heterotrophic respiration

2.2. Analytical method

Remote sensing and numerical modelling can provide guiding for the development of better coordinated monitoring efforts by analysing bias and pinpoint areas with large expected variability where new monitoring may be needed to ensure robust assessments. While large-scale climate models provide credible and convincing numerical estimates of the past and future climate and ecosystem conditions at regional-to-global scales, differences in model performance are far from perfection accumulating multiple uncertainties on current atmospheric and ecosystem processes.

The analysis was limited to areas above 59° N and excluded The Greenland Ice Sheet to focus on the arctic domain and limit bias induced by its relatively large extent compared to the entire terrestrial domain in the Arctic.

In the study we used remote sensing data for all eight variables covering the domain included in the analysis. Earth System Models (ESMs) were used to quantify the pan-Arctic scale environmental conditions as a baseline to which we compare the environmental conditions found at INTERACT research stations. Specifically, we examined how eight of the most up-to-date ESMs from the Coupled Model Intercomparison Project Phase 6 (CMIP6), included in the IPCC Sixth Assessment Report (AR6, IPCC 2022), describe the present-day and future Arctic abiotic and biotic response variables at the INTERACT stations.

Accumulation curves were then used to compare all grid-cells with grid-cells occupied by INTERACT stations. A good match would mean good representation, while differences indicate biased and hence non-representative sampling (the methodology is further explained in the paper below).

3. Proof of concept and publication

The tool has potential for assessing knowledge gaps and representative sampling of any variable across spatial scales and could therefore be used to make recommendations for improving the robustness of arctic scale monitoring efforts of importance to the scientific communities, infrastructure managers and funders and decision makers depending on reliable assessments and predictions for adaptive management responses.

To get proof of concept we chose to publish the paper in a high-ranking journal and to ensure maximum impact it was published as ‘Open source’ to reach the broadest possible audience. Nature Climate Change was chosen for publication and the manuscript was accepted in January 2024 (see section 4).

https://www.nature.com/articles/s41558-023-01903-1

4. Future perspectives and use of the tool

The tool is being applied in another EU project (POLARIN) to provide information for the design of Transnational Access calls. Analysis of observational gaps in arctic and Antarctic ecosystems for key climate and ecosystem variables will provide input to the Scientific Liaison Panel responsible for call design. At the same time, the system can also be used to assess how TA funding has improved observational capacity in polar areas for the given variables.

The analytical tool can be scaled-up with:

- Any model variables available (atmospheric, terrestrial, marine, ...)

- More ESM CMIP6 models to increase the robustness of the analysis and learn about uncertainties

Our approach can also be used to synthesize the state of knowledge, quantifying potential biases and identify gaps to guide empirical studies. We can inform:

- Station managers about which variables would be ecologically/scientifically relevant to monitor;
- Researchers about geographical gaps in circum-arctic monitoring efforts;
- Policymakers about geographical gaps in infrastructure and monitoring efforts that needs to be addressed to improve robustness of assessments, needed for well-informed management and conservation initiatives mitigating some of the negative consequences and risks exposed by climate change.

The analysis and tool have been presented at Arctic Science Summit Week 2024 and EU Polar Science Week 2024 and it will be presented as part of an accepted ICARP IV session on the importance of linking science and infrastructure planning to ensure representative sampling across the Arctic at ASSW 2025.

5. Publication

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Towards an increasingly biased view on Arctic change

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Check for updates

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The Russian invasion of Ukraine hampers the ability to adequately describe conditions across the Arctic, thus biasing the view on Arctic change. Here we benchmark the pan-Arctic representativeness of the largest high-latitude research station network, INTERACT, with or without Russian stations. Excluding Russian stations lowers representativeness markedly, with some biases being of the same magnitude as the expected shifts caused by climate change by the end of the century.

As a result of the Russian attack on Ukraine, the Western world has excluded Russia from international fora. This geopolitical conflict severely challenges transnational collaboration on global issues. This is particularly evident when it comes to the Arctic. Russia is geographically the largest Arctic nation and is, hence, also one of eight nations within the Arctic Council, an intergovernmental forum for coordinated activities across the Arctic countries (https://arctic-council.org/). However, following the invasion of Ukraine, the work of the Arctic Council was first put on hold, and as currently resumed, it is only in part and without Russia.

The Arctic is rapidly changing[1,2], and many of the ongoing changes may have global consequences[3]. While many of the key indicators of Arctic climate change (for example, refs. 4,5) and climate-induced responses (for example, refs. 6,7) can be estimated remotely, much of the understanding of Arctic change is based on in situ data measured on the ground at research stations. As ground-based observations that form the basis for assessments of the region's state will now come mainly from the non-Russian parts of the Arctic, the overall ability to monitor the status and trajectory of the Arctic biome may be severely limited over the foreseeable future. The question is to what extent this challenge may bias the overall view on Arctic change. However, to better understand this challenge, there needs to be acknowledgement that the current view on Arctic change might already be biased[8,9]. Logistical constraints and limited long-term funding for conducting research and monitoring in vast and remote areas[10] have led to the establishment of only relatively few research stations scattered across the Arctic without an optimal statistically determined sampling regime[8,11]. Most ground-based data collection and the resultant scientific publications are therefore spatially clumped[8,9,12], and may thus not be representative of the Arctic region as a whole. Siberia and the Canadian high Arctic appear particularly under-represented[8,9].

