

<https://helda.helsinki.fi>

The science-policy interfaces of the European network for observing our changing planet : From Earth Observation data to policy-oriented decisions

Pirrone, Nicola

2022-11

Pirrone , N , Mazzetti , P , Cinnirella , S , Athanasopoulou , E , Gerasopoulos , E , Klanova , J , Lehmann , A , Maso Pau , J , Petaja , T , Pokorny , L & Sebkova , K 2022 , ' The science-policy interfaces of the European network for observing our changing planet : From Earth Observation data to policy-oriented decisions ' , Environmental Science & Policy , vol. 137 , pp. 359-372 . <https://doi.org/10.1016/j.envsci.2022.09.006>

<http://hdl.handle.net/10138/354416>

<https://doi.org/10.1016/j.envsci.2022.09.006>

cc_by_nc

publishedVersion

Downloaded from Helda, University of Helsinki institutional repository.

This is an electronic reprint of the original article.

This reprint may differ from the original in pagination and typographic detail.

Please cite the original version.



The science-policy interfaces of the European network for observing our changing planet: From Earth Observation data to policy-oriented decisions

Nicola Pirrone^{a,*}, Paolo Mazzetti^b, Sergio Cinnirella^a, Eleni Athanasopoulou^c, Evangelos Gerasopoulos^c, Jana Klánová^d, Anthony Lehmann^{e,f}, Joan Masó Pau^g, Tuukka Petäjä^h, Lukáš Pokorný^d, Kateřina Šebková^d

^a CNR-Institute of Atmospheric Pollution Research, Division of Rende, UNICAL Polifunzionale, 87036 Rende (CS), Italy

^b CNR-Institute of Atmospheric Pollution Research, Division of Florence, Via Madonna del Piano, 10 50019 Sesto Fiorentino, Italy

^c Institute for Environmental Research and Sustainable Development, National Observatory of Athens, 15236 P. Penteli, Athens, Greece

^d RECETOX, Faculty of Science, Masaryk University, Kamenice 753/5 Brno 602 00, Czech Republic

^e enviroSPACE, Institute for Environmental Sciences, University of Geneva, 66 Bd. Carl-Vogt, CH-1205, Geneva, Switzerland

^f Dpt. F.-A. Forel for Environment and Water Sciences, Faculty of Sciences, University of Geneva, 66 Bd. Carl-Vogt, CH-1205, Geneva, Switzerland

^g CREAf, Campus de Bellaterra (UAB) Edifici C 08193 Cerdanyola del Valles, Spain

^h University of Helsinki, P.O. Box 64, FI-00014, Finland

ARTICLE INFO

Keywords:

Earth observation
Smart cities
Essential variables
Science-policy interface
Polar regions
Key enabling technologies

ABSTRACT

This paper reports on major outcomes of the ERA-PLANET (The European network for observing our changing planet) project, which was funded under Horizon 2020 ERA-net co-funding scheme. ERA-PLANET strengthened the European Research Area in the domain of Earth Observation (EO) in coherence with the European participation to Group on Earth Observation and the Copernicus European Union's Earth Observation programme. ERA-PLANET was implemented through four projects focused on smart cities and resilient societies (SMURBS), resource efficiency and environmental management (GEOEssential), global changes and environmental treaties (iGOSP) and polar areas and natural resources (iCUPE). These projects developed specific science-policy workflows and interfaces to address selected environmental policy issues and design cost-effective strategies aiming to achieve targeted objectives. Key Enabling Technologies were implemented to enhancing 'data to knowledge' transition for supporting environmental policy making. Data cube technologies, the Virtual Earth Laboratory, Earth Observation ontologies and Knowledge Platforms were developed and used for such applications.

SMURBS brought a substantial contribution to resilient cities and human settlements topics that were adopted by GEO as its 4th engagement priority, bringing the urban resilience topic in the GEO agenda on par with climate change, sustainable development and disaster risk reduction linked to environmental policies.

GEOEssential is contributing to the development of Essential Variables (EVs) concept, which is encouraging and should allow the EO community to complete the description of the Earth System with EVs in a close future. This will clearly improve our capacity to address intertwined environmental and development policies as a Nexus.

iGOSP supports the implementation of the GEO Flagship on Mercury (GOS⁴M) and the GEO Initiative on POPs (GOS⁴POPs) by developing a new integrated approach for global real-time monitoring of environmental quality with respect to air, water and human matrices contamination by toxic substances, like mercury and persistent organic pollutants. iGOSP developed end-user-oriented Knowledge Hubs that provide data repository systems integrated with data management consoles and knowledge information systems.

The main outcomes from iCUPE are the novel and comprehensive data sets and a modelling activity that contributed to delivering science-based insights for the Arctic region. Applications enable defining and monitoring of Arctic Essential Variables and sets up processes towards UN2030 SDGs that include health (SDG 3), clean water resources and sanitation (SDGs 6 and 14).

* Corresponding author.

E-mail address: nicola.pirrone@iia.cnr.it (N. Pirrone).

1. Introduction

The science-policy interface is a critical factor in environmental governance as exchange of information, construction of knowledge and enriching of decision-making are far from being transferred between scientists and actors in the policy making process (van den Hove, 2007). Robust and evidence-based information for policy-makers is more often demanded (The European Commission, 2022d). Hence, the main question is of how research findings can be translated into knowledge for policy (Fazey et al., 2013) and consequently transferred (Rosli, 2015; Porter et al., 2019).

Effective interactions have sometime triggered initiatives when for example International Conventions were prepared, adopted, signed and ratified (see the United Nations Glossary of terms relating to Treaty actions (UN, 2020), but in most cases siloed behaviours are observed (Ozga, 2011; Young et al., 2014). Science findings are also underutilized in environmental policy design (Jensen-Ryan and German, 2018) and current obstacles to their integration include: the inability to frame information (Jacobs and Pulwarty, 2003); poor scientific result translation and access to findings (Ascher et al., 2010; Driscoll et al., 2011); low mutual engagement and high conceptual separation (Janse, 2008); and in the recent times growing of anti-science and fake news (Scheufele and Krause, 2019), as well documented.

To overcome such obstacles, all involved actors that include knowledge generators, synthesizers, aggregator, brokers, decision- and policy-makers (Gluckman, 2016, 2018) must be involved in the process and can effectively close the gap and make science results prompt to answer policy concern on the environmental governance. Moreover, the information science it produces and exchanges, need to be credible, relevant and legitimate (Sarkki et al., 2013).

In our fast-changing environment policy is asked to replay with timely decisions, which should be based on evident scientific results, jointly planned, and effectively implemented (Plummer et al., 2010). Policy-makers are typically concerned about general public priorities which in last years posed their attention on the environment and governance of decision-making processes. For example, in the European context, in 2020 new priorities were established to cope with the growing “green” demand, which can have a deep impact on the European innovation strategy (e.g., *European Green Deal*) (Sikora, 2021) as reflected, for example, in the European Data Strategy (The European Commission, 2022c,a). Similarly, the Horizon Europe, the EU’s key Framework Programme on Research and Innovation tackles competitiveness and growth having in mind the United Nation’s (UN) Sustainable Development Goals (The European Commission, 2022b).

At the same time, major inter-governmental bodies are deeply involved to close the science-policy loop, bringing scientific results to the public and specifically to policy-makers. For example, the inter-governmental Group on Earth Observations (GEO) is “*working to improve the availability, access and use of open Earth observations, including satellite imagery, remote sensing and in situ data, to impact policy and decision making in a wide range of sectors*” (GEO, 2022). And the United Nation (UN) through its environment programme is fostering the coordination among different actors in the global political context (UNEP, 2018).

In the above scenario, the ERA-PLANET (The European network for observing our changing planet) project (<http://www.era-planet.eu>) started its activities in February 2016 with the objective of strengthening the European Research Area in the domain of Earth Observation (EO) in coherence with the European participation to GEO and the Copernicus as European Union’s EO programmes. Four transnational projects were launched through ERA-PLANET with the objective of providing more accurate, comprehensive and authoritative information to policy and decision-makers in key societal benefit areas that were: i) smart cities and resilient societies (SMURBS) (<http://smurbs.eu>); ii) resource efficiency and environmental management (GEOEssential) (<http://geoessential.eu>); iii) global changes and environmental treaties (iGOSP) (<http://igosp.eu>); and iv) polar areas and natural resources

(iCUPE) (<http://www.atm.helsinki.fi/icupe/>).

After 4-years of activity (Sep-2017 to Aug-2021) the four projects have exploited and demonstrated the opportunity to use EO data and products for actionable decision-making (Hanan et al., 2020) to fulfil EU’s strategic goals in all selected domains (e.g., International Conventions, Urban Environment, Polar Environment). The Data Sharing and Data Management Principles established in GEO were adopted with the main objective of making data accessible and improve the process of knowledge creation to ensure its reproducibility and connection to scientific evidence (Mazzetti et al., 2022).

This paper aims at describing the overall conceptual policy-driven workflow followed in the four projects by highlighting applications that were developed to address and analyse selected socio-environmental-policy scenarios. ERA-PLANET Key Enabling Technologies (KETs) (e.g.: Virtual Earth Laboratory (VLab), EO ontologies and Knowledge Hub platforms) are also described as tools to support the EO information lifecycle from the acquisition of observation to the generation of knowledge feeding environmental decision-making processes.

2. Project contributions to policy-driven workflow

Recent progress in digital information technologies and development of high-resolution sensors and tools are generating new challenges for scientists and policy-makers (Galindo-Rueda, 2020), as well as are creating new opportunities for using EO data and tools, especially in the context of big data, open science and artificial intelligence. They are expected to provide a major contribution to link key environmental, societal and policy issues for better understanding the growing global concern on sustainable development and ecological transition patterns.

ERA-PLANET devised a conceptual framework for Earth Science informed decision-making in support of environmental policies. The framework lays on relevant policy questions or political agendas that drive trusted data collection, scenario development and production of user-friendly applications (Figure 1). In such a framework, EO and socio-economic data provide the facts describing the relevant status of affairs, while Earth Science and environmental computational models encode the scientific theories to elicit the relevant knowledge about the past, present and future of the observed system in form of indicators and indices useful for policy-relevant decision-making (Mazzetti et al., 2022). The four transnational projects applied this conceptual framework by developing applications for different policy domains. In the following section, background, specific workflow and developed applications are described for each project.

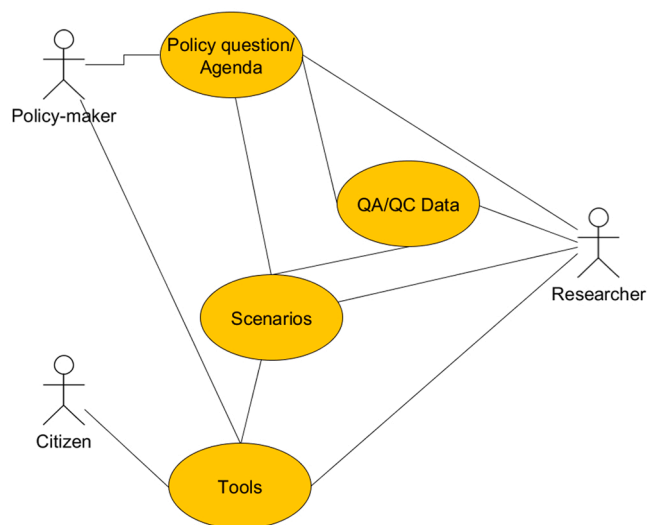


Fig. 1. Main actors and roles in the ERA-PLANET conceptual framework for developing EO-based applications for actionable decision-making.

2.1. SMURBS: Smart URBan solutions for air quality, disasters and city growth

Background.

