European Commission

JRC TECHNICAL REPORT

Risk and resilience indicators and indexes in Arctic ecoregions, protected areas and urban centres

Results from the GHSL and DOPA products

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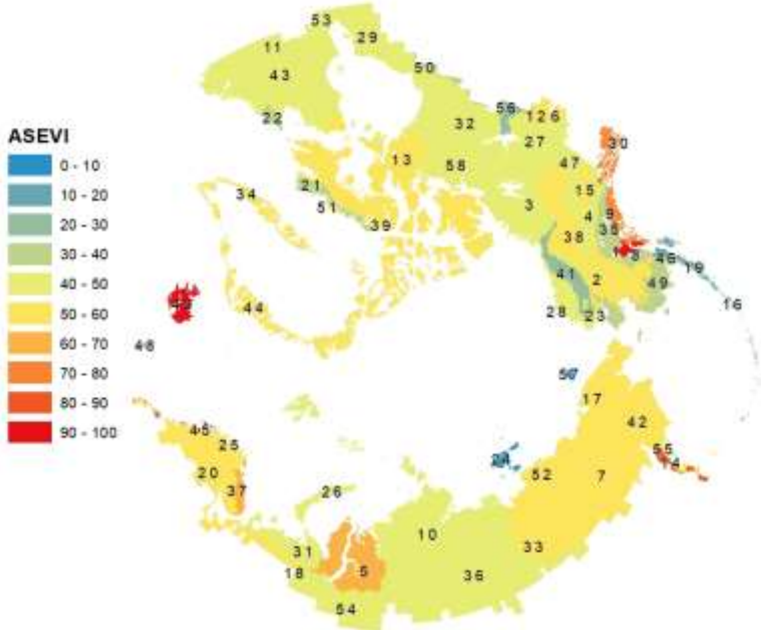
2022



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EU Science Hub
https://ec.europa.eu/jrc

JRC127176

EUR 31005 EN

PDF	ISBN 978-92-76-48851-4	ISSN 1831-9424	doi:10.2760/787321
Print	ISBN 978-92-76-48852-1	ISSN 1018-5593	doi:10.2760/017271

Luxembourg: Publications Office of the European Union, 2022

How to cite this report: Koffi, B., Wilson, J., Delli, G., Mandrici, A., Dubois, G. and Ehrlich, D., *Risk and resilience indicators and indexes in Arctic ecoregions, protected areas and urban centres – Results from the GHSL and DOPA products*, EUR 31005 EN, Publications Office of the European Union, Luxembourg, 2022, ISBN 978-92-76-48851-4, doi:10.2760/787321, JRC127176.

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Acknowledgements

This work has been undertaken within the IMPARC, GHSL and DOPA projects of the 2020-21 Institutional work-programme of the Joint Research Centre.

Abstract

The Arctic region is expected to be increasingly affected by both ecological and anthropogenic processes, as a result of the climate change and socio-economic pressures. The goal of the EC JRC Arctic resilience ongoing study is to investigate the potential of existing EC JRC products and projects to define a set of suitable Arctic resilience physical, ecological, or societal indicators that are able to monitor the major threats to Arctic communities and ecosystems, using a socioecological approach. In a previous report, we used the 40-year Global Human Settlement Layer (GHSL) 1x1 km^2 spatial grids of built-up and population density, that allows the monitoring of population in settlements and estimating human and environment exposure to various hazards. These GHSL satellite-derived products were used to analyse Arctic population dynamics, settlement and urbanisation patterns at administrative levels. In this report, we investigate the potential of both GHSL and DOPA (Digital Observatory for Protected Areas) JRC global products and indicators for the assessment of Arctic risks and resilience. A total of 28 indicators are analysed at ecoregion, protected area and urban levels and some of them are combined into preliminary vulnerability indexes at ecoregion scale. In a further step, they will be further investigated and completed with other data layers to monitor both environmental and human threats in selected Arctic natural, managed and human systems of interest, such as cities, coastal areas, river basins and vulnerable ecosystems.

1 Introduction

According to the IPCC (2018) report, "Arctic and its indigenous people" are one of the "Unique and threatened systems"[1], which are under high levels of risk of adverse consequences from global warming (Annex 1), which may in turn impact lower latitudes, e.g. through tundra greenhouse gas release and shifts in ocean and atmospheric circulations (Overland et al., 2019). Understanding how these changes interact with one another, and what they mean in terms of implications for Arctic governance, requires a holistic approach that looks at natural, managed and human systems together.

Given its role in the development and implementation of the EU adaptation strategy and its ongoing contribution to the Arctic Council activities (Wilson et al., 2015), the Joint Research Centre of the European Commission (EC JRC) was invited in 2016 to contribute to the development of the Arctic Resilience Action Framework (ARAF)[2]. ARAF defines common priorities and targets to increase our understanding of risks and uncertainties and supports and encourages measures to improve the resilience of threatened communities and ecosystems (ARAF, 2019).

This report is a follow-up of EC JRC previous activities, as part of the Arctic-COOP (2018-2019) and IMPARC (2020-2021) Arctic transversal projects, that aim to investigate the potential of existing EC JRC projects and global products for the definition of resilience indicators to the Arctic regime shifts as defined in the Arctic resilience report (Arctic Council, 2016).

In a first report (Koffi and Wilson, 2019) the potential of Global Human Settlement Layer (GHSL) and the Index for Risk Management (INFORM, 2019) products have been investigated. The GHSL R2016A and INFORM 2019 data have been analysed at national scale for the eight Arctic States (AS), and their potential for the Arctic region documented. After a general introduction and the presentation of ARAF framework and concepts, a survey has been undertaken to identify existing sources, efforts, indicators or tools having a potential for contributing to the definition and monitoring of the Arctic resilience, focusing on the "Sustainable development" and "Emergency preparedness and disaster risk reduction" areas of ARAF. The two EC JRC products have been then analysed and discussed in terms of relevance, limitations and possible adaptation to the Arctic region.

We then performed a detailed analysis of the Global Human Settlement Layer (GHSL)[3] 40-year records of human population and settlement data over the Arctic (Koffi et al., 2021), with the objective to use this data as the base from which we can quantify human and environmental exposure and resilience to various human pressures and climate change impacts, using a socio-ecological approach. Results provided a spatially detailed and cross-scale documentation of the peculiarities and diversity of Arctic population patterns in a robust and consistent way.

In this third report, the GHSL and DOPA (Digital Observatory for Protected Areas) EC JRC global products are used to perform an integrated analysis of human and environment indicators in the Arctic. The DOPA Explorer, which includes a broad number of conservation, environment, biodiversity and human pressure indicators is first presented, followed by a summary of the GHSL datasets. The two products are analysed separately (sections 3 and 4) and then together (section 5), to identify Arctic human and environment risks and resilience at circumpolar, ecoregions and local scales.

[1] ecological and human systems that have restricted geographic ranges constrained by climate-related conditions and have high endemism or other distinctive properties"

[2] https://www.sdwg.org/wp-content/uploads/2018/05/Arctic-Resilience-Action-Framework-May-2017.pdf

[3] https://ghsl.jrc.ec.europa.eu

2 Datasets and Study domain

2.1 DOPA dataset and indicators

The Digital Observatory for Protected Areas (DOPA) Explorer (Dubois et al. 2016; Bastin et al. 2017) is a web based tool (https://dopa-explorer.jrc.ec.europa.eu/) developed by the Joint Research Centre of the European Commission to support the European Union's efforts to substantially strengthen "the effectiveness of international governance for biodiversity and ecosystem services" and "the capacity to mobilise and use biodiversity data, information and forecasts so that they are readily accessible to policymakers, managers, experts and other users"[4]. To build its biodiversity metrics and indicators, DOPA uses open free environmental, ecological and social cores datasets on Country boundaries, Marine and Terrestrial Ecoregions, Protected Areas, Key Biodiversity Areas, Species Ranges and Occurrences, Threatened species, Temperature, precipitations, Sea Surface Temperature, Elevation (bathymetry and topography), Land Cover, Land Productivity Dynamics, Global Human Settlements, Soil Organic Carbon, Above-Ground Biomass, Road maps, Agricultural Areas, Inland Surface Water and Forest cover and Exclusive Economic Zones (EEZ). Using exclusively global reference datasets (Annex 2), the DOPA supports global assessments but also provides a broad range of consistent and comparable indicators that can be used to assess, monitor, report and possibly forecast the state of and the pressure on protected areas at multiple scales (country, ecoregion and protected area levels) and to identify potential priorities for further conservation research, action and funding (Dubois et al., 2018). The Terrestrial Ecoregions of the World (TEOW) are the ones delineated by Olson et al. (2001). The 2020 DOPA version includes about 45 000 protected areas (UNEP-WCMC & IUCN, 2020) characterised by more than 400 metrics and indicators. The key indicators are regularly updated (once or twice a year according to required computational effort and targeting more frequent updates to align with the monthly releases of the WDPA). A specific factsheet is provided on DOPA website for each of the key indicators (Table 1), with detailed information on the policy relevance, definition, data sources, method and caveats.

In addition to the DOPA global product, a 1°x1° gridded version of DOPA global reference datasets is being developed since 2020, which allows for the calculation of the DOPA indicators for a given region. In March 2021, a first subset of DOPA indicators has been calculated on the Arctic study domain (see 2.3) from the September 2020 DOPA gridded product. This subset, referred to as the Arctic 202009 DOPA sub-dataset, is the main source of indicators provided for this study at country (Arctic part only), ecoregion (Arctic part only) and terrestrial or coastal protected area (PA) levels. It has been completed with DOPA and GHSL global data to produce the following set of 15 core indicators as defined (*acronym from this study; PA=Protected Area indicator; ECO= ecoregion indicator) and analysed in this report:

- TPAC (ECO): Terrestrial Protected Area Coverage (%) - DOPA indicator
- *CTPAC (ECO): Change in TPAC (%)
- ProtConn (ECO): Protected Connected indicator (%) - DOPA indicator
- *CProtConn (ECO): Change in ProtConn (%)
- SOCI (ECO): Soil Organic Carbon Indicator (Mg/km^2) - DOPA indicator
- *PSOCI (ECO): Protected Soil Organic Carbon Indicator (%) - DOPA indicator
- *CISSW (ECO, PA): 1984-2018 net Changes in Inland Seasonal Surface Water (%) - DOPA indicator
- *CIPSW (ECO, PA): 1984-2018 net Changes in Inland Permanent Surface Water (%) - DOPA indicator
- *FCLOSSI (ECO, PA): 2000-2018 loss in Forest Cover (%) - DOPA indicator
- PPI (PA, ECO): Population Pressure Indicator (inh./km^2) - DOPA PA indicator, extended to ecoregions
- CPPI (PA, ECO): Change in the PPI (%) - DOPA indicator, extended to ecoregions and different periods
- *CPDI (PA, ECO): Change in the Population Density Indicator (inh./km^2) - this study
- *PNSI (ECO): Population New Settlement Indicator (%) - this study
- *URBL (ECO): Urbanisation level (%) - this study
- *CURBL (ECO): Change in Urbanisation level (%) - this study

[4] UNEP/CBD/COP/10/27

Table 1. DOPA key indicators (√) of Environment, Conservation Species and Pressure (NA = Not Applicable) [1] and core indicators analysed at ecoregion and protected level in this report. Eight DOPA key indicators and related metrics have been specifically calculated and provided on the Arctic domain (*Arctic 202009 DOPA sub-dataset*; dark grey cells). They have been completed with (a) DOPA 2016, 2018 and 2020 global data and (b) 2019 GHSL global data (clear grey cells).

DOPA key Indicators	Country	Ecoregion	PA	Factsheet[1]	DOPA and other core indicators defined[2] and/or analysed in this report	Temporal trend
PA	√	√ (a)	NA	B1, B2	TPAC, CTPAC*	YES
Connectivity of PA	√	√ (a)	NA	C1	ProtConn, CProtConn*	YES
Funding	√	-	√	K1		
KBAs	√	√	NA	B3		
Terrestrial Habitat Diversity	-	-	√	E1		
Marine Habitat Diversity	-	-	√	E2		
Threatened species	√		√	D1		
Climate and elevation	Elevation	Elevation	√	F1		
Soil organic Carbon	√	√	√	J1	SOCI, PSOCI*	NO
Above ground Carbon Stock	√	√	√	J2		
Below ground Carbon Stock	√	√	√	J3		
Land degradation	√	√	√	I1		
Land fragmentation	√	√	√	I2		
Land cover & changes	√	√	√	G1		
Forest cover & changes	√	√	√	G3	FCLOSSI*	YES
Surface water & changes	√	√	√	G2	CISSW*, CIPSW*	YES
Population pressure	√	(b)	√	H3	PPI, CPPI, CPDI* PNSI*, URBL*, CURBL*	YES
Built-up areas pressure	-	-	√	H4		
Road pressure	-	-	√	H2		
Agricultural pressure	√	-	√	H1		
Livestock pressure (3)	-	√	√	H5		

[1] Adapted from DOPA Factsheet A1 (*acronym as defined in this report) https://dopa.jrc.ec.europa.eu/dopa/documentation/en

[2] See section 3 for the acronyms as defined in DOPA and in this study (*)

2.2 GHSL datasets and indicators

The Global Human Settlement Layer project builds on past experience, different resolution settlement products and utilises 40 years of Landsat imagery to produce open information on global built-up areas and population for the reference years 1975, 1990, 2000 and 2015. Both the GHSL 2019 Data Package (GHS P2019) and GHS-Urban Centres Database (GHS-UCDB), available in open and free download as part of the GHSL collection[5] in the EC JRC open data portal[6], are used in this report (see Koffi et al., 2021 for a summary of their policy relevance, definition, data sources, methods and limitations).

The GHS P2019 data package (Schiavina et al., 2019) consists of three main datasets types: the Global Human Settlement built-up spatial grid (GHS-BUILT), the GHS population spatial grid (GHS-POP) and the GHS urban/rural

[5] https://data.jrc.ec.europa.eu/collection/ghsl

[6] https://ghsl.jrc.ec.europa.eu/ucdb2018Overview.php

classification model spatial grid (GHS-SMOD). It has been produced following Freire et al. (2016) and then incorporating improvements which had a positive effect on the final quality and accuracy of the spatial grids (Florczyk et al., 2019a; Freire et al., 2020). The GHS-BUILT, GHS-POP and GHS-SMOD 1 km x 1 km products used in this study are available as global single raster files, or split into UTM tiles, for the five epochs with 1975, 1990, 2000, 2015 reference years. These epochs approximate the temporal dimension of the Landsat multi-temporal collections.

The GHS-POP population grid (Freire et al., 2020) is derived from the combination of national population data available from the Gridded Population of the World (GPW, version 4.10) from the Center for International Earth Science Information Network (CIESIN, 2016) and the GHS Built-up areas. GPW is a gridded dataset that distributes population uniformly within administrative units of the World. GHS-POP spatially refines GPW population density by distributing population within grid cells proportionally to the area covered by built up areas in each grid cell. The current version of GHS-POP does not discriminate between residential and non-residential buildings. Future release of GHS-POP will provide improved population densities based on multi-story building and the separation between residential and non-residential. However, GHS-POP is referred as residential population to be differentiate from other population density spatial grids that distribute population also on land uses other than built-up. The resident population data are harmonised in the space and time domains into the GHS-POP grids using the baseline GHS-BU grids available from the 4 epochs. The 2019 version (GHS_POP_MT_GLOBE_R2019A) uses the new Landsat bases GHS_BUILT_LDSMT_GLOBE_R2018A (version 2.0) product.

The GHS-SMOD settlement model uses the rules set in the Degree of Urbanisation (DEGURBA)[7] classification to partition the GHS-POP in a set of settlement typologies referred as Cities, Towns and Suburbs, and Rural Areas (Florczyk, et al., 2019b). The first hierarchical level (Rural areas) of the SMOD settlement model is obtained by aggregating classes LDC 11, LDC 12 and LDC 13 Low Density grid cells; the second hierarchical level (Towns and suburbs) the MDC 21, MDC 22 and MDC 23 Medium Density Clusters; and the third hierarchical level (Cities) consists of the HDC 30 High Density Clusters. The Degree of Urbanisation as defined in GHS-SMOD avoids the distortion and reduction of the comparability between countries (e.g., with large and small local administrative units) by a using high-resolution population grid.

In this study, we used the GHS-POP and GHS-SMOD data to complete the DOPA indicators at Arctic ecoregion level, by calculating the PPI, CPPI, CPDI, PNSI (GHS-POP 1x1 km^2 data) and URBL, CURBL (GHS-SMOD data) population pressure, migration and urbanisation indicators as defined in the previous section. Additional applications are foreseen in the future, such as the analysis of the exposure of the Arctic population and built-up to natural hazards, as used in similar global scale analysis Ehrlich at al. (2018a) and Ehrlich et al. (2018b).

The GHS-UCDB DataBase is also available for the open and free download from the EC JRC open data portal. The GHS-UCDB R2019A version (Florczyk, et al., 2019b) includes more than 10,000 Urban Centres (also referred as Cities), which are uniquely labelled spatial clusters of contiguous 1 km^2 HDC grid cells with minimum population of 50.000 inhabitants. The Urban Centres Database uses seven dimensions (General such as UC name, latitude-longitude, 2015 extension; Multitemporal Urban Centre spatial domain; Geography; Socio-economic; Environment; DRR (Disaster Risk Reduction) and SDG) for a total of 28 variables, which are listed in Annex 3 to characterise each Urban Centre.

The 13 GHS-UCDB indicators documented in section 5.3 for the 5 Arctic Urban Centres are (see Florczyk et al. 2019b report for units, details and data sources):

- 1990 and 2015 Urban Centres Spatial Domain
- 1990, 2000 and 2014 average temperature
- 1990, 2000 and 2014 average precipitation
- 1975, 1990, 2000 and 2015 resident population
- 1975, 1990, 2000 and 2015 built-up area
- 1975, 1990, 2000 and 2015 built-up area per capita
- 1990, 2000 and 2015 Gross domestic product

[7] https://ec.europa.eu/eurostat/web/degree-of-urbanisation/background

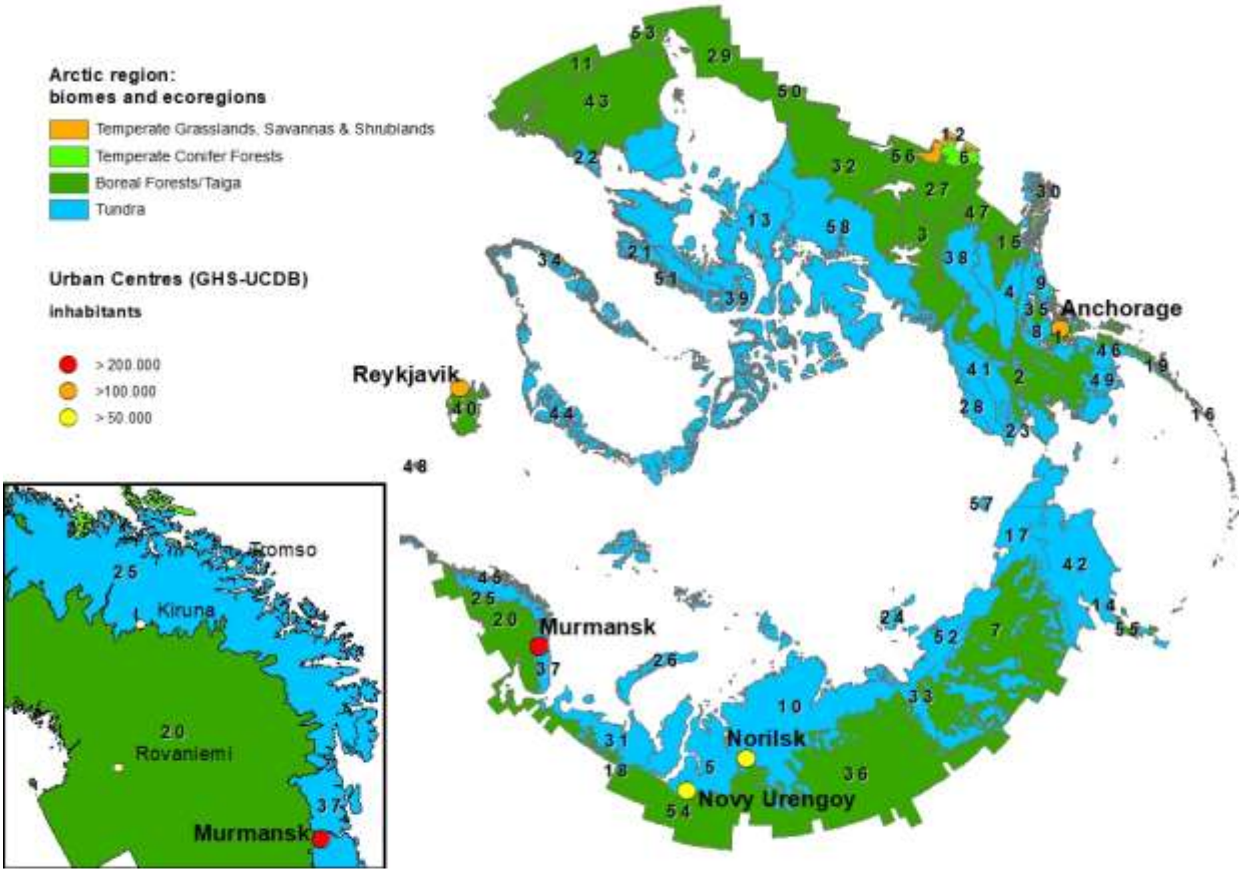
- 1975, 1990, 2000 and 2015 potential exposure of the population to floods
- 1975, 1990, 2000 and 2015 potential exposure of the built-up to floods
- 1990 and 2014 urban green
- 2018 average Peak Ground Acceleration (PGA) estimate and MMI class of the seismic risk
- 1980-2010 Maximum magnitude of the heatwaves (JRC index)
- 1990 and 2012 CO_2 emissions by activity sector (Energy, Residential, Industry, Transport and Agriculture)

2.3 Arctic ecoregions, protected areas and human population

2.3.1 Arctic domain definition

There is no single definition of the Arctic region. An Arctic study area has been defined in Koffi et al. (2021) by merging the AMAP, AHDR, and CAFF arctic domains, in order to integrate sociological and ecological indicators in the analysis of Arctic resilience. In this second report, we use the same definition but extended to the 1°X1° grid cells area (Fig. 2.1) covering this Arctic domain, which has been used to extract the *Arctic 202009 DOPA sub-dataset*. Only the 58 ecoregions at least partly included in Koffi et al. (2021) Arctic domain are considered, 39 of which are fully or nearly *fully* (> 95%) included in the Arctic area (Annex 4). The Arctic region so defined covers 14,6 M km^2 of terrestrial areas and a population of 5.2 M people.

Figure 1. The Arctic region (see Annex 4 for the list of the ecoregions) and the 5 Urban Centres as of 2015.



Source: Arctic 202009 DOPA sub-dataset and GHS-UCDB

2.3.2 Ecoregions, Protected areas and human population

The 58 ecoregions at least partly included in the Arctic region ("*Arctic ecoregions*" refers hereafter to the Arctic part only) are distributed among the 8 Arctic States as reported in Table 2. Canada and Russian Federation cover 76% of the Arctic area. Thirteen ecoregions belong to several Arctic States (see Annex 4) and represent 17% of the Arctic region. Tundra (53%; 31 ecoregions) and Boreal Forests/Taiga (F&T; 22 ecoregions) biomes dominate, whereas Temperate Conifer Forests (C.F; 3 ecoregions), Grasslands, Savannas & Shrublands (S&S; 2 ecoregions) only represent 1.0 % of the biome coverage.

Table 2. Arctic ecoregions and biomes (Tundra, Boreal Forests/Taiga (F&T), Temperate Conifer Forests (C.F) and Savannas & Shrublands (S&S)) in the Arctic states' territories (2020)

AS Territories	*ISO3*	*Tundra*	*F&T*	*C.F.*	*S&S*	*Total (km^2)*	*Total (%)*
*USA**	US	63%	23%	0%	14%	411516	2.8%
*Canada**	CAN	46%	52%	1%	1%	5255043	35.9%
*Iceland**	ISL	0%	100%	0%	0%	90917	0.6%
Kingdom of Denmark		99.7%	0%	0.3%	0%	453881	*3.1%*
Greenland	*GRL*	100%	0%	0%	0%	*452648*	*3.1%*
Faroe Islands	*FRO*	0%	0%	100%	0%	*1233*	*0.01%*
Kingdom of Norway		0%	0%	0%	100%	8725	0.1%
**Svalbard& Jan Mayen*	*SJM*	*	*	*	*	*	*
**Norway*	*NOR*	0%	0%	0%	100%	*8725*	*0.1%*
*Sweden**	SWE	*	*	*	*	*	*
*Finland**	FIN	*	*	*	*	*	*
*Russian Federation**	RUS	54%	46%	0%	0%	5873566	40.2%
**Join and disputed areas*		57%	43%	0%	0%	2533040	17.3%
Total Arctic region	km^2	7725337	6753047	110397	37907	14626688	100%
	%	53%	46%	0.3%	0.8%	100%	

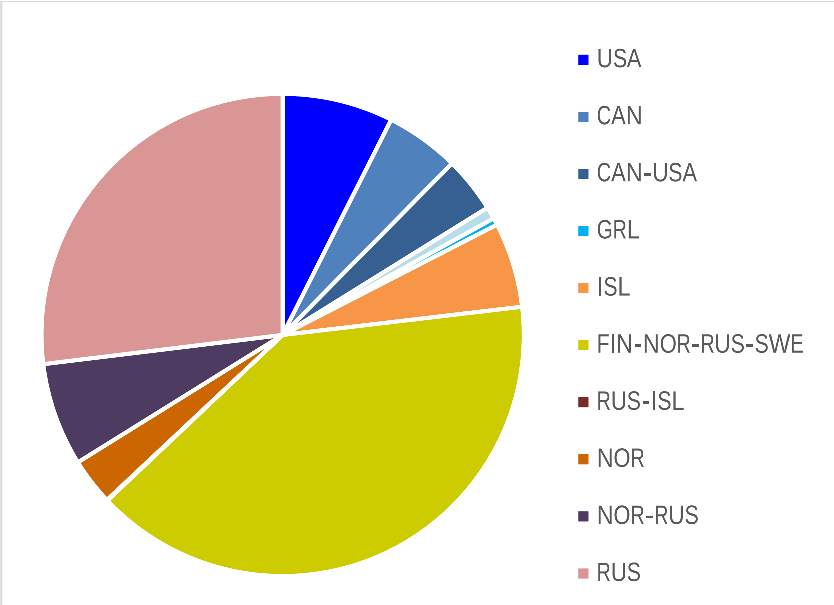
Source: Arctic 202009 DOPA sub-dataset

The 2015 Arctic population[8] of 5.2 M people (Figure 2) represents 0.8% of the total population of the Arctic states. It occupies 1554108 1x1 km^2 grid cells, i.e., 10.6 % of the Arctic region. It is extremely sparse on average (0.36 inh./km^2), but with an important diversity in the population density. It is worth noting that 40% of the Arctic inhabitants (yellow colour in Fig.2) live in the "Scandinavian or Russian taiga" (ID=20 in Fig.1)" and "Scandinavian Montane Birch forest and grasslands" (area ID=25) ecoregions, which both extend over four Arctic States (Finland, Norway, Sweden and Russian Federation) but only cover 4.3% of the Arctic domain. The population of the *Arctic ecoregions* included in the Russian Federation represents 27% of the Arctic population (see Annex 4).