In this Brief Communication, we assess potential additional biases in the view on current and projected terrestrial Arctic change amid the current geopolitical conflict. To achieve this, we quantify how well Arctic research stations, with or without Russian stations included, represent ecosystem conditions at the pan-Arctic scale. We use a suite of eight state-of-the-art Earth system models (ESMs) from the Coupled Model Intercomparison Project Phase 6 (CMIP6)[13], included in the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report[14], at their native spatial resolutions (Extended Data Table 1). We focus specifically on eight essential abiotic and biotic variables describing key conditions in high-latitude terrestrial ecosystems[2]: annual mean air temperature, total precipitation, snow depth, soil moisture, vegetation biomass, soil carbon, net primary productivity and heterotrophic respiration. These essential ecosystem variables serve as benchmarks for environmental conditions found across the circumpolar region and at Arctic research stations located above 59° N, as represented by the pan-Arctic infrastructure network

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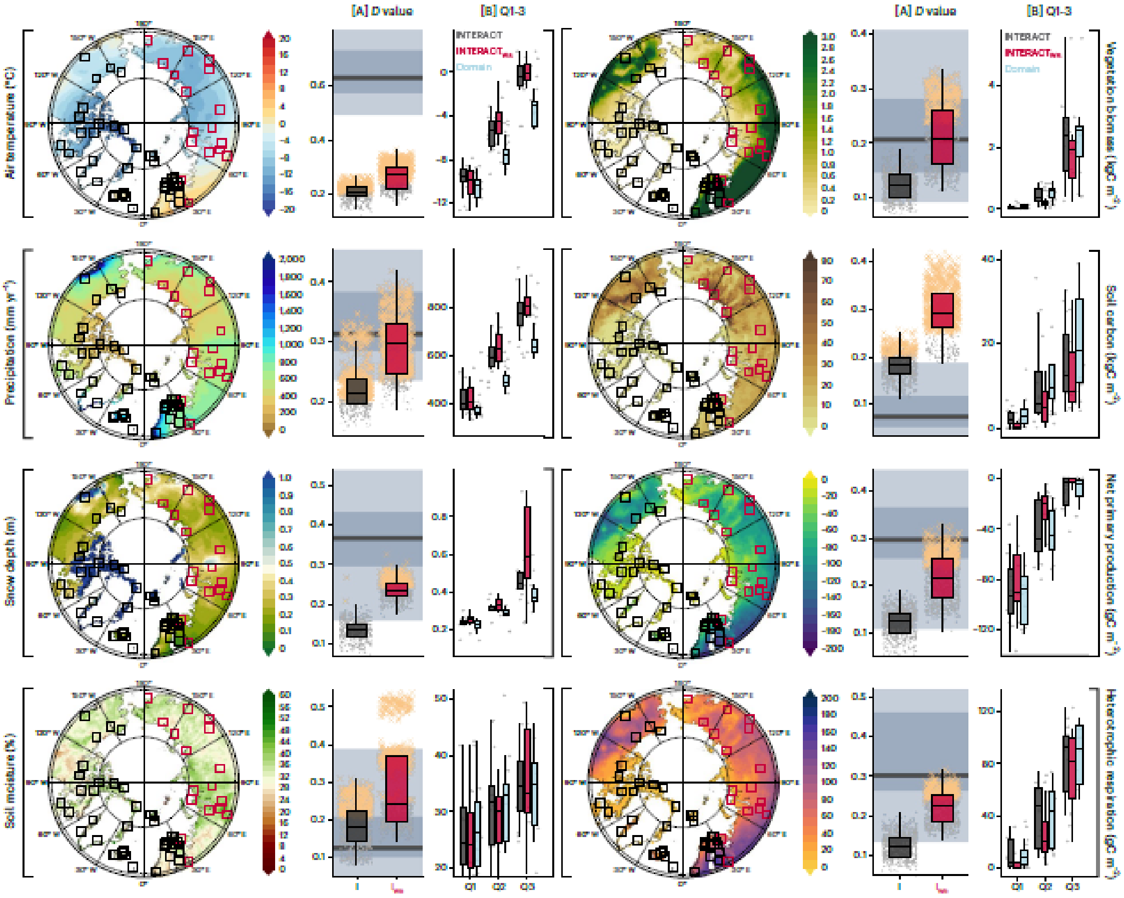

Fig. 1 | Shifts in representativeness. The effects of excluding Russian research stations (red boxes on the maps) from the INTERACT network with respect to eight ecosystem variables (air temperature, total precipitation, snow depth, soil moisture, vegetation biomass, soil carbon, net primary productivity and heterotrophic respiration). Maps visualize contemporary conditions above 59° N. For each variable, the potential biases of INTERACT with respect to the conditions in the pan-Arctic domain are depicted by two sets of box plots: [A] and [B]. [A] shows the maximum deviation (*D* values) between two cumulative distribution functions (INTERACT with (I) or without (I_{wR}) Russian stations) versus the contemporary pan-Arctic domain. The maximum deviation between the contemporary versus end-of-the-century pan-Arctic domain is shown by the horizontal grey bars, with the lighter and darker colours representing the median and the 25–75% and 2.5–97.5% confidence intervals, respectively. [B] displays the quartiles 1 to 3 values for the ecosystem contemporary conditions of INTERACT with (black) and without (red) Russian stations as well as across the pan-Arctic domain (blue). Note that, for *D* values, both the eight ESMs and the resampling from the domain contribute to the variation, while variation for quartiles 1–3 is attributable to only the ESMs. All box plots show the median and interquartile range (IQR), with the upper and lower whiskers extending to the largest value ≤1.5 × IQR from the 75th percentile and the smallest values ≤1.5 × IQR from the 25th percentile, respectively. Outliers have been omitted to increase readability but are presented in Extended Data Fig. 1.

International Network for Terrestrial Research and Monitoring in the Arctic (INTERACT, https://eu-interact.org/)[15].

