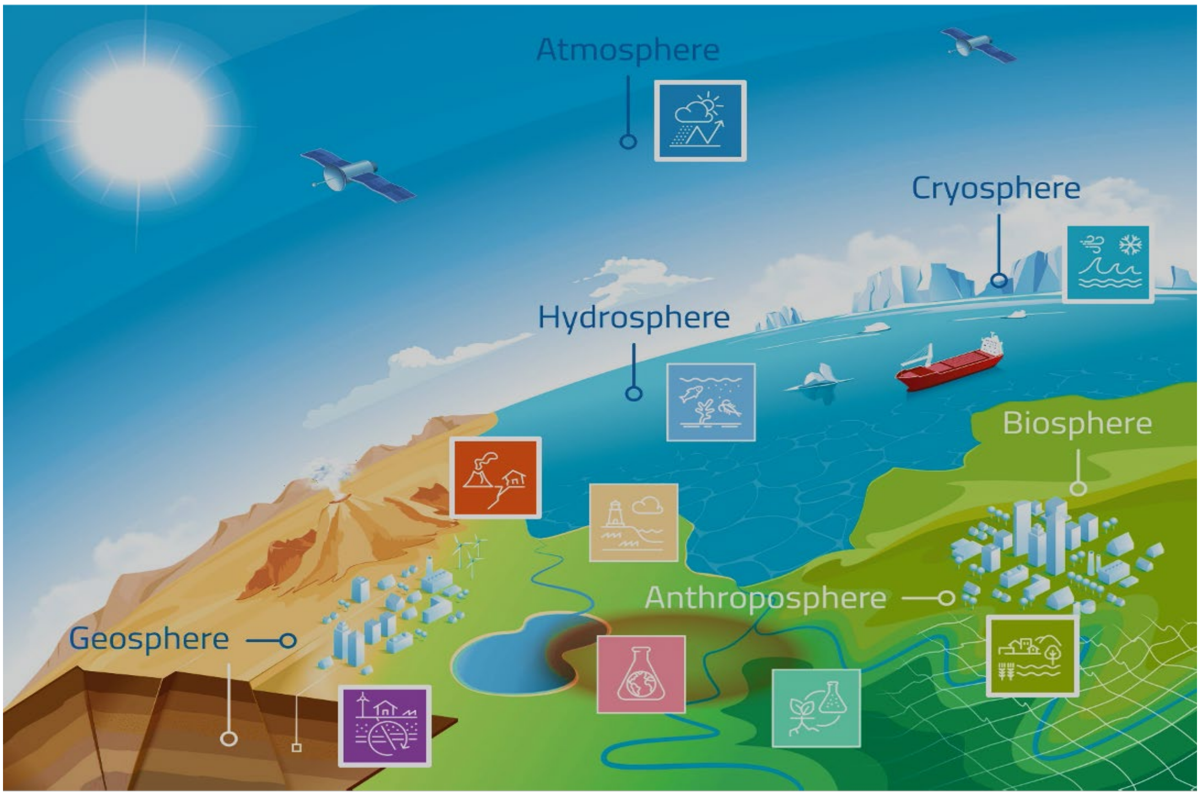
HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

# Revisiting the PoF-IV Program Objectives

Program *Changing Earth - Sustaining our Future*

Research Field *Earth & Environment*




08. November 2023

# Program *Changing Earth - Sustaining our Future*
# Research Field *Earth and Environment*

## Revisiting the PoF-IV Program Objectives

To meet the challenge of understanding the Earth system well enough for adequate management, the *Research Field Earth & Environment* proposed one single, integrated *Program* for the PoF-IV period (2021 - 2027). The ultimate goal of this program is to pioneer a high degree of interaction across its broad scientific scope and, through interdisciplinary and transdisciplinary science, achieve substantial societal impacts.

The *Program* consists of nine, mission-driven thematic *Topics* which bundle the scientific effort in the program. The overarching *Program Objectives* (***POs***) integrate and synthesize *Topic* results to address important societal objectives by pulling together relevant work between the nine *Topics*.

Because of their close link to societally relevant outcomes, it was clear from the start of PoF IV that the *Program Objectives* would need to be adaptable to changes in society, and that this was one of the key tasks for the *Program Board* (***PB***) to keep them up to date. The *Program Objectives* originally were described in 1-2 short sentences (see p.2). Although this allowed for vast flexibility in the interpretation of the objectives (and for adapting them to a world which has changed enormously since 2019), it made them less-than-ideal for steering the *Program* to a successful conclusion in 2027.