The Arctic region includes 5734 protected areas (4.56 M km^2) with120 002 inhabitants. They are composed of 5060 terrestrial and 674 coastal PAs (Fig. 3), from which only 967 are populated. 1276 PAs are at least as large as 10 km^2, 528 of which are populated (105011 inhabitants corresponding to 2 % of the total Arctic population). The 10 largest populated PAs (Annex 5) are located in USA and Canada (CAN), Svalbard& Jan Mayen, (SJM) and Russian Federation (RUS). They cover 14% of the total Arctic PAs area but only 4 % of the Arctic population living in protected areas. The 35 populated PAs (19 817 km^2) identified from their high human pressure (section 5.2) and covering 40% of the Arctic PA population are also reported in Figure 4.

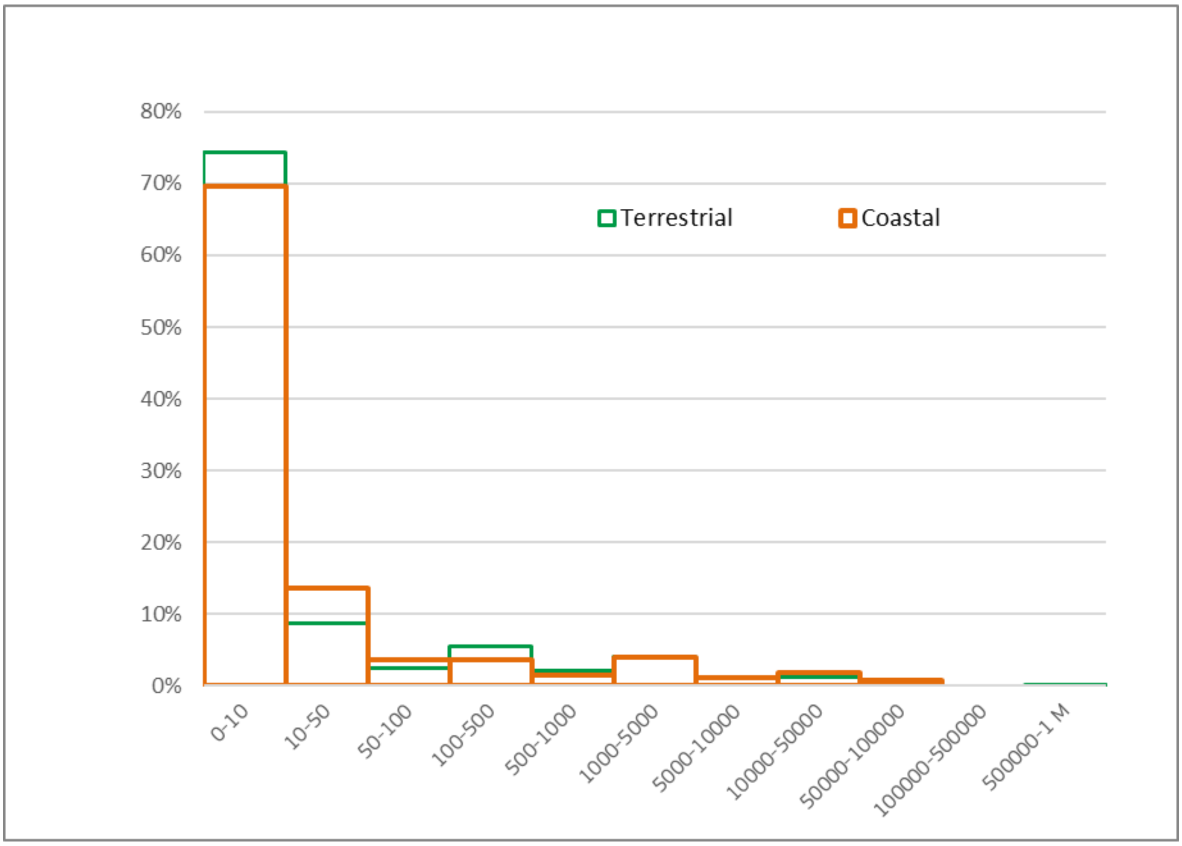
[8] See Koffi et al. (2021) for Arctic population statistics at administrative and local levels

Figure 2. 2015 Arctic population shares in Arctic states' ecoregions.



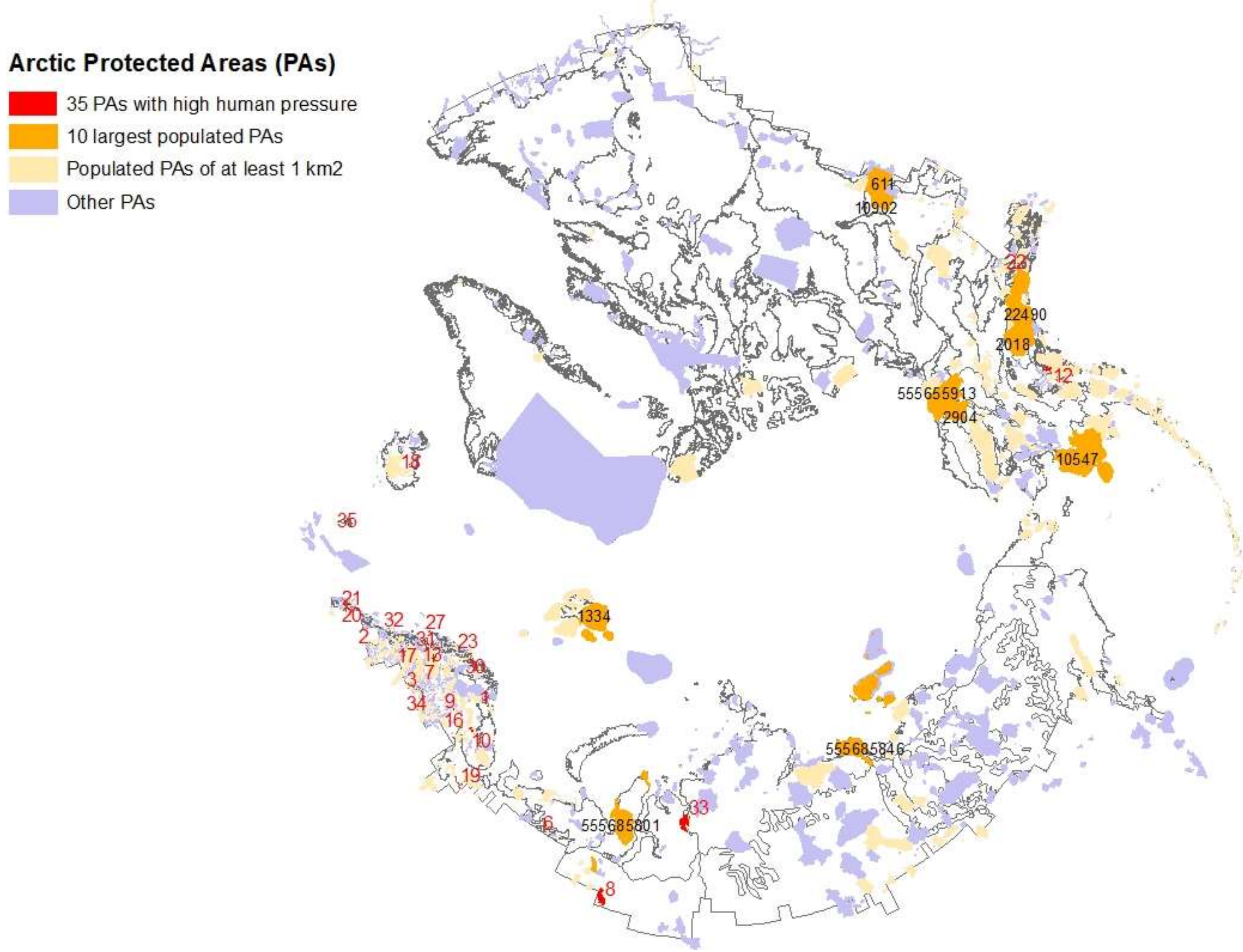
Source: Arctic 202009 DOPA sub-dataset

Figure 3. Frequency distribution of the size of Arctic inland (N=5060) and Coastal (N=674) protected areas (km^2).



Source: Arctic 202009 DOPA sub-dataset

Figure 4. Map of Arctic Terrestrial and Coastal protected areas (N=5734). The 10 largest populated PAs are identified through their WDPA id (in black). Red IDs correspond to the 35 PAs of at least 10 km² showing high population pressure as identified and numbered (PAID) in section 5.2.



Source: September 2020 version of the World Database on Protected Areas (WDPA)

3 Environment indicators in the Arctic ecoregions

In this section, the DOPA indicators are used to highlight specific ecoregions and protected areas (e.g., with worrying ecological patterns or trends), show the beneficial effects of conservation and sustainable use of ecosystems on resilience and provision of ecosystem services and assess their potential relevance for the documentation of the Arctic shifts at ecoregion level. The 58 Arctic ecoregions at least partly included in the Arctic region are identified by their name, ID and Arctic State(s) in which they are found, as reported in Annex 4.

3.1 Conservation and connectivity

Protecting and conserving the environment is critical in order to maintain and increase the resilience of ecosystems and people in the face of the adverse effects of climate change. Well designed and managed PA systems can effectively safeguard species and ecosystems and deliver essential ecosystem services to people. The connectivity of PA systems facilitates large-scale ecological and evolutionary processes (e.g. gene flow, migration and species range shifts), which are all essential for the persistence of viable populations, especially when facing climatic and environmental changes. In 2010, the parties to the United Nations Convention on Biological Diversity (CBD) adopted a Strategic Plan for Biodiversity for the 2011–2020 period, including the twenty Aichi Biodiversity Targets. In Aichi Target 11 the international community agreed to increase by 2020 the terrestrial area under protection to at least 17% in 'effectively and equitably managed, ecologically representative and well-connected systems of protected areas' (CBD, 2010).

The DOPA protection and connectivity indicators explored in this section are:

The Terrestrial Protected Area Coverage (TPAC) provided in the *Arctic 202009 DOPA sub-dataset*. It is based on September 2020 WDPA protected areas (UNEP-WCMC & IUCN, 2020) and other input datasets as defined in Annex 2. It indicates how much are terrestrial and inland water areas covered by protected areas at the Arctic State and ecoregion level. The data calculated for the 58 Arctic ecoregions are explored in section 3.1.1.

In 2017, to further enrich DOPA, the Protected Connected indicator (ProtConn), which considers different categories of land (unprotected, protected or transboundary) through which movement between protected locations may occur was developed (Saura et al., 2017). ProtConn is defined as the percentage of a country or a region covered by protected and connected lands. It considers both intra-PA and inter-PA connectivity, i.e. it accounts for both the amount of protected land that is available within individual PAs and that is reachable by moving between different PAs. ProtConn can be compared with PA coverage and used directly to quantify shortfalls, or successes, in achieving the connectivity element of Aichi Target 11 (Saura et al., 2018). This indicator, which requires very specific computing work, is not part of *Arctic 202009 DOPA sub-dataset*. Therefore, it is only investigated in section 3.1.1 for the 39 ecoregions *fully* (> 95%) included in the Arctic domain, which cover 67% of it.

Changes in both TPAC and ProtConn September 2020 data, as compared to 2016 and 2018 are then analysed and discussed for the 39 above ecoregions (3.1.2).

3.1.1 Terrestrial coverage by protected areas (TPAC) and Connectivity (ProtConn)

TPAC indicator

The 5734 Arctic terrestrial ad coastal protected areas cover 17% of the Arctic domain (Fig. 5), which is below the Aichi Target 11 of 17% for *well-connected systems* of PA. Only 23 out of the 58 *Arctic ecoregions*, corresponding to 28.5% of the Arctic area, have a TCPA equal to or larger than 17%.

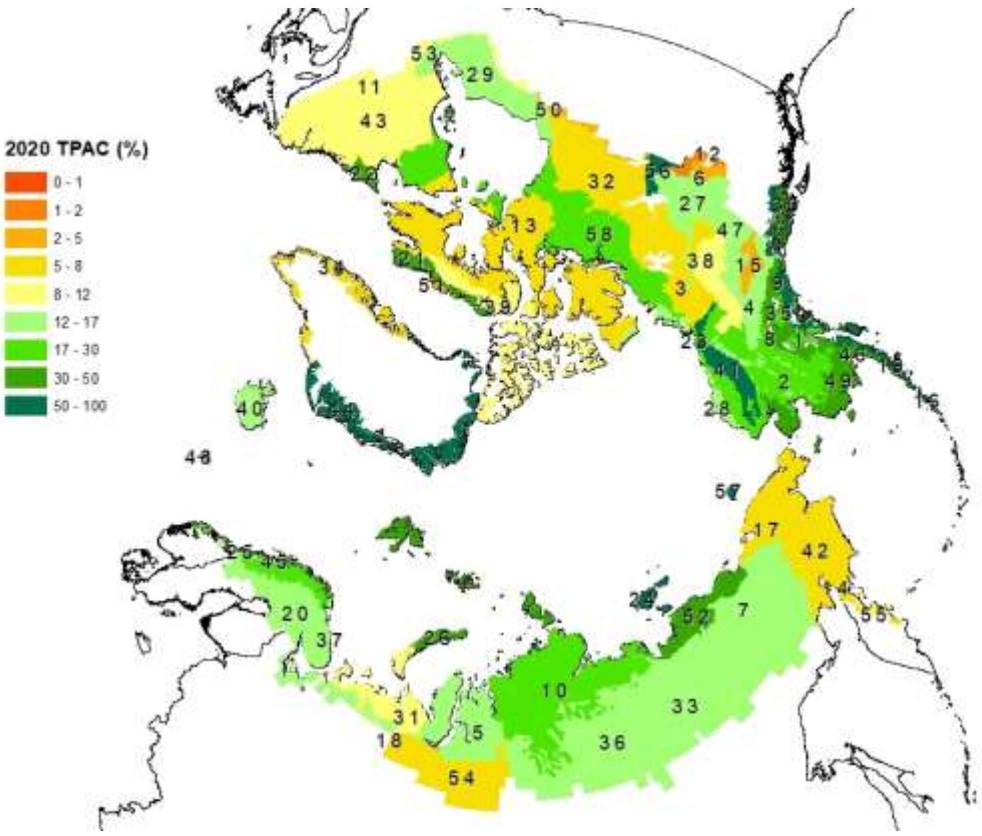
Fifteen *Arctic ecoregions*, covering 25% of the Arctic, have less than 8% of the land covered by PA. They are (with ID into bracket, followed by the acronym of the Arctic State):

- Northwest Territories taiga (3), CAN
- Alberta-British Columbia foothills forests (6), CAN

- Canadian Aspen forests and parklands (12), CAN
- Middle Arctic tundra (13), CAN
- Kamchatka Mountain tundra and forest tundra (14), RUS
- Yukon Interior dry forests (15), CAN
- Chukchi Peninsula tundra (17), RUS
- Ural montane forests and tundra (18), RUS
- Northern Canadian Shield taiga (32), CAN
- Kalaallit Nunaat low arctic tundra (34), GRL
- Bering tundra (42), RUS
- Faroe Islands boreal grasslands (48), FRO
- Midwestern Canadian Shield forests (50), CAN
- Baffin coastal tundra (51), CAN
- West Siberian taiga (54), RUS

In some regions, like Alaska, the coverage of PA is high, but the current trend is negative (see 3.1.2). These results show that a lot of effort is still needed to increase the Arctic conversation level or to maintain it in well protected ecoregions.

Figure 5. Level of protection coverage (TPAC in %) of the 58 *Arctic ecoregions* as of September 2020.



Source: Arctic 202009 DOPA sub-dataset

ProtConn indicator

Because of its definition, the Protected Connected indicator (ProtConn) cannot be higher than the TPAC indicator. In the case of September 2020 ProtConn data (Fig. 6 and Table 3), only 13 out of the 39 ecoregions *fully* (> 95%) included in the Arctic reach the 17% Aichi target of well-connected systems of protected areas. These

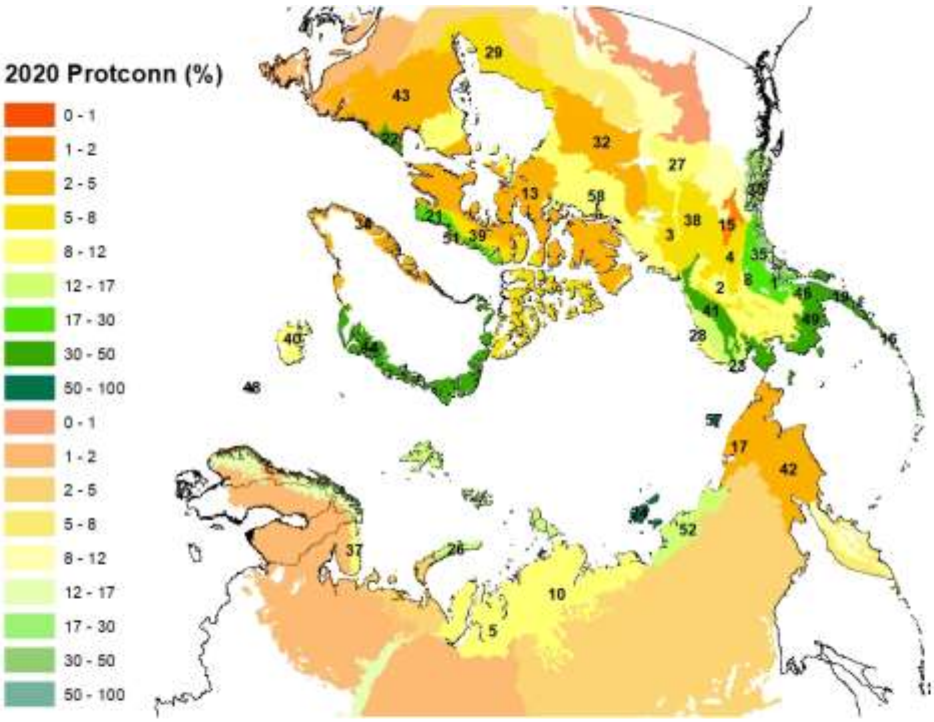
13 ecoregions only cover 7.6 % of the Arctic region. Moreover, the 2016-2020 ProtConn changes (section 3.1.2) show that 10 of these regions are becoming less well connected since 2016.

Fourteen ecoregions included (> 95%) in the Arctic and covering 34% of the region have a ProtConn below 8%:

- Northwest Territories taiga (3), CAN
- Interior Yukon-Alaska alpine (4), CAN-USA
- Middle Arctic tundra (13), CAN
- Yukon Interior dry forests (15), CAN
- Chukchi Peninsula tundra (17), RUS
- Southern Hudson Bay taiga (29), CAN
- Northern Canadian Shield taiga (32), CAN
- Kalaallit Nunaat low arctic tundra (34), GRL
- Ogilvie-MacKenzie alpine tundra (38), CAN-USA
- High Arctic tundra (39), CAN
- Bering tundra (42), RUS
- Eastern Canadian Shield taiga (43), CAN
- Faroe Islands boreal grasslands (48), FRO
- Baffin coastal tundra (51), CAN
-

All but one (ID=9) Arctic ecoregions only partly included in the Arctic region show a connectivity below 17% (covering 32% of the Arctic), of which 13 out 18 have a ProtConn below 8% (Fig. 6).

Figure 6. Protected Connected indicator (ProtConn in %) as of September 2020. The 39 ecoregions fully included in the Arctic region are numbered. The ecoregions not entirely included in the Arctic region are not numbered and shown in shaded colour.



Source: DOPA key indicators

3.1.2 Change in Arctic protection coverage and connectivity (39 ecoregions)

The 2016 to 2020 changes in TPAC (CTPAC) and ProtConn (CProtConn)[9] have been calculated (Table 3) and mapped (Annexes 6 and 7) for the 39 ecoregions *fully* (> 95%) included in the Arctic domain.

2016-2020 CTPAC

19 out of the 39 regions, representing 32% of the area and 22% of the Arctic region, experienced a 2016-2020 decrease in the PA coverage. The decrease is particularly worrying in 4 ecoregions of North America, which lost more than 10% of their PA coverage within the 4-yrs period:

- Interior Alaska-Yukon lowland taiga (2), CAN-USA: CTPAC=-12%
- Aleutian Islands tundra (16), USA: CTPAC=-23%
- Northern Pacific coastal forests (30), USA: CTPAC=-29%
- Beringia lowland tundra (46), USA: CTPAC=-20%

It is also worrying in the two Chukchi Peninsula (17) and Bering tundra (42) ecoregions of the Russian Federation that show both low and decreasing protection levels. On the other hand, 18 ecoregions representing 45.5 % of the Arctic domain show PAs positive changes.

2016-2020 CProtConn

A 2016 to 2020 ProtConn decrease is calculated for 20 out of the 39 fully included Arctic ecoregions, corresponding to 23% of the total Arctic region. In most of the cases (24/39) the change in the Protection level of well-connected ecoregions is less pronounced than for the TPAC indicator.

Among the 13 cases with more pronounced change in ProtConn than in TPAC, three ecoregions, covering 46% of the 39 regions, are particularly remarkable and worrying. They are:

- Alaska Peninsula montane taiga (19), USA: CTPAC: -5.62%; CProtConn: -21.8%
- Brooks-British Range tundra (41), CAN-USA: CTPAC: -3.73%; CProtConn: -17.2%
- Kalaallit Nunaat high arctic tundra (44), GRL: CTPAC:-0.6%; CProtConn: -19.9%

The positive changes in ProtConn (14 regions; 43% of the area covered by the 39 regions) are generally lower than for TPAC, with a maximum of +6% for the Taimyr-Central Siberian tundra (10).

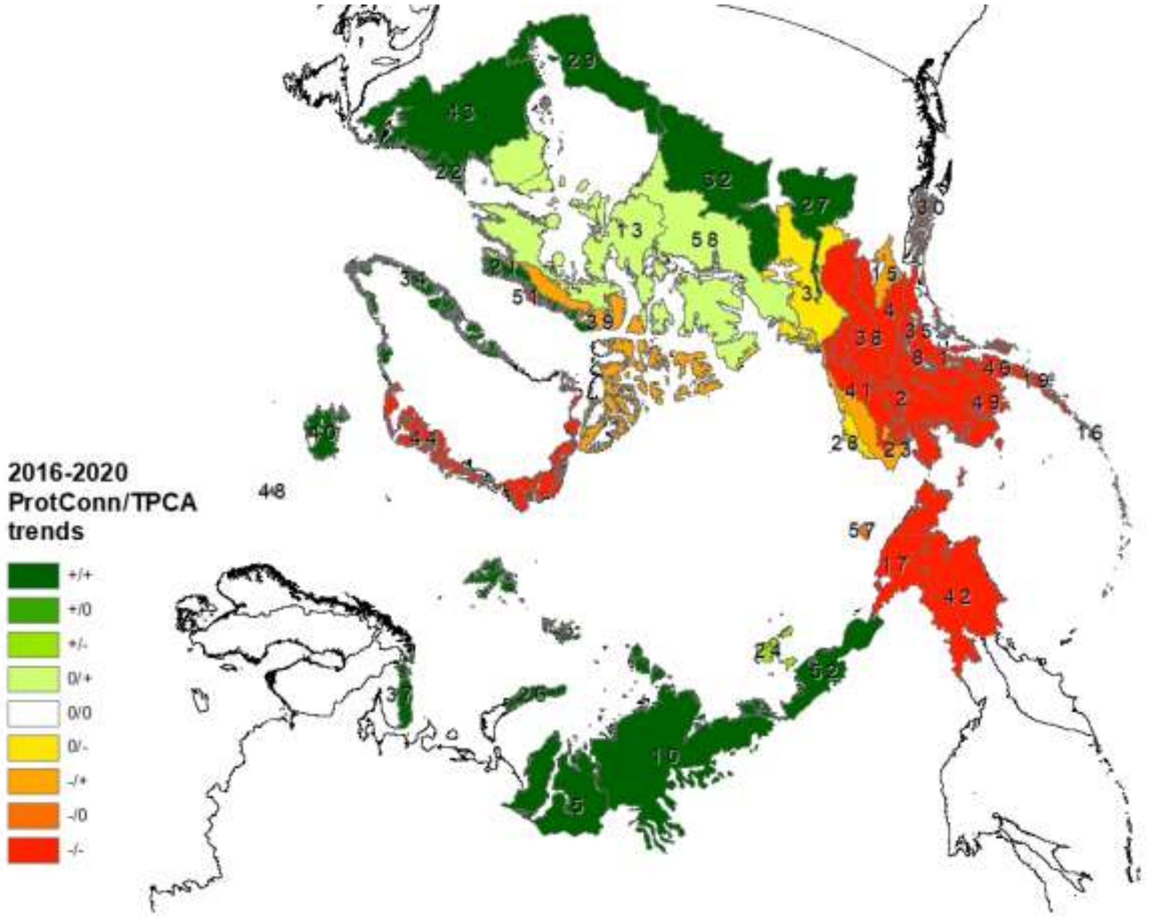
Mapping of CProtConn and CTPAC combined trends

CTPAC and CProtConn changes have been mapped so as to provide a semi-quantitative indicator of Arctic regions showing potential ecological risk and decrease in resilience (Fig. 7). The combines result allows to highlight the 16 ecoregions with both negative changes, whereas 14 regions are improving both in terms of conservation and connectivity.