In the urban domain, both European and international policies have demonstrated the urgency for sustainable urbanization and development, in which all means are necessary to achieve objectives in a holistic manner. The smart city concept is one of these means, which has also been considered a key component of the Shaping Europe's digital future Policy (The European Commission, 2013) in the EU 2014–2020 Programming Period, while it also permeates into other EU policies, as for example the regional policy's Urban Development (The European Commission, 2020). In parallel, the 2030 UN Agenda for Sustainable Development has been adopted by UN-Habitat III, which has included the city-oriented Sustainable Development Goal (SDG) 11: "Make cities and human settlements inclusive, safe, resilient and sustainable", and has set the New Urban Agenda as the global framework to localize actions through improved access to science, technology and innovation. Lastly, through Europe's new growth strategy - the *European Green Deal* (The European Commission, 2021b) - the transformation into a fair and prosperous society - where EU's natural capital is enhanced and citizen's well-being is promoted will be pursued, the important impacts on cities and the opportunities arising from and within cities have been highlighted, and the acceleration of a sustainable transition of cities and towns will be followed (The European Commission, 2021a).

Workflow.

SMURBS' a team, during the initial stage of its implementation, made a thorough analysis of the legal and policy framework under the three themes it has been addressing, starting from the international level - passing on to the European Union level and ending with the national and local level, for the latter drawing mainly information from its pilot cities (SMURBS, 2018). Follow the main findings, which also have set the stage for the design and implementation of the project's solutions. In the air quality domain, where the European Commission (EC) has been proactive in defining a comprehensive strategy and an implementation methodology, the Framework Directive, as well as its Daughter Directives requires the assessment of the ambient air quality existing in Member States based on common methods and criteria. The penetration of the EU legal framework into the national/regional/local frameworks has been considered high, while the competences of implementation and evaluation have been collocated at regional and local levels. The legal obligations of the air quality regulatory networks have been established with respect to the exceedances of specific legal limits. In the urban growth domain, the relevant legislation exploration has shown several strengths relating to the coverage of soil threats and functions by existing EU laws. The two international Agendas, the Urban Agenda for the EU (EU - UA) and the New Urban Agenda (UN - NUA), share the same vision for a balanced, sustainable and integrated urban development. However, since they do not include specific indicators or indices and lack of executive instruments, this might make them less effective for the adoption of sustainable policies, at least at the first stages of implementation. It has been generally deduced that there is no EU level political or legislative driver for establishing integration and coherence towards an agreed strategic aim and objectives, while concentrating on the national/regional/local level, it seems that the lack of strategic coordination is an important obstacle. Finally, in the disaster domain, the relevant international legal reference is laid down by the Sendai framework that contains a set of common standards, achievable targets, and a legally-based instrument for disaster risk reduction. This disaster framework has been translated into a disaster risk-informed approach for all EU policies. The penetration of the UN Sendai framework and the European-to-National law has been found to reach a good level, while gaps in legal obligations are related to spatial planning, the lack of regular coordination between disaster management service and research institutions that can provide high-end products and comprehensive solutions for decision makers.

The SMURBS project gathers several solutions for creating bottom-up EO-driven solutions (SMURBS, 2020) against modern environmental urban pressures. The project has set up a real-world laboratory to test and evaluate how easily and efficiently EO can be used to address urban issues, focusing on air pollution (including health implications), natural and manmade disasters and urban growth (including migration aspects). The main outcome of the project has been the development of a portfolio of solutions, adopting a process where engagement with the users to match needs and gaps and co-design products and services has been central (Georgiadis et al., 2022; Gerasopoulos et al., 2022).

Applications.

SMURBS portfolio of Smart Urban Solutions attempted to provide answers to relevant policy questions and suggest possible solutions based on current legal framework. Along this line, indicative solution types, policy and smart aspects for air quality (Table 1), urban growth (Table 2) and disaster in urban environment (Table 3) have been developed and adopted.

Further, SMURBS has helped to materialize the vision of EO4SDGs Initiative by utilizing its network to build specific EO-based applications of SDG monitoring indicator (e.g., 11.1.1, 11.3.1, 11.6.2) (Figure 2) and provide feedback on the Initiative's compilation of use cases and good practices. Along the same line and through iterations within all four strands of ERA-PLANET, the project has arrived at a set of Essential Urban Variables (EUVs) that, in line with the established process, aims to proposing them for consideration to the EO community for further discussion.

2.2. GEOEssential: Essential Variables workflows for resource efficiency and environmental management

Background.

The international environmental policy agenda on climate, biodiversity, energy, water, and more widely SDGs is percolating quickly into European and National agendas. While policy makers are requesting new accurate spatial-temporal indicators to assess their progress towards policy objectives at various scales, science is struggling to bring the necessary data and tools on the table in a timely manner. However, significant progress has been made in EO to gather a variety of

Table 1

Indicative solution types, policy and smart aspects for air quality.

Air Quality		
Solution type	Policy support	Smart aspects
Advancing in situ monitoring networks	Decision making: Identification of AQ hot spots and proposed cost-effective mitigation measures; feedback on effects of source-targeted mitigation policies	Smart dissemination through web and smartphone app, crowdsourcing, integration of fragmented EO information and provision of tailored and comprehensible indices
Modelling solutions targeting the city scale	Quantitative evaluation of current and planned mitigation measures	Utilization and fusion of AQ data from a state-of-the-art satellite, integration to regular monitoring
Addressing AQ impacts on health	Personalized AQ information and alerts	Real time and forecast air quality and health risk information for citizens utilizing concentration
Utilizing innovative platforms and IoT	Spatially resolved exposure concentrations	Response functions from epidemiological studies
	Methodologies for incorporating smart sensors in monitoring networks Tools for citizen engagement and crowdsourcing Present situation and forecasts of AQ and health risks	

Table 2
Indicative solution types, policy and smart aspects for urban growth.

Urban growth		
<i>Solution type</i>	<i>Policy support</i>	<i>Smart aspects</i>
Assessing suitability of migrant host areas–	Identification of new built-up areas with a pixel resolution of 5 m within the urban fabric	Integration of EO data and socio-economic data
Urban classification and detection of changes	Identification of illegal building in post-fire situations	Weighted indicators based on local policy prioritization
Supporting city planning and mitigation of health impacts due to extreme weather	Direct or indirect monitoring of the ratio of land consumption rate to population growth rate (SDG indicator 11.3.1) Calculation of urban indicators, e.g.annual percentage increase in soil, consumption, loss of agricultural, natural and semi-natural areas Support for city authorities and relevant stakeholders for changes and urban development monitoring Protection of citizens and management of extreme temperature events Baseline establishment of current city resilience to migration processes, enabling future resilience scenario analysis also involving other policy sectors	Online and open access to all products Automated analysis that enables extraction of class trends in large areas Tailored Multiple Hazards Risk Assessment based on the specific needs of the relevant end-users High resolution data that is beyond the usual <i>modus operandi</i> in current city authorities' approach

Table 3
Indicative solution types, policy and smart aspects for disaster.

Disasters		
<i>Solution type</i>	<i>Policy support</i>	<i>Smart aspects</i>
Pre-, during and post-flood management	Support for decisions e.g. local/regional authorities during and immediately after disaster; disaster preparedness via mapping of critical urban infrastructure and disaster scenario simulation; preparedness for peri-urban fire management	Near real time information during the disaster for floods management and monitoring
Mapping urban infrastructure for disasters' management	Urban and peri-urban flood early warning system using operational crowdsourced data collection platforms	Synergy of a wide variety of EO platforms, including crowdsourcing
Monitoring urban land deformation	Flood risk management plans	User friendly frontend for stakeholders provided via web-portals
Urban and peri-urban fires detection and management	Industrial infrastructure for accidents pre-and post-assessment- Alerts to specific networks	Dedicated crowdsourcing by providing e.g. firefighters with GPS devices A web portal based on open-source and free software delivering information to relevant public services and public organizations

environmental observations from both space-based platforms and in-situ observatories. The key question is where these data sets are? What is the degree of their utilization by end users? In most cases, these data sets are

very difficult to find. It can be frustrating to see the gap expanding between our capacity to monitor our planet and its urgent environmental challenges, and the few examples where this knowledge is truly being used to improve decision making. While time is passing by, opportunities to reverse the general unsustainable trend are shrinking. The question becomes therefore, how we can improve the access to scientific knowledge on the functioning of our socio-ecological systems based on our increased capacities to observe temporal variations of key parameters on the functioning of our planet.

Workflow.

To tackle the above issues GEOessential adopted two main strategies.

First, GEOessential proposed to improve and generalize the concept of Essential Variables across all spheres of the Earth System (Atmo-, Bio-, Hydro-, and Geo-), as well as key domains of human activities such as Agriculture, Energy, Transport and infrastructure, Urban development and Health (Lehmann et al., 2022). Essential Variables are indeed classes of EO data that fit in between available EO and selected policy indicators. It is becoming indeed essential to clearly define what needs to be monitored through time and space in order to evaluate the selected policy indicators, as well as cost-effective adaptation and mitigation strategies.

Second, GEOessential developed functional workflows from data sources to indicators with sets of identified Essential Variables. These workflows are addressing different environmental policies at various scales as a demonstration that if they can be developed for one policy context, they could be generalized to most of them, and therefore lower the barriers for accessing state of the art scientific knowledge for policy making (Lehmann et al., 2022).

Application.

Most applications and workflows developed in GEOessential are related to the SDG indicators, however the approach can be generalized to other global environmental policies, as well as regional, national and even local ones (Lehmann et al., 2020). The idea of better defining what is essential to be monitored in order to inform policy indicators and/or fully define a system is crucial to build sustainable information systems and to identify potential gaps in the information workflows. By promoting the development of Essential Variables across all domains of activity of GEO, the GEOessential project is starting to have an impact on the most important observation systems and their communities. We show how Essential Variables are rapidly spreading into the description of the natural Earth System (atmosphere, hydrosphere, geosphere and biosphere) (Lehmann et al., 2022), while the work is starting on the description of the socio-economic spheres of human activities in Agriculture, Health, Energy, Infrastructure and Transport as well as Urban. It appears now evident to more and more experts that we need to have quick access to quality data in many different domains to address complex issues such as those raised by our sustainability quest. All four priority policies of GEO (SDGs, Sendai framework on natural risks, Climate Change and Urban Development) necessitate the access and integration of data across scientific domains. Indeed, most of the present environmental crises could be mitigated by reducing the pressure of human activities by implementing more efficient and less energy demanding technologies in the industrial sectors.

The development of Essential Variables across all GEO domains creates a pyramid of information that needs to be clearly embedded in information and knowledge systems. Therefore, the GEOessential project has been working on defining a knowledge-based platform linking policy indicators with Essential Variables (Figure 3), and a geo-processing data platform to implement dedicated workflows for data processing and analysis (Mazzetti et al., 2022).