For this reason the *PB* in 2022 decided to re-visit the *POs*, considering the structure of and linkages between the *POs* as well as the proportions of the *Topics* that contribute to them with the aim of arriving at a consensus definition of the scope and aim of each objective. To this end writing teams for each *PO* were set up, coordinated by a *PB* member with strong support from the *Topic Speakers*. We also invited input from additional colleagues from outside the *PB*, aiming at experience-driven descriptions of wide breadth, and used the PoF-IV General Assembly in May 2023 to both strengthen and interrogate the community behind the objectives, for instance by organizing poster sessions around the *POs*, or by considering them during discussions in the ideas market.

The results of this process are presented here, as 3-page descriptions of the scope of the individual *Program Objectives*. The original *PO*2 and *PO3* have been combined to reflect their strong interaction. The original *PO10* has been abandoned as a distinct objective because it is identical to the aim of the *Program* as a whole. To avoid confusion with the original *PO* numbering scheme, these revised objectives have an "R" before their number, thus are labelled ***POR***.

Our collection of these eight *POR* explanations does not intend to be (and could not be) a description or report of all work in the program towards a particular objective. Instead we summarize, in an accessible way, what we believe these objectives encompass and what is necessary to achieve them within the current PoF-IV period.

Potsdam, November 2023
Charlotte Krawczyk, for the Program Board

## Program Objectives- original (POs, 2018, PoF-IV Proposal p. 40)

**Scientific Objective 1:** Provide improved quantitative forecasts of weather, atmospheric composition, and seasonal extremes by extending the practical limits of predictability based on advanced modeling, data assimilation, and observational capabilities. The focus will be on regional to local scales as the basis for better informing emergency measures and climate change adaptation (T1 T2 T3 T4 T5 T7).

**Scientific Objective 2:** Develop science-based scenarios for effective mitigation measures taking into account climate drivers as well as biogeochemical cycles, including critical fluxes between Earth system compartments (all nine Topics).

**Scientific Objective 3:** Underpin climate adaptation action with science. The focus will be on systemic solutions and their implementation (T1 T4 T5 T7 T8).

**Scientific Objective 4:** Provide a new understanding of the drivers of geo-hazards (including cascading phenomena) and their impacts, and develop the means of providing tailored forecasts on local and global scales (T1 T2 T3 T4 T5 T8 T9).

**Scientific Objective 5:** Mitigate urban climate change risks and increase the adaptive capacities and resilience of urban areas. This encompasses developing proposals that i) enable urban spaces to cope with multi-hazards and climate risks, ii) provide healthy environments for their inhabitants, and iii) develop novel technological and system solutions for infrastructure management (T1 T3 T4 T5 T7 T8 T9).

**Scientific Objective 6:** Synthesize data, processes, and their multiple interactions, models, and forecasts as well as the theory of biodiversity change and the consequences for ecosystem functions and services. The main common target is to explore, derive, and design solutions for sustainable use of marine and terrestrial ecosystems under the conditions of global and climate change (T4 T5 T6 T7 T9).

**Scientific Objective 7:** Develop solutions for a more sustainable, climate-resilient, and climate-protective production and consumption contributing to food/feed and water security and quality. The focus will be on a nested approach optimizing biological resources for breeding and production systems with stewardship to terrestrial, atmospheric and marine natural resources and on sustainable land management in rural and urban areas (T1 T4 T5 T6 T7 T9).

**Scientific Objective 8:** Establish sustainable options with regard to the use of natural resources in demand by industry and society. The focus will be on solutions towards resourcing, production, and processing that may contribute to the vision of a circular economy by technical, social, and economic opportunities (T4 T5 T6 T7 T8 T9).

**Scientific Objective 9:** Organize coherent concepts for understanding and assessing the interaction between environmental pollution and human and ecological health across diverse settings to overcome current fragmented 'silo' approaches and provide options for solution-oriented management strategies towards sustainable chemical use in a non-toxic environment (T1 T4 T5 T6 T7 T9).

**Scientific Objective 10:** Synthesize insights from all nine Topics to a comprehensive, multi-sectorial picture of a sustainable future of humankind on an Earth that has endured substantial climate change (all nine Topics).

## Program Objectives- revisited (PORs, 2023)

Following the above introduction to this document, we present here our collection of *Revisited Program Objective* descriptions. They all have the same structural layout with a length of 3 pages each to facilitate comprehension: the introduction describes the scientific background and challenges, followed by our approach with exemplified research performed in the current *Program*. Finally, the infrastructure which underpins the *POR*s' work is stated, as are the contributions of the individual *Program Topics*. Thereby, each *POR* now has a clear content and is clearly distinguished from the others, while interfaces are mentioned.

## Program Objective *POR1*: Weather and climate – Improved predictive skills

**Aim:** To improve predictive skills of weather, climate, atmospheric composition, and seasonal extremes through advanced modelling, observational capabilities, and data science, at all scales from global to local (e.g., urban), to better inform emergency measures and climate change adaptation and mitigation.