Although partial (67% of the Arctic area), these preliminary analyses show the usefulness of the DOPA TPAC and ProtConn indicators to identify the regions at risk in terms of biodiversity and ecosystem services. Four DOPA sub-indicators exist[10], which allow to depict different categories of land through which movement between protected locations may occur (Saura et al., 2018).

[9] Data source: https://dopa.jrc.ec.europa.eu/dopa/
[10] ProtConn[Within], ProtConn[Contig], ProtConn[Unprot] and ProtConn[Trans]

Figure 7. Positive and negative 2016 to 2020 changes in ProtConn (CProtConn) and TPAC (CTPAC) in the 39 ecoregions *fully* in the Arctic region, with red areas experiencing decreases in both indicators. See the mapping of % values in Annex 6.



Source: DOPA key indicators as of September 2020

Table 3. PA protection (TPAC) and ecological connectivity (ProtConn) of the 39 ecoregions *fully* (> 95%) included in the Arctic region (see Annex 6 for the maps of the changes).

ID	TPAC% 202009	TPAC% 2016	2016-2020 CTPAC%	2016-2018 CTPAC%(1)	ProtConn% 202009	ProtConn% 2016	2016-2020 CProtConn%
1	26.6	30.3	-3.72	0.39	17.7	21.8	-4.1
2	20.9	33.2	-12.23	-1.51	9.1	21.7	-12.6
3	7.8	8.6	-0.79	-1.15	5.5	5.5	0
4	15.5	17.0	-1.48	0.42	6.6	12.6	-6
5	12.5	7.7	4.73	0.00	8.7	3.2	5.5
8	41.4	44.7	-3.32	0.18	29.7	31.5	-1.8
10	22.1	13.8	8.26	0.00	10.9	4.9	6
13	5.5	4.9	0.56	-0.03	2.5	2.5	0
15	2.4	0.7	1.73	2.88	1.6	2.3	-0.7
16	73.9	97.4	-23.50	-0.01	25.5	42.3	-16.8
17	6.0	10.4	-4.40	-0.01	2.7	9.6	-6.9
19	77.3	82.9	-5.62	0.20	44.6	66.4	-21.8
21	31.5	31.1	0.40	0.00	22.4	22.2	0.2
22	41.9	39.9	2.03	0.50	40.9	40.3	0.6
23	23.0	20.4	2.56	0.99	13.8	19.2	-5.4
24	99.5	100.0	-0.50	0.00	70.9	70.4	0.5
26	40.8	37.5	3.28	0.02	15.3	15.0	0.3
27	14.0	9.1	4.93	0.00	9.8	8.5	1.3
28	12.8	12.8	-0.01	0.00	9.4	9.4	0
29	12.2	11.1	1.07	0.00	7.0	6.9	0.1
30	35.4	64.2	-28.77	-23.64	13.4	15.8	-2.4
32	6.6	5.4	1.19	0.12	2.7	2.4	0.3
34	5.2	5.1	0.14	0.00	3.3	3.2	0.1
35	29.4	30.3	-0.86	-0.85	27.7	28.2	-0.5
37	14.4	8.0	6.43	0.00	9.3	5.7	3.6
38	11.0	11.5	-0.52	-0.05	5.5	7.0	-1.5
39	10.2	8.1	2.13	2.05	5.2	5.7	-0.5
40	13.5	11.7	1.83	0.76	10.3	8.6	1.7
41	60.3	64.0	-3.73	-0.88	45.7	62.9	-17.2
42	7.0	9.2	-2.16	0.00	4.0	4.5	-0.5
43	9.7	3.5	6.18	1.05	4.1	3.5	0.6
44	71.3	71.9	-0.60	0.01	49.9	69.8	-19.9
46	45.7	66.2	-20.47	-0.33	30.3	47.3	-17
48	0.0	0.0	0.00	0.00			
49	41.0	43.6	-2.53	-0.23	32.6	36.3	-3.7
51	4.7	5.4	-0.69	0.00	4.1	4.8	-0.7
52	30.6	22.9	7.7	0.00	14.7	12.3	2.4
57	100	100	0.00	-0.1	94.4	99.6	-5.2
58	17.2	16.1	1.1	0.0	9.8	9.8	0

Source: Arctic 202009 DOPA sub-dataset

3.2 Ecological indicators

Change in inland surface water (Bastin et al., 2019), Forest loss (Hansen et al., 2013) and soil organic carbon (FAO and ITPS, 2018b) indicators are provided in *Arctic 202009 DOPA sub-dataset* for each country (Arctic part only), ecoregion (Arctic part only) and Arctic terrestrial or coastal protected area of size ≥ 10 km^2.

3.2.1 Change in Inland surface water (CIPSW and CISSW)

Many inland surface waters are unique ecosystems upon which numerous plants and animals depend. They also provide key ecosystem services such as primary production, water provisioning, water purification and recreation.

It is important to monitor the consequences of human pressures on the environment, in particular inside and around protected areas (see also section 5.2.3), to ensure that natural ecosystems and their associated species and ecosystem functions (e.g., goods and services) are preserved (DOPA Factsheet G.2.; http://dopa.jrc.ec.europa.eu). In the Arctic, inland waters are highly abundant and also important pathways for the export of terrestrial carbon in permafrost landscapes where a large part of the global soil organic carbon pool is stored (see also section 3.2.3). This carbon is increasingly vulnerable to destabilisation and release due to permafrost thaw driven by rising Arctic air temperatures (Dean et al., 2020). By comparing surface water maps over time, changes in water regimes can be identified.

1984-2018 net changes in inland permanent and seasonal surface water (CIPSW and CISSW indicators, respectively, hereafter) in the Arctic region both show general positive trends, due to increases in precipitation and temperature, with somewhat higher changes in average for the PAs than for the ecoregions (Fig. 8). Examining the large differences in the seasonal surface water change (Fig.9) between some ecoregions and their PAs (e.g., Kalaallit Nunaat low and high arctic tundra in Greenland, Northeast Siberian coastal tundra) could reveal particular patterns, which would require further investigation on the PAs' specificity. Higher values of changes and higher ecoregion-PA correlations are calculated for the seasonal (CISSW) than for the permanent (CIPSW) surface water (Fig.8 and Fig. 9). The size of the changes in permanent and seasonal surface water, suggest a high sensitivity of this dataset (GSW Transitions) to the impacts of climate change and the need for in depth analysis of these types of changes in the Arctic region.

The 5 ecoregions with the highest 1984-2018 increase (> + 200 %) in seasonal surface water are (Fig.8):

- Bering tundra	(42), RUS:	CISSW=+209%
- Northeast Siberian taiga	(7), RUS:	CISSW=+296%
- Kalaallit Nunaat high arctic tundra	(44), GRL:	CISSW=+495%
- Iceland boreal birch forests and alpine tundra	(40), ISL:	CISSW=+499%
- Northeast Siberian coastal tundra	(52), RUS:	CISSW=+553%

The 5 ecoregions with the lowest increase or a decrease in seasonal surface water are (Fig.8):

- Arctic desert	(26), RUS:	CISSW=-97%
- Novosibirsk Islands arctic desert	(24), RUS:	CISSW=-49%
- Wrangel Island arctic desert	(57), RUS:	CISSW=-20%
- Faroe Islands boreal grasslands	(48), FRO:	CISSW =-6%
- Aleutian Islands tundra	(16), USA:	CISSW=+10%

In addition to the CISSW and CIPSW statistics here documented for the Arctic region, DOPA explorer provides *Water Transitions maps*, which would also be of high relevance for the documentation of the Arctic shifts, on: new permanent and seasonal water surfaces, unchanging permanent and seasonal water surfaces, lost permanent and seasonal water surfaces, conversion of permanent water into seasonal water and conversion of seasonal water into permanent water.

3.2.2 Forest loss (FCLOSSI)

Forests are one of the most important terrestrial habitats and a carbon sink that needs to be conserved to achieve both biodiversity conservation and climate change mitigation targets. They are in risk in many areas due human pressures, and notably agricultural expansion, extractive activities (such as mining), urbanisation, infrastructure development or wildfires, among others. The forest change statistics and maps provided in DOPA Explorer produced from the Global Forest Change (GFC) product include the forest cover 2000 and change for the period 2001–2018 at country, ecoregion, and protected area levels. They are expressed as the trend in the percent of the land covered by forests, as well as the total forest area (km^2) gained or lost when compared to the reference year 2000. The forest is defined based on tree cover, which means that is considered as forest loss the temporarily unstocked areas, and that trees in agricultural lands may be classified as forests. Trees are defined as vegetation taller than 5m in height and are expressed as a percentage per output grid cell. 'Forest Cover Loss' is defined as a stand-replacement disturbance, or a change from a forest to non-forest state. We choose to look at the loss only (and not at the net change), to focus on areas with negative shifts as the signature of increased vulnerability.

The 2000-2018 loss in forest cover (FCLOSSI, hereafter) calculated for the *Arctic ecoregions* (Fig.8 and Fig.9), which mainly concerns boreal forests/taiga areas, is somewhat higher in average (2.2%) than for the PAs only (1.8%).

The 6 ecoregions with the highest forest loss (> 7%) are all located in North America:

- Midwestern Canadian Shield forests	(50), CAN	FCLOSSI=19% (PAs 13%)
- Mid-Continental Canadian forests	(56), CAN	FCLOSSI=12% (PAs 16%)
- Canadian Aspen forests and parklands	(12), CAN	FCLOSSI=10% (PAs 0.4%)
- Interior Alaska-Yukon lowland taiga	(2), CAN-USA	FCLOSSI=10% (PAs 9%)
- Alberta-British Columbia foothills forests	(6), CAN	FCLOSSI=8.5% (PAs 0.2%)
- Interior Yukon-Alaska alpine tundra	(4), CAN-USA	FCLOSSI=7% (PAs 3%)

The 23 tundra ecoregions with tree cover all have 2000-2018 forest loss below 0.5%, excepted:

- Interior Yukon-Alaska alpine tundra	(4), CAN-USA	FCLOSSI=7%
- Ogilvie-MacKenzie alpine tundra	(38), CAN-USA	FCLOSSI =1.7%
- Cherskii-Kolyma mountain tundra	(33), RUS	FCLOSSI =0.6%
- Bering tundra	(42), RUS	FCLOSSI =0.5%

The main differences between the Ecoregions and PAs (FCLOSSI Ecoregion/FCLOSSI PA > 10) are observed for:

- Arctic coastal tundra	(28), CAN-USA	FCLOSSI: Ecoregion/PA= 98
- Alberta-British Columbia foothills forests	(6), CAN	FCLOSSI: Ecoregion/PA= 41
- Canadian Aspen forests and parklands	(12), CAN	FCLOSSI: Ecoregion/PA= 24
- Yamal-Gydan tundra	(5), RUS	FCLOSSI: Ecoregion/PA= 15
- Scandinavian and Russian taiga	(20), FIN-NOR-RUS-SWE	FCLOSSI: Ecoregion/PA= 12
- Brooks-British Range tundra	(41), CAN-USA	FCLOSSI: Ecoregion/PA= 12

3.2.3 Total and protected Soil Organic carbon (SOCI and PSOCI)

Soil organic matter is critical for the stabilisation of soil structure, retention and release of plant nutrients, and water infiltration and storage in soil. Its main component, the Soil organic carbon (SOC) is therefore essential to ensuring soil health, fertility and food production, whereas the loss of SOC indicates a certain degree of soil degradation, which can happen through unsustainable management practices (DOPA Factsheet J.1.; http://dopa.jrc.ec.europa.eu/). Changes in land use and land cover can cause SOC decreases and carbon emissions, which are one of the largest sources of human-caused carbon emissions to the atmosphere. Protected areas may contribute to soil carbon retention and hence to the reduction of net emissions of greenhouse gasses responsible for climate change. The largest amounts of SOC are stored in the northern permafrost region, mostly in peat soils, where carbon accumulates in soils in huge quantities due to the low temperatures leading to low biological activity and slow decomposition of soil organic matter.

The Soil Organic Carbon indicator is based on the information provided by the global soil organic carbon (GSOC) map (version 1.2.0), which quantifies, with a spatial resolution of 1 km, the amount of organic carbon (Mg/km^2) stored in the soil worldwide, considering a soil depth of up to 30 cm (FAO and ITPS, 2018a; FAO and ITPS, 2018b). It provides useful information about the soil condition in protected areas, particularly when compared with other unprotected areas with similar environmental conditions. This information can contribute to identify potentially degraded areas, evaluate the conservation performance of protected areas, set restoration targets, and assess the contribution of protected areas to reduce net global carbon emissions. It is analysed hereafter in terms of total amount (SOCI) and protected percentage (PSOCI) of soil organic carbon at ecoregional level.

The lowest Mean amount of soil organic carbon (< 1000 Mg/km^2) are calculated for (Fig.10):

- Kalaallit Nunaat low arctic tundra	(34), GRL	SOCI=0 Mg/km^2
- Kalaallit Nunaat high arctic tundra	(44), GRL	SOCI=0 Mg/km^2
- Arctic desert	(26), RUS	SOCI=25 Mg/km^2
- Davis Highlands tundra	(21), CAN	SOCI=209 Mg/km^2
- Baffin coastal tundra	(51), CAN	SOCI=293 Mg/km^2
- Novosibirsk Islands arctic desert	(24), RUS	SOCI=698 Mg/km^2
- High Arctic tundra	(39), CAN	SOCI=979 Mg/km^2

The lowest percentages of protected carbon (<1%) are calculated for (Fig.10):

- Ural montane forests and tundra	(18), RUS	PSOCI=0.00%
- Faroe Islands boreal grasslands	(48), FRO	PSOCI=0.00%
- Canadian Aspen forests and parklands	(12), CAN	PSOCI=0.29%
- Midwestern Canadian Shield forests	(50), CAN	PSOCI=0.53%
- Alberta-British Columbia foothills forests	(6), CAN	PSOCI=0.91%

The highest Mean amount of soil organic carbon (> 6000 Mg/km^2) are calculated for (Fig.11):

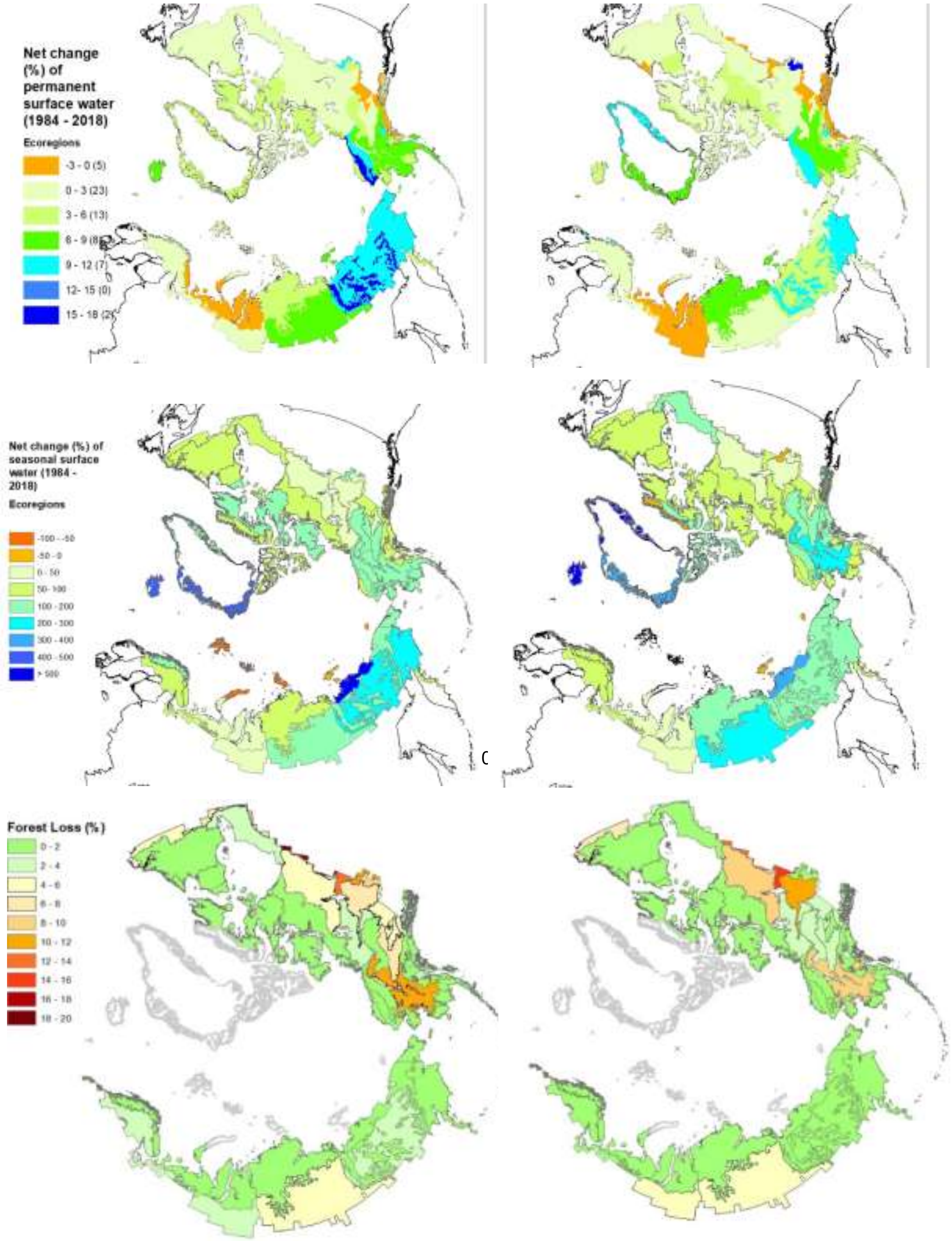
- Beringia lowland tundra	(46), USA	SOCI=6124 Mg/km^2
- Interior Alaska-Yukon lowland taiga	(2),CAN-USA	SOCI=6188 Mg/km^2
- Southern Hudson Bay taiga	(29), CAN	SOCI=6233 Mg/km^2
- Northern Pacific coastal forests	(30), USA	SOCI=7786 Mg/km^2
- Faroe Islands boreal grasslands	(48), FRO	SOCI=12028 Mg/km^2

The highest percentage of protected carbon (> 50%) are calculated for (Fig.11):

- Brooks-British Range tundra	(41), CAN-USA	PSOCI=57%
- Aleutian Islands tundra	(16), USA	PSOCI=73%
- Alaska Peninsula montane taiga	(19), USA	PSOCI=73%
- Novosibirsk Islands arctic desert	(24), RUS	PSOCI=99.6%
- Wrangel Island arctic desert	(57), RUS	PSOCI=100%

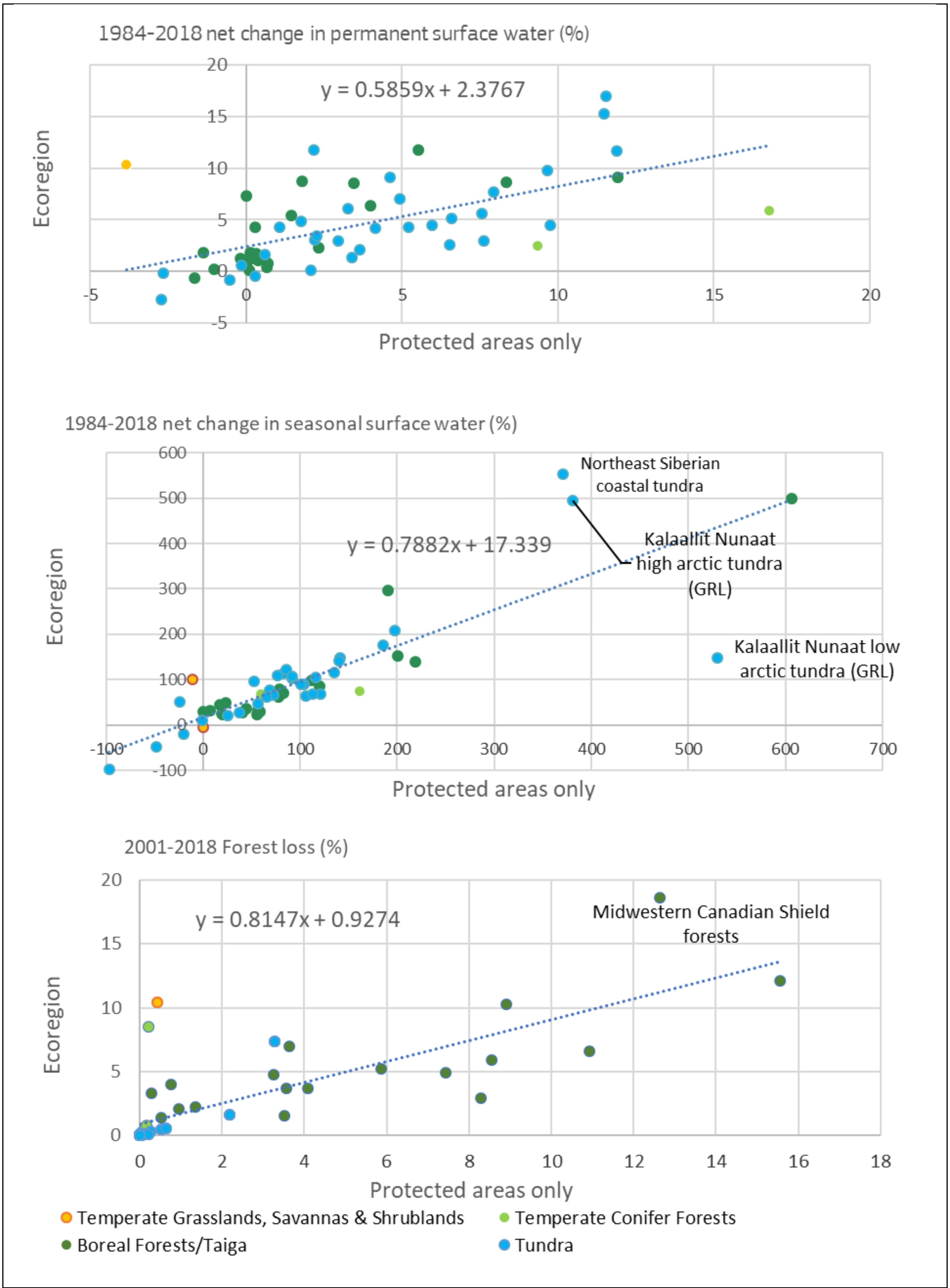
Figure 8. Maps of 1984-2018 changes in surface water and 2000-2018 forest loss in the *Arctic ecoregions*.

Ecoregions | Protected Areas



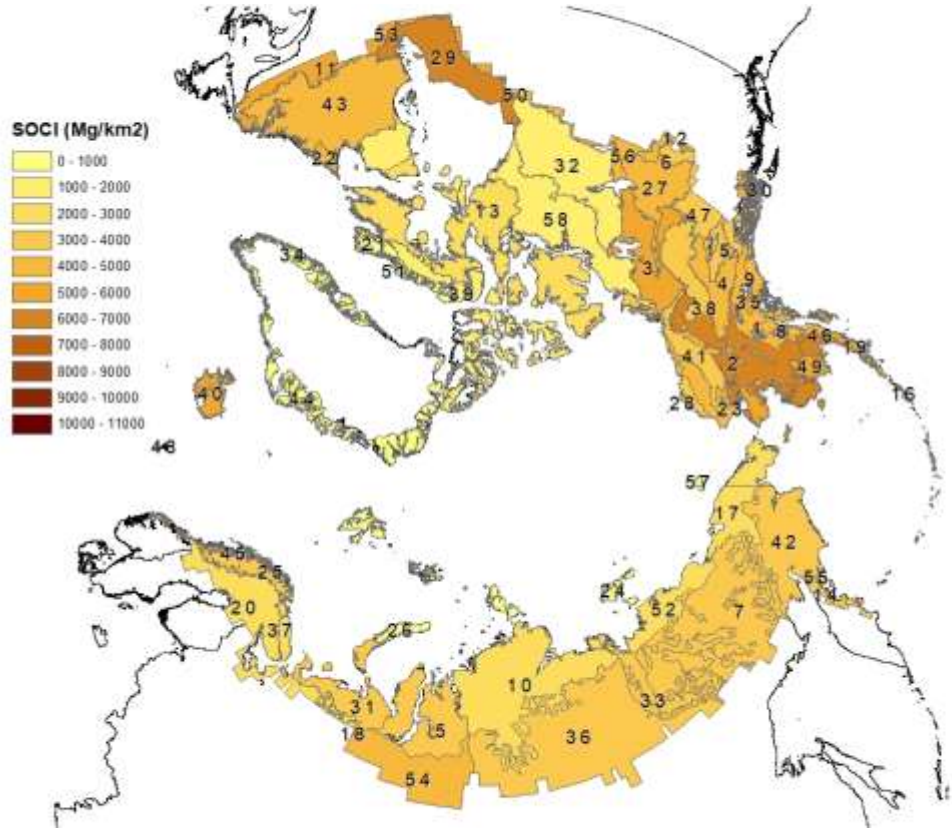
Source: Arctic 202009 DOPA sub-dataset

Figure 9. 1984-2018 changes in surface water and 2000-2018 forest loss in the *Arctic ecoregions* and Pas.