Acknowledging that the INTERACT network may not be fully representative of the Arctic as a whole[9], we first quantify any bias of the network in representing the contemporary spatial variability of key abiotic and biotic ecosystem conditions across the pan-Arctic region. We then ask whether the exclusion of Russia from INTERACT accentuates any potential bias. To quantify the discrepancies between the pan-Arctic domain and INTERACT research stations with or without those in Russia, we calculated two metrics. First, we calculated the maximum differences between the cumulative distribution functions (the *D* values from Kolmogorov–Smirnov (K–S) tests) of the pan-Arctic domain and INTERACT stations with or without Russian stations across the eight CMIP6 ESMs for each of the eight ecosystem variables (Fig. 1a). Significant *D* values ($P < 0.05$) were regarded as lack of representativeness between the INTERACT network with or without Russia and the pan-Arctic region. As a yardstick of magnitude, we compared these *D* values with those derived from the projected shifts in ecosystem conditions between the years 2016–2020 and 2096–2100 using the Shared Socioeconomic Pathway (SSP) 5-85 scenario. Second, to visualize the possible biases we also extracted the first (25%), second (median) and third (75%) quartile (Q1–Q3) values of the distribution functions for each ESM and ecosystem variable from the INTERACT research stations with or without Russian stations and compared those with the conditions across the entire pan-Arctic region (Fig. 1b). We do acknowledge that ecosystem models are associated with uncertainties (Methods), and are as such not an absolute descriptor of environmental variation. Still, ecosystem models are the best tool we have for inferring

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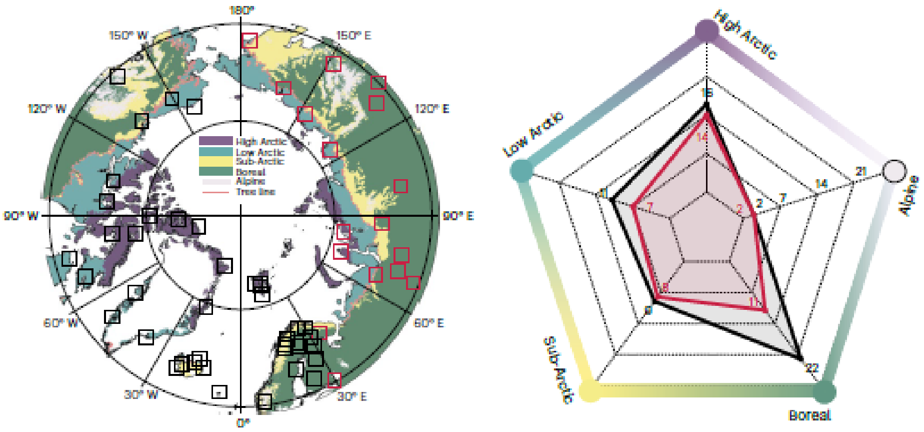

Fig. 2 | Loss of ecoregion representation. The impact of excluding Russian research stations from the INTERACT network on the count of research stations across the range of high-latitude ecoregions covered by the network. The INTERACT research stations are represented in the map by squares, and the red squares indicate the positions of the Russian stations. The radar plot to the right illustrates the number of stations within the various ecoregions, with the black polygon depicting all INTERACT stations and red polygon depicting the non-Russian stations only.

large-scale patterns in contemporary ecosystem conditions in a consistent manner and for projecting into the future.

Our results suggest that, even with all Russian stations included, the INTERACT network is consistently biased for some ecosystem variables and is thus not fully representative of the ecosystem conditions across the pan-Arctic domain (Fig. 1). The INTERACT stations are generally located in the slightly warmer and wetter parts of the Arctic in areas with generally deeper snowpacks. INTERACT stations are also located in areas with lower vegetation biomass and soil carbon than the Arctic region as a whole. This pattern is the same across the three quartiles examined (Fig. 1b), suggesting that the lack of representativeness for these key ecosystem variables is consistent across the parameter space. Hence, the knowledge based on ground-collected science may be biased, even when based on data from all Arctic INTERACT research stations. This corroborates the findings of previous studies[8,9]. Yet, local-scale spatial (subgrid) variability in ecosystem conditions around many research stations means that the environmental span covered by each INTERACT research station is broader than depicted by our large-scale analyses here (see, for example, ref. 16). The representativeness bias is thus probably different from what we have estimated here, but it is not possible to say whether subgrid variation generally contributes to lower or higher bias. On the other hand, as current ecosystem monitoring conducted locally at INTERACT stations is not fully coordinated nor standardized, the representativeness of the network for the pan-Arctic region may be even lower for some variables. It is only when research stations across the pan-Arctic region measure the same variables in a consistent manner across sites that we can achieve a more comprehensive and less biased understanding on Arctic change. Our measure of representativeness is thus rather a measure of potential representativeness.

Making matters more challenging, the exclusion of the Russian stations from the network (17 out of 60) resulted in a marked further loss of representativeness across almost all ecosystem variables, compared to modelled variables for the pan-Arctic region as a whole. For example, about half of the INTERACT stations located in the boreal zone are lost with the exclusion of Russia (Fig. 2), and with that, Siberia's extensive taiga forest is no longer represented in the network. This results in additional biases, particularly with respect to vegetation biomass, with a concomitant increased bias in net primary productivity and heterotrophic respiration (Fig. 1a and Extended Data Table 2). Being a region characterized by rapid climate change[17], the loss of Siberian research stations may be particularly detrimental for the ability to track global implications of thawing permafrost[18], shifts in biodiversity, including shrubification[19] and carbon dynamics[20]. Notably, for some variables (for example, precipitation and vegetation biomass) the offset increase was of a similar magnitude as the shifts inflicted by almost 80 years of projected climate change (Fig. 1a).

Because of the geopolitical consequences of the Russian attack on Ukraine, the ability to both track and further project the development of the Arctic biome following climate-induced ecosystem change has deteriorated. And with that, the ability to initiate well-informed management and conservation initiatives that would help mitigate some of the negative consequences and risks exposed by climate change is greatly reduced. Understanding the gaps and biases is a prerequisite to, at least to some extent, consider and address them, and thereby improve the ability to make credible predictions despite imperfect coverage. Still, to be able to track the changing Arctic properly, the international community should, however, continue to strive for establishing and improving a research infrastructure and standardized monitoring programmes representative of the entire Arctic. This system should also promote open-access data sharing to increase accessibility and coherency. Sadly, until that is implemented, the ability to support and advise local and global communities will decrease further due to the loss of Russian stations representing half of the Arctic's landmass.