Within the scope of the project, GEOessential has developed for instance the following workflows on SDGs:

- SDG 2.4.1 - The “productive agricultural land” workflow is targeting policy and decision-makers whose work may affect or may be affected by land productivity, biodiversity or nature’s contributions

The SMURBS SDG Indicator 11.6.2 Earth Observation Platform

Powered by Copernicus Services and JRC's Global Human Settlement

City Data

UniqueID	Co...	Na...	Population (2012)	20...	20...	20...	20...	201...
173	EE	Narva	58,591	7.65	7.68	8.17	5.21	7.73
174	EL	Athina	3,699,481	12.46	13.40	13.59	9.12	12.35
175	EL	Thessal...	927,217	12.16	13.92	14.52	9.50	12.23

Add To Chart

Country Data

Coun...	Name	Number of FUAs	2014 ...	2015 ...	2016 ...	2017 ...	2018 ...
EE	Estonia	3	6.98	5.91	6.46	4.12	6.75
EL	Greece	9	11.95	13.26	13.51	8.91	12.09

Add To Chart

Overview

Capitals of Europe (FUA)

City Comparison

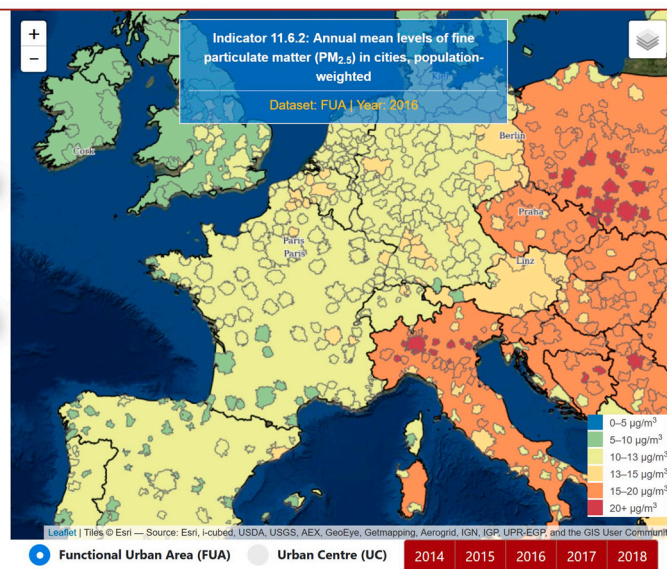
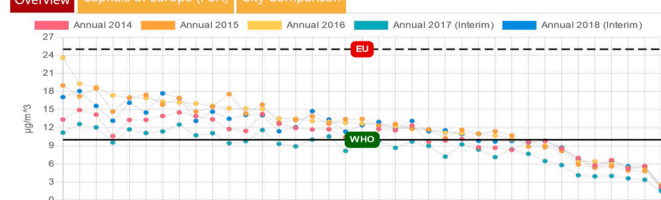


Fig. 2. SMURBS' Earth observation platform on SDG 11.6.2 indicator covering Europe.

to people at all levels (local, national and global), as well as the United Nations entities and multilateral environmental agreements. This workflow has been developed across Ukraine.

- SDG 6.4.2 - The “levels of water stress” workflow quantifies a decade (2011–2020) of monthly (agricultural) water stress levels across Europe using satellite-derived Evapotranspiration (ET) data and Evaporative Stress Index (ESI) anomalies at 4 km spatial resolution.
- SDG 11.3.1 - The “Land consumption” workflow estimates land consumption rate based on land cover classification for urban areas, on the basis of which it is possible to estimate built-up area for large territory of interest and even for the whole country of Ukraine at 10 m resolution.
- SDG 15.1.1 - The “forest area as a proportion of total land area” workflows is calculating for any region of the world the trend in the proportion of forest and agricultural areas.
- SDG 15.3.1 - The “land degradation” workflow is using the Trends. Earth model published in the GEOessential Virtual Laboratory (VLab) in order to assess the area degraded, using information from sub- indicators: Land cover, Land productivity and Carbon stocks.

While developing these workflows based on Essential Variables, GEOessential also contributed to improving and creating new web user interfaces such as UNEP/MapX (<http://www.mapx.org>) and the Radiance Light Trends application (<http://lighttrends.lightpollutionmap.info>).

2.3. iGOSP: Integrated Global Observing Systems for persistent pollutants

Background.

The international policy context is showing that there is a high interest to gain additional insights into the cycling of persistent organic pollutants (POPs) regulated under the Stockholm Convention and mercury (Hg) regulated under the Minamata Convention on Mercury. The integration of EO and in-situ data into various atmospheric, ocean and terrestrial models can give information on the relative contributions of different chemical and physical processes involved in the cycling of these pollutants between environmental compartments. This action aims to lay down the foundation on a possible extension of the usage of already available satellite data to further improve our understanding on

the environmental cycling of the aforementioned substances.

iGOSP is contributing to the development of a Knowledge Hub in support of the Minamata Convention on Mercury (MCM) and a Global Monitoring Plan Data Warehouse (GMP-DWH) of the Stockholm Convention. These activities are taking place in the framework of the GEO Flagship on Mercury (GOS⁴M) and the GEO Initiative on POPs (GOS⁴POPs).

Workflow.

iGOSP has developed the following workflow integrated in an interoperable Knowledge Hub (GOS⁴M-KH):

- Interaction with policy-makers to define relevant policy questions.
- Design of up-stream and down-stream tools/applications for data analytics and trend analysis.
- Co-design (with policy makers and stakeholders) of policy-driven emission reduction scenarios that would be used to run a set of multimedia models¹ to derive the relationship between mercury releases to air and water and mercury bioaccumulation in marine biota.
- Definition of a set of cost-effective strategies of emission reductions that would allow nations to achieve the objectives of the MCM in reducing the risk for human health and ecosystems.
- Design of the Graphical User Interface to facilitate the use of the GOS⁴M-KH.

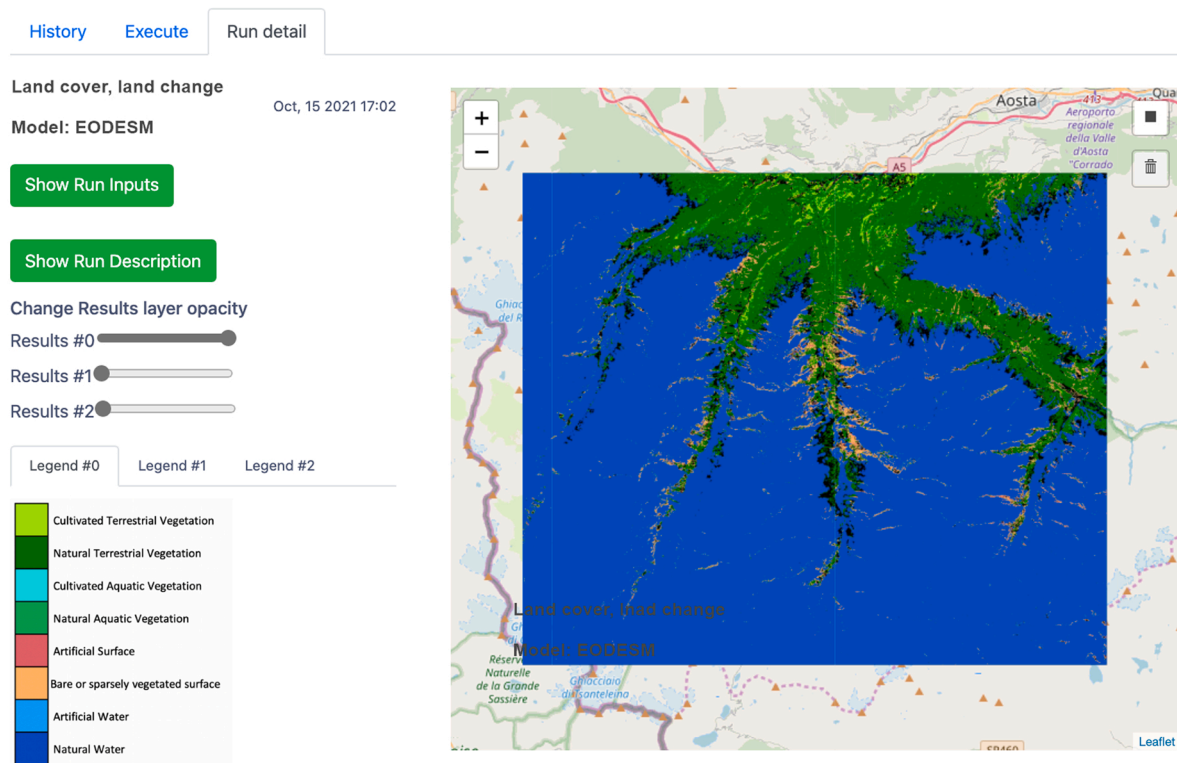
As outcome of policy-driven meetings a number of key policy relevant questions were considered as basis for developing the science-policy interface such as (to mention a few among the most relevant):

- What is the relative contribution of each anthropogenic emission source to the global mercury budget?
- What are the possible cost-effective emission reduction scenarios for major anthropogenic emission sources?

¹ A multimedia model is a numerical model that predicts the behaviour of a contaminant released to the environment, at a spatial location and at a specified temporal point. It includes fate, transport and the ecological exposure modules each one based on physical and chemical equations.



Protected Areas Analysis Demo



Co-Designed and Co-Developed with:



Fig. 3. Web application which utilizes the VLab enhanced in the GEOessential project to run the EODESM model ((Lucas and Mitchell, 2017)) for calculating land cover and land cover changes in a set of protected areas; the depicted output shows the result of the computation over the Gran Paradiso protected area in Italy. The showcase is built through a collaboration of ERA-PLANET and other institutions and projects.

- For selected emission reduction scenarios what would be the time necessary to observe a significant reduction of mercury bioaccumulated in biological end points such as fish and marine mammals?
 - What is the relative contribution of anthropogenic emission regions to mercury deposition in another region (export/import ratio)?
- The design of tools and applications was based on the above policy-

relevant questions for contributing to the on-going work at global level to shape a standard methodology for assessing the effectiveness of policy measures undertaken by nations to reduce the risk associated to mercury exposure.

A second challenge for iGOSP was to contribute to the GEO initiative GOS⁴POPs (Global Observation System for Persistent Organic Pollutants, POPs) by developing a new integrated approach for global real-time monitoring of environmental quality with respect to air, water and human matrices contamination by toxic substances. The outputs are designed to serve nations that ratified the Stockholm Convention on Persistent Organic Pollutants and represent a key pillar for evaluating the effectiveness of established global measures to mitigate POPs releases and protect human health and the environment from the exposure to POPs. For that the iGOSP developed a fully integrated system of advanced monitoring sensors and established a complex and fully harmonized knowledge hub. The POPs Knowledge Hub is a data repository with data management console and knowledge information system complemented by visualization platform created within iGOSP.

The workflow supporting global POPs management as part of the GOS⁴POPs Initiative includes the following components:

- Interaction with policy-makers and experts for finalizing parameters and harmonization needs.
- Design of tools/parameters to involve all relevant data producers.
- Implementation of technologies and standards to provide data management tools.
- Design of new technologies enabling sharing outputs with end-users.
- Design of the Graphical User Interface.

With the POPs Knowledge Hub (GMP–DWH), the iGOSP increased the availability of real-time data to policy-makers to make better decisions and design more effective policies in the area of regulating persistent pollutants and minimizing the risk associated to POPs exposure.

Application for the Minamata Convention.

The growing perception of nations on the strategic importance of using EO datasets to better characterize the magnitude and spatial distributions of Hg pollution led to the creation of the GEO Flagship on Hg (GOS⁴M, <http://www.gos4m.org>) (as part of the GEO WP 2016–2025). GOS⁴M was designed to support policy makers by enhancing EO data sharing, fostering the design and development of integrated modelling tools to allow decision makers to evaluate the linkages between causes and effects of Hg pollution and elaborate possible cost-effective strategies that nations may implement to achieve the objectives of the MCM.

The main goal of the GOS⁴M Flagship was the development of an operational Knowledge Hub that all interested parties (i.e., nations, stakeholders, policy makers) may use for characterizing the linkages between impacts and effect of mercury contamination on Earth system and human health at different geographical and temporal scales. The multimedia and multi-domain computational system was designed to evaluate the potential effectiveness of measures that nations may undertake to reduce the impact of mercury contamination on human health and ecosystems for selected policy scenarios. The first level macro-indicator is the Hg bioaccumulation in biological endpoints, which can be Hg in fish at upper trophic levels (level 3 or 4) while the second level is the Hg concentration in ambient air and precipitation samples. Long-term trends of macro-indicators can be analysed to assess the effectiveness of measures on medium-long term basis and eventually estimate associated socio-economic costs.