### Introduction

The global climate system is warming at an accelerating rate, and it is beyond any doubt that the principal forcing of this change is the accumulation of greenhouse gases (GHG), caused by human-induced emissions. Without drastic and rapid reductions, humanity could soon face global temperatures higher than any experienced in the last 3.5 million years. This atmospheric warming sets off cascades of changes to virtually all aspects of the climate system, characterized by complex feedback loops between the atmosphere, hydrosphere, cryosphere, and the biosphere. Our observational records show (and our models predict) that climate warming does not happen gradually and evenly, but in irregular "leaps and bounds", with strong variations regionally and from year to year. Over the last several decades the world has experienced more frequent and more severe extreme events, including high-impact storms, flooding, persistent droughts and heat waves, poor air quality, wild fires, harvest failures, outbreaks of pests and disease in fauna and flora that endanger ecosystem services, cause economic damage and lead to the loss of life.

For mitigation and adaptation efforts to be effective (see *POR2*) in the face of climate extremes, they need to be applied timely, precisely and targeted at the specific nature and magnitude of extreme events. In other words: we need to be able to predict what to expect when and where, as accurately and as far in advance as possible. To achieve this goal, we need to improve our skills for reliable and quantitative forecasts, including high-resolution forecasts of severe weather events and seasonal prediction of relentless droughts and heat waves. In addition, improved predictive models need to be developed, initiated and evaluated with enhanced observations that match the resolution and coverage of the models.

What kind of weather and seasonal extremes can we expect with ongoing climate warming? A warmer climate changes the boundary conditions that may or may not trigger a storm, induce a drought, or a toxic combination of heat and pollution in urban areas or water bodies. Such boundary conditions include not just the atmosphere, but, for example, the hydrological state of soils and water bodies, the viability of vegetation, the way agricultural land or urban air quality is managed. Thus, enhanced climate impact modelling needs to be combined with improved climate and Earth system modelling capacities.

How effective will climate mitigation measures be? Currently, the most important climate mitigation service is provided by land ecosystems (primarily forests), closely followed by the ocean sink, through their removal of atmospheric $CO_2$ and storage in their biomass. How viable will that climate mitigation service be under conditions of more severe storms, heat, droughts, and wild fires? What will be potential side-effects of large-scale or long-term adaptation efforts (e.g., climate engineering)? How will agricultural land management help to feed a growing population without increased GHG emissions or large-scale changes to the water cycle? Reliable answers to all such questions (see *POR2*) require not only improved predictive skills of weather and climate models, but also comprehensive observation programs to develop and evaluate models, and to assess the effectiveness of mitigation measures. Such observations need to target a wider spectrum of variables at higher resolution and wider coverage in the atmosphere, at the land surface, and over ocean and sea-ice.

Historically, weather forecasts and climate projections have been two very different fields of study with distinct methods and goals, partially due to limitations in computing capacities. Weather forecasts, on the one hand, are focused on short-term changes (typically days to weeks) in temperature, precipitation, and wind patterns in high spatial resolution. Projections of future climatic conditions, on the other hand, are focused on long-term changes (decadal and longer) in the Earth's climate based on factors such as greenhouse gas emissions and concepts like climate sensitivity. Bridging the gap between initial value problems (forecasts) and boundary value problems (projections) in terms of flexible and seamless modelling systems will be highly beneficial for high-quality predictions across scales.

### Research within the *Program* to achieve this objective

To develop the revised Program Objective *POR1* and to achieve the goal for improved climate and weather information on multiple scales, the following active research areas within our *Program* are key to success.

**Better models** – We develop and follow strategies to improve models for better environmental predictions on daily to decadal timescales, for improved and regionally more reliable climate projections, and for assessments of adaptation options. First, we push the limits of feasible model resolutions by optimizing numerical techniques and making our models fit for emerging computing and data technologies. This enables us to resolve a growing fraction of processes explicitly instead of relying on parameterizations (e.g., DestinE, EERIE, WarmWorld; Rackow et al., 2022; Beech et al., 2022). Second, we equip models with key Earth-system components and processes to further constrain uncertainties of previous climate projections, and enable discovery of climate surprises before they unfold, including potential tipping elements. This includes (e.g.) sub-models for land- and sea-ice, biogeochemistry in atmosphere and ocean, as well as land-surface processes (e.g., land use or GHG emissions; Martín Belda et al., 2022; Mwanake et al., 2023). Third, we apply novel techniques to evaluate models against observations, including from field campaigns (e.g., MOSES), with very high efficiency. This includes the evaluation of model simulations that allow direct comparison even for spatio-temporally limited observations and simulations (Pithan et al., 2023). Finally, we will contribute to the Coupled Model Intercomparison Project (CMIP6 and beyond) with our climate models in order to feed our research and developments into broad international data usages for all kinds of analyses, including impact modelling and IPCC assessments (Semmler et al., 2020).