Online content

Any methods, additional references, Nature Portfolio reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41558-023-01903-1.

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Methods

Research stations in the Arctic

With 94 research stations in total, of which 21 are located in Russia, INTERACT (https://eu-interact.org/) is the most extensive network of research stations in the Northern Hemisphere. The INTERACT network aims to build capacity for documenting, understanding, predicting and responding to environmental changes achieved through the close integration of research and monitoring. The INTERACT stations cover a wide selection of climatic (high/low Arctic, sub-Arctic, boreal and alpine) and permafrost (continuous, discontinuous and sporadic) zones. To represent the network in the Arctic properly, we identified 60 grid cells containing the location of INTERACT stations above 59° N, excluding the Greenland Ice Sheet and INTERACT sites located in Svalbard sharing the same coordinates. Seventeen of these stations are located in Russia. The coordinates for the INTERACT stations have been obtained from the INTERACT Station Catalogue 2020 (available at https://eu-interact.org/).

Spatial variability in ecosystem variables

We characterized the spatial variability of key abiotic and biotic ecosystem variables across the pan-Arctic domain using extracts from eight different ESMs (Extended Data Table 1) within the CMIP6 projections included in the IPCC Sixth Assessment Report[14]. Although today more ESMs are available, the ESMs included here were selected because they (1) include all ecosystem variables of interest (see below) and (2) are a diverse sample of most of the CMIP6 models as a function of effective climate sensitivity[21]. The CMIP6 datasets were downloaded from the open-source data repositories[22,23]. The model variant used for the eight ESMs was r1i1p1f1 (r, realization/ensemble member; i, initialization method; p, physics; f, forcing) to allow for appropriate comparability.

We assessed the spatial variability in eight key ecosystem variables: air temperature (°C), total precipitation (mm per year), snow depth (m), soil moisture (%), vegetation biomass (kgC m^{-2}), soil carbon (kgC m^{-2}), net primary productivity (gC m^{-2}) and heterotrophic respiration (gC m^{-2}). These variables not only characterize the spatial variability in ecosystem conditions but are also known to be undergoing rapid changes across the pan-Arctic region[1]. The choice of variables was motivated by the key most recent trends and impacts from Arctic climate change reported by the *Arctic Climate Change Update 2021: Key Trends and Impacts* report[1]. For instance, air temperature is an excellent indicator that locally aggregates surface and atmospheric (vertical and horizontal) energy budgets. The temperatures in the Arctic have warmed three[1] to four[5] times that of the globe, increasing by ~3 °C during the 1971–2019 period according to EU Copernicus ERA5 monthly dataset. The total precipitation, together with air temperatures, are drivers of change for multiple ecosystem components. Precipitation in the Arctic is increasing nearly 10% in the same period and is driven by a 25% rainfall increase over-compensating for a loss of snow cover[1]. The Arctic system is typically covered by snow in the winter months, making the shoulder seasons (spring and autumn) especially sensitive to changes due to warming. The snow cover extent between May and June has decreased by 21% over the 1971–2019 period[1]; this is a percent loss rate greater than the loss of sea ice in September. Both rainfall and snow dynamics are among the key factors driving soil moisture availability that, at the same time, have important implications over plant phenology and productivity[24]. The tundra greenness has increased by 10% between 1982 and 2019 despite some regions exhibiting browning[1]. Greener tundra can increase the accumulated carbon storage and leaf area index further enhancing the photosynthetic capacity and stimulating higher gross carbon fluxes[25] but also have important implications for land surface energy budget as does the reduction in spring snow cover[26]. Finally, the terrestrial C pool in the Arctic accounts for approximately 50% of the global soil organic C pool[27]—changes in soil temperature and permafrost dynamics can have strong implications on atmospheric release of greenhouse gasses and feedback to the global climate[28].

For each ecosystem variable and each ESM, we collated and processed monthly aggregated gridded information across the pan-Arctic domain. To describe the contemporary ecosystem conditions, we used the means of the years 2016–2020. To allow for comparison of spatial versus temporal changes (see below), we also estimated the spatial variability in the eight ecosystem parameters by the end of the twenty-first century (2096–2100) for each ESM. We used the SSP greenhouse gas emission scenario 5-85, equivalent to the former Representative Concentration Pathway 8.5 in the IPCC Fifth Assessment Report. We focused on this business-as-usual scenario as it has been recently found that we are very close to the upper part of, if not exceeding, the most drastic projection at least until the middle of the twenty-first century[5].

From the monthly aggregated global CMIP6 ESM products, we then cropped out latitudes below 59° N and excluded the fractional Greenland Ice Sheet cover[29]. The spatial resolution of the individual ESMs was retained.

Data analysis

To assess the representativeness of the INTERACT stations of the entire pan-Arctic region, we calculated the density distribution for each individual abiotic and biotic ecosystem variable. As contemporary and future conditions, we used the mean across the years 2016–2020 and 2096–2100, respectively. First, we estimated the density distributions (Extended Data Fig. 2) for INTERACT with all stations included, and then with all Russian stations excluded. To describe the baseline conditions across the pan-Arctic domain, we randomly sampled the same number of grid cells from all ESMs, regardless of their native spatial resolution, equal to the smallest population size among all models (that is, the CanESM5 with 496 datapoints, excluding pixels containing ocean and the Greenland Ice Sheet; Extended Data Table 1). To minimize potential artefacts emerging from the arbitrary sample size choice, we retrieved 100 replicates of the random sample populations of 496 datapoints per ESM and variable. A simple sensitivity analysis assessing the impact of the number of samples and the number of replicates on the K–S statistics can be found in Extended Data Fig. 3.