In addition, the GOS⁴M through iGOSP is contributing to the UNEP Global Mercury Fate and Transport Partnership (UNEP F&T) which was launched in 2006, with the objective to provide state of the art knowledge on different aspects related to mercury releases to the atmosphere, its long-range atmospheric transport and deposition patterns to aquatic and terrestrial ecosystems and its potential impact on human health and ecosystems.

Having in mind relevant policy questions a set of reduction scenarios were defined (De Simone et al., 2020), which were based on 2010 inventories (AMAP/UNEnvironment, 2013) that grouped anthropogenic mercury emissions in well characterised industrial macro-sectors. The policy-driven scenarios were simulated by means of a Chemical Transport Model (CTM), namely ECHMERIT (Jung et al., 2009; De Simone et al., 2014). The scope of the simulation was to assess the impact of the emission reduction on the global mercury deposition. Main results highlight that an action on a single industrial sector does not provide significant deposition reduction over any receptor region. While a reduction of emissions on all sectors has an impact on different receptors at different levels.

To make accessible all developed scenarios and provide a user-friendly tool for analysis, some widgets were developed (Figure 4). The analysis tool is based on a statistical emulator that help the scenario assessment (De Simone et al., 2021). The application developed through specific widgets interacts with a biogeochemical model to provide long-term changes of the mercury burden in the oceans. The end-point of the application is a trophic model that gives information on mercury uptake by marine biota. The running application that implements the iGOSP workflow can be explored at <http://www.gos4m.org/kh>.

Moreover, an optimisation framework was developed to extend the capabilities of the emulator (De Simone et al., 2022). It gives the possibility to define a deposition reduction target in one or more regions and obtain the optimal set of emissions reductions in different industrial macro-sectors by considering all the geographical source regions.

Application for the Stockholm Convention.

The overarching goal of the GOS⁴POPs (Global Observing System for Persistent Organic Pollutants) Initiative is to further develop the Global Monitoring Plan (GMP) for POPs by harmonizing standard operating procedures for monitoring these substances in core environmental and human matrices and support the sharing of standardized data (Hülek et al., 2020).

GOS⁴POPs initiative has a clear policy mandate from the Stockholm Convention on POPs. Article 16 of the Stockholm Convention requires periodic assessment and evaluation of the effectiveness of measures adopted by the Convention to eliminate or significantly reduce POPs releases into the environment. To this regard, the GMP was established to collect comparable, harmonized and reliable information on POP levels in core environmental matrices (air, human tissues (breast milk/blood), and water).

The GOS⁴POPs Initiative should further improve and strengthen the GMP by including newly listed POPs and core media into existing and newly developed monitoring networks, by extension of the GMP Data Warehouse, and by allowing for more efficient data sharing and access to historical and newly collected data sets. A specific consideration was given to the necessity to ensure internal consistency of data within programmes; and at the same time, to strive for comparability of data among programmes so that data sets can be combined (Melymuk et al., 2021).

The POPs part of the iGOSP project was designed to deal with:

- enhanced monitoring of newly listed POPs in core matrices through their implementation into existing monitoring programmes,
- improved spatial coverage, quality, comparability and accessibility of data from existing (atmospheric, water, human) (bio)monitoring networks,
- establishment of new monitoring efforts enhancing monitoring capacity for new POPs in relevant core media,
- further development of the GMP Data Warehouse (<https://www.pops-gmp.org/index.php>) to support the 3rd GMP data collection campaign in 2020 (including new POPs, core matrices, or programmes),
- improved access to information on environmental and human exposure allowing for joint interpretation and assessment of human risks, and

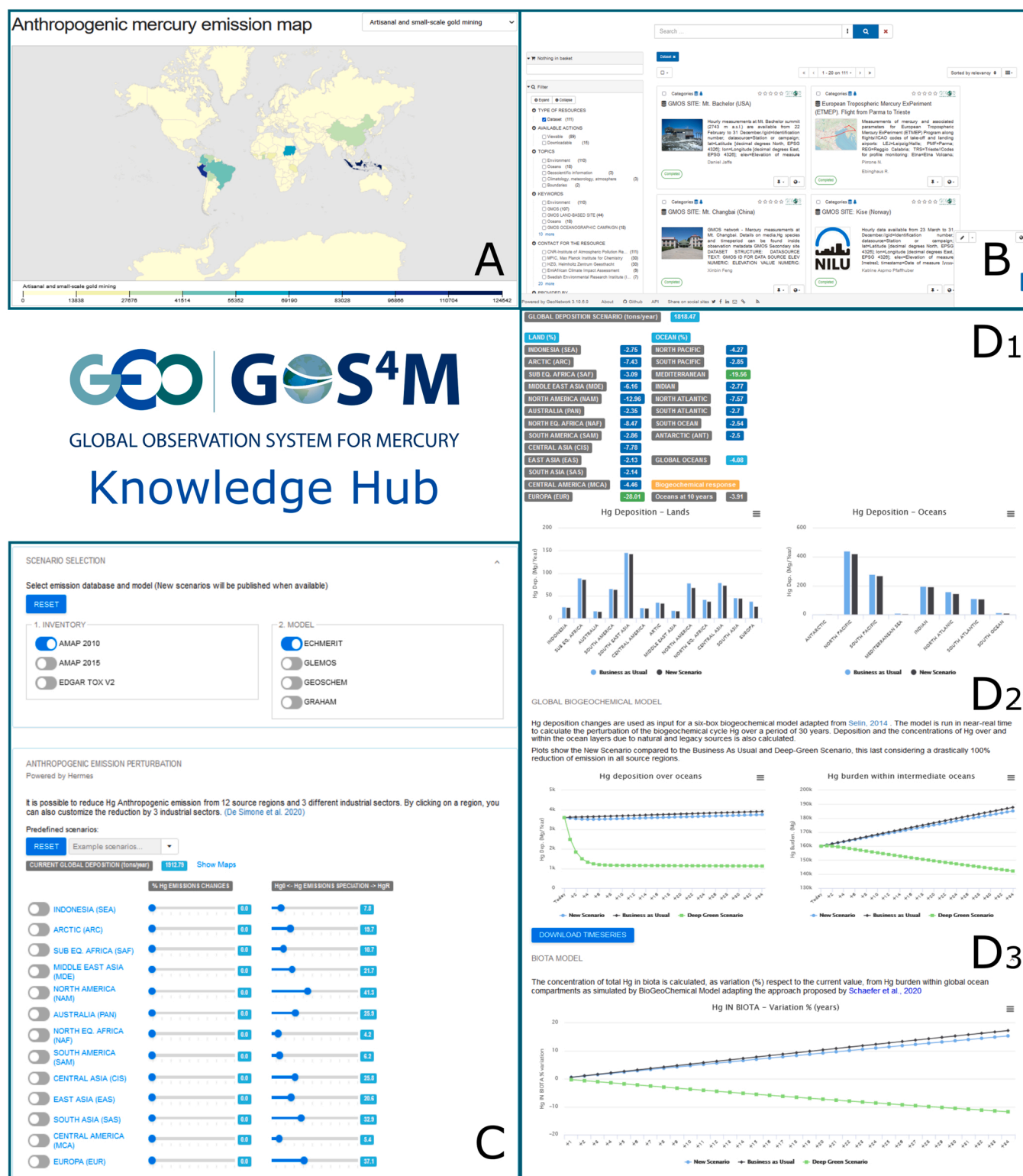


Fig. 4. Widgets of the GOS⁴M Knowledge Hub useful to assess Hg deposition scenarios and uptake by marine biota. The emission map (A) based on 2015 inventories (AMAP/UN Environment, 2019) can give amount of emission by country and sector; the data catalog browser (B) can guide to data discovery and download; the Chemical-Transport model emulator (C) can give information on deposition reduction over land and oceans (D₁), trends of Hg burden in the ocean (D₂) and the Hg uptake by marine biota (D₃).

- informed decision making in chemical management and disease/health control.

Open access to comparable long-term data from the existing networks (Figure 5) will enhance our understanding of temporal and spatial

patterns in releases, distribution, transport, deposition to and evasion from terrestrial and aquatic ecosystems. Such data will support the validation of regional and global atmospheric models for use in the evaluation of different policy options for reducing pollution impacts on human health and ecosystems.

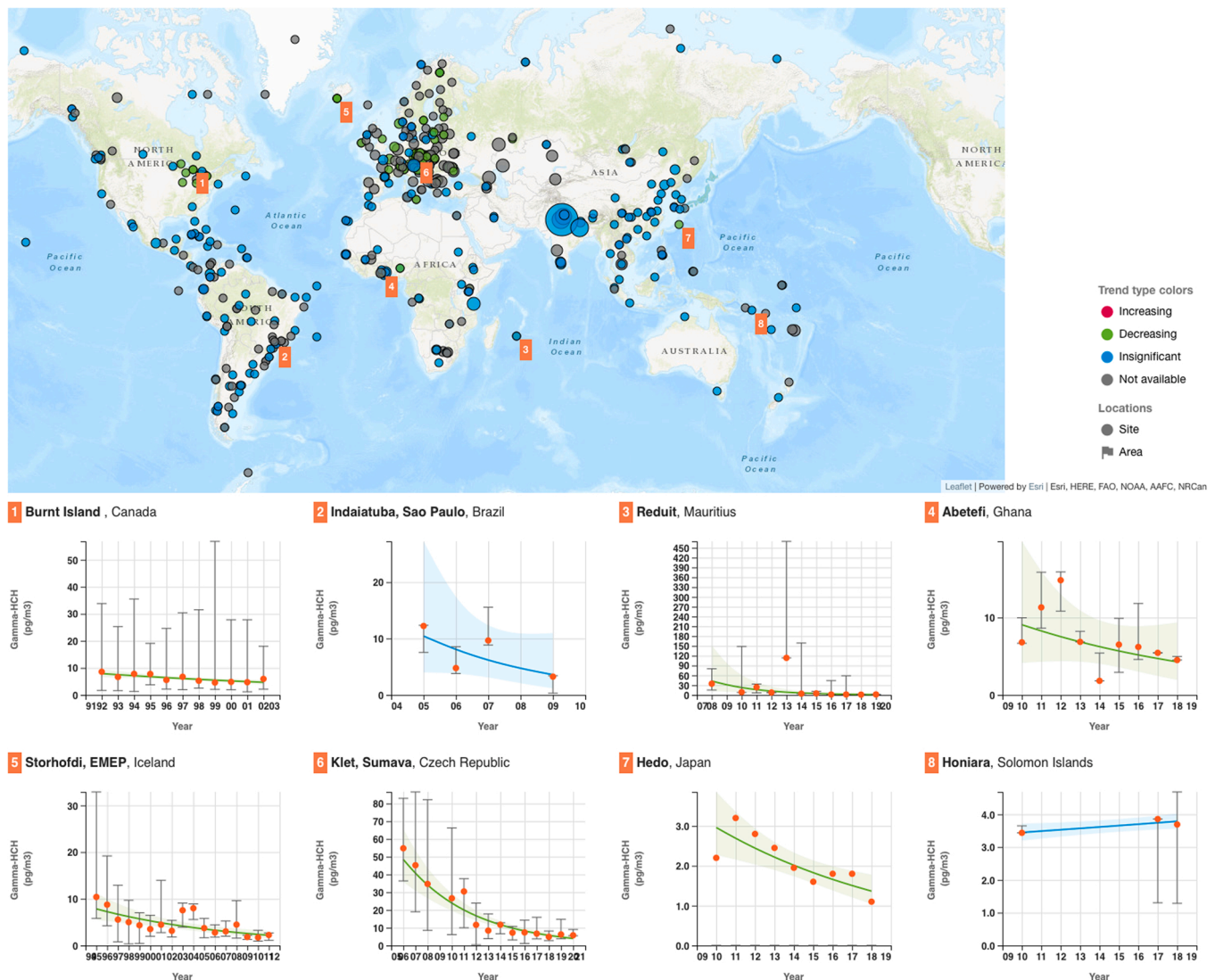


Fig. 5. Trend analysis module for changes in levels of gamma hexachlorocyclohexane (gammaHCH) in ambient air between 1991 and 2019. Decreasing trend is marked in green, statistically non-significant trend in blue, and no trend/not available trend in grey. Size of the circle represents the median of the concentrations (Hůlek et al., 2020).