**Targeted observations** – We conduct targeted observational campaigns, develop retrieval algorithms, and apply AI algorithms to fill critical gaps that hamper process understanding and model improvements. This includes large field campaigns, such as the MOSAiC expedition 2019/20 along the Arctic transpolar sea-ice drift (Nicolaus et al., 2022), or the recently accomplished Swabian-MOSES campaigns (2021, 2023; Kunz et al., 2022).

### Key Infrastructures

- Modeling infrastructure: Building an advanced modelling infrastructure is a key goal of the program and aims at different applications, including, e.g., aerosol-chemistry-climate interactions (ICON-ART; e.g., Eckstein et al., 2019), ocean-climate dynamics (AWI-CM-1-1; Semmler et al., 2020) or atmosphere-land interactions (LPJ-GUESS; Martín Belda et al., 2022;

LandscapeDNDC; e.g., Butterbach-Bahl et al., 2019) and data driven modelling concepts (e.g., explainable AI/ML). Other models are focussed on improving specific processes in the Earth system (e.g., Lagrangian transport, gravity waves, aerosol and clouds).

- Observational infrastructure: We aim to enhance and integrate observational networks for characterising and monitoring climate processes and changes, by making their components interoperable, their operation autonomous, and their data openly accessible in near-realtime. This includes an increased number of variables, and their integration from diverse instruments/ platforms for different Earth sub-systems, assisted by novel machine learning methods. Examples include: Satellite- (e.g., CAIRT) and airborne-platforms (e.g., IAGOS, CARIBIC, HALO), balloon- and ground-based remote sensing (e.g., NDACC, TCCON, COCCON, GNSS), and modular in-situ/remote sensing instrumentation (e.g., KITcube, MOSES), experimental chambers (e.g., AIDA, SAPHIR), and observatories (e.g., TERENO, ICOS, ICOS-Cities, AWIPEV).

- High Performance Computing (HPC) and data infrastructure: We have access to large-scale HPC infrastructure, for instance at FZJ, KIT, DKRZ, and operate a number of HPC clusters dedicated to our research. Our data management and data science activities follow the FAIR principles (data from models and observations) and are largely organised in the Helmholtz Earth & Environment DataHub (https://datahub.erde-und-umwelt.de) and a comprehensive link to the NFDI (also as a service for the national and international community). This provides a basis for (data driven) model developments and process understanding that originates from the new combination of diverse variables.

### Contributions from *Program Topics* in *Changing Earth – Sustaining our Future*

Topics 1, 2, 3, 4, 5, 7.

### Selected key references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## Program Objective *POR2*: Climate mitigation and adaptation - Better cope with environmental changes

**Aim:** To enable and enhance climate resilient development of our society to a net-zero lifestyle and to cope with challenges but also chances due to climate change, we will develop and deliver pathways, storylines and instruments, such as digital twins and toolboxes.

### Introduction

Environmental change involves changes in the physical, chemical, and biological systems that make up our planet, including changes in the atmosphere, oceans, and land. Climate is a major driver of environmental change, as rising temperatures, changing precipitation patterns, more and more intense extremes, and other effects of a warming planet have profound impacts on the natural world. Such changes also have significant impacts on ecosystems and human societies. Some examples include effects of ocean alkalinity, coastal sediments, rapid melting of ice, changes in ocean currents and vegetation patterns, as well as changes in the frequency and intensity of extreme weather events. The far-reaching consequences include displacement of people and life, reduced food security, and increased risks to the economy, human health, and well-being. To develop effective mitigation and adaptation strategies – and hence enable climate resilient development – it is important to understand the causes and potential impacts of environmental change.

The aim of **mitigation** is to reduce greenhouse gas emissions and hence reduce the magnitude of environmental changes. The reduction of greenhouse gas emissions can be achieved through measures such as increasing energy efficiency, switching to low-carbon energy sources, and low emission agricultural practices. In addition, technical solutions and land-use practices can contribute to removing carbon from the atmosphere (Mengis et al., 2022). The aim of *POR2* is to develop and assess science-based scenarios for effective mitigation measures taking into account climate drivers, biogeochemical cycles and critical fluxes between Earth system compartments.

**Adaptation** refers to efforts to prepare for the impacts of changes and in particular to changing extreme events (droughts, floods and heat waves) with respect to frequency, intensity and duration. This can include measures such as adapted water supply schemes, drought-resistant forest management, or relocation of communities from areas at risk.