To describe any bias between ecosystem conditions between INTERACT with and without Russian stations and the pan-Arctic domain further, we used the *D* values from non-parametric K–S tests as a measure of the maximum offset between the density distributions (Fig. 1a). *D* values represent the maximum vertical distance between the cumulative distribution function described by the INTERACT network (with or without Russia) and the cumulative distribution function describing the pan-Arctic domain. The null hypothesis is that both groups were sampled from identical distributions, and significant K–S tests thus indicate that distributions differ. As a yardstick for the magnitude of the potential bias, we used the *D* values derived from comparing the projected shifts in ecosystem conditions between the years 2016–2020 and 2096–2100 (see above). To visualize potential biases further, we extracted the first, second (median) and third quartiles (Q1–Q3) from the density distributions, as general indicators of the ecosystem conditions at the INTERACT stations (with and without Russian stations) and across the pan-Arctic region (Fig. 1b).

To visualize the impacts of the exclusion of Russia from INTERACT as loss of ecoregion representation across the pan-Arctic region, we calculated the distribution of INTERACT stations per ecoregion with and without Russian stations. The ecoregions in Fig. 2 were defined as follows: (1) the High Arctic region covered the bioclimatic subzones A, B and C, from the Circumpolar Arctic Vegetation Map[30] (CAVM; accessible in ref. 31), (2) the Low Arctic region covered the CAVM subzones D and E and (3) the Sub-Arctic region is derived from the tundra forest subzone in the Ecoregion 2017 classification[32] (available at https://ecoregions.appspot.com/) situated below the tree line. The Boreal region corresponded to the Ecoregion 2017 boreal forest subzone, and the Alpine region covered altitudes above 1,000 m but below the tree line. The latter was derived by the ArcticDEM product[33] (accessible in ref. 34).

Data and analysis caveats

Incorporating in situ field information holds the potential to reduce the anticipated uncertainties associated with the type of analysis presented in this paper. A growing abundance of high-temporal, quality-checked, long-term data is now accessible through online repositories for both scientific papers and data (for example, thematic scientific networks like FLUXNET, International Permafrost Association and so on). However, a substantial gap still remains in terms of a unified, coordinated approach to harmonize and integrate diverse monitoring data from various sources (spanning across countries or disciplines), as highlighted in refs. 8,9. Moreover, the absence of standardized methodologies (such as instrument branding, variable units or temporal resolutions) among research stations presents a challenge to comprehensive in situ field data intercomparisons.

Additionally, while robust spatial products are available, such as re-analysis climate forcing (for example, ERA5 (ref. 35)), remote sensing products (for example, ESA Climate Change Initiative for vegetation-related variables such as biomass[36]) and machine learning-derived estimates (for example, FLUXCOM for terrestrial C fluxes[37]), it is important to acknowledge that such datasets are associated with inherent biases and uncertainties (as highlighted in, for example, ref. 38). Similarly, bottom-up exercises from land cover/vegetation type classification maps, though valuable for upscaling, can be affected by heterogeneity issues and uncertainties, leading to potential biases when extrapolating from such analyses.

Coupled climate models remain the best and currently the only tools available for evaluating shifts and trends in the future climate system[13], along with the associated ecosystem responses and feedback loops[39]. While large-scale climate models provide credible and convincing numerical estimations for recent past and future scenarios on a regional-to-global scale[40], differences in model performance are far from perfection[41]. For instance, model uncertainties stem from various sources, including differences in model structure and parameterization (for example, ref. 42), external forcing (for example, ref. 43) and emission scenarios (for example, ref. 44). Such limitations introduce uncertainties on both atmospheric (for example, refs. 45,46) and ecosystem processes (for example, refs. 47,48), particularly those related to land (for example, refs. 38,49). Currently, the terrestrial carbon cycle remains the least constrained component of the global carbon budget (for example, ref. 50). For example, the models account for equilibrium states, but it has been recognized since the 1980s that plant species are unlikely to relocate as fast as their appropriate climate envelopes (for example, ref. 51). Also, models of treeline movement overestimate latitudinal relocation by up to 2,000 times[52]. A consequence of this is that some vegetation will remain in climate envelopes to which they are not adapted and will/are experiencing impacts of extreme events. These impacts have local implications[53], and some have regional impacts, for example, the movement of the Circum-Arctic treeline[54] and the impacts of thawing permafrost on wetland dynamics and vegetation/biodiversity[6,55].

Data availability

All CMIP6 modelling datasets used in this study can be accessed and downloaded freely from ESGF repositories (for example, https://esgf-node.llnl.gov/projects/cmip6/ and https://esgf-data.dkrz.de/search/cmip6-dkrz/). Locations of Arctic research stations are available at the INTERACT GIS portal https://www.interact-gis.org/Home/Stations. The source datasets generated and/or analysed during the current study are provided, corresponding to each figure and table. Any additional data are available from the corresponding author. Source data are provided with this paper.

Code availability

The script employed in this study to quantify maximum differences in cumulative distribution functions (*D* and *P* values from K–S tests) between various sample populations (the pan-Arctic domain and INTERACT stations, with or without Russian stations), and extract the quartiles (Q1–Q3) values of the distribution functions of the same populations, is available in the GitHub repository at https://github.com/EfrenLB/KST.

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Author contributions

E.L.-B. and N.M.S. designed the study based on discussions between all authors. E.L.-B. analysed the data and performed the statistical analyses. E.L.-B. and N.M.S. drafted the paper with input from all co-authors. All authors read and approved the final version of the paper.

Competing interests

The authors declare no competing interests.