2.4. iCUPE: integrative and comprehensive understanding on polar environments

Background.

The iCUPE project was motivated by the critical role of the polar regions in the Earth System functioning being the most rapidly changing environment in the on-going climate change (Steffen, 2006; Overland et al., 2019). Particularly global megatrends, such as globalization and consequent demand for natural resources are driving the accelerated climate change in the fragile polar environments. In order to tackling the grand challenges, there is a need for comprehensive ground-based and satellite observational data to monitor the current state of the environment (Kulmala et al., 2021).

Workflow.

The iCUPE concept and work answered to this critical gap in several ways:

- iCUPE contributed to the Roadmap for Arctic Observing and Data Systems (ROADS) of Sustaining Arctic Observing Networks (SAON). This roadmap transformed the SAON approach towards a systematic design and implementation of observations. At the same time, the roadmap introduced a new concept of Shared Arctic Variables (SAVs)

(Murray and Members, 2020), which co-developed with the Arctic stakeholders to incorporate diverse perspectives, knowledge and data across thematic domains and Social Benefit Areas (SBA). Furthermore, the multidisciplinary infrastructure development and integration between marine and terrestrial ecology was tackled in Arena for gap analysis of the existing Arctic Science Co-operation (AASCO) process funded by Prince Albert Foundation for 2020–2022. Here iCUPE contributed to delivering science-based insights (Petäjä et al., 2021) for the Arctic policy making, for example pertinent to climate change in that can drive globalization, new transport routes, demography, and the use of natural resources.

- iCUPE contributed to the urban air quality and environmental impacts of anthropogenic activities in Arctic cities. In this way, iCUPE is thematically connected to SMURBS but with an Arctic angle. The World Meteorological Organization (WMO) through the UN SDGs and New Urban Agenda promotes resilient city development. A key ingredient in this activity is science-based Integrated Urban Weather, Environment and Climate Systems and Services (IUS) in the changing climate. On a global scale, the WMO developed Urban Integrated Hydro-Meteorological, Climate and Environmental Services (Baklanov et al., 2020; Grimmond et al., 2020) and very recently more than 30 cities around the World have provided examples on how different

IUS have been planned or already implemented in their administrative frameworks (Anon, 2019; Anon, 2021). The work is closely performed with WMO Global Atmospheric Watch Urban Research Meteorology and Environment project (GURME) (Sokhi et al., 2021). However, there is a lack of Arctic cities in this work. In close coordination with the International Global Atmospheric Chemistry (IGAC) associated PACES (air Pollution in the Arctic: Climate, Environment and Societies) project, iCUPE contributed to the development of the twin-city concept (Simpson et al., 2018). The driving force is the notion that the Arctic cities suffer from very poor air quality particularly during winter-time, when the cold weather enhances the need for heating concurrently with the very stable Arctic boundary layer, which hinders vertical dilution of the pollution. Under these conditions the ground-level air pollutant concentrations can reach very high concentrations (Arnold et al., 2016). In the twin-city concept, we develop observational capacities and provide science-based data for the Arctic cities across the circumpolar Arctic. The key cities contributing to this work are Fairbanks in Alaska, Apatity and Norilsk in Russia (Konstantinov et al., 2018). Other Arctic cities are welcome to join the initiative in the years to come.

- c. The iCUPE work is driven by the same conventions as iGOSP in relation to mercury (Minamata convention) and Stockholm Convention on Persistent Organic Pollutants. Again, the role of iCUPE was to provide the specific view from the Arctic environment. As a practical step in responding to these conventions and policy needs, iCUPE developed 24 multiplatform data sets, which connect to UN Sustainable Development Goals (Noe et al., 2022).

Applications.

The main outcomes from iCUPE are the novel and comprehensive data sets (Table 4) (Noe et al., 2022). In addition, modelling work of (McLachlan et al., 2018) with the key method developments during iCUPE provided novel model results on concentration of Polychlorinated biphenyl-153 in breast milk at a global scale. This was done by integrating the results from the multimedia fate and transport model BETR Global 3.0 (MacLeod et al., 2011) and the human exposure model ACC-HUMAN (Czub and McLachlan, 2004). The former provided the emission estimates and environmental concentration data while the latter depicted the chemical transfer to humans. The results indicated that the human exposure in the Arctic is driven by accumulation through the marine food chain, which is in turn proportional to concentrations of pollutants in air and marine water. In addition, there is a high uncertainty on the Arctic diet scenario, and there are very little Arctic monitoring data for comparison. The work expanded towards decabromodiphenyl (e.g., BDE-209, a brominated flame retardant) (Vorkamp et al., 2019) in the Arctic environment, which require considering partitioning of the pollutant between the gas and aerosol phases. Further analysis is limited by availability of observational data in the Arctic. Particularly iCUPE datasets on emerging organic contaminants from the Arctic composed of datasets for air, snow, and water, responded to this need.

The iCUPE data sets and applications (Table 4) enable defining and monitoring of Arctic Essential Variables and sets up processes towards SDGs (Figure 6). The most pertinent SDGs for iCUPE include health (SDG 3), clean water resources and sanitation (SDGs 6 and 14), life below water because of Arctic fisheries are important both locally and globally traded food source (SDG 14). SDG 13, the climate action, is a crucial target as the Arctic is warming faster than the global average. The changes in the sea ice in the future, in connection with the enhanced mobility through the Arctic will open new opportunities for global transport routes. The natural resources in the Arctic (natural gas, oil, and other resources) and their extraction will influence the greenhouse gas emissions as well as short-lived climate forcers, such as black carbon through flaring. These topics were addressed by the iCUPE datasets, for example through novel analysis of Arctic artificial light sources, which

Table 4

A summary of iCUPE datasets, model results and applications with their respective connections to Sustainable Development Goals (SDG) (see also (Noe et al., 2022) for additional details.

#	iCUPE Datasets, model results and applications	Relevant SDGs
1	Aerosol physical and optical characteristics including equivalent black carbon at Ny-Ålesund, Svalbard (with 3 datasets for aerosol ultrafine particle size distribution, aerosol large particle size distribution, scattering, absorption)	13, 3, 4
2	Anthropogenic contaminants from polar regions (with 2 datasets for ice cores and snow)	13, 3, 4
3	Arctic atmospheric mercury observations (with 2 datasets for Hg(0) isotope and Hg(II))	13, 3, 4, 14, 15, 17
4	Artificial light sources in the Yamal Peninsula, Western Siberia	13, 3, 4, 11, 17
5	Blueprint for novel proxy variables integrating in-situ and satellite remote sensing data (with 2 datasets on condensation sink and mixing layer height)	13, 3, 4
6	Emerging organic contaminants from the Arctic (with 3 datasets for air, snow, and water)	13, 3, 4, 14, 17
7	Fractional snow cover area in selected sites of Svalbard islands, Norway, and associated Vlab application	13, 4
8	Ground-validation of precipitation measurements in high-latitudes	13, 4
9	Long-term monitoring of gaseous elementary mercury in background air at the polar station Amderma, Russian Arctic, and associated mercury visualization pilot	13, 3, 4, 14, 15
10	Near-Real-Time aerosol absorption measurements from Zeppelin Station, Ny-Ålesund, Svalbard	13, 3, 4
11	Organic aerosol composition in the circumpolar Arctic environments	13, 3, 4
12	Small-scale vertical and horizontal variability of the atmospheric boundary layer aerosol using unmanned aerial systems	13, 3, 4
13	Snow spectral reflectance measurements at Ny-Ålesund, Svalbard	13, 4
14	Time-series of lakes' size changes in Northeast Greenland	13, 9, 4, 17, 6, 7
15	Validated aerosol vertical profiles from ground-based and satellite observations above selected sites (with 2 datasets for Finland and Siberia)	13, 3, 4
16	Vertical profiles of equivalent black carbon in the Arctic boundary layer at Ny-Ålesund, Svalbard	13, 3, 4
17	Visible Near Infrared airborne and simulated EnMAP satellite hyperspectral imagery of Toolik Lake, Alaska	13, 14, 15, 6, 4

are indicative for oil and gas extraction. The long-term aerosol observations provided perspectives on the concentrations of short-lived climate forcers and the detailed data set on aerosol source analysis gave insights into relative roles of local and remote pollution sources. These data sets contributed towards pollution emission mitigation measures, which supports promotion of clean energy (SDG 7), clean air (SDG 3) and climate benefits (SDG 13) (Petäjä et al., 2021). In this respect iCUPE contributed to the work of the Arctic Council Arctic Monitoring and Assessment Programme on Short-Lived Climate Forcers including the use of observations for evaluation of models run with state-of-the-art emission inventories and to the related EU Action on Black Carbon in the Arctic (EUA-BCA) which reviews and proposes black carbon emission reduction measures for specific sectors that affect the Arctic such as gas flaring.

2.5. Key-enabling technologies

The objective of strengthening the European Research Area on EO to better support decision-making addressing environmental policies requires to face the so-called Big Earth Data and Open Science challenges. Indeed: a) the interdisciplinary and multidisciplinary character of global policies demand the access to and integration of heterogeneous data and information sources (Variety challenge); b) the complexity of the Earth System requires fast processing of a huge amount of observations and models' generated data sets to elaborate reliable indicators and indexes

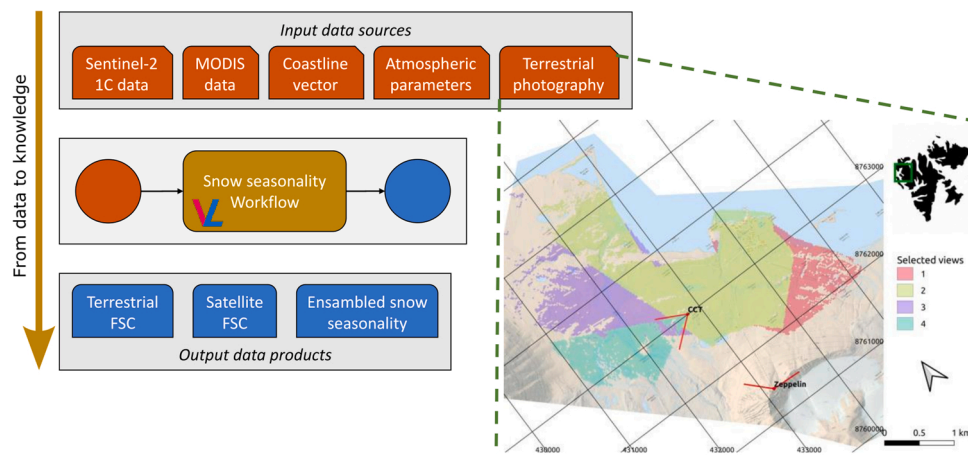


Fig. 6. VLAB Workflow (left side) knowledge on fractional snow cover assessment utilizing local data and linking atmospheric parameters with satellite data products. Use of terrestrial photography (right side) in the Ny-Ålesund area, Svalbard enhanced the output data products.

(Volume and Velocity challenges); c) the necessary transparency of the decision-making process imposes the capability to share and run computational models in complex workflows (Open Science challenge).