**Climate Resilient Development** is the process of implementing greenhouse gas mitigation and adaptation measures to support sustainable development for all. It is enabled by increased international cooperation including improved access to adequate financial resources, particularly for vulnerable regions, sectors and groups, and inclusive governance and coordinated policies worldwide.  In the *Program*, we are aiming for the resilience of Earth's subsystems. A resilient system is one that can continue to function and provide important services as environmental conditions change.

While mitigation aims to prevent the worst impacts of climate and environmental change, adaptation and resilience aim to help communities and ecosystems cope with impacts that have already occurred or are unavoidable.

### Research within the *Program* to achieve this objective

To estimate climate impacts we need highly resolved and bias-corrected hydrometeorological projections (see *POR1*) under different climate scenarios (RCP 2.6, 4.5 and 8.5; RCP - representative concentration pathway of greenhouse gas concentration: RCP 2.6 known as “very stringent pathway”, RCP 4.5 as “intermediate pathway with less stringent mitigation effort”, and RCP 8.5 as pathway with continuously rising emissions). Using 88 climate ensemble projections and the corresponding hydrological projections for Germany, several different event chains will be investigated. For example, different hydrological and agricultural climate indicators are helping water suppliers in Germany to develop adapted water supply schemes (Marx et al, 2021). The cascading impacts of the 2018-2022 multi-year drought event in Germany through different societal domains have been quantified (Sodoge et al., 2023). In urban areas, the impacts of urban extreme heat, drought and wind (Hertel & Schlink, 2022), of urban flash floods (Apel et al., 2022), and sewage (Yang et al., 2022) have been studied and an investigation of the paradoxical impact of frequent flood experience on exposed households (Köhler et al., 2023) has begun. In rural areas the climate projections allow the impact of extreme events on forest systems, which cover 30% of Germany´s land area, to be investigated. Forest productivity (and hence CO2 fixation) will decrease by about 50% under a 4°C global temperature increase (RCP 8.5) if forest structure and species composition does not change in the future. Spruce monocultures are much more at risk than mixed deciduous forests with a moderate tree size mixture. If the proportion of such deciduous forests increases in the coming decades and the Paris Agreement is adhered to, the CO2 fixation rate of native forests could, however, remain stable (Henninger et al., 2023). In this POR we will bring all these methods and single approaches together and combine them to a whole systemic view on mitigation and adaptation measures equally across sectors and Earth systems domains.

As well as understanding the possible future environmental pathways it is important to make the impact of climate change on extreme events more tangible to stakeholders. Hence, we will provide insights on how recently experienced extreme events, such as summer heat-waves or the July 2021 Ahrtal floods, would have evolved in a pre-industrial climate and how they would evolve for different future warming levels (e.g., +1.5, +2.0 or +3.0°C). For the recording-breaking heatwave in Germany in July 2019 (42.6°C), for example, it was found that in pre-industrial times this heatwave, albeit extreme, would have stayed below 40°C. Meanwhile, in a future +4°C warmer world maximum temperatures in western Germany can be expected to near 50°C – a reality experienced in Southern Europe during summer 2023 (Sánchez-Benítez et al., 2022). To provide such fit-for-purpose information, we will not only use unique and the newest generation of modelling and visualization tools but also jointly develop new information instruments, climate services, and products by enhanced co-development processes in true partnerships with selected stakeholders.

We will strongly make use of the new EU's Destination Earth (DestinE) Initiative, which focuses on developing climate system digital twins to aid adaptation efforts, and in which we already play a pivotal role. DestinE's innovative information system is designed for superior responsiveness and adaptation to environmental challenges like extreme events and climate change. Capitalizing on recent strides in climate modeling integration and user-centric climate data generation, the DestinE Climate Change Adaptation Digital Twin utilizes advanced global climate modeling, high-performance computing, and an enhanced understanding of user needs. This progress empowers stakeholders from pertinent sectors to actively shape the digital twin's structure through co-design, signifying a revolutionary approach to dispensing climate information and ushering in a paradigm shift in this field.

We will use the great potential in the area of interdisciplinary and integrative cooperation between climate mitigation and adaptation. The analysis of adaptation strategies and climate mitigation concepts of over 60 German municipalities (Bender et al. 2022, conducted as part of the Helmholtz Climate Initiative's Net-Zero-2050 Cluster), for example, shows that many of them have already addressed measures to reduce $CO_2$ emissions and adapt to the consequences of climate change. When developing adaptation measures in urban areas, preference should be given to those approaches that can develop a multifunctional effect and are also suitable for leveraging synergies in several areas at the same time: climate protection and adaptation, environmental protection and sustainability. In this way, they enable a benefit that is independent of the current and future impact of climate change and its consequences.