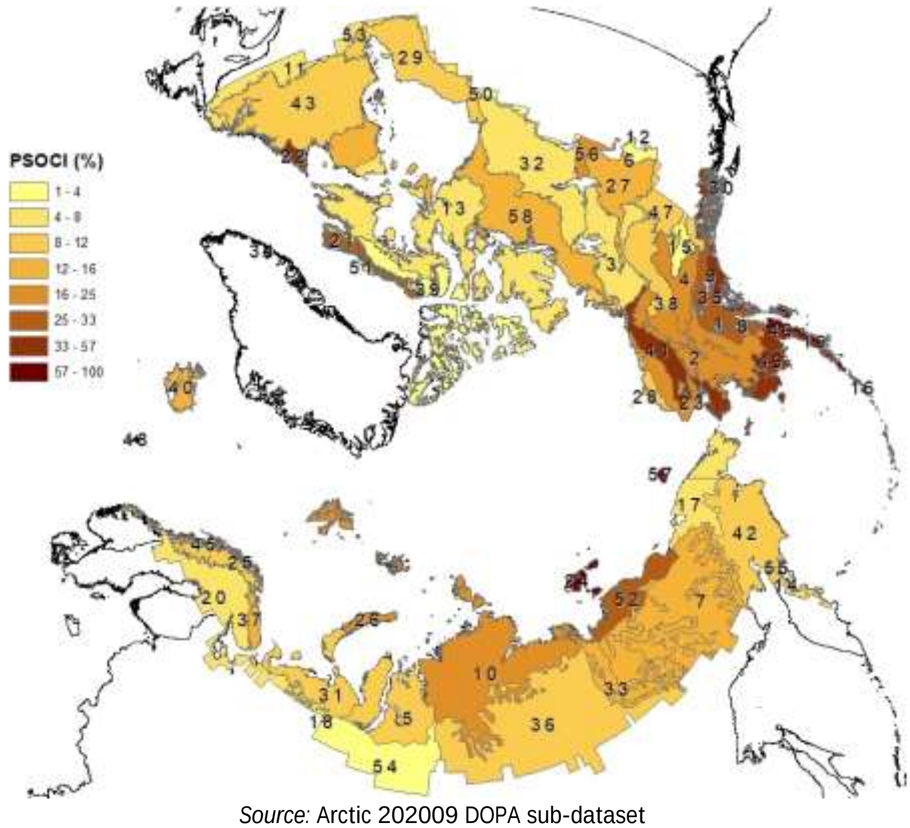
Source: Arctic 202009 DOPA sub-dataset

Figure 10. Mean amount (Mg/km²) of soil organic carbon (0-30 cm depth) in the *Arctic ecoregions*.



Source: Arctic 202009 DOPA sub-dataset

Figure 11. Protected Soil Organic carbon in *Arctic ecoregions* (%).



Source: Arctic 202009 DOPA sub-dataset

4 Human population settlement indicators in the Arctic ecoregions

The Arctic is settled in a rather contrasting way, with vast sparsely inhabited or uninhabited regions interspersed with a few relatively big cities. The total Arctic population is projected to remain relatively constant in the future, but with substantial differences in growth rates and migration processes between the different Arctic regions (Heleniak, 2020). Long-term monitoring based on an integrated approach that explores the trends in population, urbanisation and migration is of importance for assessing the Arctic socio-ecological risks and resilience.

4.1 Population density and change

In Koffi et al. (2021), we examined the Arctic population and dynamics at national and administrative levels as derived from the GHS-POP data. We showed both positive (USA, Canada, Iceland, Kingdom of Denmark) and negative Kingdom of Norway, Finland, Russian Federation and Sweden) population trends. The mapping the 1990-2015 population changes allowed to identify the Arctic at administrative regions experiencing the highest positive (e.g., Yukon, Svalbard and Jan Mayen) and negative (e.g., Russian Krasnoyarsk region) population changes. They also clearly illustrated the impact of the definition of the Arctic domain on the conclusions in terms of Arctic total population change. Results are revisited hereafter at the ecoregion level for the extended Arctic domain as defined in this report. The DOPA PPI and CPPI human pressure indicators (see section 2.1) have been calculated at ecoregion level and for additional time periods from the GHS P2019 global data.

4.1.1 2015 population density (PPI)

As shown in Figure 12 (see also Koffi et al., 2021), a large part of the Arctic region is either uninhabited or extremely sparsely inhabited (< 0.1 inh./km^2). Only four ecoregions have a mean population density above 5 inh./km^2, whereas no population is found in four other ones.

The 5 *Arctic ecoregions* (id) with the highest 2015 population density (PPI, inh./km^2) are:

- Scandinavian and Russian taiga (20), FIN-NOR-RUS-SWE PPI=3.48 inh./km^2
- Kola Peninsula tundra (37), NOR-RUS PPI=6.36 inh./km^2
- Cook Inlet taiga (1), USA PPI=10.6 inh./km^2
- Scandinavian coastal conifer forests (45), USA PPI=17.0 inh./km^2
- Faroe Islands boreal grasslands (48), FRO PPI=30.9 inh./km^2

The 5 *Arctic ecoregions* with the lowest 2015 population density (inh.km2) are:

- Ural montane forests and tundra (18), RUS PPI=0 inh./km^2
- Torngat Mountain tundra (22), CAN PPI=0 inh./km^2
- Novosibirsk Islands arctic desert (24), RUS PPI=0 inh./km^2
- Wrangel Island arctic desert (57), RUS PPI=0 inh./km^2
- Copper Plateau taiga (35), USA PPI=0.0002 inh./km^2

4.1.2 1990-2015 population change (CPPI)

The extended Arctic domain used in this study leads to a more pronounced 1990-2015 decrease in population (-3.8%) than for Koffi et al. (2021) Arctic domain (-3.0%), which totally excludes the Sakha and Krasnoyarsk southern Russian regions. The 1990-2015 population change at ecoregion level includes both positive and negative trends (Fig. 13).

The 7 *Arctic ecoregions* with the highest 1990-2015 increase in population (> 50%) are:

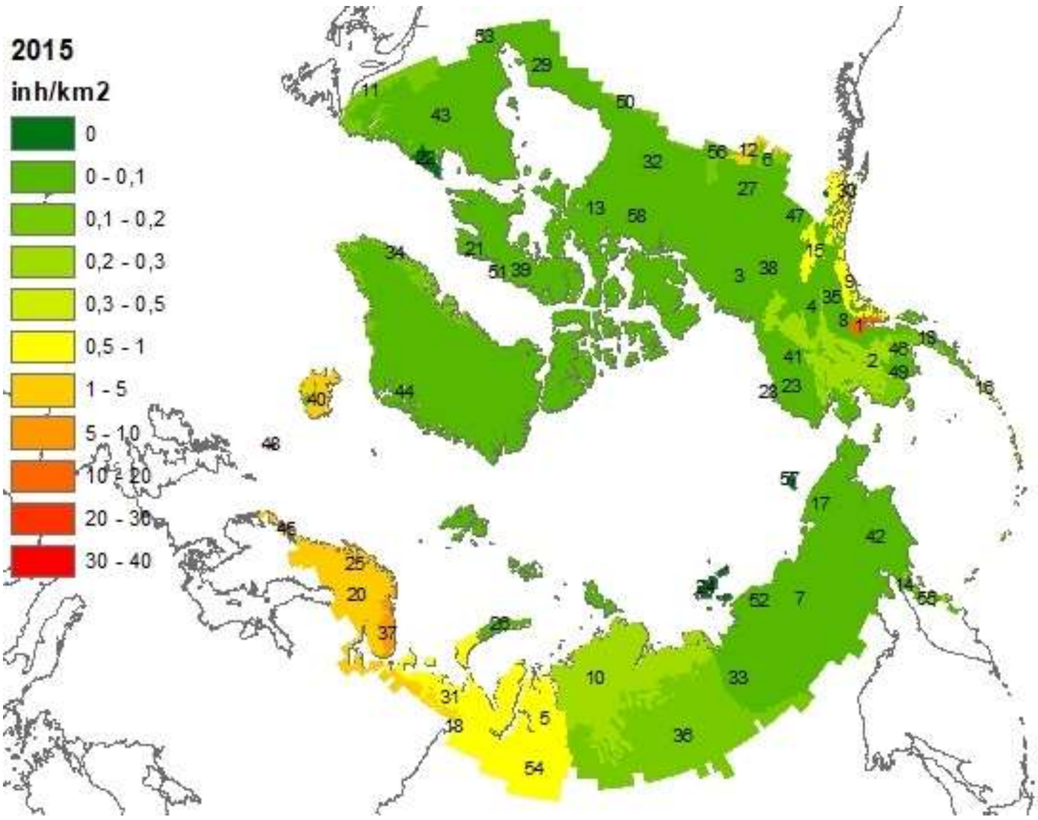
- Ogilvie-MacKenzie alpine tundra (38), CAN-USA CPPI=+55%
- Interior Yukon-Alaska alpine tundra (4), CAN-USA CPPI=+69%
- Arctic desert (26), RUS CPPI=+69%
- Yukon Interior dry forests (15), CAN CPPI=+71%

- Aleutian Islands tundra (16), USA CPPI=+72%
- Kamchatka-Kurile meadows& sparse forests (55), RUS CPPI=+76%
- Kamchatka Mountain tundra & forest tundra (14), RUS CPPI=+1389%

The 5 *Arctic ecoregions* with the highest 1990-2015 decrease in population (<-20 %) are (name (country, id)):

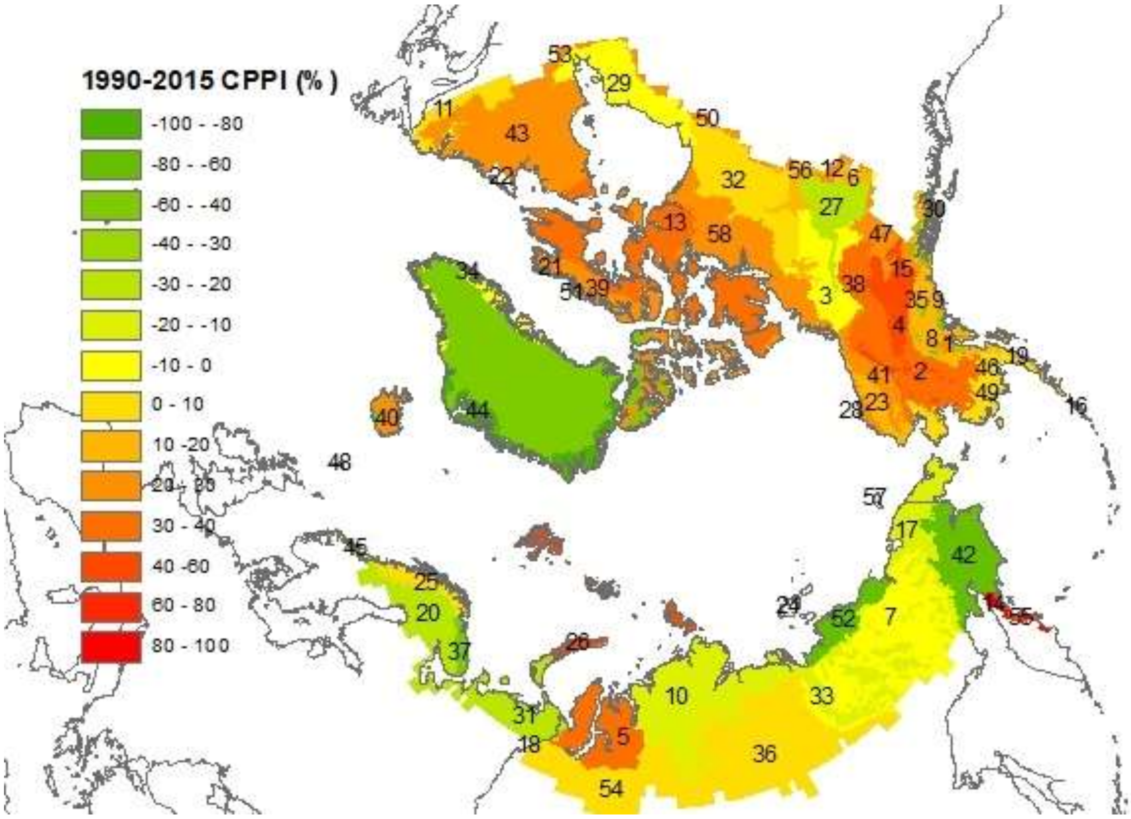
- Kalaallit Nunaat high arctic tundra (44), GRL CPPI=-47%
- Bering tundra (42), RUS CPPI=-39%
- Northeast Siberian coastal tundra (52), RUS CPPI=-39%
- Kola Peninsula tundra (37) NOR-RUS CPPI=-29%
- Muskwa-Slave Lake forests (27), CAN CPPI=-21%

Figure 12. 2015 population density (PPI) in the 58 *Arctic ecoregions*.



Source: GHS P2019

Figure 13. 1990-2015 population change (CPPI) in the 58 *Arctic ecoregions*.



Source: GHS P2019

4.1.3 2000-2015 population change (CPPI)

A mean Arctic population change of -1.8% is calculated for the last 2000-2015 period from GHS P2019 data. Two new ecoregions with high increase of population (Yamal-Gydan tundra, Northern Cordillera forests) are highlighted as compared to the 1990-2015 period.

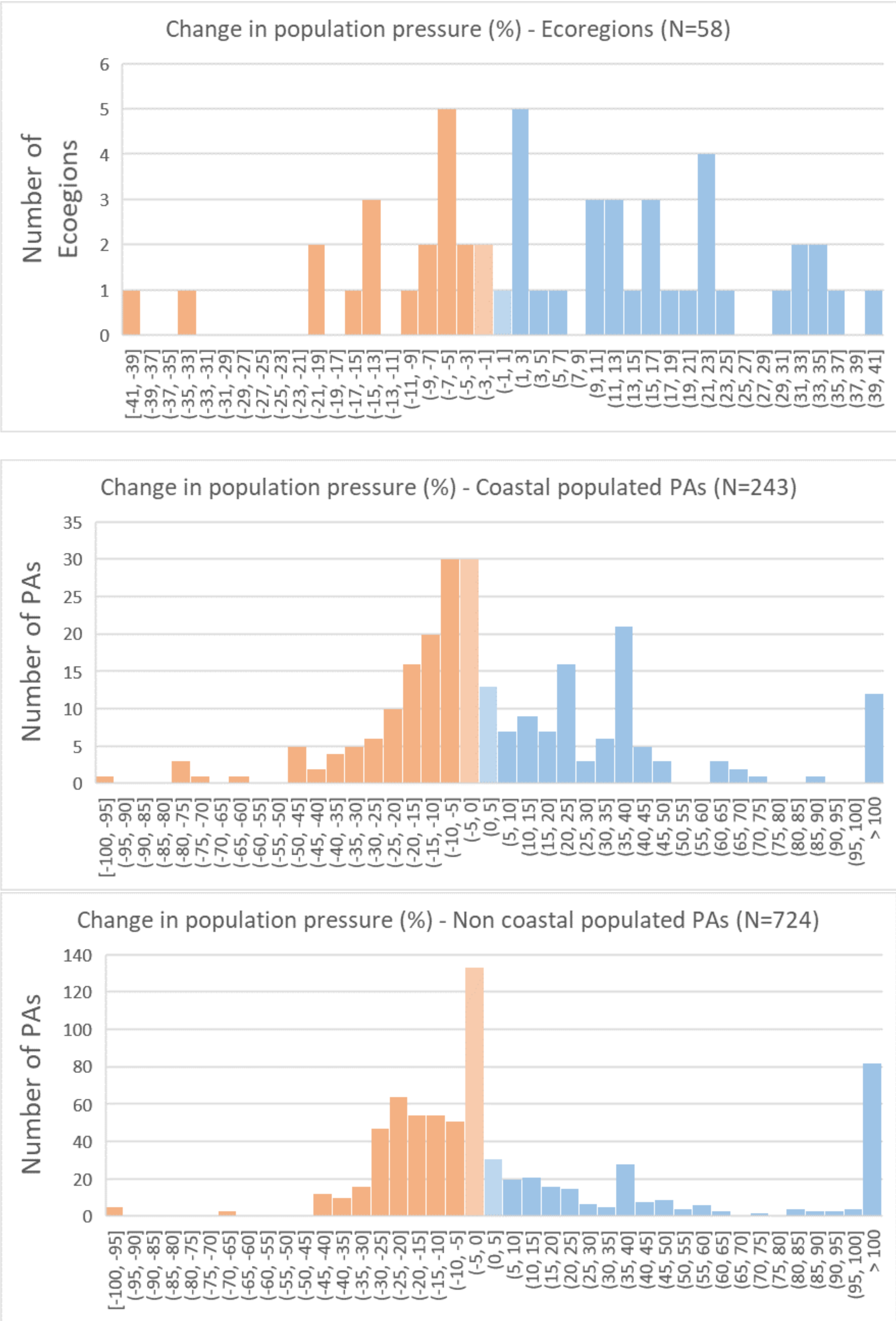
The highest 2000-2015 increase in population (> 30%) are observed for:

- Ogilvie-MacKenzie alpine tundra (38), USA-CAN: CPPI=+31.0%
- Yamal-Gydan tundra (5), RUS: CPPI=+31.5%
- Interior Yukon-Alaska alpine tundra (4), USA-CAN: CPPI=+32.9%
- Arctic coastal tundra (28), USA-CAN: CPPI=+34.4%
- Northern Cordillera forests (47), USA-CAN: CPPI=+35.3%
- Yukon Interior dry forests (15), CAN: CPPI=+37.3%
- Arctic desert (26), RUS: CPPI=+39.8%

The highest 2000-2015 decrease in population (<-15 %) are observed for:

- Northeast Siberian coastal tundra (52), RUS: CPPI=-40.6%
- Bering tundra (42), RUS: CPPI=-33.8%
- Kalaallit Nunaat high arctic tundra (44), GRL: CPPI=-19.6%
- Kola Peninsula tundra (37), RUS: CPPI=-19.4%
- Northwest Russian-Novaya Zemlya tundra (31), RUS: CPPI=-15.4%

Figure 14. Frequency distribution of 2000-2015 population change in the *Arctic ecoregions* and populated PAs.



Source: Arctic 202009 DOPA sub-dataset and GHS P2019

Figure 14 compares 2000-2015 population changes (CPPI indicator) at ecoregion level with the populated PAs (N=967). It shows more population increases (36 ecoregions i.e. 62%) than decreases at ecoregion level, whereas populated protected areas experienced more decreases (49% of decrease against 39% of increase). This is more particularly true for the non-coastal (49% of decrease against 38% of increase) than for the coastal ones (49% of decrease against 45% of increase) PAs. A more detailed analysis of the population pressure on Arctic coastal and not coastal protected areas is provided in section 5.2.

4.2 Urbanisation and migration

4.2.1 Urbanisation level (URBL and CURBL)

The GHS-SMOD settlement model uses a global definition of cities, towns and rural areas to generate the settlement model spatial grid that partitions the world land masses into High Density Clusters (HDC), Moderate Density Clusters (MDC) and Rural Grid cells (LDC), divided in HDC 30, MDC 23, MDC 22, LDC 13, LDC 12 and LDC 11 land cells, from the highest to lowest population density and connectivity (see Pesaresi et al, 2019 for details). It of particular interest for monitoring trends in urbanisation and population migration within the Arctic, because of the harmonised definitions of the categories, which are independent from the administrative boundaries of the municipalities and applicable to any region of interest. Looking only at the populated cells only (9,4% of the Arctic domain as defined in Koffi et al. 2021), we showed in this previous report that the LDC 11 most rural Arctic cells (< 50 people/km^2) represent the large majority (99.38%) of the *inhabited areas*, followed by LDC 12 (0,45%) and LDC 13 (0,08%) more populated cells. Results also showed that changes in the Arctic population's *urbanisation degree* (MDC and HDC cells, 0.1% of the populated cells) and their population density are positively related.

In this report, we further define and analyse the *urbanisation level* (URBL indicator) and change (CURBL) indicators at Arctic and eco-regional levels: The urbanisation level and trend are still expressed in terms of the presence and changes in MDC (towns, sub-urban areas) and HDC (cities) cells over the 1990 to 2015 period, which are referred to as urban cells. Rural ecoregions (N=38) are regions covered by LDC rural cells only, while urbanised ecoregions (N=21) at least include one MDC or HDC cell over the period. The URBL indicator is defined as the percentage of urban cells over the *total land cells* and the CURBL indicator as the *change in percentage of the URBL*. In order to provide a full picture of the changes in human settlement at Arctic circumpolar scale, all the HDC 30, MDC 23, MDC 22, LDC 13, LDC 12 are further documented in section in terms of change in km^2 (Fig. 15) and in terms of percentage for the LDC 13 and LDC 12 most densely populated rural cells.

The 2015 population covers 10.6% of the Arctic domain as defined in the present study. The Arctic mean urbanisation level (URBL=0,014%) increased by 2.5 % since 1990 (CURBL=+2.5%).

Urbanised areas (21 ecoregions)

The 2015 most urbanised ecoregions (> 0.1% of urban cells) are:

- Cook Inlet taiga	(1), USA:	URBL=0.63%
- Scandinavian coastal conifer forests	(45), NOR:	URBL=0.63%
- Kola Peninsula tundra	(37), NOR-RUS:	URBL=0.24%
- Scandinavian and Russian taiga	(20),FI-NO-RU-SW:	URBL=0.17%
- Iceland boreal birch forests and alpine tundra	(40), ISL:	URBL=0.13%

The highest 1990 to 2015 increase in the urbanised level (> 10 %) are observed for:

- Iceland boreal birch forests and alpine tundra	(40), ISL:	CURBL=+54%
- Yamal-Gydan tundra	(5), RUS:	CURBL=+32%
- Interior Alaska-Yukon lowland	(2), CAN-USA:	CURBL=+19%
- Cook Inlet taiga	(1), USA:	CURBL=+17%

Four ecoregions shifted from rural to urbanised over the period:

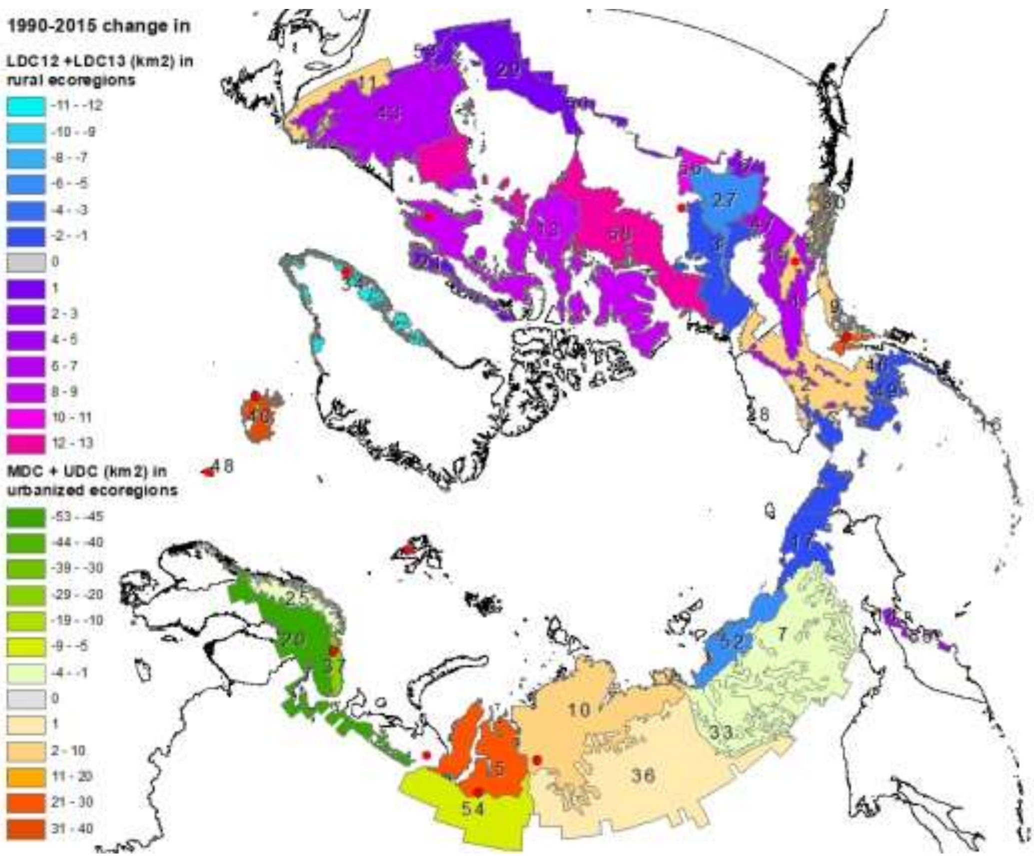
- Northern Pacific coastal forests (30), USA: URBL=0.023%
- Yukon Interior dry forests (15), CAN: URBL=0.010%
- Pacific Coastal Mountain icefields and tundra (9), CAN-USA: URBL=0.007%
- Eastern Canadian forests (11), CAN: URBL=0.003%

Rural areas (38 ecoregions)

Most of the rural ecoregions showed a 1990-2015 increase (16 out of 36), or no change (13 out of 36) in LDC 12 and LDC 13 areas. The highest 1990 to 2015 increase in LDC12 and LDC13 rural areas (% total cells) are observed for:

- Faroe Islands boreal grasslands (48), FRO: +0,974%
- Kamchatka-Kurile meadows& sparse forests (55), RUS: +0,071%
- Mid-Continental Canadian forests (56), CAN: +0,019%
- Aleutian Islands tundra (16), USA +0,017%
- Kamchatka Mountain tundra and forest tundra (14), RUS +0,016%

Figure 15. 1990-2015 change in the most populated (SMOD) cells (km^2) in Arctic rural (LDC 12, LDC 13) and urbanised (MDC and UDC) ecoregions.