Luckily, the fast advancements in digital information technologies provides great opportunities for addressing these challenges. ERA-PLANET proposed, designed and developed a set of transversal technological solutions, leveraging the existing efforts at global and European level, to efficiently and effectively enable the development of multidisciplinary applications for decision-makers. They constitute the so-called ERA-PLANET Key Enabling Technologies (KETs) supporting the EO information lifecycle from the acquisition of observation to the generation of knowledge in alignment with the evolution of the international and European context (Nativi et al., 2021). In particular:

- The challenge related to the variety of data sources - e.g., in terms of data formats and access protocols - has been addressed adopting *de-iure* and *de-facto* geospatial standards²
- The Virtual Earth Laboratory (VLab) framework (Nativi et al., 2013; Santoro et al., 2016, 2020) enables the sharing of computational models as source code or executable code and their execution as Web services or on multiple clouds including Copernicus DIAS, EOSC, AWS (<https://confluence.geodab.eu>; <https://vl.geodab.org>).

ERA-PLANET through its transversal activities in the four transnational projects, developed science-policy interfaces aimed to close the science-policy gap, bringing scientific results to the public and specifically to policy-makers. According to its conceptual framework, each project specifically worked for enabling the ‘data to knowledge’ transition as a necessary shift of perspective for supporting environmental decision.

Beside the ERA-PLANET KETs, the four Transnational Project experimented technological solutions and good practices to address their specific requirements:

- Smart Urban Solutions were provided to answers relevant policy questions and suggest possible solutions for air quality, urban growth and disasters. They rely on advanced in situ monitoring networks, modelling tools for assessing air quality impacts on human health by means of innovative platforms and Internet of Things, mapping tools for migrant host areas and urban detection of changes, monitoring of

urban land deformation, tools for planning and mitigation of health impacts due to extreme weather events, and tools for urban and peri-urban fires detection and management (Gerasopoulos et al., 2022).

- Data cube technologies have been experimented for serving Analysis Ready Data feeding the computational models running through the VLab for the generation of indicators and indexes (Mazzetti et al., 2022).
- The formalization of knowledge through the integration of domain and EO ontologies in the VLab has been experimented to build the ERA-PLANET Knowledge Platform.
- Knowledge hubs and dashboards have been developed to provide an entry point and friendly user-interfaces for decision makers entangled with environmental policies with respect to air, water and human matrices contamination by toxic substances, like mercury and persistent organic pollutants (De Simone et al., 2022; Hůlek et al., 2020). Tools for data sharing, data analysis and assessment of policy-option are provided for mercury and persistent organic pollutants allowing evaluation of human health risk.
- Datasets and applications can enable defining and monitoring of Arctic Essential Variables and sets up processes towards SDGs. While the long-term aerosol observations provided perspectives on the concentrations of short-lived climate forcers and the detailed data set on aerosol source analysis gave insights into relative roles of local and remote pollution sources.
- The four projects fully adopted the Data Sharing and the Data Management Principles developed in GEO with the main objective to make data accessible and the process of knowledge creation reproducible and transparent.

The articles published in this special issue provide specific details on the conceptual and technical implementation of workflows for enabling the transition from data to knowledge for decision-makers by the four transnational projects.

3. Discussion on research and innovation challenges and opportunities brought by ERA-PLANET to science-policy interfaces

ERA-PLANET has demonstrated how EO data can be transformed into knowledge to support decision-makers and policy implementation, by developing specific policy-driven workflows under four domains: smart cities and resilient societies, resource efficiency and environmental management, global changes and environmental treaties, and polar areas and natural resources. The workflow designed and implemented under each domain has brought to the design, development and implementation of Key Enabling Technologies to enhance ‘data to

² Geospatial standards are patterns for location-based information to allow data sources, services, applications and systems to operate with each other. Geospatial standards facilitate the development, sharing, and use of geospatial data (<https://www.ogc.org/standards>).

knowledge' transition for supporting environmental policy making.

EO-driven solutions were provided by SMURBS to address environmental urban pressures. A real-world laboratory was implemented to test and evaluate how easily and efficiently EO can be used to address urban issues, focusing on air pollution (including health implications), natural and manmade disasters and urban growth (including migration aspects). A solution to provide rapidly SDG monitoring indicator was described and brought to the reader.

GEOessential has improved the development of the Essential Variable concept to improve our capacity to address intertwined environmental and development policies as a Nexus. A general workflow providing EO-based knowledge to policy-makers to adopt sustainable decisions was devised based on the assessment of specific SDG indicators (SDG 2.4.1, SDG 6.4.2, SDG 11.3.1, SDG 15.1.1, SDG 15.3.1).

A new integrated approach for global real-time monitoring of environmental quality with respect to air, water and human matrices contamination by toxic substances was provided by iGOSP. Knowledge Hubs designed and implemented provide the data repository system integrated with data management console and knowledge information system based on policy-driven scenarios. A strict interaction with policy-makers has driven the development of tools and applications based on policy-relevant questions for contributing to the on-going activity at the Conference of Parties level.

iCUPE developed novel and comprehensive data sets and a modelling activity that contributed to delivering science-based insights for the Arctic region. Applications enable defining and monitoring of Arctic Essential Variables and sets up processes towards SDGs. It also was determinant in the work of the Arctic Council Arctic Monitoring and Assessment Programme on Short-Lived Climate Forcers including the use of observations for evaluation of models run with state-of-the-art emission inventories and to the related EU Action on Black Carbon in the Arctic.

The ERA-PLANET consortium brought the legacy of this large EO program into relevant science-policy initiatives, with the objective to make scientific outputs more usable in support of policy co-design and assessment (Dilling and Lemos, 2011). The developed applications demonstrate how scientific outcomes can be made usable in a way that is more responsive and flexible to user needs (Dilling and Lemos, 2011). It highlighted that EO data (i.e. remote sensing data providing information on physical and chemical parameters that describe an environment or a process) and derived products are themselves knowledge for scientists but not for decision-makers, and that such data require a transformation process. For example, satellite data on marine water temperature are numbers well known to experts but very obscure to the latter, while temperature maps are very familiar.

GEO as a key reference intergovernmental programme on EO is leveraging the international efforts to achieve the objectives of international environmental policies, which include, but are not limited to, the UN 2030 Agenda on Sustainable Development, the Paris Agreement on Climate Change, the Sendai Framework for Disasters Risk Reduction, and more recently the goals of the New Urban Agenda. GEO is delivering solutions to bridge the gap between science and policy as well as to foster a wider access to end-users to environmental observations (Giu-liani et al., 2018). The mediated approach proposed by ERA-PLANET for science-policy interface can be categorized as a co-production interaction that leverages much more knowledge than a traditional science-push, policy-pull interaction (Dunn et al., 2018).

4. Conclusion

To ensure an efficient science-policy interaction a major shift and change of paradigm is required to scientists because the type and format of the information and knowledge needed to support the decision-making process often seems different if compared to those needed to address other end-users' needs. Decision-making is characterized by a strong focus on trust and transparency, and consequently on handling

quality and uncertainty evaluations throughout the process (Kano and Hayashi, 2021). ERA-PLANET contribution to policy-oriented decision-making required the definition and implementation of a clear and sound science-policy interface, which was even more challenging when moving from global/regional to national/local scale (Sutherland et al., 2013). This stimulated the clarification of the role and contribution from different groups of stakeholders, including the science component for generating the required knowledge (data, models), the engineering component to deliver high-level products and services, the end-users, but also intermediate users such as applications' developers who create tools tailored to decision-makers. It should be noted that the interaction with end-users, especially with the local stakeholders (e.g., city authorities and planners), is still weak in GEO and ERA-PLANET has played a significant role with a solid ground for future empowerment. Such real strategic interaction has facilitated mutual understanding and improved knowledge transfer (López-Rodríguez et al., 2015; Rosli, 2015; Porter et al., 2019).

EO and Earth Science both play a fundamental role for supporting policy-making since most of the policy goals and targets include relevant environmental components. However, it is worth noting that most policy targets are inherently multidisciplinary, posing key challenges on integrating knowledge from different scientific domains for delivering effective tools and services, like for example through a participatory science-policy interface mechanism (Bremer and Glavovic, 2013; MacDonald et al., 2016). In the international context were "planet sensing" can strongly support the environmental shift, ERA-PLANET has drawn a comprehensive approach to the generation and delivery of insights and knowledge from EO and Earth Sciences to policy- and decision-makers (Plummer et al., 2010).

Several solutions were proposed to reinforce the science-evidence component of policy-oriented multidisciplinary applications. Enhancing the EO / in-situ data ecosystem would be a direct contribution to the creation of data spaces and an indirect contribution to deliver effective and trusted tools including Digital Twins. Supporting the transition from EO data to Earth system knowledge for decision-makers would be a direct contribution to the creation of an effective and efficient science-policy interface and a contribution to the European Key Enabling Technologies for the EO data value-chain.

Finally, the reinforcement of EO data exploitation by knowledge generation on environmental conditions will benefit a plethora of actors ranging from sensor operators, data providers, infrastructure operators, service providers, to mention a few. The delivery of services will generate specific EO business revenues that is expected to grow exponentially in forthcoming years.

Author statement

The paper has been conceptualized with the joint contribution of all Authors but specific sections were drafted and revised as follow. Ch. 1 Introduction and Ch. 3 Conclusion: NP, PM & SC; Ch. 2 Smurbs: EA & EG; Ch. 2 GeoEssential: AL & PM; Ch. 2 iGOSP: NP, SC, JK, LP & KS; Ch. 2 iCUPE: TP; Ch. 2 KETs: PM & JMP.

Declaration of Competing Interest

The authors declare that they have no competing financial interests or personal relationships that could influence the work reported in this paper.

Data Availability

No data was used for the research described in the article.

Acknowledgements

The Authors would like to acknowledge the contribution received

from EU-H2020 projects which includes ERA-PLANET (Grant Agreement: 689443) – through the funded projects SMURBS, GEOessential, iGOSP and iCUPE – and E-Shape (Grant Agreement: 820852).