### Key Infrastructures

- High Performance Computing infrastructure on all Tier-levels for modelling, especially HPC platforms at DKRZ, JSC, and institutional clusters on centre level.
- Observational infrastructure, e.g. MOSES infrastructures and sensor networks like in TERENO.
- Visualization infrastructure, such as innovative VR-facilities (caves, holo benches, etc.).

### Contributions from *Program Topics* in *Changing Earth – Sustaining our Future*

Topics 1, 2, 4, 5, 6.

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## Program Objective *POR3*: Solid earth and hydrometeorological hazards- Enhanced impact assessment in a modern world

**Aim:** While atmospheric hazards may be increasing as a result of environmental change, solid earth hazards are potentially staying constant but their impact is increasing as society becomes more vulnerable to disruption. This objective aims to improve our assessment of risk from solid-earth and environmental hazards and so help to inform and improve risk management.

### Introduction

Earthquakes and volcanic eruptions sending tsunamis across whole ocean basins, aeroplanes grounded by volcanic ash, temperature extremes, droughts across all of Europe, flooding and deaths from storms,... The physical world around us seems to increasingly impinge on all of our lives. Is this impression real? If so, why are the impacts of these natural events increasing? What changes can we expect in the next decades? We look at these questions from numerous perspectives in the *Research Field* Earth and Environment, giving a background to the information we collect and how it is used to make forecasts for the future.

### Research within the *Program* to achieve this objective

**Earthquakes and cascades** - Earthquakes have always been a part of humanity´s environment but never before have they been so disruptive. This is mainly because our infrastructure is vulnerable to their effects - from the collapse of buildings due to shaking in large earthquakes to the effects on coastal harbours and cities (and therefore on international sea trade) from tsunamis. This means that to assess the impact of earthquakes, we need to look not just at what causes them but also how they impact our urban centres and interact with our infrastructure (Martínez-Garzón et al., 2023). This part of *POR3* has a strong connection to *POR4* and will be examined there.

*<u>Cascading Hazards</u>*

*Most geohazards are parts of a cascade, where one hazardous event triggers another. A recent example of such a cascade was linked to the Tohoku earthquake in March 2011. This hazardous event of itself triggered a major tsunami which in turn led to damage to the Fukushima Daichi nuclear reactor resulting in a core meltdown. Other relatively common cascades are extreme rainfall leading to landslides in mountainous regions and eruptions on volcanic islands leading to tsunamogenic flank collapse.*

Assessing the hazard potential of underwater structures is complicated by their inaccessibility, making them much more difficult to measure and monitor. A major challenge is to detect the build-up of strain on submarine faults. Recent successes in the Marmara Sea and offshore Chile have shown that measuring seafloor deformation with an accuracy of better than 5 mm is an important tool to identify the current state of locking along active faults (Lange et al., 2019; Petersen et al., 2019). The monitoring reveals the significant seismic hazard for metropolitan Istanbul where stress release of the accumulated tectonic strain along the offshore fault system would correspond to an earthquake of magnitude 7.1-7.4 (Becker et al., 2023).

**Volcanic hazards, near and far** - Forecasting the behaviour of volcanoes in the long-term is challenging and maybe even impossible for some volcanoes. But the processes leading up to an eruption may well allow unrest to be detected several days, weeks or even months prior to an eruption.

Volcanism in the German Eifel region had been considered extinct, with the last major eruption occurring about 13,000 years ago. Low-frequency earthquakes measured there in recent years indicate, however, that the subsurface has not yet completely come to rest. Helmholtz researchers are now trying to find out what the magmatic system under the Eifel looks like, whether volcanism there is only dormant after all, and whether it could be reactivating. Together with universities, international institutions and federal agencies, the "Large-N" project has deployed 350 geophones to measure the underground tremors.

Further volcanoes around the world are the focus of the Helmholtz rapid response task force, which monitors and analyzes damaging eruptions as they occur. For example, a team was sent in 2022 to La Palma where, together with experts from Spain, the eruption and surface deformation on land was studied in combination with work at sea investigating the consequences of the eruption on the stability of the flanks of the volcano. Volcano flanks are also studied in the Mediterranean, where volcanic islands have a complex hazard potential as both eruptions and landslides can lead to tsunamis (see box). Etna and submarine volcanoes near Santorini are the focus of our work as both are known to have created large, society-altering tsunamis in the past (Jousset et al., 2022).

**Floods or drought ? What can we expect** - In the last decade, Europe has experienced both extreme and ongoing multi-year drought events and extreme flood catastrophes. Wildfires and flooding in, e.g., Canada, California, Australia and Asia show that this is a global phenomenon. Such extreme events seem to be occurring more regularly and are often more severe than in the past. Will this be the new normal for a world under accelerating climate und land use change?