Additional information

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Extended Data Table 1 | List of ESM simulations used in the analysis (metadata derived from https://wcrp-cmip.github.io/CMIP6_CVs/docs/CMIP6_source_id.html)

Model ID	Origin	Institution ID	Atmosphere model	Aerosol model	Land surface and and vegetation model	Spatial resolution
EC-Earth3-CC	Europe	EC-Earth Consortium	IFS cy36r4 (TL255; 512 × 256; 91 levels)	–	HTESSEL (land surface scheme built in IFS) and LPJ-GUESS v4	0.703125°
NorESM2-MM	Norway	Norwegian Climate Center	CAM-OSLO (1 degree; 288x192; 32 levels)	OsloAero	CLM5	1.25° × 0.94°
ACCESS-ESM1-5	Australia	The Commonwealth Scientific and Industrial Research Organisation	HadGAM2 (r1.1; N96; 192x145; 38 250km levels)	CLASSIC (v1.0)	CABLE2.4	1.875°x 0.125°
BCC-CSM2-MR	China	Beijing Climate Center	BCC_AGCM3_MR (T106; 320x160; 46 levels)	–	BCC_AVIM2	1.125°
CanESM5	Canada	Canadian Centre for Climate Modelling and Analysis	CanAM5 (T63L49; 128x64; 49 levels)	interactive	CLASS3.6/CTEM1.2	2.8125°
CMCC-ESM2	Italy	Euro-Mediterranean Centre on Climate Change	CAM5.3 (1degree; 288x192; 30 levels)	–	CLM4.5 (BGC mode)	1.25° × 0.94°
IPSL-CM6A-LR	France	Institute Pierre Simon Laplace	LMDZ (N96; 144x143; 79 levels)	–	ORCHIDEE (v2.0, Water/Carbon/Energy mode)	2.5° × 1.27°
MPI-ESM1-2-LR	Germany	Max Planck Institute	ECHAM v6.3 (T63; 192x96, 47 levels)	none, prescribed MACv2-SP	JSBACH3.20	1.875°

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Extended Data Table 2 | Summary of the mean Q1-3 and mean KS D-values for the eight ecosystem variables (air temperature, TA; total precipitation, TP; snow depth, SD; and soil moisture, SM; vegetation biomass, VB; soil carbon, SC net primary production, NPP; and heterotrophic respiration, RH). 'INTERACT' refers to the INTERACT network with all stations above 59°N included, 'INTERACT$_{WR}$' to the INTERACT network without the Russian stations, and 'Arctic 2020' to the pan-Arctic conditions during the period 2016–2020. 'Arctic 2100' refers to the projected shift in ecosystem conditions between contemporary (2016–2020) and future (2096–2100)

	Variable	INTERACT	INTERACT$_{WR}$	Arctic 2020
Q2 (Medians)	TAS (°C)	–5.32	–4.57	–7.7
	PR (mm y^{-1})	588	625	490
	SD (m)	0.302	0.33	0.277
	SM (%)	31.6	30	32.8
	VB (kg C m^{-2})	0.349	0.163	0.559
	SC (kg C m^{-2})	5.76	4.92	9.52
	NPP (g C m^{-2})	–48.6	–20.2	–46.1
	RH (g C m^{-2})	47.3	20.6	43.9
	Variable	INTERACT	INTERACT$_{WR}$	Arctic 2020
Q1	TAS (°C)	–9.62	–9.99	–10.4
	PR (mm y^{-1})	402	408	366
	SD (m)	0.229	0.253	0.225
	SM (%)	24.3	24	26.3
	VB (kg C m^{-2})	0.0192	0.00005	0.0624
	SC (kg C m^{-2})	2.04	0.22	2.87
	NPP (g C m^{-2})	–93.5	–91	–87.7
	RH (g C m^{-2})	3.85	0.0205	7.77
	Variable	INTERACT	INTERACT$_{WR}$	Arctic 2020
Q3	TAS (°C)	–0.532	–0.0927	–3.05
	PR (mm y^{-1})	773	803	633
	SD (m)	0.44	0.58	0.369
	SM (%)	34.4	33.1	34.7
	VB (kg C m^{-2})	2.34	1.89	2.52
	SC (kg C m^{-2})	12.5	8.54	18.4
	NPP (g C m^{-2})	–3.71	–0.00365	–4.39
	RH (g C m^{-2})	91.8	81.8	91.2
	Variable	INTERACT	INTERACT$_{WR}$	Arctic 2100
D-values	TAS	0.206	0.271	0.621
	PR	0.214	0.294	0.31
	SD	0.13	0.23	0.363
	SM	0.177	0.236	0.121
	VB	0.123	0.21	0.206
	SC	0.183	0.294	0.0726
	NPP	0.125	0.215	0.296
	RH	0.122	0.227	0.3