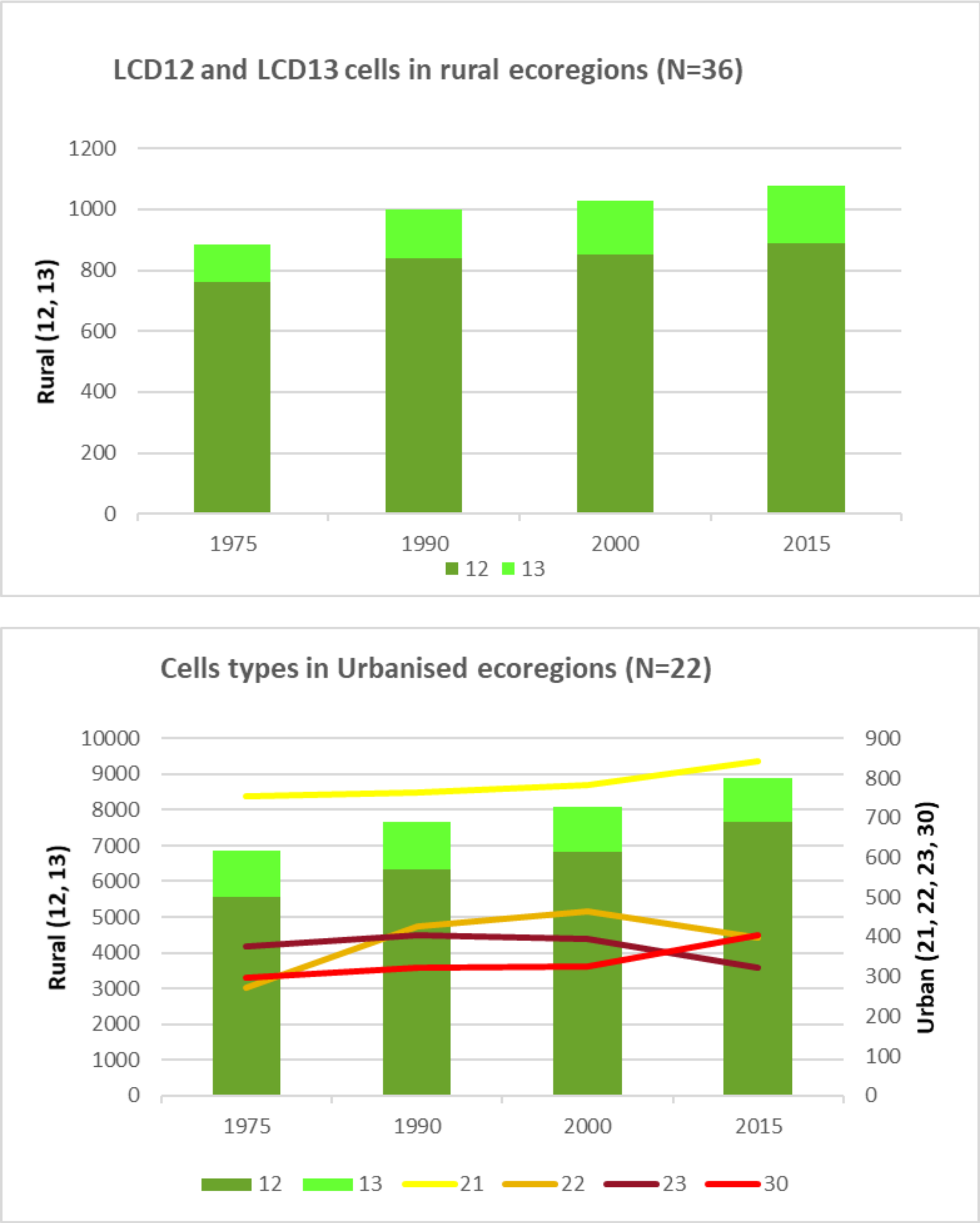


Source: GHS P2019

Figure 16 provides a synthetic view of the 1990-2015 Arctic urbanisation process for rural and urbanised ecoregions. It shows a mean increase in the population density for the rural ecoregions and a densification of the urbanised areas from MDC to HDC categories.

This documentation of the Arctic urbanisation is completed in the next section by an analysis of the population migration (PNSI indicator) for both 1990-2000 and 2000 -2015 periods.

Figure 16. Trends in the LDC 12 and LDC 13 rural cells and in MDC 21, MDC 22, MDC 23 and HDC 30 urban cells.



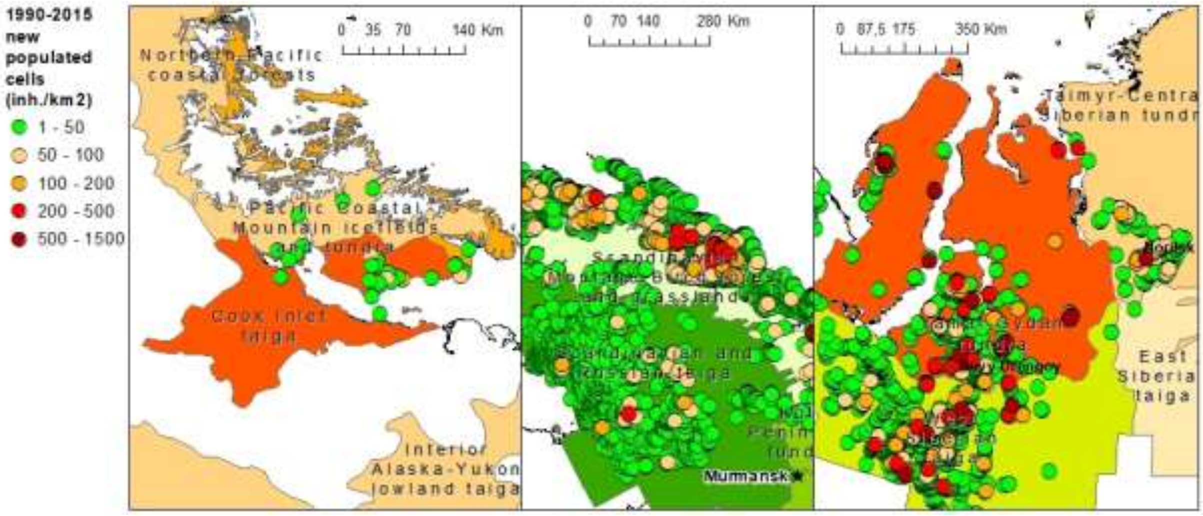
Source: GHS P2019

4.2.2 Population New Settlement (PNSI)

The documentation of the Arctic population dynamics (growing, shrinking, new populated and abandoned cells) at circumpolar, national and administrative levels (Koffi et al., 2021) showed that both rural and urban areas have experienced either growing or shrinking populations. Many regions which decreasing urbanisation were shown to also present many new settlements in the rural areas, whereas increasing urbanisation regions have experienced the abandon of rural territories and/or new settlements in the neighbourhood of cities as the result of urban growth (e.g., Fairbanks and Anchorage in Alaska; Novy Urengoy, Norislk and Murmansk in the Russian Federation; Reykjavik in Iceland).

This new analysis focuses on the Population New Settlement Indicator (PNSI) but calculated at the ecoregion level. As in the previous report, it is defined as the percentage of newly populated[11] 1X1 km² GHS-POP grid cells. The three maps provided in Figure 17 for illustration show that migration to unpopulated areas since 1990 has been occurring in ecoregions with both decreasing and increasing urbanisation trends. The main new settlements in Norway are primary coastal, while in the Russian federation they include a lot of inland settlement.

Figure 17. 1990-2015 new populated cells: examples of ecoregions (see ecoregion colour legend in Fig. 15).



Source: GHS P2019

1990-2000 PNSI

A total of 4802 newly populated 1X1 km² cells have been identified, in 30 (16 rural and 14 urbanised) out of the 58 ecoregions, from the GHS-SMOD data. They consist in LDC11"very low density rural" (94,3%), LDC12 "Low Density Rural grid cell" (5,3%), LDC13 "Rural cluster grid cell" (0,37%) and MDC21 "Suburban or per-urban grid cell" (0,04%) 2000 cells.

The five ecoregions with the highest percentage of 1990 to 2000 newly populated areas are all 2015 urbanised ecoregions (U). They are located in Scandinavia, Russian federation and Canada (Fig. 18).

- Scandinavian coastal conifer forests (45; U), NOR: PNSI +3.2%
- Scandinavian Montane Birch forest (25;U), FI-NO-RU-SW: PNSI +0.88%
- Kola Peninsula tundra (37; U), NOR-RUS: PNSI +0.40%
- Scandinavian and Russian taiga (20; U), FI-NO-RU-SW: PNSI+0.35%
- Canadian Aspen forests and parklands (12; U), CAN: PNSI +0,25%

2000-2015 PNSI

Over the 2000-2015 period, a total of 6713 newly populated 1X1 km² cells, in 16 (7 rural and 9 urbanised) out of the 58 ecoregions have been identified (Annex 7).

The five ecoregions (1 rural (R) and 4 urbanised (U)) with the highest rate of 2000 to 2015 newly populated areas are located in North America and Iceland. All but one are different from the above ones (Fig. 18):

- the Northern Pacific coastal forests (30; U), USA: PNSI +3.8%
- the Pacific Coastal Mountain icefields and tundra (9; U), CAN-USA: PNSI +2.2%

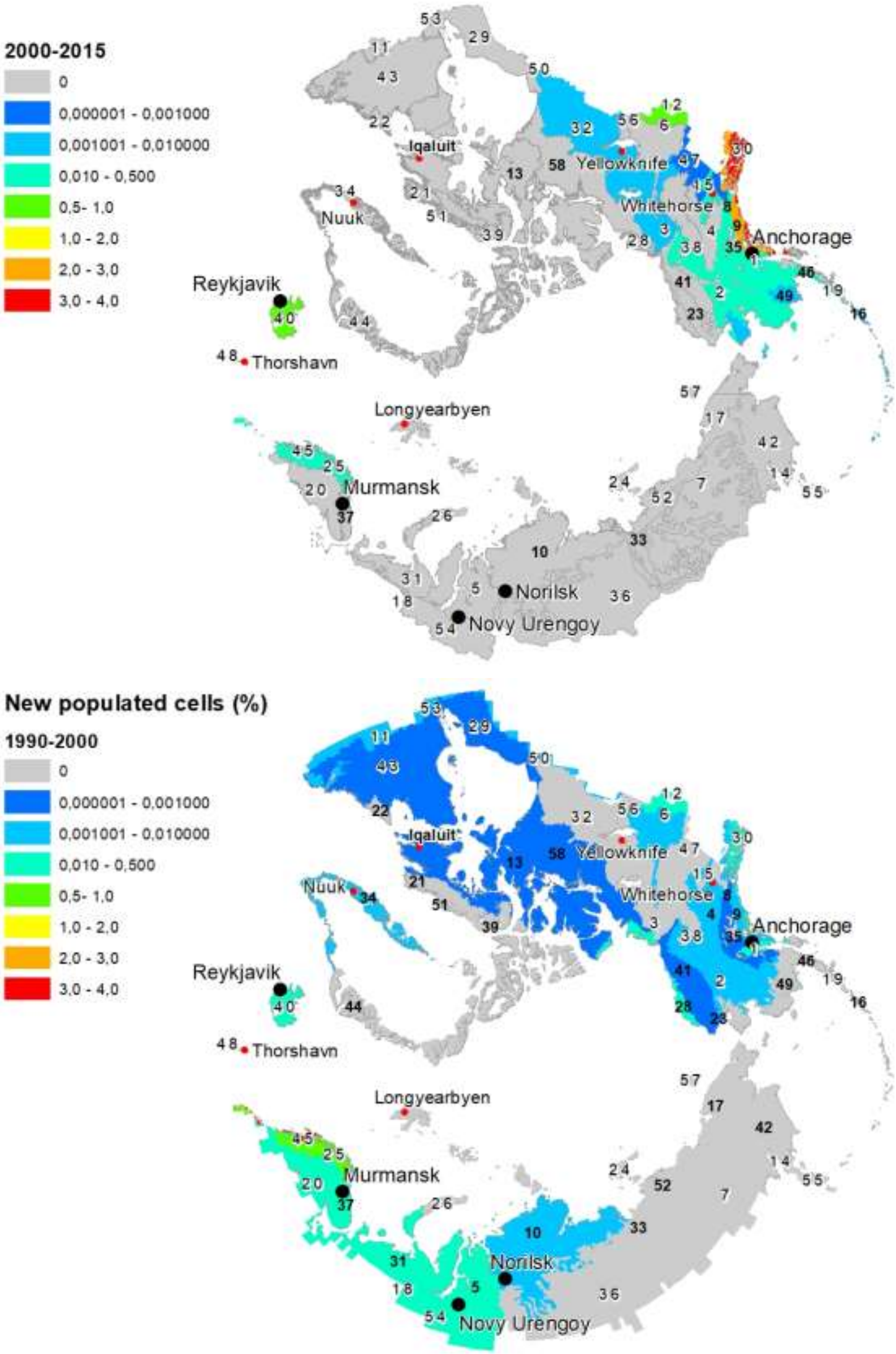
[11] cells that change from zero to non-zero inhabitants

- the Alberta-British Columbia foothills forests (6; R), CAN: PNSI +0.94%
- the boreal birch forests and alpine tundra (40; U), ISL: PNSI +0.86%
- the Canadian Aspen forests and parklands (12; U), CAN: PNSI +0.57%

Unlike the 1990 to 2000 new populated cells, the 2000-2015 newly settled cells are all (still) classified as LDC11"very low density rural" cells by the SMOD model.

These results show how such data and analyses allow highlighting - and potentially understanding - long-term changes in Arctic human migration and the regions the most under recent urbanisation and migration pressures. It is worth noting that for the two above periods, no significant correlation is obtained at ecoregional level between the change in the urbanisation level (URBL) and the new settlements (PNSI).

Figure 18. New populated 1 km^2 cells (% of populated cells) in *Arctic ecoregions* (see Annex 7 for details on the 2000-2015 new settlements).



Source: GHS P2019

5 Multi-scale socio-ecological analysis

A combination of ecological and human pressure indicators can be used to identify areas of socio-ecological vulnerability and resilience. A multi-scale geo-spatial analysis is provided in this Chapter as an illustration of the potential of DOPA and GHSL data to assess the Arctic socio-ecological resilience through composite indicators (indexes).

5.1 Vulnerability at Arctic ecoregional level

Ten of the indicators calculated for the 58 *Arctic ecoregions* (Table 1) have been normalised[12] on the same scale (0-100, with 100 being higher risk) and combined in order to calculate and map 3 mean normalised indexes. The indexes are calculated by averaging the Normalised Values (NV) of the indicators and applying a subsequent normalisation on the result: The two first preliminary indexes assess the Arctic Ecological Vulnerability (AEVI index) and the Human Pressure (AHPI index). A first assessment of the Arctic socio-ecological vulnerability of the *Arctic ecoregions* is then proposed by combining the two indexes into the PASEVI Index.

5.1.1 Preliminary Arctic Ecological Vulnerability Index (AEVI)

An Arctic Ecological Vulnerability Index (AEVI) has been defined and analysed at ecoregional level by normalising and combining 4 indicators: the 2020 conservation level (TPAC), the 1984-2018 absolute change (%) of seasonal surface water (CISSW), and the total (SOCI) and protected (PSOCI) fraction of the soil organic carbon content, applying a 100 – NV factor to TPAC, SOCI and PSOCI. The AEVI values (Annex 8) allows to highlight ecoregions with higher values, as a signature of higher ecological vulnerability (Fig. 19). The ten most ecologically vulnerable ecoregions are located in Russian Federation (4 ecoregions), Canada (3 ecoregions), Greenland (2 ecoregions) and Iceland (1 ecoregion).

- Iceland boreal birch forests and alpine tundra (40), ISL AEVI=100
- Northeast Siberian coastal tundra (52), RUS AEVI=92
- Kalaallit Nunaat low arctic tundra (34), GRL AEVI=89
- Kalaallit Nunaat high arctic tundra (44), GRL AEVI=88
- Northeast Siberian taiga (7), RUS AEVI=85
- Bering tundra (42), RUS AEVI=85
- Chukchi Peninsula tundra (17), RUS AEVI=83
- Baffin coastal tundra (51), CAN AEVI=82
- Middle Arctic tundra (13), CAN AEVI=82
- High Arctic tundra (39), CAN AEVI=80

Future development of the AEVI could include the combination of other resilience relevant DOPA indicators, which are not available in the *Arctic 202009 DOPA sub-dataset* (e.g, CTPAC, ProtConn, CProtConn, land degradation, land fragmentation).

5.1.1 5.1.2. Preliminary Arctic Human Pressure Index (AHPI)

An Arctic Human pressure Index (AHPI) has been calculated at ecoregional level by combining 5 normalised indicators: the population density level (2015 and 2000-2015 % change), the urbanisation level (2015 and 2000-2015 % change) and the 2000-2015 new settlements (% of populated cells).

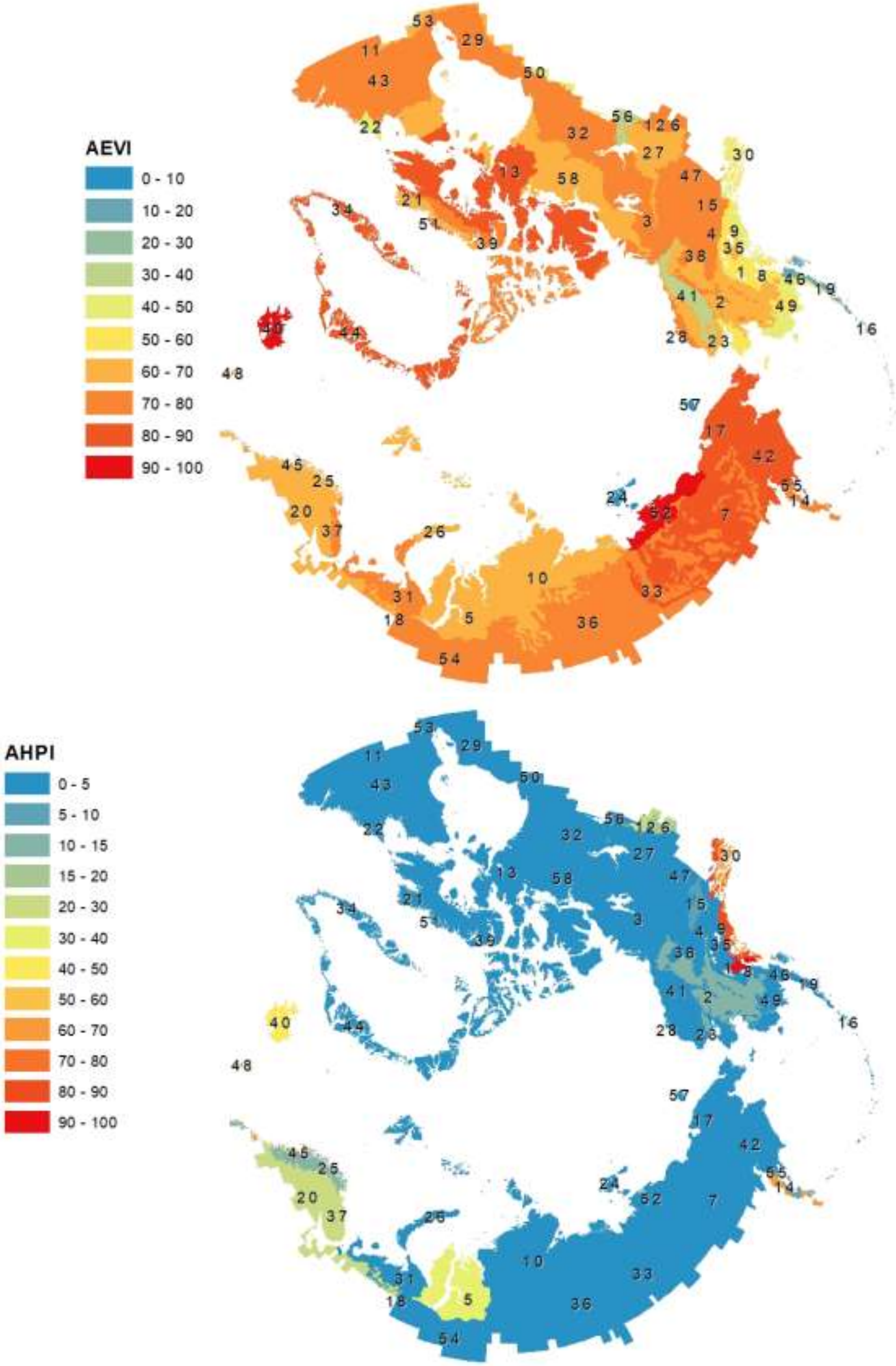
The AHPI values (Annex 8) allows to identify the ecoregions with the highest human pressure (Fig. 19). The ten ecoregions most under human pressure are located in North America (3 ecoregions), Russian Federation (2

[12] (Ecoregion value – Min(58 Ecoregions' values)*100/(Max(58 Ecoregions' values - Min(58 Ecoregions' values))

ecoregions), Norway (1 ecoregion), Scandinavia and Russian ecoregions (2 ecoregions), Faroe Island (1 ecoregion) and Iceland (1 ecoregion):

-	Cook Inlet taiga	(1), USA:	AHPI=100
-	Pacific Coastal Mountain icefields and tundra	(9), CAN-USA:	AHPI=80
-	Scandinavian coastal conifer forests	(45), NOR:	AHPI=74
-	Northern Pacific coastal forests	(30), USA:	AHPI=66
-	Faroe Islands boreal grasslands	(48), FRO:	AHPI=62
-	Kamchatka Mountain tundra and forest tundra	(14), RUS:	AHPI=60
-	Iceland boreal birch forests and alpine tundra	(40), ISL:	AHPI=50
-	Yamal-Gydan tundra	(5), RUS:	AHPI=31
-	Kola Peninsula tundra	(37), NOR-RUS:	AHPI=26
-	Scandinavian and Russian taiga	(20),FI-NO-RU-SW:	AHPI=20

Figure 19. Arctic Ecological Vulnerability Index (AEVI) and Arctic Human Pressure Index (AHPI).



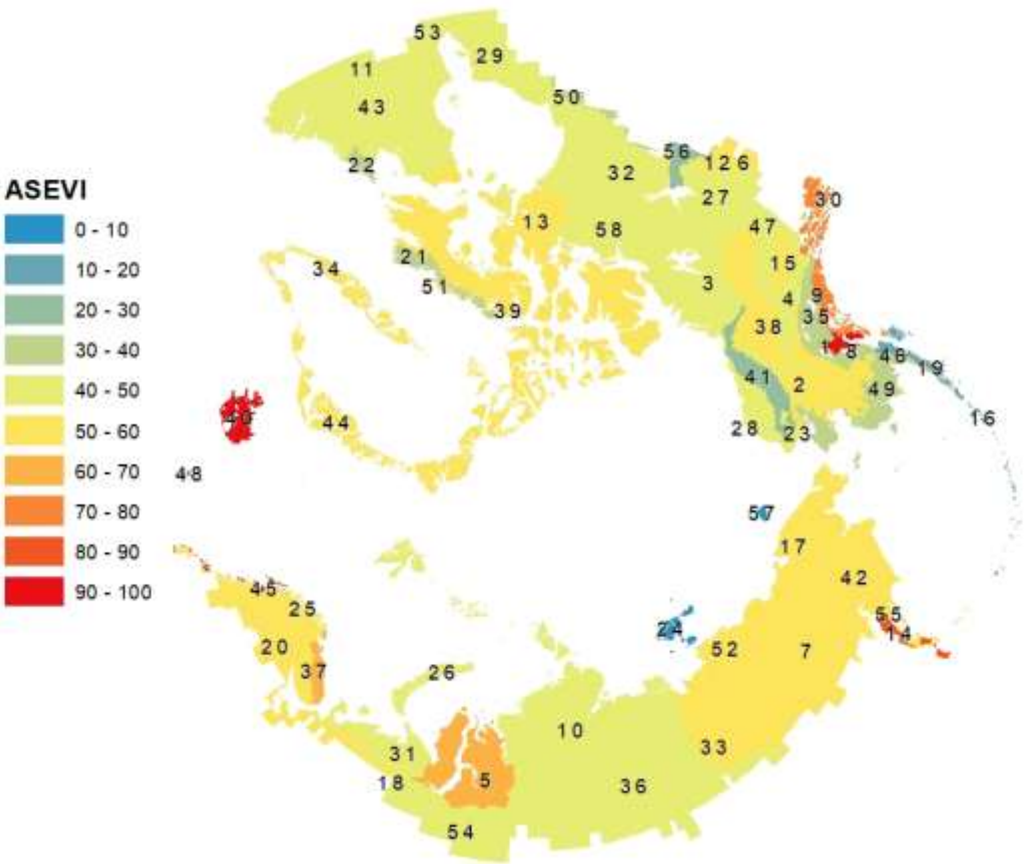
Source: Arctic 202009 DOPA sub-dataset for AEVI and GHS P2019 for AHPI

5.1.3. Preliminary Arctic Socio-ecological Vulnerability index (ASEVI)

Combining the ecological and human pressure indices, the top ten ecoregions under combined ecological and human pressure are located in USA (2 ecoregions), Canada (1 ecoregion), USA-Canada (1 ecoregion), Russian Federation (2 ecoregions), Norway (1 ecoregion), Norway-Russian Federation (1 ecoregion), Faroe Islands (1 ecoregion) and Iceland (1 ecoregion):

- Cook Inlet taiga	(1), USA:	ASEVI=100
- Iceland boreal birch forests and alpine tundra	(40), ISL:	ASEVI=96
- Scandinavian coastal conifer forests	(45), NOR:	ASEVI=95
- Kamchatka Mountain tundra and forest tundra	(14), RUS	ASEVI=86
- Faroe Islands boreal grasslands	(48), FRO	ASEVI=85
- Pacific Coastal Mountain icefields and tundra	(9), CAN-USA	ASEVI=80
- Northern Pacific coastal forests	(30), USA	ASEVI=75
- Yamal-Gydan tundra	(5), RUS	ASEVI=63
- Kola Peninsula tundra	(37), NOR-RUS	ASEVI=62
- Canadian Aspen forests and parklands	(12), CAN	ASEVI=59

Figure 20. Arctic socio-ecological vulnerability index (ASEVI).