Reconstruction of historic events from 1750 onwards shows the 2018-2020 European drought was exceptional, with unprecedented intensity, coverage, duration and air-temperature anomaly. Climate simulations (see also *POR*s 1, 2) suggest that, while these events will stay exceptional, they may re-occur with comparable intensities and even longer durations (Rakovec et al., 2022).

*<u>Hazard and Risk</u>*

*Whenever we examine how processes affect our lives we need to clearly distinguish hazard and risk. Hazard relates to the physical processes or agents which have the potential to cause harm. Risk is the probability that this hazard will actually cause harm and is related to the exposure and vulnerability present:*

*Risk = f (hazard, exposure, vulnerability)*

*Exposure is the amount of assets (people, economy, infrastructure, or ecosystems) in hazard-prone areas, and vulnerability is the likelihood of these assets being damaged, severely impacted or destroyed. Risk thus depends on both natural factors (a coastal city is more exposed to tsunami hazard than an inland city) and societal factors (earthquake-strengthened buildings are less vulnerable when the ground shakes than un-strengthened buildings).*

Within Germany, the catastrophic flood event in the Ahr River in 2021 was one of the five costliest natural disaster in Europe in the last 50 years (Mohr et al., 2022). Many factors contributed to its impact: flood data from 1804 and 1910 had not been included in modern risk assessment; landscape use changes enhanced flood risk; modern infrastructure (e.g., waste water treatment plants, supply networks) are vulnerable to disruption, that can lead to pollution (Ludwig et al., 2022). Climate change projections suggest flood hazard to increase, and also the area affected by such events to increase. Global risk management strategies are generally not keeping pace with these developments, the impact from unprecedented events (of a magnitude not previously seen) is generally not reduced (Kreibich et al., 2022).

Future development will focus on a better understanding and prediction of flood and drought extremes and their impacts on society under predicted climate change to improve risk management. An example is the development of 'impact forecasting', predicting not only the impending meteorological and hydrological extreme event, but the expected impacts on society (e.g., Which roads will be disrupted? Which hospitals will be flooded?). Additional complications can be expected from sequences of droughts and floods, rapid drought-flood transitions, and spatially concurrent droughts or floods. Such so-called compound events often lead to disproportionate impacts but are presently poorly represented in risk assessments and often require novel methodological approaches (Bevacqua et a., 2021).

### Key Infrastructures

- GEOFON and facilities which are critical to monitor earthquake hazards, specially designed fibre-optic cables both on land and underwater keep an eye on earth movements, both fast and slow (e.g., Etna, Turkey, EU-project GeoInquire, SAFAtor proposal). Seafloor seismometers and strainmeters of the GEOSEAS array searching for locked faults (around Greece, Turkey).
- Monitoring volcanic unrest: with highly sensitive seismometers and GPS stations deployed by GFZ and universities in the Eifel; with robotic vehicles and autonomous seismometers under water, which GEOMAR runs as part of the GEOSEAS infrastructure.
- TERENO, MOSES: monitor water, matter and energy fluxes in all compartments of the terrestrial system over longer time periods. MOSES: platform for rapid-response monitoring of extreme events. Helmholtz HPC systems: run terrestrial system models monitoring data, to assess the impact of future climate and extreme events.

### Contributions from *Program Topics* in *Changing Earth – Sustaining our Future*

Topics 1, 3, 4, 5, 8, 9.

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## Program Objective *POR4*: Urban Risk – Increase urban quality of life and resilience

**Aim:** To co-develop solutions that help mitigate urban risks and increase the adaptive capacities and resilience of urban areas, encompassing research that i) enables urban spaces to cope with multi-hazards and climate risks, ii) provides healthy environments for their inhabitants, and iii) develops novel technological and system solutions for urban management.

### Introduction

The process of urbanisation is a worldwide phenomenon. Cities and urban agglomerations host the majority of the human population, man-made infrastructures, and economic assets, are responsible for more than 70% of global $CO_2$ emissions and are hotspots of environmental pollution. At the same time, cities are drivers of knowledge and technological innovation, with massive potentials for mitigating climate change. Cities are highly complex, multi-scale systems where climate, environmental and societal risks can amplify, accumulate and impact infrastructure, economy and population. Cities can intensify extreme events through physical amplification and compound effects (e.g., regional air pollution episodes, urban heat islands). Climate impacts in cities can further trigger and increase economic and societal consequences (e.g., infrastructure collapse, amplified social vulnerability, injustice and displacement).