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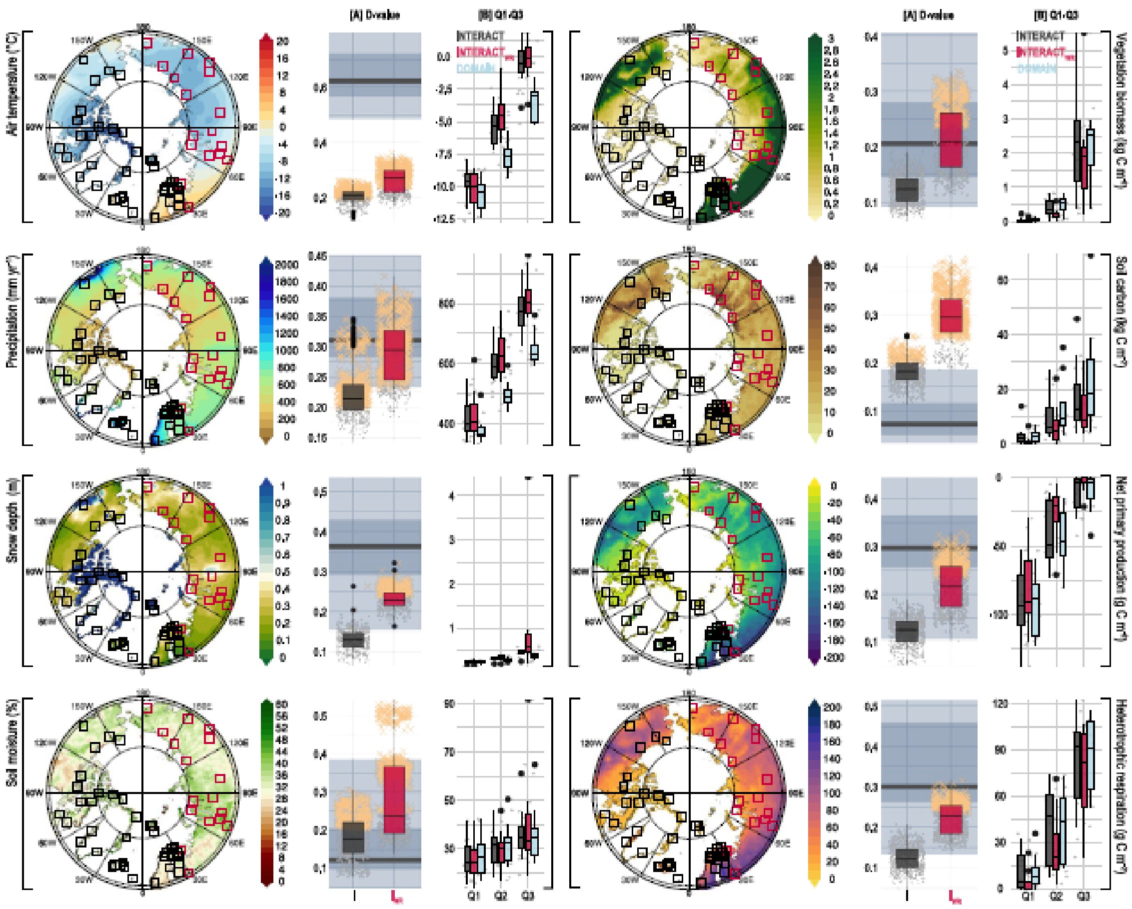

Extended Data Fig. 1 | Shifts in representativeness (including outliers). The effects of excluding Russian research stations (red boxes on the maps) from the INTERACT network with respect to eight ecosystem variables (air temperature, total precipitation, snow depth, soil moisture, vegetation biomass, soil carbon, net primary productivity, and heterotrophic respiration). Maps visualize contemporary conditions above 59°N. For each variable, the potential biases of INTERACT with respect to the conditions in the pan-Arctic domain are depicted by two sets of boxplots [A] and [B]. [A] shows the maximum deviation (D-values) between two cumulative distribution functions (INTERACT with (I) or without Russian stations (I_{WR})) versus the contemporary pan-Arctic domain. The maximum deviation between the contemporary versus end of the century pan-Arctic domain is shown by the horizontal grey bars with the lighter and darker colours representing the median and the 25–75% and 2.5–97.5% confidence intervals, respectively). [B] displays the quartiles 1 through 3 values for the ecosystem contemporary conditions of INTERACT with (in black) and without Russian stations (in red) as well as across the pan-Arctic domain (in blue). Note that for D-values both the eight ESMs and the resampling from the domain contribute to the variation, while for the quartiles 1–3 variation is only attributable to the ESMs. All box plots show the median and interquartile range (IQR), with the upper and lower whiskers extending to the largest value ≤ 1.5 × IQR from the 75th percentile and the smallest values ≤ 1.5 × IQR from the 25th percentile, respectively.

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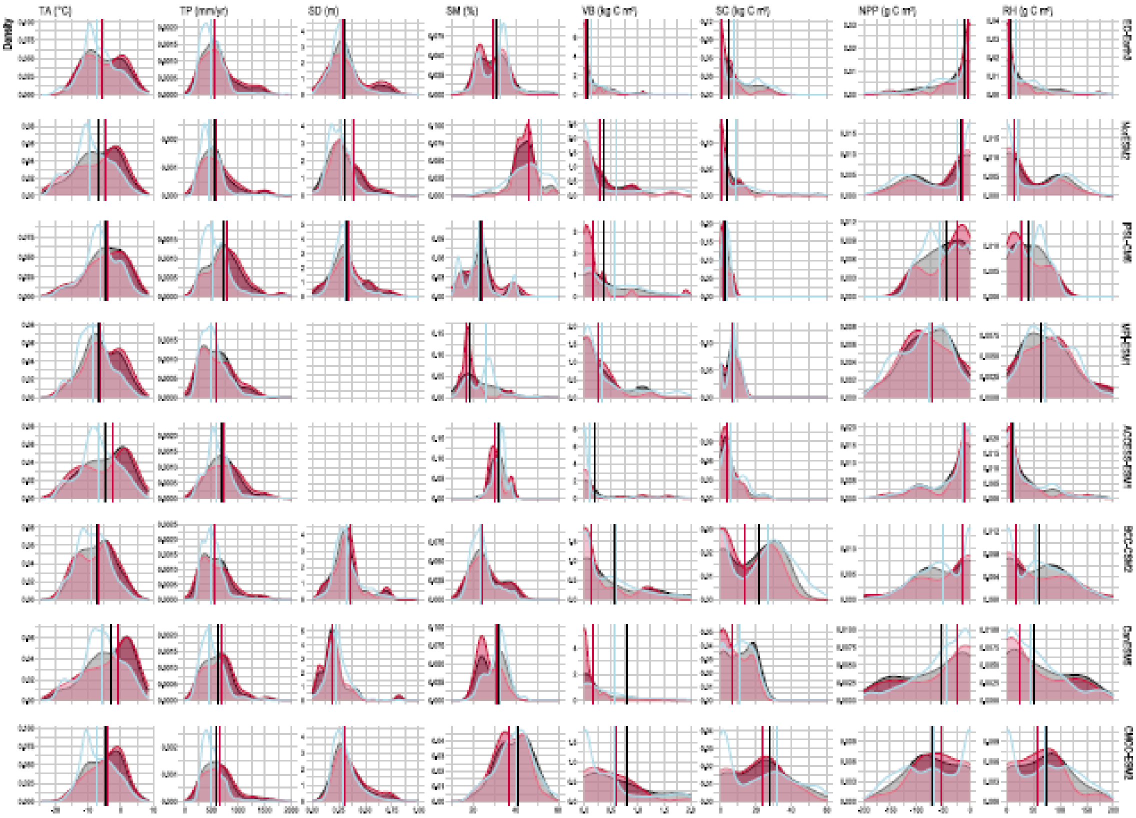