References

- AMAP/UNEnvironment, 2019. Technical Background Report for the Global Mercury Assessment 2018. Technical report, Arctic Monitoring and Assessment Programme, Oslo, Norway / UNEP Chemicals Branch, Geneva, Switzerland. (<https://web.unep.org/globalmercurypartnership/technical-background-report-global-mercury-assessment-2018>).
- AMAP/UNEnvironment, 2013. Technical Background Report for the Global Mercury Assessment 2013. Technical report, Arctic Monitoring and Assessment Programme, Oslo, Norway / UNEP Chemicals Branch, Geneva, Switzerland. (<https://www.amap.no/documents/doc/technical-background-report-for-the-global-mercury-assessment-2013/848>).
- WMO, 2019. Guidance on integrated urban hydrometeorological, climate and environmental services. volume 1: Concept and methodology. (https://library.wmo.int/doc_num.php?explnum_id=9903).
- SMURBS, 2020. Smart city solutions and projects. (<https://smurbs.eu/smart-city-solutions-and-projects/>).
- UN, 2020. Glossary of terms relating to treaty actions. (https://treaties.un.org/pages/overview.aspx?path=overview/glossary/page1_en.xml).
- WMO, 2021. Guidance on integrated urban hydrometeorological, climate and environmental services. volume ii: Demonstration cities. (https://library.wmo.int/doc_num.php?explnum_id=10547).
- GEO, 2022. Earth observations for impact. (<https://earthobservations.org/index.php>).
- Arnold, S., Law, K., Brock, C., Thomas, J., Starkweather, S., vonSalzen, K., Stohl, A., Sharma, S., Lund, M., Flanner, M., Petäjä, T., Tanimoto, H., Gamble, J., Dibb, J., Melamed, M., Johnson, N., Fidel, M., Tynkynen, V.P., Baklanov, A., Eckhardt, S., Monks, S., Browne, J., Bozem, H., 2016. Arctic air pollution: Challenges and opportunities for the next decade. *Elem.: Sci. Anthr.* 4 <https://doi.org/10.12952/journal.elementa.000104>.
- Ascher, W., Steelman, T., Healy, R., 2010. Knowledge and Environmental Policy: Re-Imagining the Boundaries of Science and Politics. The MIT Press, Cambridge, MA USA. (<http://www.jstor.org/stable/j.ctt5vj55g.5>).
- Baklanov, A., Cárdenas, B., Lee, T.C., Leroyer, S., Masson, V., Molina, L.T., Müller, T., Ren, C., Vogel, F.R., Voogt, J.A., 2020. Integrated urban services: Experience from four cities on different continents. *Urban Clim.* 32, 100610 <https://doi.org/10.1016/j.uclim.2020.100610>.
- Bremer, S., Glavovic, B., 2013. Exploring the science-policy interface for integrated coastal management in New Zealand. *Ocean Coast. Manag.* 84, 107–118. <https://doi.org/10.1016/j.ocecoaman.2013.08.008>.
- Czub, G., McLachlan, M.S., 2004. A food chain model to predict the levels of lipophilic organic contaminants in humans. *Environ. Toxicol. Chem.* 23, 2356–2366. <https://doi.org/10.1897/03-317>.
- De Simone, F., Gencarelli, C., Hedgecock, I.M., Pirrone, N., 2014. Global atmospheric cycle of mercury: A model study on the impact of oxidation mechanisms. *Environ. Sci. Pollut. Res.* 21, 4110–4123. <https://doi.org/10.1007/s11356-013-2451-x>.
- De Simone, F., D'Amore, F., Marasco, F., Carbone, F., Bencardino, M., Hedgecock, I.M., Cinnirella, S., Sprovieri, F., Pirrone, N., 2020. A chemical transport model emulator for the interactive evaluation of mercury emission reduction scenarios. *Atmosphere* 11. <https://doi.org/10.3390/atmos11080878>. (<https://www.mdpi.com/2073-4433/11/8/878>).
- De Simone, F., D'Amore, F., Bencardino, M., Carbone, F., Hedgecock, I.M., Sprovieri, F., Cinnirella, S., Pirrone, N., 2021. The GOSTM Knowledge Hub: A web-based effectiveness evaluation platform in support of the Minamata Convention on Mercury. *Environ. Sci. Policy* 124, 235–246. <https://doi.org/10.3390/atmos11080878>. (<https://www.mdpi.com/2073-4433/11/8/878>).
- De Simone, F., D'Amore, F., Hedgecock, I.M., Bruno, D., Cinnirella, S., Sprovieri, F., Pirrone, N., 2022. Will action taken under the Minamata Convention on Mercury need to be coordinated internationally? Evidence from an optimisation study suggests it will. *Environ. Sci. Policy* 22–30. <https://doi.org/10.1016/j.envsci.2021.10.006>.
- Dilling, L., Lemos, M.C., 2011. Creating usable science: Opportunities and constraints for climate knowledge use and their implications for science policy. *Glob. Environ. Change* 21, 680–689. <https://doi.org/10.1016/j.gloenvcha.2010.11.006>.
- Driscoll, C.T., Lambert, K.F., Weathers, K.C., 2011. Integrating science and policy: A case study of the Hubbard Brook Research Foundation Science Links Program. *BioScience* 61, 791–801. <https://doi.org/10.1525/bio.2011.61.10.9>.
- Dunn, G., Bos, J., Brown, R., 2018. Mediating the science-policy interface: Insights from the urban water sector in Melbourne, Australia. *Environ. Sci. Policy* 82, 143–150. <https://doi.org/10.1016/j.envsci.2018.02.001>.
- Fazey, I., Evely, A.C., Reed, M.S., Stringer, L.C., Kruijsen, J., White, P.C.L., Newsham, A., Jin, L., Cortazzi, M., Phillipson, J., et al., 2013. Knowledge exchange: A review and research agenda for environmental management. *Environ. Conserv.* 40, 19–36. <https://doi.org/10.1017/S037689291200029X>.
- Galindo-Rueda, F., 2020. How are science, technology and innovation going digital? The statistical evidence. OECD Library. chapter 2.p.182.10.1787/b9e4a2c0-en.
- Georgiadis, C., Patias, P., Verde, N., Tsioukas, V., Kaimaris, D., Georgoulas, O., Kocman, D., Athanasopoulou, E., Speyer, O., Raudner, A., Karl, M., Gerasopoulos, E., 2022. State-of-play in addressing urban environmental pressures: Mind the gaps. *Environ. Sci. Policy* 132, 308–322. <https://doi.org/10.1016/j.envsci.2022.02.030>.
- Gerasopoulos, E., Bailey, J., Athanasopoulou, E., Speyer, O., Kocman, D., Raudner, A., Tsouni, A., Kontoes, H., Johansson, C., Georgiadis, C., Matthias, V., Kussul, N., Aquilino, M., Paasonen, P., 2022. Earth observation: An integral part of a smart and sustainable city. *Environ. Sci. Policy* 132, 296–307. <https://doi.org/10.1016/j.envsci.2022.02.033>.
- Giuliani, G., Camara, G., Killough, B., Minchin, S., 2018. Earth observation open science: Enhancing reproducible science using data cubes. *Data* 4, 147. <https://doi.org/10.3390/data4040147>.
- Gluckman, S., 2016. The science-policy interface. *Science* 353, 969. <https://doi.org/10.1126/science.aai8837>.
- Gluckman, S., 2018. The role of evidence and expertise in policy-making: The politics and practice of science advice. *Journal & Proceedings of the Royal Society of New South Wales* 151 (part 1), 91–101. (<https://ingsa.org/wp-content/uploads/2018/08/Gluckman-18-JProcRoyalSocNSW-The-role-of-evidence-expertise-in-policy-making-politics-practice-of-science-advice.pdf>).
- Grimmond, S., Bouchet, V., Molina, L.T., Baklanov, A., Tan, J., Schlünzen, K.H., Mills, G., Golding, B., Masson, V., Ren, C., Voogt, J., Miao, S., Lean, H., Heusinkveld, B., Hovespyan, A., Teruggi, G., Parrish, P., Joe, P., 2020. Integrated urban hydrometeorological, climate and environmental services: Concept, methodology and key messages. *Urban Clim.* 33, 100623 <https://doi.org/10.1016/j.uclim.2020.100623>. (<https://www.sciencedirect.com/science/article/pii/S221209551930207X>).
- Hanan, N., Limaye, A., Irwin, D., 2020. Editorial: Use of earth observations for actionable decision making in the developing world. *Front. Environ. Sci.* 27, 1–3. <https://doi.org/10.3389/fenvs.2020.601340>.
- The European Commission, 2020. Cities and urban development. EC.
- The European Commission, 2013. Smart cities - Smart living, shaping Europe's digital future.
- UNEP, 2018. Strengthening the science-policy interface: A gap analysis.
- van den Hove, S., 2007. A rationale for science-policy interfaces. *Futures* 39, 807–826. <https://doi.org/10.1016/j.futures.2006.12.004>.
- Hůlek, R., Boruvková, J., Kalina, J., Bednářová, Z., Šebková, K., Hruban, T., Novotný, V., Ismael, M., Klánová, J., 2020. Global monitoring plan data warehouse of the stockholm convention on persistent organic pollutants: visualisation platform and on-line tool for the analysis of global levels of pops in air, water, breast milk and.
- Jacobs, K., Pulwarty, R., 2003. Water resource management: Science, planning and decision-making. *Am. Geophys. Union* 177–204.
- Janse, G., 2008. Communication between forest scientists and forest policy-makers in Europe a survey on both sides of the science/policy interface. *For. Policy Econ.* 10, 183–194. <https://doi.org/10.1016/j.forpol.2007.10.001>.
- Jensen-Ryan, D.K., German, L.A., 2018. Environmental science and policy: A meta-synthesis of case studies on boundary organizations and spanning processes. *Sci. Public Policy* 46, 13–27. <https://doi.org/10.1093/scipol/scy032>.
- Jung, G., Hedgecock, I.M., Pirrone, N., 2009. Echmerit v1.0 – A new global fully coupled mercury-chemistry and transport model. *Geosci. Model Dev.* 2, 175–195. <https://doi.org/10.5194/gmd-2-175-2009>. (<https://gmd.copernicus.org/articles/2/175/2009/>).
- Kano, H., Hayashi, T.I., 2021. A framework for implementing evidence in policymaking: Perspectives and phases of evidence evaluation in the science-policy interaction. *Environ. Sci. Policy* 116, 86–95. <https://doi.org/10.1016/j.envsci.2020.09.001>.
- Konstantinov, P., Varentsov, M., Esau, I., 2018. A high density urban temperature network deployed in several cities of Eurasian Arctic. *Environ. Res. Lett.* 13, 075007 <https://doi.org/10.1088/1748-9326/aac84>. (<https://iopscience.iop.org/article/10.1088/1748-9326/aac84>).
- Kulmala, M., Lintunen, A., Ylivinkka, I., Makkala, J., Rantanen, R., Kujansuu, J., Petäjä, T., Lappalainen, H.K., 2021. Atmospheric and ecosystem big data providing key contributions in reaching United Nations Sustainable Development Goals. *Big Earth Data* 5, 277–305. <https://doi.org/10.1080/20964471.2021.1936943>.
- Lehmann, A., Nativi, S., Mazzetti, P., Masó Pau, J., Serral, I., Spengler, D., Niamir, A., McCallum, I., Lacroix, P., Patias, P., Rodila, D., Ray, N., Giuliani, G., 2020. Geoessential – Mainstreaming workflows from data sources to environment policy indicators with Essential Variables. *Int. J. Digit. Earth* 13, 322–338. <https://doi.org/10.1080/17538947.2019.1585977>.
- Lehmann, A., Mazzetti, P., Santoro, M., Nativi, S., Masó Pau, J., Serral, I., Spengler, D., Niamir, A., Lacroix, P., Ambrosone, M., McCallum, I., Kussul, N., Patias, P., Rodila, D., Ray, N., Giuliani, G., 2022. Essential Earth Observation Variables for high-level multi-scale indicators and policies. *Environ. Sci. Policy* 131, 105–117. <https://doi.org/10.1016/j.envsci.2021.12.024>.
- López-Rodríguez, M., Castro, A., Castro, H., Jorrote, S., Cabello, J., 2015. Science-policy interface for addressing environmental problems in arid Spain. *Environ. Sci. Policy* 50, 1–14. <https://doi.org/10.1016/j.envsci.2015.01.013>.
- Lucas, R., Mitchell, A., 2017. Integrated Land Cover and Change Classifications. Springer International Publishing, pp. 295–308. https://doi.org/10.1007/978-3-319-64332-8_15.
- MacDonald, B., Soomai, S., De Santo, E., Wells, P.E., 2016. Understanding the science-policy interface in integrated coastal and ocean management. pp. 19–43.
- MacLeod, M., vonWaldow, H., Tay, P., Armitage, J.M., Wöhrnschimmel, H., Riley, W.J., McKone, T.E., Hungerbühler, K., 2011. BETR global – A geographically-explicit global-scale multimedia contaminant fate model. *Environ. Pollut.* 159, 1442–1445. <https://doi.org/10.1016/j.envpol.2011.01.038>.
- Mazzetti, P., Nativi, S., Santoro, M., Giuliani, G., Rodila, D., Folino, A., Caruso, S., Aracri, G., Lehmann, A., 2022. Knowledge formalization for Earth Science informed decision-making: The GEOessential knowledge base. *Environ. Sci. Policy* 131, 93–104. <https://doi.org/10.1016/j.envsci.2021.12.023>.