Source: Arctic 202009 DOPA sub-dataset and GHS P2019

The AEVI, AHPI and ASEVI indexes, as defined in this report using a simple methodological approach (arithmetic mean of normalised indicators), illustrate how aggregating individual indicators can help identify and rank Arctic terrestrial regions at higher risks and/or lower socio-ecological resilience. Statistical and sensitivity tests are needed at this stage to confirm the relevance of the indicators and the calculation method. Moreover, many more DOPA ecological and human pressure indicators and sub-indicators exist (see Table 1 and DOPA Factsheets), which can complete the documentation of the Arctic socio-ecological resilience, including changes in ProtConn and TPAC for the AEVI (see Fig. 7 for 39 ecoregions).

Such analyses could also be further improved, e.g. by crossing the ecoregion boundaries with the administrative boundaries and by adding socio-economic (e.g., ASI (2015) social indicators and INFORM (2019) vulnerability indicators) and other (e.g. exposure to natural hazards) indicators. More generally, further investigation and developments (choice of the dimensions and core indicators, weighting and other methodological aspects) are needed for the selection of relevant Arctic resilience indicators and the definition of an Arctic resilience conceptual model (see for instance Manca et al., 2017 and Koffi and Wilson, 2019). They should also account for the limitations and caveats of the DOPA and GHSL data, which are detailed in the two products' documentation but not yet all investigated in this preliminary analysis.

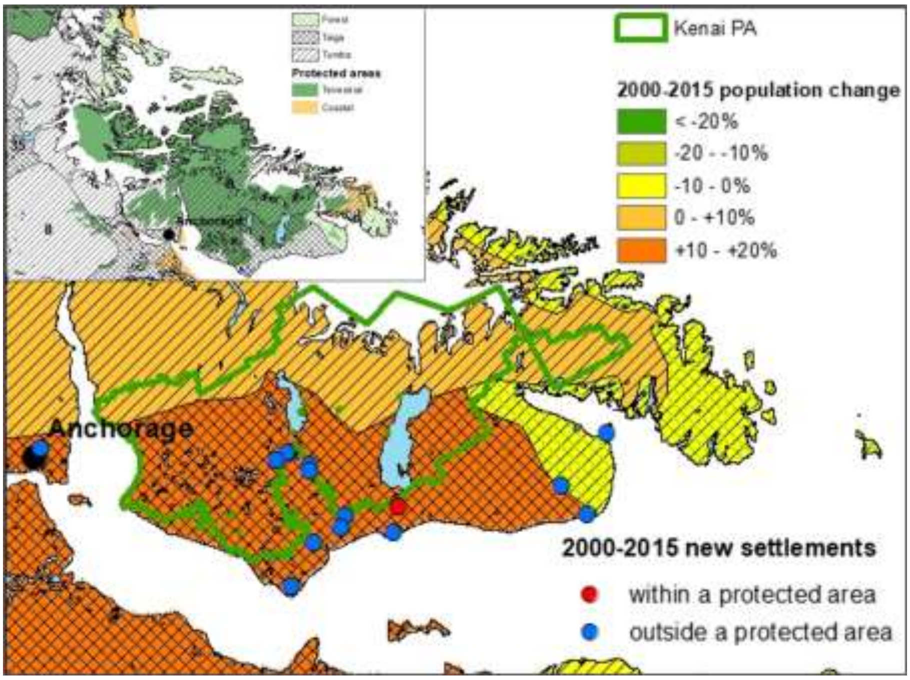
5.2 Human pressure on protected areas

A total of 1276 protected areas larger than 10 km^2 have been identified in *September 2020 DOPA Arctic dataset* (section 2.3), 527 of which are populated. In this section, we analyse these 528 populated PAs for the three following human pressure indicators: the Population Pressure Indicator for 2015 (PPI; people per km^2), the change in the population pressure indicator from 2000 to 2015 expressed in percentage (CPPI; %) and in density (CPDI; inh./km^2). These 527 PAs cover 1.78 M km^2 (39 % of the total Arctic protected area). Their population (105011 inhabitants) represent 2% of the total Arctic population and 87.5% of the people living in Arctic protected areas.

5.2.1 Example of the Kenai protected area in the Cook Inlet taiga (Alaska)

Figure 21 shows that the Cook Inlet taiga ecoregion in Alaska experienced 2000-2015 population increases at both ecoregion and protected area levels (e.g., +18% in Kenai PA (WDPAID=370437). Moreover, many of newly populated areas (Annex 7) are identified near the boundaries of the Kenai PA from the GHS-POP data, as the result of the population pressure from the higher populated surrounding and unprotected coastal zone.

Figure 21. 2000-2015 population changes and new settlements in the vicinity of *Kenai* Protected Area.



Source: Arctic 202009 DOPA sub-dataset and GHS P2019

5.2.2 Statistics on PPI, CPPI and CPDI population pressure indicators

The PPI and CPPI human pressure indicators are defined and calculated in DOPA explorer for each terrestrial protected area of size ≥ 10 km^2 and for the terrestrial parts of each coastal protected area of size ≥ 10 km^2. To assess pressures around protected areas, the 10 km unprotected buffer zone around the protected areas of size ≥ 5 km^2 is also provided). The statistical analysis of the 528 populated PAs and buffers (Fig. 22) allows to characterise the patterns of the human pressure in non-coastal and coastal protected areas as summarised in Table 4, where a CPDI indicator (change in population pressure as expressed in population density) is used instead of the DOPA CPPI indicator (expressed in %), as the latter can lead to less relevant information on population change, i.e. in case of initially low or uninhabited populated areas (see section 5.1.4).

Non-coastal PAs (N=417)

As expected, both the mean population density (0,85 inh./km^2) and the 2000-2015 absolute change (+0,17 inh./km^2) in the Arctic non-coastal PAs are lower than the ones at Arctic scale (0,36 inh./km^2 and -1.8% inh./km^2, respectively). Nevertheless, a much higher mean density (2,49 inh./km^2) is calculated for their non-protected surrounding buffers. On the other hand, a mean population change around zero is obtained in average for the buffers, as the result of diverse demographical and migration processes, among which the population migration to the PAs is probably not the major one (no significant correlation between the CPDI of the PAs and buffers).

Coastal PAs (N=111)

The mean population density in the coastal PAs (2, 5 inh./km^2) is three times the one in the non-coastal areas, whereas the one in the buffer zone (32 inh./km^2 in average) is 13 times the one of the non-coastal buffers. While higher changes are observed for the non-protected buffer (+2,10) compared to the PAs (+0,07), a statistically significant correlation is obtained between the two CPDI indicators, showing a general pressure from the surrounding population onto the coastal protected areas.

Table 4. PPI and CPDI statistics of the 528 populated Arctic PAs of size ≥ 10 km^2 and their buffer zones.

INDICATOR	AREA	STATISTICS	NON-COASTAL PA	COASTAL PA	ALL PA
PPI (INH./KM2)	PA	mean	0,85	2,49	1,20
	PA	media	0,03	0,24	0,04
	PA	Std dev.	5,32	8,48	6,15
	Buffers	mean	2,43	32,2	8,67
	Buffers	media	0,23	3,69	0,33
	Buffers	Std dev.	13,1	84,5	42,1
CPDI (INH./KM2)	PA	mean	+0,17	+0,07	+0,15
	PA	media	+0,00	+0,00	+0,00
	PA	Std dev.	0,68	1,65	0,96
	Buffers	mean	0,00	+2,10	+0,44
	Buffers	media	0,00	+0,01	0,00
	Buffers	Std dev.	1,28	11,1	5,27
	PA/Buffers	Linear regression	R=0,001	R=0,535 (0,277*)	R=0,394
			No correlation	α =0.001 (0.01*)	α=0.001

*removing the three PAs with most extreme CPDI buffer values (see Fig. 22)

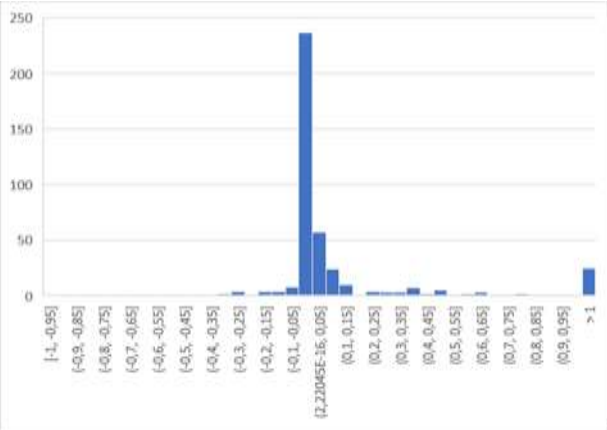
Source: Arctic 202009 DOPA sub-dataset

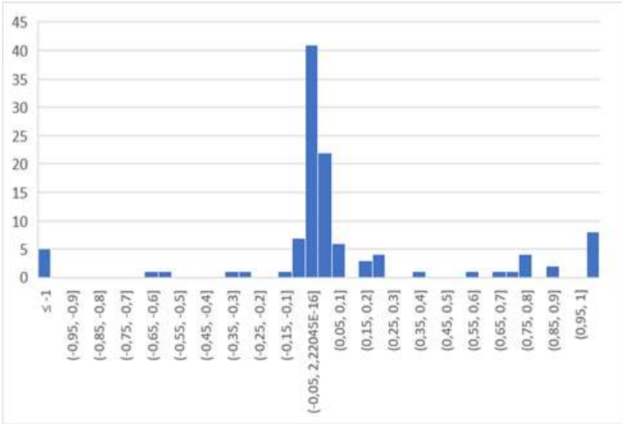
These results confirm an increasing population pressure on Arctic protected areas, especially coastal ones as already suggested by Figure 14 (section 4.1.3.). Illustrations for selected PAs are provided in the following paragraph.

Figure 22. 2000-2015 change in the population density (CPDI; inh./km^2) in the Arctic PAs and unprotected buffer zones.

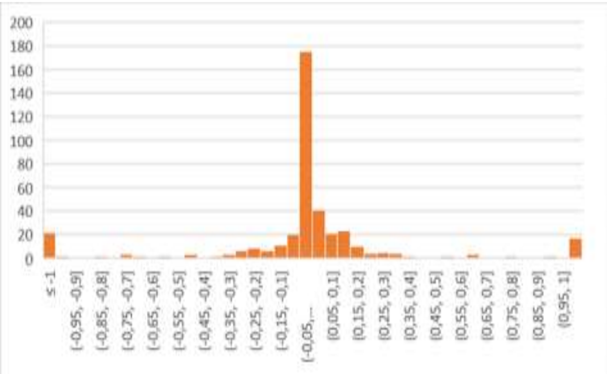
Non-coastal areas (N=417 PAs) | Coastal areas (N=111 PAs)

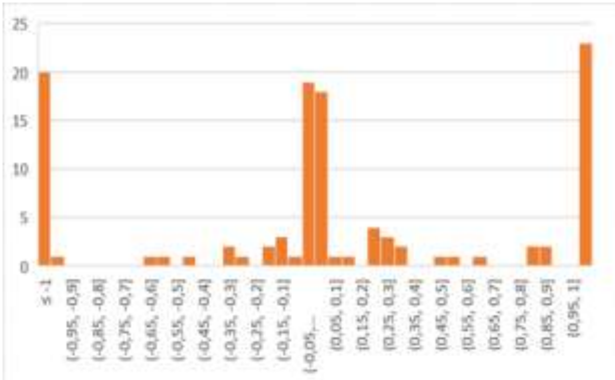
a) 2000-2015 change in the population density: PA



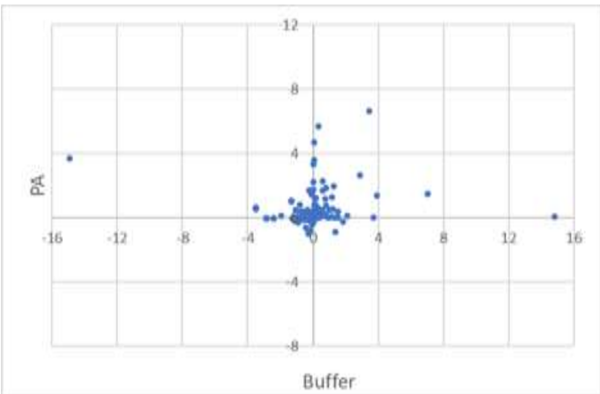


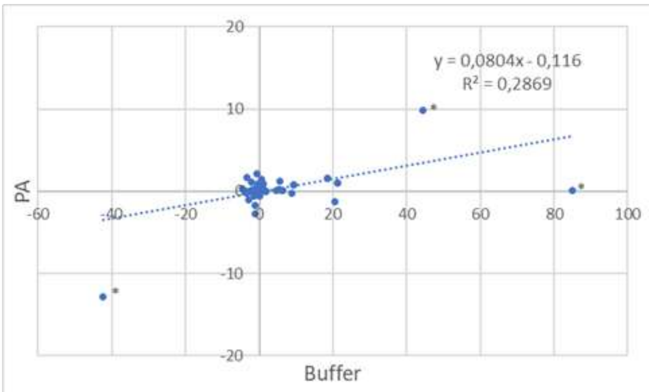
b) 2000-2015 change in the population density: buffer





c) 2000-2015 change in the population density: PA/buffer





Source: Arctic 202009 DOPA sub-dataset

5.2.3 Analysis of selected PA with high population pressure

The four highest PPI (2015), 2000-2015 CPPI and CPDI indicators for the PAs and the buffer zones are provided and discussed in this section, for the non-coastal (Table 5) and coastal (Table 6) PA areas. The 35 PAs identified in this way only cover 47908 km^2, i.e., 1% of the total Arctic protected area, but 40% of its population (Fig. 4).

Non-coastal PAs (N=18):

- Results show that the PAs areas with the 4 highest population density are located in Norway and Sweden and have all experienced 2000-2015 population growth. The 4 highest population changes expressed in percentage (CPPI) are obtained for PAs in Norway, Sweden and Russia but all concern very low (< 0.02 inh./km^2) 2000 population density. The change in inhabitant per km^2 (CPDI) allows to further highlight two more PAs (Ellitsan L. and Хибиныith) with increasing human pressure in Finland and Russian Federation, respectively.
- Results for the buffer zones reveals high population pressure for 4 of the above PA and 8 additional ones, including one in USA and one in Iceland.
- A total of 18 PAs or Buffer zone are identified at population pressure risk from this analysis: 5 in Norway, 4 in Sweden, 4 in Finland, 3 in Russian Federation, one in USA and one in Iceland.

Coastal PAs (N=17):

- PA areas with the highest population pressures are located in the Russian Federation (Беломорский), Norway (Giske and Malesanden Og Huse) and USA (Mendenhall Wetlands State). Unlike the 3 latter PAs, Беломорский showed a population density decrease from 2000 and 2015. The 4 highest population changes expressed in percentage are obtained for PAs in Norway and Sweden. As for the non-coastal zones, they correspond to low populated areas (< 0.3 inh./km^2 in 2000). The four highest changes in the PA population density highlights two additional PAs in Norway (Lofotodden and Bliksvær), leading to a total of ten PAs as for the non-coastal areas.
- Results for the buffer zones includes 8 additional PAs in USA, Norway, Russian Federation, Finland and Faroe Islands.
- A total of 18 PAs or Buffer zone are identified at population pressure risk in Norway (11), Sweden (1), Finland (1), Russian Federation (2), one in USA (2) and one in Faroe Island (1).

Maps of the 2015 population density and 2000-2015 change are provided for 6 (out of the 35 identified PAs, covering 6% of the total Arctic PA population in Figure 23 and 24, respectively. These images, downloaded from DOPA explorer (January 2021 WDPA version), usually show higher population pressure and change in the buffer zone of the coastal areas as compared to the non-coastal ones. It is also interesting to note that the non-coastal PAs the most at risk are often surrounded with coastal buffers.

On the monitoring point of view, it is worth noting that 5 (four in the Russian Federation and one in Norway) out of the 35 identified PAs have been removed from the WPDA classification since September 2020. Another important aspect is the resolution of the GHS input data (1X1 km^2) used to assess the human pressure in DOPA, which appears to be low (Fig. 23 and 24) as compared to the size of most of the PAs analysed in this section. Higher resolution data would be required to allow for a more accurate investigation of small PAs, which results are also affected by the accuracy of the available PAs'boundaries.

This analysis is only an illustration of the usefulness of the DOPA PA indicators to identify particularly high human pressure on protected areas. A full set of human pressure indicators (population, population change, built-up areas, roads and agriculture) is provided for each individual PA and its surroundings in DOPA explorer (see for instance https://dopa-explorer.jrc.ec.europa.eu/wdpa/22493). An overview plot (country normalised values for the 5 indicators) also provides a synthetic picture of the human pressure affecting the Protected Areas. Different selecting and sorting criteria could be defined as a function of the type of the PAs (managed/not managed; type of ecosystem, etc) and pressure (Population, Built-up areas, Road, Agriculture) in order to identify the most threaten areas.

As done at ecoregional level in section 5.1, different human and environment indicators could be then combined to define a set of risk and resilience indices and potential solutions. It is worth noting that DOPA explorer also includes indicators of natural disaster risks at PA level for Fires, Floods and Droughts (which accounts for both the exposure and the socio-economic vulnerability of the area). It is also the case at urban level for the GHS-Urban Centres Database and illustrated in the next and last section.

Table 5. Highest PPI (inh./km^2), CPPI (%) and CPDI (inh./km^2) population pressure.

	PROTECTED AREA	PAID	WDPAID	ISO	AREA (KM2)	2015 PPI	CPDI	CPPI
PPI	Kirkeneshalvøya	1	156696	NOR	57	97	+5,7	+6%
	Åreälven	2	555534356	SWE	124	33	+1,2	+4%
	Lake Persöfjärden	3	68217	SWE	35	23	+2,3	+11%
	Runde*	4	555558422	NOR	13	21	+0,07	+0,4%
CPPI	Strandå/Os	5	9916	NOR	16	6,7	+6,6	+33130%
	Небесанюр (Небеса-Нюр)*	6	555686089	RUS	269	0,34	+0,3	+16604%
	2001219 Stora Sjöfallet	7	3998	SWE	1280	0,07	+0,07	+3547%
	Нумто*	8	555684228	RUS	5769	0,16	+0,15	+1549%
CPDI	Strandå/Os	5	9916	NOR	16	6,7	+6,6	+33130%
	Kirkeneshalvøya	1	156696	NOR	57	97	+5,7	+6,28%
	Ellitsan L.	9	555633093	FIN	28	6,0	+4,7	+355%
	Хибины*	10	555685129	RUS	911	5,6	+3,7	+196%
	BUFFER ZONES OF	PAID	WDPAID	ISO	Area (km2)	2015 PPI	CPDI	CPPI
PPI	2021406 Ormberget-H.	11	391264	SWE	22	230	7	+3%
	Chugach	12	22493	USA	1723	103	15	+17%
	Хибины*	10	555685129	RUS	911	51	-15	-23%
	Sjunkhatten	13	392918	NOR	418	26	4	+18%
CPPI	Vuotostunturin L.	14	555633085	FIN	25	0,11	+0,09	+403%
	Maltion Luonnonpuisto	15	1519	FIN	148	0,45	+0,34	+302%
	MALTIO	16	555525483	FIN	147	0,45	+0,34	+302%
	Spjeltfjelldalen	17	156612	NOR	30	0,25	+0,19	+298%
CPDI	Chugach	12	22493	USA	1723	103	+14,8	+17%
	2021406 Ormberget-H.	11	391264	SWE	22	230	+7,0	+3,2%
	Sjunkhatten	13	392918	NOR	418	26	+3,9	+18%
	Glerárdalur	18	555589820	ISL	74	23	+3,7	+19%

*removed from wpda classification between September 2020 and January 2021

Source: Arctic 202009 DOPA sub-dataset

Table 6. Highest PPI (inh./km²), CPPI (%) and CDPI (inh./km²).

	PROTECTED AREA	PAID	WDPAID	ISO	Area (km2)	2015 PPI	CPDI	CPPI
FOUR HIGHEST PPI	Беломорский*	19	555686535	RUS	399	74	-12,93	-15%
	Giske	20	156690	NOR	12	42	9,75	+31%
	Malesanden Og Huse	21	156711	NOR	14	20	0,79	+4%
	Mendenhall Wetlands State	22	777719	USA	12	20	0,25	+1,2%
FOUR HIGHEST CPPI	Nordkvaløya Rebbenesøya	23	193440	NOR	286	0,64	+0,6	+1543%
	Skorpa-Nøklan	24	193465	NOR	13	2,34	+2,06	+735%
	Skipsfjord	25	9915	NOR	54	0,91	+0,78	+606%
	Rånefjärden	26	555534932	SWE	57	0,09	+0,06	+214%
FOUR HIGHEST CPDI	Giske	20	156690	NOR	12	41,7	+9,75	+31%
	Skorpa-Nøklan	24	193465	NOR	13	2,34	+2,06	+735%
	Lofotodden	27	555639837	NOR	99	4,13	+1,59	+63%
	Bliksvær	28	62114	NOR	43	3,05	+1,56	+105%
	BUFFER ZONE OF	PAID	WDPAID	ISO	Area (km2)	2015 PPI	CPDI	CPPI
FOUR HIGHEST PPI	Anchorage Coastal	29	307568	USA	123	588	85,15	16,94
	Bliksvær	28	62114	NOR	43	324	18,56	6,09
	Giske	20	156690	NOR	12	309	44,5	16,83
	Беломорский*	19	555686535	RUS	399	258	-42,24	-14,05
FOUR HIGHEST CPPI	Nord-Fugløya	30	3200	NOR	24	7,64	+5,83	+322%
	Karlsøyvær	31	3207	NOR	49	9,40	+5,43	+137%
	Borgan Og Frelsøy	32	156686	NOR	28	1,44	+0,48	+50%
	Brekhovsky Islands in the Yenisei estuary	33	103550	RUS	7419	0,04	+0,01	+47%
FOUR HIGHEST CPDI	Anchorage Coastal	29	307568	USA	123	588	+85	+17%
	Giske	20	156690	NOR	12	309	+44	+17%
	Perämeren saaret	34	555539156	FIN	71	173	+21	+14%
	Nólsoy	35	555547977	FRO	22	221	+21	+10%

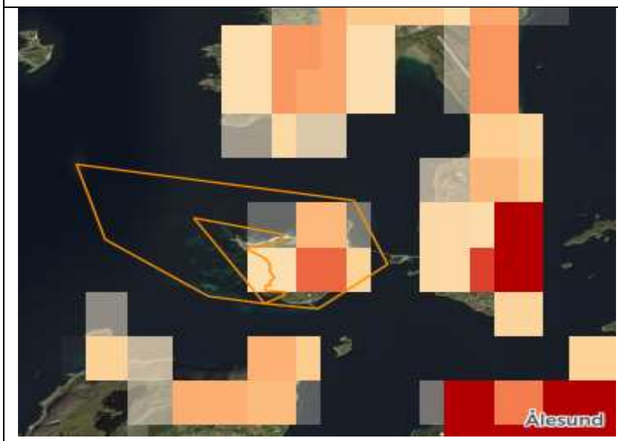
*removed from wpda classification between September 2020 and January 2021

Source: Arctic 202009 DOPA sub-dataset

Figure 23. Examples of 2015 population pressure on Arctic Protected Areas (orange outline) and surrounding areas. See population pressure statistics in Tables 5 and 6.