Extended Data Fig. 2 | Density distribution functions for the ecosystem variables (air temperature, TA; total precipitation, TP; snow depth, SD; soil moisture, SM; vegetation biomass, VB; soil carbon, SC net primary production, NPP; and heterotrophic respiration, RH) for each of the CMIP6 ESMs comparing the ecosystem conditions at the INTERACT stations with (black) and without (red) Russian stations as compared to the pan-Arctic domain (light blue). Vertical bars indicate the median values. The first and third quartiles are not shown. Note that the x-axis range has been truncated to improve readability. The complete dataset can be found in Source Data Extended Data Fig. 2.

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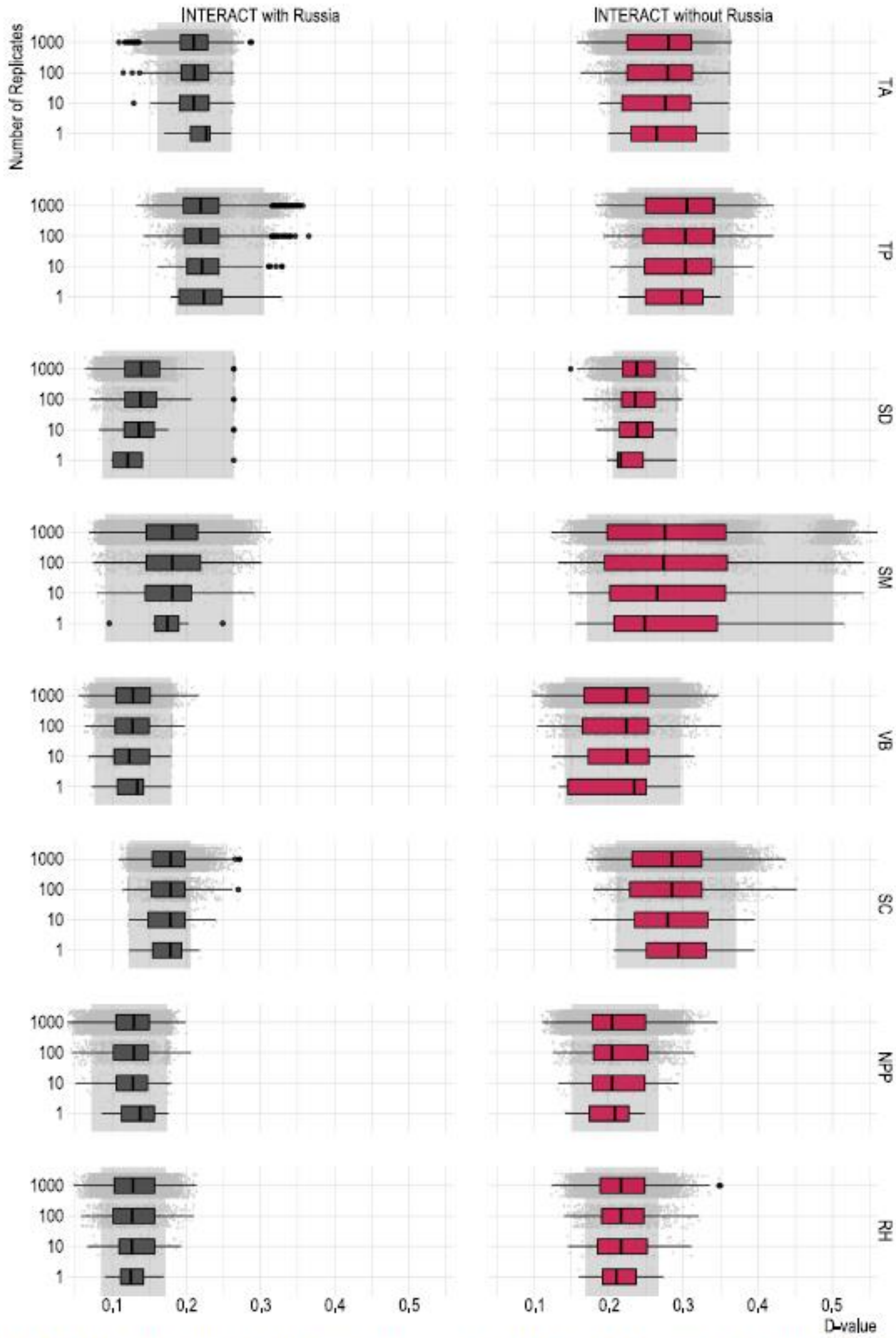

Extended Data Fig. 3 | Sensitivity of offsets (KS D-values) to sample size for each ecosystem variable. Box plots show the impact on K-S D-values when using different numbers of replicates (1, 10, 100, 1000) in the resampling procedure with 494 grid cells (see above). Grey boxes indicate the range (minimum to maximum) when resampling was performed using the native ESM resolution. The box plots show the median and interquartile range (IQR), with the upper and lower whiskers extending to the largest value ≤ 1.5 × IQR from the 75[th] percentile and the smallest values ≤ 1.5 × IQR from the 25[th] percentile, respectively.