- McLachlan, M.S., Undeman, E., Zhao, F., MacLeod, M., 2018. Predicting global scale exposure of humans to PCB-153 from historical emissions. *Environ. Sci. Process. Impacts* 20, 747–756. <https://doi.org/10.1039/C8EM00023A>.
- Melymuk, L., BohlinNizzetto, P., Harner, T., White, K., Wang, X., Tominaga, M., He, J., Li, J., Ma, J., Ma, W.L., Aristizábal, B., Dryer, A., Jiménez, B., Muñoz-Arnanz, J., Odabasi, M., Dumanoglu, Y., Yaman, B., Graf, C., Sweetman, A., Klánová, J., 2021. Global intercomparison of polyurethane foam passive air samplers evaluating variability in SVOCs due to sampler design and analysis. *Environ. Sci. Policy* 125, 1–9. <https://doi.org/10.1016/j.envsci.2021.08.003>.
- Murray, M., Members, A.O.S.C., 2020. Arctic observing summit 2020: Conference statement and call to action. *Arctic* 73, 273–275. (<https://journalhosting.ucalgary.ca/index.php/arctic/article/download/70689/54183/206833>).
- Nativi, S., Mazzetti, P., Geller, G.N., 2013. Environmental model access and interoperability: The geo model web initiative. *Environ. Model. Softw.* 39, 214–228. <https://doi.org/10.1016/j.envsoft.2012.03.007>. (<https://www.sciencedirect.com/science/article/pii/S1364815212000898>).
- Nativi, S., Mazzetti, P., Craglia, M., 2021. Digital ecosystems for developing digital twins of the earth: the destination earth case. *Remote Sens.* 13. <https://doi.org/10.3390/rs13112119>.
- Noe, S., Tabakova, K., Mahura, A., Lappalainen, H., Kosmale, M., Heilimo, J., Salzano, R., Santoro, M., Salvatori, R., Spolaor, A., Cairns, W., Barbante, C., Pankratov, F., Humbert, A., Sonke, J., Law, K., Onishi, T., Paris, J.D., Skov, H., Massling, A., Dommergue, A., Arshinov, A., Davydov, D., Belan, B., Petäjä, T., 2022. Arctic observations and Sustainable Development Goals - Contributions and examples from ERA-PLANET iCUPE data. *Environ. Sci. Policy* 132, 323–336. <https://doi.org/10.1016/j.envsci.2022.02.034>.
- Overland, J., Dunlea, E., Box, J.E., Corell, R., Forsius, M., Kattsov, V., Olsen, M.S., Pawlak, B., Reiersen, L.O., Wang, M., 2019. The urgency of Arctic change. *Polar Sci.* 21, 6–13. <https://doi.org/10.1016/j.polar.2018.11.008>. (<https://www.sciencedirect.com/science/article/pii/S1873965218301543>).
- Ozga, J., 2011. Knowledge transfer and transformation: Moving knowledge from research to policy. *Perspectiva* 29, 49–67. <https://doi.org/10.5007/2175-795X.2011v29n1p49>.
- Petäjä, T., Duplissy, E.M., Tabakova, K., Schmale, J., Altstädter, B., Ancellet, G., Arshinov, M., Balin, Y., Baltensperger, U., Bange, J., Beamish, A., Belan, B., Berchet, A., Bossi, R., Cairns, W.R.L., Ebinghaus, R., ElHaddad, I., Ferreira-Araujo, B., Franck, A., Huang, L., Hyvärinen, A., Humbert, A., Kalogridis, A.C., Konstantinov, P., Lampert, A., MacLeod, M., Magand, O., Mahura, A., Marelle, L., Masloboev, V., Moiseev, D., Moschos, V., Neckel, N., Onishi, T., Osterwalder, S., Ovaska, A., Paasonen, P., Panchenko, M., Pankratov, F., Pernov, J.B., Platias, A., Popovicheva, O., Raut, J.C., Riandet, A., Sachs, T., Salvatori, R., Salzano, R., Schröder, L., Schön, M., Shevchenko, V., Skov, H., Sonke, J.E., Spolaor, A., Stathopoulos, V.K., Strahlendorff, M., Thomas, J.L., Vitale, V., Vratolis, S., Barbante, C., Chabrilat, S., Dommergue, A., Eleftheriadis, K., Heilimo, J., Law, K.S., Massling, A., Noe, S.M., Paris, J.D., Prévôt, A.S.H., Riipinen, I., Wehner, B., Xie, Z., Lappalainen, H.K., 2021. Overview: Integrative and comprehensive understanding on polar environments (iCUPE) – Concept and initial results. *Atmos. Chem. Phys.* 20, 8551–8592. <https://doi.org/10.5194/acp-20-8551-2020>. (<https://acp.copernicus.org/articles/20/8551/2020/>).
- Plummer, R., Velaniškis, J., de Grosbois, D., Kreutzweiser, R.D., de Loë, R., 2010. The development of new environmental policies and processes in response to a crisis: The case of the multiple barrier approach for safe drinking water. *Environ. Sci. Policy* 13, 535–548. <https://doi.org/10.1016/j.envsci.2010.05.004>.
- Porter, K.M., Cheallacháin, C.N., Bayliss-Brown, G.D., Murphy, D., 2019. Research to Policy Impact through Effective Knowledge Transfer. (https://www.epa.ie/publications/research/communicating-research/Research_Report_284a.pdf).
- Rosli, A.F. R., 2015. Assessing the impact of knowledge transfer policies: An international comparison of models and indicators of universities' knowledge transfer performance, pp.1–37. (<https://core.ac.uk/download/pdf/109868989.pdf>).
- Santoro, M., Stefano, N., Paolo, M., 2016. Contributing to the GEO model web implementation: A brokering service for business processes. *Environ. Model. Softw.* 84, 18–34. <https://doi.org/10.1016/j.envsoft.2016.06.010>. (<https://www.sciencedirect.com/science/article/pii/S1364815216302389>).
- Santoro, M., Mazzetti, P., Nativi, S., 2020. The Vlab framework: An orchestrator component to support data to knowledge transition. *Remote Sens.* 12. <https://doi.org/10.3390/rs12111795>. (<https://www.mdpi.com/2072-4292/12/11/1795>).
- Sarkki, S., Niemelä, J., Tinch, R., van den Hove, S., Watt, A., Young, J., 2013. Balancing credibility, relevance and legitimacy: A critical assessment of trade-offs in science-policy interfaces. *Sci. Public Policy* 41, 194–206. <https://doi.org/10.1093/scipol/scp046>.
- Scheufele, D.A., Krause, N.M., 2019. Science audiences, misinformation, and fake news. *Proc. Natl. Acad. Sci.* 116, 7662–7669. <https://doi.org/10.1073/pnas.1805871115>.
- Sikora, A., 2021. European green deal – legal and financial challenges of the climate change. *ERA Forum* 21, 681–697. <https://doi.org/10.1007/s12027-020-00637-3>.
- Simpson, W., Law, K., Schmale, J., Pratt, K., Arnold, S., Mao, J., 2018. Alpaca study whitepaper. (<https://alpaca.community.uaf.edu/wp-content/uploads/sites/758/2018/11/ALPACA-whitepaper-30Nov2018.pdf>).
- SMURBS, 2018. Policy, principles and legal framework regarding urban air quality (incl. health aspects), urban growth (incl. migration issues) and (peri-)urban disasters. (<https://smurbs.eu/legal-framework/>).
- Sokhi, R.S., Singh, V., Querol, X., Finardi, S., Targino, A.C., de Fatima Andrade, M., Pavlovic, R., Garland, R.M., Massagué, J., Kong, S., Baklanov, A., Ren, L., Tarasova, O., Carmichael, G., Peuch, V.H., Anand, V., Arbilla, G., Badali, K., Beig, G., Belacazar, L.C., Bolignano, A., Brimblecombe, P., Camacho, P., Casallas, A., Charland, J.P., Choi, J., Chourdakis, E., Coll, I., Collins, M., Cyrus, J., da Silva, C.M., Di Giosa, A.D., Di Leo, A., Ferro, C., Gavidia-Calderon, M., Gayen, A., Ginzburg, A., Godefroy, F., Gonzalez, Y.A., Guevara-Luna, M., Haque, S.M., Havenga, H., Herod, D., Horrak, U., Hussein, T., Ibarra, S., Jaimes, M., Kaasik, M., Khaiwal, R., Kim, J., Kousa, A., Kukkonen, J., Kulmala, M., Kuula, J., La Violette, N., Lanzani, G., Liu, X., MacDougall, S., Manseau, P.M., Marchegiani, G., McDonald, B., Mishra, S.V., Molina, L.T., Mooibroek, D., Mor, S., Moussiopoulos, N., Murena, F., Niemi, J.V., Noe, S., Nogueira, T., Norman, M., Pérez-Camano, J.L., Petäjä, T., Piketh, S., Rathod, A., Reid, K., Retama, A., Rivera, O., Rojas, N.Y., Rojas-Quincho, J.P., San José, R., Sánchez, O., Seguel, R.J., Sillanpää, S., Su, Y., Tapper, N., Terrazas, A., Timonen, H., Toscano, D., Tsegas, G., Velders, G.J., Vachokostas, C., von Schneidmesser, E., VPM, R., Yadav, R., Zalakeviciute, R., Zavala, M., 2021. A global observational analysis to understand changes in air quality during exceptionally low anthropogenic emission conditions. *Environ. Int.* 157, 106818. <https://doi.org/10.1016/j.envint.2021.106818>. (<https://www.sciencedirect.com/science/article/pii/S0160412021004438>).
- Steffen, W., 2006. The Arctic in an Earth System context: From brake to accelerator of change. *Ambio* 35, 153–159. (www.jstor.org/stable/4315713).
- Sutherland, W.J., Spiegelhalter, D., Burgman, M., 2013. Policy: Twenty tips for interpreting scientific claims. *Nature* 503, 335–337. <https://doi.org/10.1038/503335a>.
- The European Commission, 2021a. A blueprint for cities to make the most of the eu green deal. (<https://www.intelligentcitieschallenge.eu/sites/default/files/2021-06/Local%20Green%20Deals-8.pdf>).
- The European Commission, 2021b. A european green deal. (<https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal>).
- The European Commission, 2022a. European data strategy. (https://ec.europa.eu/info/strategy/priorities-2019-2024/europe-fit-digital-age/european-data-strategy_en).
- The European Commission, 2022b. Horizon europe. (https://ec.europa.eu/info/research-and-innovation/funding/funding-opportunities/funding-programmes-and-open-calls/horizon-europe_en).
- The European Commission, 2022c. Research and innovation strategy 2020–2024. (https://ec.europa.eu/info/research-and-innovation/strategy/strategy-2020-2024_en#helping-deliver-the-commissions-6-goals).
- The European Commission, 2022d. Supporting policy with scientific evidence. (https://knowledge4policy.ec.europa.eu/projects-activities/strengthening-connecting-science-policy-ecosystems-across-eu_en).
- Vorkamp, K., Balmer, J., Hung, H., Letcher, R.J., Rigét, F.F., de Wit, C.A., 2019. Current-use halogenated and organophosphorous flame retardants: A review of their presence in Arctic ecosystems. *Emerg. Contam.* 5, 179–200. <https://doi.org/10.1016/j.emcon.2019.05.004>. (<https://www.sciencedirect.com/science/article/pii/S240566501930006X>).
- Young, J.C., Waylen, K.A., Sarkki, S., Albon, S., Bainbridge, I., Balian, E., Davidson, J., Edwards, D., Fairley, R., Margerison, C., McCracken, D., Owen, R., Quine, C.P., Stewart-Roper, C., Thompson, D., Tinch, R., Van den Hove, S., Watt, A., 2014. Improving the science-policy dialogue to meet the challenges of biodiversity conservation: Having conversations rather than talking at one-another. *Biodivers. Conserv.* 23, 387–404. <https://doi.org/10.1007/s10531-013-0607-0>.