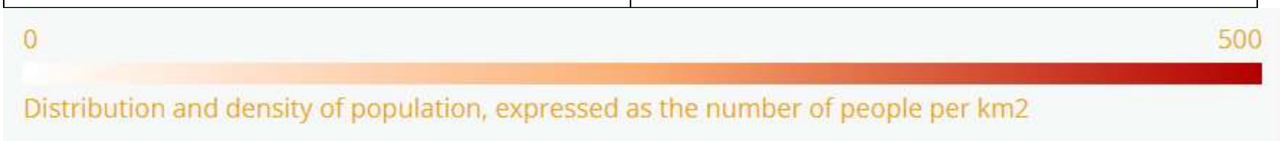
Kirkeneshalvøya (57 km²; non-coastal PA; Norway)

Chugach (1723 km²; non-coastal PA; USA)



Giske (12 km²; coastal PA, Norway)

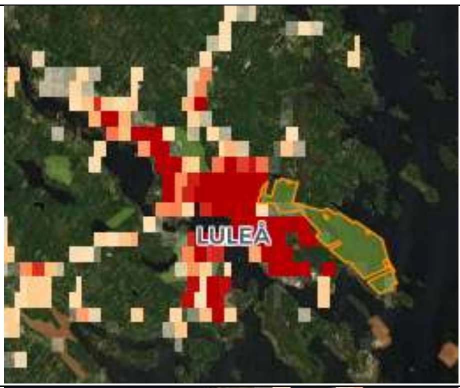
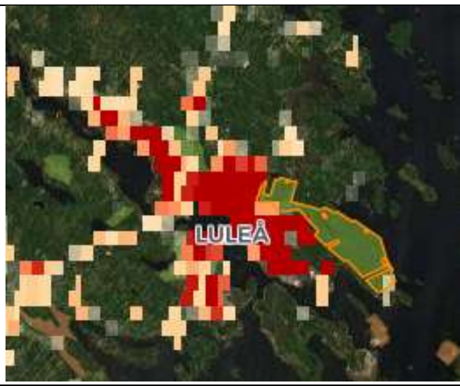
Mendenhall Wetlands State (12 km²; coastal PA, USA)



Source: DOPA explorer (https://dopa-explorer.jrc.ec.europa.eu/wdpa/) including January 2021 version of the World Database on Protected Areas (WDPA) and 2019 GHS Population 1 km x 1 km Grid (2015 density of population, in number of people per km²).

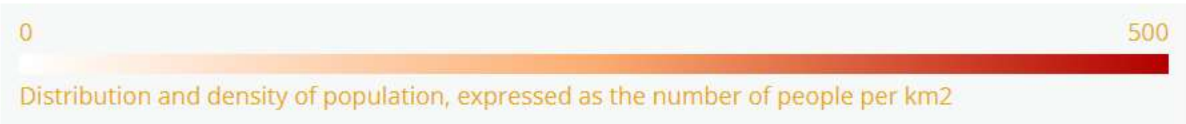
Figure 24. Examples of increasing population pressure on Arctic Protected areas (orange outline) and/or surrounding areas. See population pressure statistics in Tables 5 and 6.

<table>
<tr><th>PA</th><th>2000</th><th>2015</th></tr>
<tr><td>Ormberget-Hertsölandet
22 km^2

Sweden
(non-coastal PA)</td><td>
</td><td>
</td></tr>
<tr><td>Giske
12 km^2

Norway
(coastal PA)</td><td>
</td><td>
</td></tr>
<tr><td>Nólsoy
22 km^2

Faroe Islands
(coastal PA)</td><td>
</td><td>
</td></tr>
</table>



Source: DOPA explorer (https://dopa-explorer.jrc.ec.europa.eu/wdpa/) including January 2021 version of the World Database on Protected Areas (WDPA) and 2019 GHS Population 1 km x 1 km Grid (2000 and 2015 density of population, in number of people per km^2).

5.3 Urban Resilience relevant indicators

In the previous report (Koffi et al., 2021), the 1975, 1990, 2000 and 2015 urbanisation level has been mapped and discussed for 18 Arctic selected places in North America, European Nordic region and Russian Federation using the GHS urban/rural classification 1 km x 1 km grid (GHS-SMOD) of the GHS P2019 data package. The GHS-Urban Centres Database (GHS-UCDB), also available in open and free download, provides more than 20 indicators of Geography, Socio-economy, Environment, Disaster Risk Reduction and Sustainability (Annex 3) for more than 10000 Urban Centres (referred as UC hereafter). The full list, definition and sources are provided in Florczyk, et al. (2019b).

Five Urban Centres (Anchorage, Reykjavik, Murmansk, Novy Urengoy, and Norilsk) are identified in the Arctic domain, representing 19% of the 2015 total Arctic population, with the largest populations in Murmansk and Reykjavik UCs (Table 7). Four out of the five UCs have experienced a decreasing population density, due to the decrease in the total population (Murmansk and Norilsk) or to the spreading of the urban area (Reykjavik and Novy Urengoy), which – unlike municipal data – is provided by the UCDB data because of the UC definition (see section 2.2). This aspect is one of the major added value of UCDB data as compared to other urban datasets.

Table 7. Arctic Urban Centres (UC): 2015 resident population (inhabitants), area (km^2) and population density (inhabitants/km^2) and 1990-2015 changes[13].

URBAN CENTRE		2015			1990-2015 CHANGE		
		Population (inhabitants)	Extension (km^2)	Population density	Population (inhabitants)	Extension (km^2)	Population density
ANCHORAGE[(1)]	USA	123,090	60	2,051	*+30%*	*0%*	*+30%*
REYKJAVIK	ISL	184,357	82	2,248	+30%	+64%	-21%
MURMANSK	RUS	281,928	72	3,916	-29%	0%	-29%
NOVY URENGOY	RUS	96,123	36	2,670	+22%	+44%	-15%
NORILSK	RUS	69,024	23	3,001	-11%	0%	-11%
TOTAL ARCTIC UCS		754,522	273	2,764	-5%	+19%	-20%

(1) Anchorage has been identified as an Urban Centre since 2015 epoch only.

(2) Since 2005, the Norilsk municipality includes Talnach, Kajerkan, Valeka and Oganer towns and Snežnogorsk village, which offset the population drop after the fall of the USSR Norilsk municipality.

Source: GHS-UCDB R2019A database (Florczyk, et al., 2019b)

The 11 indicators plotted in Figure 25 show common (increase in temperature, total built-up area and urban green) and different temporal trends (e.g. for the resident population, built-up per capita and the gross domestic product) according to the urban centre, calling for specific action and monitoring of the urban risks and resilience. They also highlight natural disaster risks for some UC (e.g. Earthquake in Anchorage and Reykjavik; Floods in Murmansk), which could be further completed at Arctic circumpolar scale using the same or additional data sources.

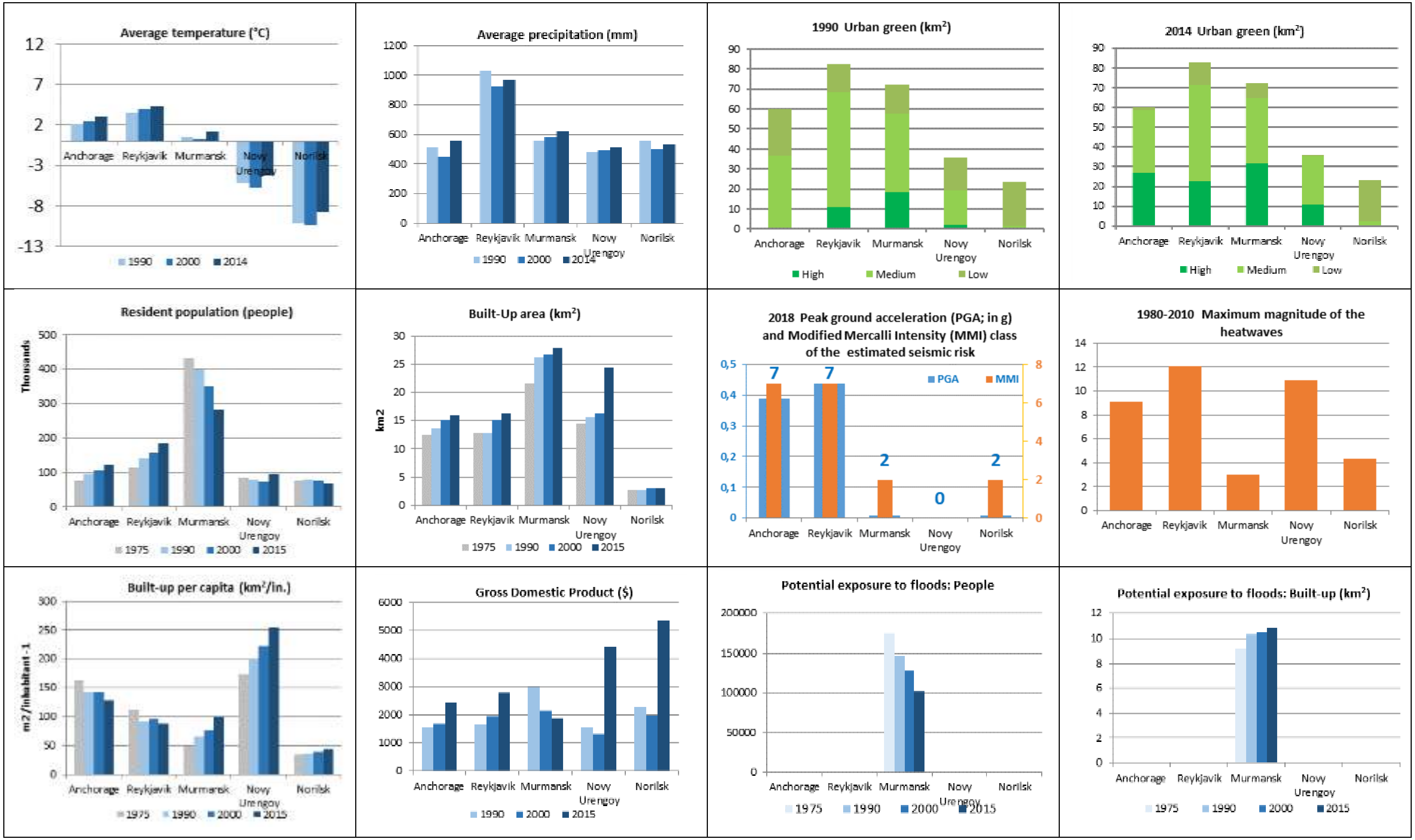
The CO_2[14] emissions by activity sector (Energy, Residential, Industry, Transport and Agriculture) in 1990 and 2012 are also provided in the UCDB. This sustainability indicator allows to monitor the emission trends (1990-2012 change in %) and to highlight the main sectors (expressed below in % of 2012 emissions) to be tackled to reduce their impact on climate change (Fig. 26):

- Anchorage UC (+2%): Residential (35%), Transport (32%) and Industry (31%) sectors
- Reykjavik UC (+8%): Industry (60%), Residential (23%) and Transport (16%) sectors
- Murmansk UC (-38%): Energy (35%), Industry (29%), Residential (18%) and Transport (18%) sectors.
- Novy Urengoy and Norilsk UCs: Energy sector (96% and 94%, respectively).

[13] See also Koffi et al. (2021) for the municipal data

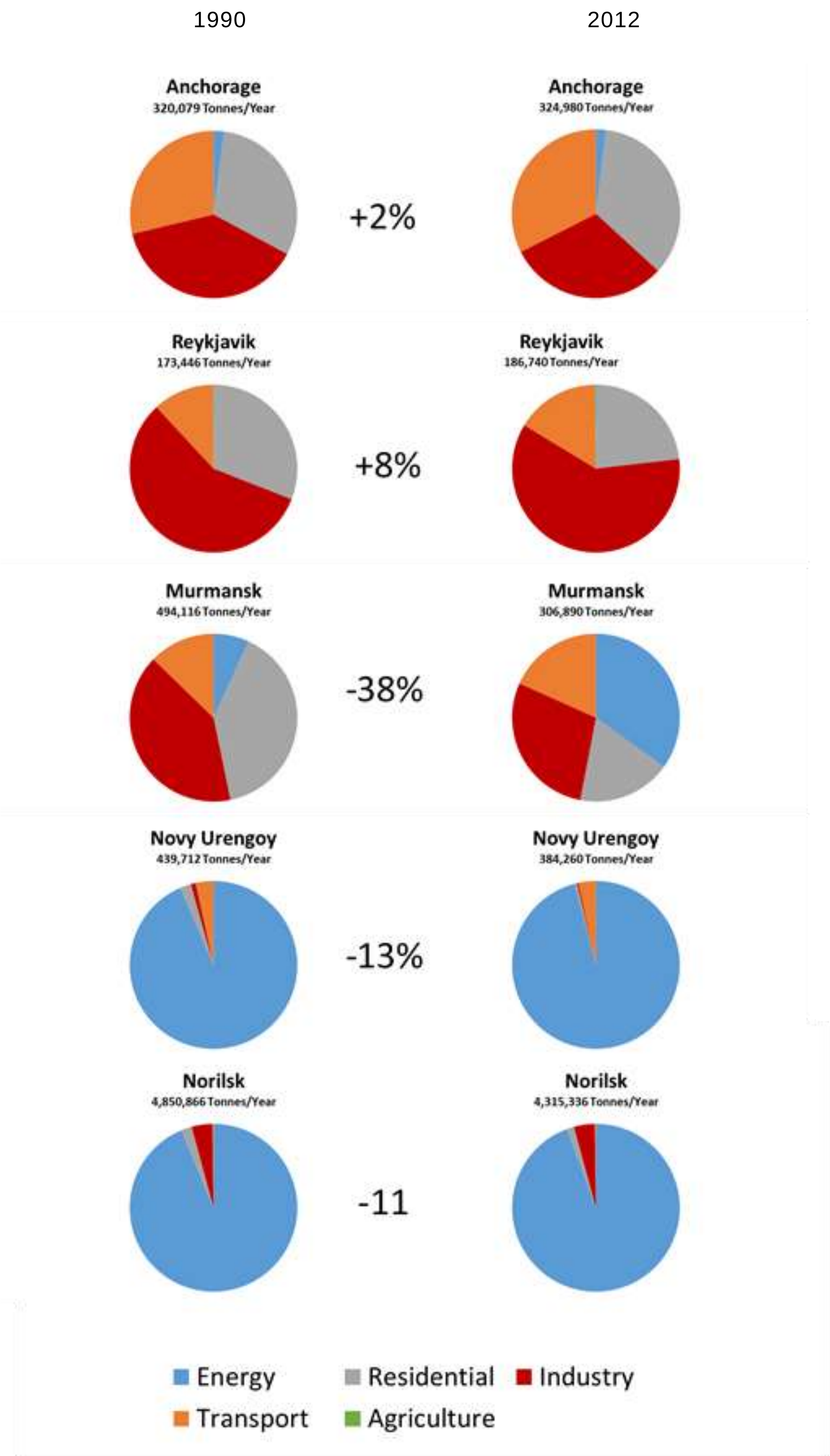
[14] PM2.5 emissions are also part of UCDB but not shown described in this report

Figure 25. GHS-UCDB Geography, Socio-economy, Environment, Disaster risks and SDG indicators for the 5 Arctic Urban Centres.



Source: GHS_STAT_UCDB2015MT_GLOBE_R2019A_V1_0.xls (see Florczyk, et al (2019b) for the full description of the variables, related sources and references)

Figure 26. CO_2 emissions by activity sector in 1990 (left) and 2012 (right) in the 5 Arctic Urban Centres.



Source: GHS_STAT_UCDB2015MT_GLOBE_R2019A_V1_0.xls (see Florczyk, et al (2019b)

6 Conclusion and developments

The goal of this ongoing study (Koffi and Wilson, 2019; Koffi et al., 2021) on the Arctic is to define a set of indicators that can be used to identify and monitor major risks, exposure and resilience on any Arctic region and scale of interest, by integrating multiple spatial datasets. The overall aim is to identify both policy needs at the local and regional scale that reinforce resilience and in the longer term to evaluate the effectiveness of policy interventions for maintaining or increasing socio-ecological resilience in the Arctic. Results could lead to the definition of Arctic resilience index(es) combining the ecological and human indicators available and extractable at Arctic circumpolar scale.

The present report is based on a first Arctic DOPA sub-dataset completed with DOPA and GHSL global data. Using a total of 28 ecological, human population and other indicators at Arctic ecoregion, protected area and urban levels, we variously:

- provide relevant information on the state of the Arctic terrestrial ecoregions and protected areas, in terms of ecological vulnerability, human pressure and their changes (*Arctic 202009 DOPA sub-dataset);*
- highlight - and potentially understand - long-term and recent changes in Arctic human urbanisation and migration pressures from ecoregion to local scales (GHS P2019 data);
- identify some limits or redundancy in the investigated indicators;
- identify areas of potential socio-ecological vulnerability from the definition of 3 preliminary composite indicators (AEVI, AHPI and ASEVI indexes), as an illustration of the potential of DOPA and GHSL data to monitor the Arctic resilience at ecoregion level;
- provide a first overview of the possibilities offered by the two products.

This preliminary study could serve as a basis for the definition of a set of relevant core indicators and/or indexes to identify and monitor major risks, exposure and resilience of the Arctic on any region and scale of interest, using a socio-ecological-based approach. As future developments, we notably suggest (see also Koffi and Wilson, 2019):

- Looking at more risk and resilience DOPA indicators for both the terrestrial (PA connectivity, land fragmentation, built-up pressure, water transitions (i.e., loss of water surfaces and new water surfaces, conversion from permanent to seasonal and vice versa) and maritime (% protected areas, habitat diversity etc.) environments. Complete indicators of natural disaster risks for Fires, Floods and Droughts at PA (DOPA) and urban (GHS-UCDB) levels with other EC JRC open free global gridded datasets (e.g., GloFAS and FIRES) to assess populations, infrastructure and ecosystems risk exposure to natural hazards at Arctic circumpolar scale;
- Performing higher resolution analyses (e.g. by looking at specific socio-ecological system level such as Arctic peatlands or by crossing the ecoregion and administrative levels) also using higher resolution GHSL data;
- Completing with socio-economic indicators to further assess the human resilience;
- Accounting for the limitations and caveats of the DOPA, GHSL and other global datasets, as described in the products' documentation and further investigated for the Arctic region;
- Selecting the most relevant Arctic core indicators (e.g., as a function of the Arctic shifts, areas and scales of interest) to develop an Arctic resilience conceptual model (choice of the dimensions and core indicators, weighting and other methodological aspects for the definition of indexes);
- Updating the selected indicators and indexes (at least yearly) for the monitoring of the Arctic terrestrial and marine environments, also accounting for (potential) changes in the PA (and ecoregions) definition and areas.

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List of abbreviations and definitions

AACA	Adaptation Actions for a Changing Arctic
AC	Arctic Council
AEVI	Arctic Ecological Vulnerability Index (preliminary index, this study)
AHDR	Arctic Human Development Report
AHPI	Arctic Human pressure Index (preliminary index, this study)
AMAP	Arctic Monitoring and Assessment Programme (AC Working Group)
ARAF	Arctic Resilience Action Framework
Arctic-COOP	JRC Project on the Arctic Cooperation
AS	Arctic States
ASEVI	Arctic Socio-Ecological Vulnerability Index (preliminary index, this study)
CAFF	Conservation of Arctic Flora and Fauna (AC Working Group)
CAN	Canada
CBD	Convention on Biological Diversity (United Nations)
CIESIN	Center for International Earth Science Information Network
CISSW	Change in Inland Seasonal Surface Water (DOPA indicator)
CIPSW	Change in Inland Permanent Surface Water (DOPA indicator)
CPDI	Change in Population Density indicator (this study)
CPPI	Change in Population Pressure indicator (DOPA indicator)
CProtconn	Change in Protconn DOPA indicator
CTPAC	Change in TPAC DOPA indicator
CURBL	Change in URBanisation Level indicator
DOPA	Digital Observatory of Protected Areas
EC JRC	Joint Research Centre of the European Commission
ECO_ID	Arctic Ecoregion Identifier as in defined in TEOW
EEZ	Exclusive Economic Zones
FAO	Food and Agriculture Organization of the United Nations
FAO-ITPS	FAO Intergovernmental Technical Panel on Soils
FCLOSSI	Forest Cover Loss Indicator
FIN	Finland
FRO	Faroe Islands
GAUL	Global Administrative Unit Layers
GHS-BUILT	Global Human Settlement BUilt-up grid
GHSL	Global Human Settlement Layer
GHS-POP	Global Human Settlement POPulation grid
GHS-SMOD	Global Human Settlement MODel grid
GHS-UCDB	Global Human Settlement Urban Centres Database
GPW	Gridded Population of the World
GRL	Greenland
GSOC	Global Soil Organic Carbon
HDC	High Density Clusters (GHSL definition)
ID	Arctic Ecoregion Identifier as defined in this report (ecoregions 1 to 58)
IMPARC	JRC Project on the Arctic
INFORM	Index for Risk Management
IPCC	Intergovernmental Panel on Climate Change

ISL	Iceland
IUCN	International Union for Conservation of Nature
JRC	Joint Research Centre of the European Commission
LDC	Low Density grid Cells (GHSL-SMOD definition)
MDC	Moderate Density Clusters (GHSL-SMOD definition)
MMI	Modified Mercalli intensity scale (seismic intensity scale)
NOR	Norway
PA	Protected Area
PAID	Protected Area Identifier used in this study for 35 selected PAs
PGA	Peak Ground Acceleration estimate of the seismic risk
PNSI	Population New Settlement Indicator
PPI	Population Pressure Indicator (DOPA indicator)
ProtConn	Protected Connected indicator (DOPA indicator)
PSOCI	Protected Soil Organic Carbon Indicator
RUS	Russian Federation
SDG	UN Sustainable Development Goals
SJM	Svalbard and Jan Mayen islands
SMOD	Settlement MODel
SOC	Soil organic carbon
SOCI	Soil Organic Carbon Indicator (DOPA indicator)
SWE	Sweden
TEOW	Terrestrial Ecoregions of the World
TPAC	Terrestrial Protected Area Coverage (DOPA indicator)
UC	Urban Centres (GHSL-SMOD definition
UNEP	United Nations Environment Programme
UNEP-WCMC	UNEP World Conservation Monitoring Centre
URBL	Urbanisation Level indicator
WDPA	World Database on Protected Area
WDPAID	World Database on Protected Area Identifier

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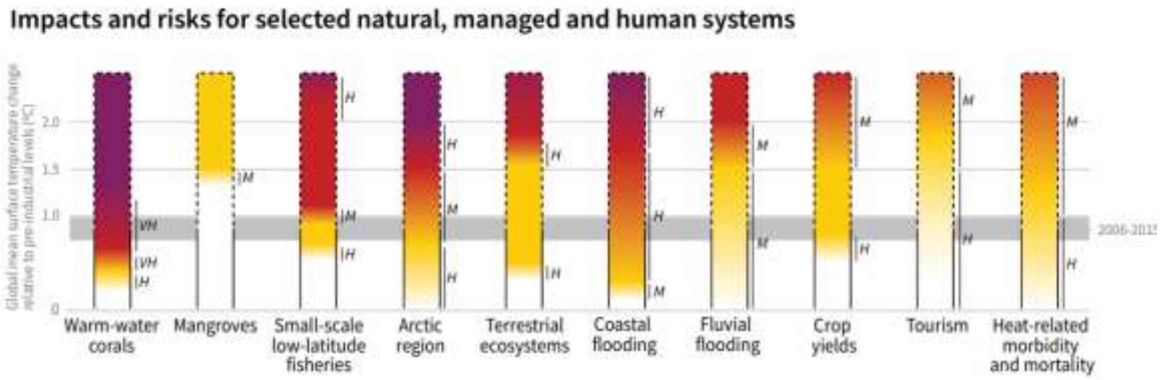
Annexes

Annex 1. Impacts and risks for the Arctic region presently, at 1.5ºC and 2ºC warming, as compared to other selected natural, managed and human ecosystems.

Source: IPCC (2018) Summary for Policymakers. In: Global warming of 1.5°C, p. 13. Confidence level for transition: L=Low, M=Medium, H=High, VH=Very High. Colour reference: Purple indicates very high risks of sever impacts and significant irreversibility or persistence of climate-related hazards. Red indicates severe and widespread impacts/risks. Yellow indicates that impacts/risks are detectable and attributable to climate change with at least medium confidence. White indicates that no impacts are detectable or attributable to climate change.



Source: IPCC, 2018

Annex 2: Input data sources of the DOPA indicators as of September 2020. The ones analysed in this report are shown in bold.

Input data	Source (last available - or specified - version)
Country boundaries	Global Administrative Unit Layers (GAUL), revision 2015 (2017-02-02). http://www.fao.org/geonetwork/srv/en/metadata.show?id=12691 Exclusive Economic Zones (EEZ), World EEZ v9 (2016-10-21) http://www.marineregions.org/downloads.php
Terrestrial Ecoregions of the World	Terrestrial Ecoregions Of the World (TEOW) https://www.worldwildlife.org/publications/terrestrial-ecoregions-of-the-world
Marine Ecoregions of the World	Marine Ecoregions Of the World (MEOW) and Pelagic provinces of the world (PPOW) • MEOW: https://www.worldwildlife.org/publications/marine-ecoregions-of-the-world-a-bioregionalization-of-coastal-and-shelf-areas • PPOW: http://data.unep-wcmc.org/datasets/38
Protected Areas	World Database on Protected Areas (WDPA) as of September 2020. http://www.protectedplanet.net
Key Biodiversity Areas	World Database of Key Biodiversity Areas (2019 version) http://www.keybiodiversityareas.org
Species Ranges	IUCN Red List of Threatened Species TM 2020 version 1. http://www.iucnredlist.org
Threatened species statistics by country	IUCN Red List of Threatened Species TM country summaries 2020 version 1 http://www.iucnredlist.org/about/summary-statistics
Temperature and precipitations	WorldClim 2, Release 1, June 2016 (www.worldclim.org/version2)
Sea Surface Temperature	2007-2016 Global monthly data from Copernicus Marine Environment Monitoring Service (SST_GLO_SST_L4_NRT_OBSERVATIONS_010_001): http://marine.copernicus.eu
Elevation (bathymetry and topography)	GEBCO 2020 Grid: http://www.gebco.net/data_and_products/gridded_bathymetry_data/
Land Cover	Annual global land cover maps for the years 1995, 2000, 2005, 2010, 2015: http://maps.elie.ucl.ac.be/CCI/viewer/index.html
Land Productivity Dynamics	15 years trends (1999-2013) of World Atlas of Desertification. https://wad.jrc.ec.europa.eu/landproductivity
Global Human Settlements	Global Human Settlements built-up areas and population grid for 1975, 1990, 2000 and 2015: http://ghsl.jrc.ec.europa.eu/datasets.php
Soil Organic Carbon	Global Soil Organic Carbon (GSOC) map: http://www.fao.org/global-soil-partnership/pillars-action/4-information-and-data-new/global-soil-organic-carbon-gsoc-map
Above-Ground Biomass	GlobBiomass global map of forest above-ground biomass (40°x 40°) http://globbiomass.org/products/global-mapping/
Roads map	Global Roads (gROADS) version 1. 1980-2010. http://sedac.ciesin.columbia.edu/data/set/groads-global-roads-open-access-v1
Agricultural Areas	Copernicus Global Land Operations , Global 100m Land Cover map for the year 2019 https://land.copernicus.eu/global/products/lc
Inland Surface Water	Global Surface Water Explorer https://global-surface-water.appspot.com/
Forest cover: 2000 and 2001–2019 change	Global Forest Change: http://earthenginepartners.appspot.com/science-2013-global-forest/download_v1.7.html

Annex 3. GHSL Urban Centres Database: Derived from Florczyk et al. 2019b (see Florczyk et al. 2019b report for units, details and data sources).

Dimension	Variable	Attribute	Temporal coverage			
			1975	1990	2000	2015
General Characteristics	Control code	Unique ID				
		Quality Code				
	Extension	Area				
		Bounding Box (WGS 84)				
	Location	Geometric Centroid (WGS 84)				
		Main Country Identification: name				
		Main Country Identification: ISO 3				
		Cross border flag				
		Number of intersected countries				
		List of intersected countries: names				
		List of intersected countries: ISO 3				
		Major Geographical Region				
		Geographical Region				
	Naming	Name of the Urban Centre				
		List of names				
		Source of the names				
Multitemporal Urban Centre Spatial Domain	Numb. of Urban Centres in the past	Number of Urban Centres in				
	Total area of Urban Centres in the past	Total area of Urban Centres in				
Geography	Biome	Biome type(s)				
	Soil	Soil group(s)				
	Elevation	Average Elevation				
	Climate	Climate class(es)				
	River basin	Major river basin(s)				
	Precipitation	Average precipitation in				
	Temperature	Average temperature in				
Socio-economic	Built-up surface	Total built-up area				
	Resident population	Total resident population				
	Built-up per capita	Surface of the built-up area per person				
	Night time light emission	Average night time light emission in 2015				
	Gross Domestic Product	Sum of GDP PPP				
	Development Indicators	UN income class				2018
		UN development group				2018
	Accessibility & Remoteness	Travel time to country capital				
Environment	Urban green	Greenness Value				
		Greenness class area				
	Emission of Pollutants	CO_2 (non-short-cycle-organic fuels)				2012
		CO_2 (short-cycle-organic fuels)				
		$PM_{2.5}$				
	Concentration of Pollutants	$PM_{2.5}$			2000,2005,2010,2014	
DRR	Flood exposure	Total surface potentially exposed to floods				
		Total built-up area potentially exposed to floods in				
		Total resident population potentially exposed to floods				
	Storm surge exposure	Total surface potentially exposed to storm surges				
		Total built-up area potentially exposed to storm surges				
		Total resident population potentially exposed to storm				
	Earthquake	Average peak ground acceleration (PGA) estimate of the seismic risk (s.r.)				
		MMI class of the s.r. derived from PGA estimate				
		Quality control value				
	Heatwave	Maximum magnitude of the heatwaves	1980-2010			
SDG	Land Use Efficiency (11.3.1)	Land use efficiency 1990-2015	1990-2015			
	Open spaces (11.7.1 –proxy)	Share of population living in the high green area				
		Percentage of the open spaces				

Annex 4. The 58 *Arctic ecoregions* defined as the fraction of the TEOW ecoregions *fully* (> 95%; bold IDs) or partly included in the Arctic region.

They are covered by Tundra, Boreal Forests/Taiga (Boreal F/T), Temperate Conifer Forest(Temp. C. F.) and Temperate Grasslands, Savannas & Shrublands (Temp. G., S. & S.) biomes (see Fig. 1). Eco_id is the TEOW identifier of the ecoregion (Olson et al. 2001) and ID is the one used in this study for the Arctic part.

	Ecoregions			Arctic domain		
ID	Eco_id	Biome	Name	km²	%	AS
1	50603	Boreal F/T	Cook Inlet taiga	27952	100%	USA
2	50607	Boreal F/T	Interior Alaska-Yukon lowland taiga	446230	100%	CAN-USA
3	50614	Boreal F/T	Northwest Territories taiga	348139	100%	CAN
4	51111	Tundra	Interior Yukon-Alaska alpine tundra	234133	100%	CAN-USA
5	81114	Tundra	Yamal-Gydan tundra	407967	100%	RUS
6	50502	Temp. C. F.	Alberta-British Columbia foothills forests	42222	35%	CAN
7	80605	Boreal F/T	Northeast Siberian taiga	930980	82%	RUS
8	51101	Tundra	Alaska-St. Elias Range tundra	152680	100%	CAN-USA
9	51117	Tundra	Pacific Coastal Mountain icefields and tundra	100824	94%	CAN-USA
10	81111	Tundra	Taimyr-Central Siberian tundra	953479	100%	RUS
11	50605	Boreal F/T	Eastern Canadian forests	162147	33%	CAN
12	50802	Temp. G., S. & S.	Canadian Aspen forests and parklands	36674	9%	CAN
13	51115	Tundra	Middle Arctic tundra	1031945	100%	CAN
14	81105	Tundra	Kamchatka Mountain tundra and forest tundra	31384	26%	RUS
15	50617	Boreal F/T	Yukon Interior dry forests	62564	100%	CAN
16	51102	Tundra	Aleutian Islands tundra	11347	100%	USA
17	81104	Tundra	Chukchi Peninsula tundra	296083	100%	RUS
18	80610	Boreal F/T	Ural montane forests and tundra	219	0%	RUS
19	50601	Boreal F/T	Alaska Peninsula montane taiga	47461	100%	USA
20	80608	Boreal F/T	Scandinavian and Russian taiga	493269	23%	FIN-NOR-RUS-SWE
21	51109	Tundra	Davis Highlands tundra	87112	100%	CAN
22	51118	Tundra	Torngat Mountain tundra	32076	100%	CAN
23	51104	Tundra	Arctic foothills tundra	129905	100%	CAN-USA
24	81109	Tundra	Novosibirsk Islands arctic desert	35145	100%	RUS
25	81110	Tundra	Scandinavian Montane Birch forest and grasslands	144075	61%	FIN-NOR-RUS-SWE
26	81101	Tundra	Arctic desert	148496	100%	RUS-ISL
27	50610	Boreal F/T	Muskwa-Slave Lake forests	263805	100%	CAN
28	51103	Tundra	Arctic coastal tundra	97936	100%	CAN-USA

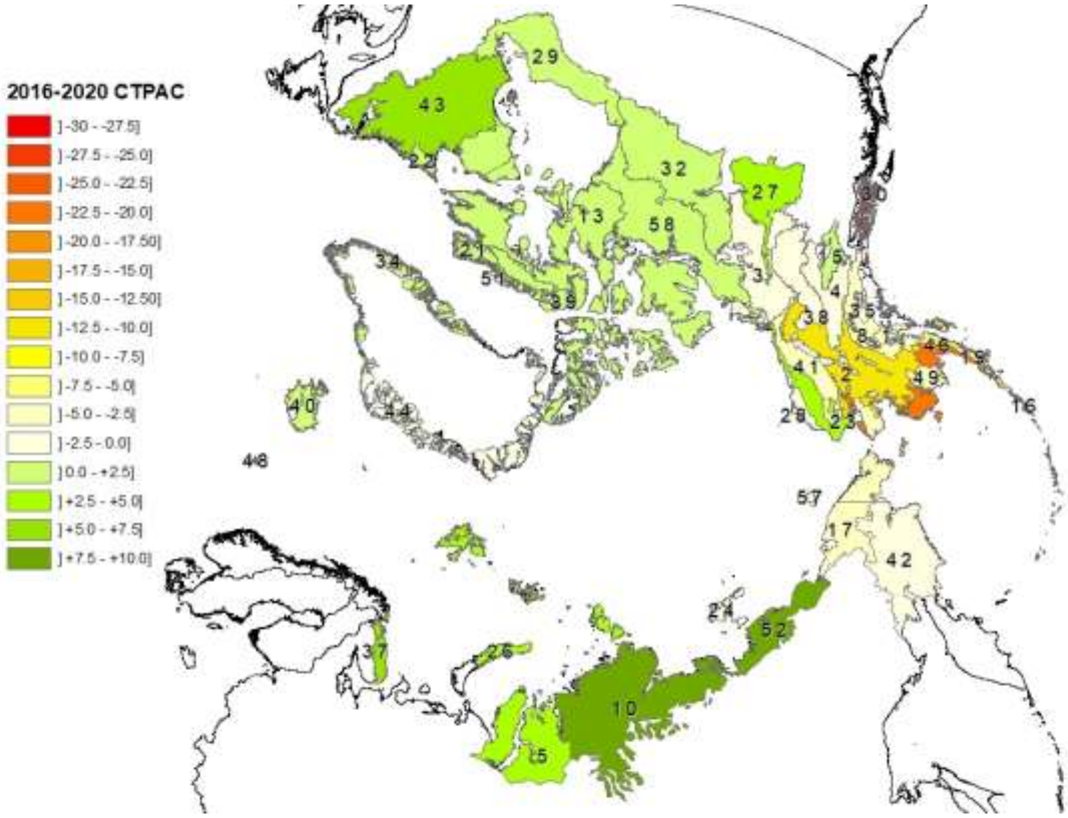
	Ecoregions			Arctic domain		
29	50616	Boreal F/T	Southern Hudson Bay taiga	373397	100%	CAN
30	50520	Temp. C. F.	Northern Pacific coastal forests	59451	100%	USA
31	81108	Tundra	Northwest Russian-Novaya Zemlya tundra	259848	95%	RUS
32	50612	Boreal F/T	Northern Canadian Shield taiga	616501	100%	CAN
33	81103	Tundra	Cherskii-Kolyma mountain tundra	471320	84%	RUS
34	51113	Tundra	Kalaallit Nunaat low arctic tundra	163521	100%	GRL
35	50604	Boreal F/T	Copper Plateau taiga	17275	100%	USA
36	80601	Boreal F/T	East Siberian taiga	1310841	33%	RUS
37	81106	Tundra	Kola Peninsula tundra	56224	100%	NOR-RUS
38	51116	Tundra	Ogilvie-MacKenzie alpine tundra	209807	100%	CAN-USA
39	51110	Tundra	High Arctic tundra	461770	100%	CAN
40	80602	Boreal F/T	Iceland boreal birch forests and alpine tundra	90917	100%	ISL
41	51108	Tundra	Brooks-British Range tundra	160646	100%	CAN-USA
42	81102	Tundra	Bering tundra	473752	100%	RUS
43	50606	Boreal F/T	Eastern Canadian Shield taiga	756082	100%	CAN
44	51112	Tundra	Kalaallit Nunaat high arctic tundra	289127	100%	GRL
45	80520	Temp. C. F.	Scandinavian coastal conifer forests	8725	51%	NOR
46	51106	Tundra	Beringia lowland tundra	150214	100%	USA
47	50613	Boreal F/T	Northern Cordillera forests	158814	60%	CAN-USA
48	80807	Temp. G., S. & S.	Faroe Islands boreal grasslands	1233	100%	FRO
49	51107	Tundra	Beringia upland tundra	97817	100%	USA
50	50609	Boreal F/T	Midwestern Canadian Shield forests	41232	8%	CAN
51	51105	Tundra	Baffin coastal tundra	8931	100%	CAN
52	81107	Tundra	Northeast Siberian coastal tundra	221232	100%	RUS
53	50602	Boreal F/T	Central Canadian Shield forests	76594	17%	CAN
54	80611	Boreal F/T	West Siberian taiga	452528	27%	RUS
55	80603	Boreal F/T	Kamchatka-Kurile meadows and sparse forests	21401	15%	RUS
56	50608	Boreal F/T	Mid-Continental Canadian forests	54699	15%	CAN
57	81113	Tundra	Wrangel Island arctic desert	7386	100%	RUS
58	51114	Tundra	Low Arctic tundra	799153	100%	CAN
	Arctic region			14626688	63%	8 AS

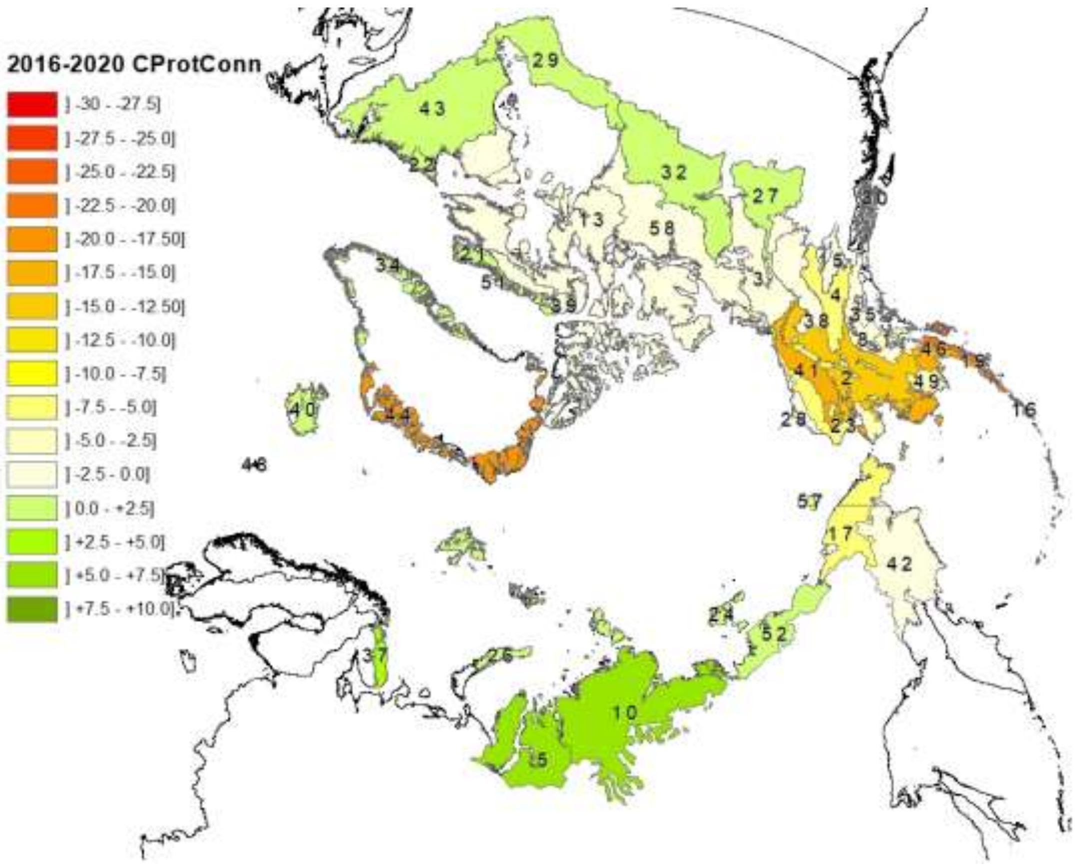
Annex 5. Ten largest non-populated and populated Terrestrial Protected Areas (Type 0 inland; 1 coastal)

Name		WPDA id (1)	Type	AS	Area (km2)	2015 people
Nationalparken I Nord-Og Østgrønland	National Park	650	0	GRL	966788	-
Русская Арктика	National Park	555689610	1	RUS	87562	-
Новосибирские острова	State Nature Reserve	555690094	1	RUS	65761	-
Queen Maud Gulf Bird Sanctuary	Migratory Bird Sanctuary	13394	1	CAN	62928	-
Queen Maud Gulf	Ramsar Site, Wetland of International Importance	67836	0	CAN	56609	-
Thelon Wildlife Sanctuary	Wildlife Sanctuary	18704	0	CAN	56217	-
Большой Арктический	State Nature Reserve	555685209	1	RUS	40228	-
Volcanoes of Kamchatka	World Heritage Site (natural or mixed)	124387	0	RUS	39914	-
Хоту	Resource Reserve	555685377	0	RUS	30889	-
Попигай	Traditional nature use	555685604	0	RUS	27017	-
Kluane/Wrangell-St Elias/ Glacier Bay/Tatshenshini-Alsek	World Heritage Site	2018	0	CAN;USA	97629	68
Yukon Delta National Wildlife Refuge	Marine Protected Area	10547	1	USA	84395	2012
Arctic National Wildlife Refuge	Marine Protected Area	2904	0	USA	80325	290
Arctic	National Wildlife Refuge	555655913	0	USA	79533	66
Лена-Дельта	Resource Reserve	555685846	0	RUS	67011	44
Nordaust-Svalbard	Nature Reserve (Svalbard)	1334	1	SJM	55344	857
Wrangell-St. Elias	National Park	22490	0	USA	49714	11
Wood Buffalo National Park	World Heritage Site (natural or mixed)	10902	0	CAN	45616	746
Wood Buffalo National Park Of Canada	National Park	611	0	CAN	45616	746
Ямальский	State Nature Reserve	555685801	0	RUS	44723	33

(1) Unique identifier for the protected area as defined in the World Database on Protected Areas (WDPA). See http://protectedplanet.net for more information.

Annex 6. 2016 to 2020 change in TPAC and connectivity: 39 ecoregions *fully* (> 95%) included in the Arctic domain. The values are reported in Table 3.





Annex 7. 2000-2015 new populated cells (in km^2 and % of 2000 populated cells) in the rural (R) and urbanised (U) Arctic (part of) ecoregions as defined in section 4.2.1. Only the 16 ecoregions with new settlements are reported (see Annex 4 for **other columns' definition**).

ID	U/R	ECO_ID	BIOME	NAME	KM^2	%	AS
1	U	50603	Boreal F/T	Cook Inlet taiga	98	0,360%	USA
2	U	50607	Boreal F/T	Interior Alaska-Yukon lowland taiga	227	0,051%	CAN-USA
3	R	50614	Boreal F/T	Northwest Territories taiga	11	0,003%	CAN
6	R	50502	Temp. C. F.	Alberta-British Columbia foothills forests	390	0,936%	CAN
8	R	51101	Tundra	Alaska-St. Elias Range tundra	224	0,148%	CAN-USA
9	U	51117	Tundra	Pacific Coastal Mountain icefields and tundra	2203	2,258%	CAN-USA
12	U	50802	Temp. G., S. & S.	Canadian Aspen forests and parklands	206	0,570%	CAN
15	U	50617	Boreal F/T	Yukon Interior dry forests	14	0,023%	CAN
16	R	51102	Tundra	Aleutian Islands tundra	1	0,009%	USA
25	U	81110	Tundra	Scandinavian Montane Birch forest and grasslands	299	0,214%	FIN-NOR-RUS-SWE
30	U	50520	Temp. C. F.	Northern Pacific coastal forests	2178	3,785%	USA
32	U	50612	Boreal F/T	Northern Canadian Shield taiga	22	0,004%	CAN
40	U	80602	Boreal F/T	Iceland boreal birch forests and alpine tundra	770	0,859%	ISL
46	R	51106	Tundra	Beringia lowland tundra	67	0,048%	USA
47	R	50613	Boreal F/T	Northern Cordillera forests	1	0,001%	CAN-USA
49	R	51107	Tundra	Beringia upland tundra	2	0,002%	USA

Annex 8. Arctic Human Pressure (AHPI), Ecological vulnerability (AEVI) and Socio-Ecological vulnerability (ASEVI) normalised indexes **(see Annex 4 for other columns' definition).** Higher values mean higher potential vulnerability.

ECOREGIONS

ID	Eco_id	Biome	Name	AS	AEVI	AHPI	ASEVI
1	50603	Boreal F/T	Cook Inlet taiga	USA	56	100	100
2	50607	Boreal F/T	Interior Alaska-Yukon lowland taiga	CAN-USA	69	15	53
3	50614	Boreal F/T	Northwest Territories taiga	CAN	73	1	47
4	51111	Tundra	Interior Yukon-Alaska alpine tundra	CAN-USA	73	3	48
5	81114	Tundra	Yamal-Gydan tundra	RUS	68	31	63
6	50502	Temp. C. F.	Alberta-British Columbia foothills forests	CAN	74	18	58
7	80605	Boreal F/T	Northeast Siberian taiga	RUS	85	2	55
8	51101	Tundra	Alaska-St. Elias Range tundra	CAN-USA	56	4	38
9	51117	Tundra	Pacific Coastal Mountain icefields and tundra	CAN-USA	45	80	80
10	81111	Tundra	Taimyr-Central Siberian tundra	RUS	67	4	45
11	50605	Boreal F/T	Eastern Canadian forests	CAN	73	2	47
12	50802	Temp.G.,S.& S.	Canadian Aspen forests and parklands	CAN	73	20	59
13	51115	Tundra	Middle Arctic tundra	CAN	82	2	53
14	81105	Tundra	Kamchatka Mountain tundra and forest tundra	RUS	74	60	86
15	50617	Boreal F/T	Yukon Interior dry forests	CAN	80	5	54
16	51102	Tundra	Aleutian Islands tundra	USA	22	3	15
17	81104	Tundra	Chukchi Peninsula tundra	RUS	83	1	54
18	80610	Boreal F/T	Ural montane forests and tundra	RUS	43	1	28
19	50601	Boreal F/T	Alaska Peninsula montane taiga	USA	19	2	13
20	80608	Boreal F/T	Scandinavian and Russian taiga	FIN-NOR-RUS-SWE	68	20	56
21	51109	Tundra	Davis Highlands tundra	CAN	62	2	40
22	51118	Tundra	Torngat Mountain tundra	CAN	49	1	31
23	51104	Tundra	Arctic foothills tundra	CAN-USA	64	2	42
24	81109	Tundra	Novosibirsk Islands arctic desert	RUS	4	1	3
25	81110	Tundra	Scandinavian Montane Birch forest and grasslands	FIN-NOR-RUS-SWE	69	10	51
26	81101	Tundra	Arctic desert	RUS-ISL	64	3	42
27	50610	Boreal F/T	Muskwa-Slave Lake forests	CAN	68	1	43

ID	ECO_ID	BIOME	NAME	AS	AEVI	AHPI	ASEVI
28	51103	Tundra	Arctic coastal tundra	CAN-USA	74	3	49
29	50616	Boreal F/T	Southern Hudson Bay taiga	CAN	73	1	47
30	50520	Temp. C. F.	Northern Pacific coastal forests	USA	53	66	75
31	81108	Tundra	Northwest Russian-Novaya Zemlya tundra	RUS	72	0	46
32	50612	Boreal F/T	Northern Canadian Shield taiga	CAN	77	2	50
33	81103	Tundra	Cherskii-Kolyma mountain tundra	RUS	79	1	51
34	51113	Tundra	Kalaallit Nunaat low arctic tundra	GRL	89	2	58
35	50604	Boreal F/T	Copper Plateau taiga	USA	61	1	39
36	80601	Boreal F/T	East Siberian taiga	RUS	75	4	50
37	81106	Tundra	Kola Peninsula tundra	NOR-RUS	72	26	62
38	51116	Tundra	Ogilvie-MacKenzie alpine tundra	CAN-USA	77	3	51
39	51110	Tundra	High Arctic tundra	CAN	80	2	52
40	80602	Boreal F/T	Iceland boreal birch forests and alpine tundra	ISL	100	50	96
41	51108	Tundra	Brooks-British Range tundra	CAN-USA	39	2	25
42	81102	Tundra	Bering tundra	RUS	85	0	54
43	50606	Boreal F/T	Eastern Canadian Shield taiga	CAN	74	2	48
44	51112	Tundra	Kalaallit Nunaat high arctic tundra	GRL	88	1	57
45	80520	Temp. C. F.	Scandinavian coastal conifer forests	NOR	75	74	95
46	51106	Tundra	Beringia lowland tundra	USA	48	3	31
47	50613	Boreal F/T	Northern Cordillera forests	CAN-USA	72	2	47
48	80807	Temp.G.,S.& S	Faroe Islands boreal grasslands	FRO	71	62	85
49	51107	Tundra	Beringia upland tundra	USA	52	2	34
50	50609	Boreal F/T	Midwestern Canadian Shield forests	CAN	47	2	31
51	51105	Tundra	Baffin coastal tundra	CAN	82	2	54
52	81107	Tundra	Northeast Siberian coastal tundra	RUS	92	0	58
53	50602	Boreal F/T	Central Canadian Shield forests	CAN	67	2	44
54	80611	Boreal F/T	West Siberian taiga	RUS	71	4	47
55	80603	Boreal F/T	Kamchatka-Kurile meadows and sparse forests	RUS	75	6	51
56	50608	Boreal F/T	Mid-Continental Canadian forests	CAN	37	2	24
57	81113	Tundra	Wrangel Island arctic desert	RUS	0	1	0
58	51114	Tundra	Low Arctic tundra	CAN	70	2	46

KJ-NA-31005-EN-N

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Publications Office of the European Union

doi:10.2760/787321

ISBN 978-92-76-48851-4