### Research within the *Program* to achieve this objective

Within *POR4* we respond to an urgent need for integrative research that links environmental, technological and societal processes in cities across different disciplines. We aim at co-designing integrated urban environmental assessments tools, policy-solutions, technologies and infrastructures that guide and enhance climate mitigation and adaptation measures (see also *POR2*). Therefore, our approach is based on both (1) data, models and assessments predicting climate change and environmental impacts at local and regional scales (see also *PORs 1, 2, 3*), and also on (2) urban development, transformation pathways, governance and corresponding exposures/vulnerabilities considered across multiple scales, from a global policy perspective down to the urban system, addressing neighbourhoods and individuals. Methodologically, we employ different inter- and transdisciplinary approaches including a co-design approach that is realised in real-world laboratories and, therefore, allows close collaboration with stakeholders, policy-makers, representatives of civil society, businesses as well as residents. Since this opens vast options for research, we focus here on four activities rooted in the core of our *Program*.

**Urban seismic risks scenarios and awareness raising** - As recent events have shown, it is essential to evaluate the possible impacts of strong earthquakes on modern cities and to reduce these impacts by adapted earthquake-resistant constructions. However, as the seismic risks in urban areas remain poorly known and uncertainties remain great in specific details, new methods are especially needed to locate hidden faults that may give rise to earthquakes, to predict areas where vibrations are amplified because of the local geology, to evaluate the vulnerability and the number of buildings or structures that may be affected (see also *POR3*). For this purpose, we started pursuing the following research tasks.

(1) Developing urban seismic scenarios to increase the awareness among stakeholder and policy-makers. Such scenarios have for example recently been developed for the city of Cologne and several cities in South America and Europe (e.g., Nievas, 2022). These scenarios will also include possible cascades (tsunami, landslide, impact on infrastructure; see also *POR3*). (2) Further develop new geophysical methods allowing the use of optical fibres to

record seismic movements (e.g., Jousset et al., 2018) and reaching very high resolution (a recording every 5-10 meters along the fibre). The ambition is to develop “digital twins” of the urban subsoil and to follow/predict their evolution (water table monitoring, fault detection, quantification of wave amplifications). (3) Investigating the feedback between a city and an earthquake. Tall buildings generate waves in the subsurface when they vibrate during an earthquake, making earthquakes in a city very complex, including "secondary" sources related to these vibrations. The urban geological environments need to be treated as a meta-material (Roux et al., 2018) whose properties are little known. (4) During an earthquake, citizens' reactions on social networks or their smartphones or even measurements of the acceleration of smartphone sensors are all new data we want to exploit for research purposes.

**Urban climate, heat islands, adaptation and quality of life** - State-of-the-art convection-permitting models can provide the underpinning science to improve the development of knowledge-based climate information for urban regions (connect to *POR2*). A mid-term goal is to enhance urban heat resilience measures, ranging from improved and contextual urban-scale heat health warning systems (HHWS) to long-term heat action plans based on knowledge and tools generated in the *Program Topics*.

Very detailed climate information at the local level is provided by urban climate models such as PALM-4U and MITRAS. They allow high-resolution simulation of urban climate from entire city scale down to individual building blocks. PALM-4U is co-developed with practice partners to ensure its practical implementation through designing and testing fields of application for this model that include thermal comfort, cold air balance, local wind comfort as well as dispersion of pollutants (Cortekar et al., 2020).

For personal well-being and health, the personal exposure to heat (as well as air pollutants and noise) is an important factor that can vary heavily from person to person. To improve individual protection from environmental stressors, we seek to include personal measurements (wearable sensors) that can stimulate behaviour change, improve environmental literacy and awareness, and teach citizens to be more competent with and in their environment (Marquart et al., 2022).

**Water-sensitive urban development** - Cities are generally at higher risk to flooding and weather hazards than rural areas due to widespread surface imperviousness, lack of water retention structures, and the concentration of critical infrastructure and people. The water-sensitive city is already a widely recognized urban vision for urban transformation and there is currently a high level of research and design momentum. Since up to now, urban water management is dominated by engineering approaches, which are lacking ecological processes (including vegetation) and the high spatial and temporal complexity of urban systems. We seek to increase resilience to extreme flooding events through improving both short-term warnings and long-term flooding-sensitive design and planning. In addition to *POR3*, we focus specifically on the following aspects:

(1) Maintenance of the targeted system functions in times of drought, storms and pluvial flooding. Together with decision makers from the cities (municipal companies, local authorities, SMEs, national Agencies) we are investigating how urban integrated water management e.g. with multifunctional BlueGreen infrastructure can locally store, treat and re-use the precipitation and wastewater collected on the urban surface.

(2) The barriers, drivers and levers for realising urban water management, including the analysis of legal, economic, institutional, political, social and cultural factors (Han et al, 2023).

(3) Property-level flood risk adaptation as an important complimentary element to publicly funded climate adaptation on the urban level (Kuhlicke et al., 2020, Steinhausen et al., 2022). We aim to link short-term processes (flooding) to the long-term water balance and by coupling

to the groundwater and rivers also allowing to assess the resilience of cities to droughts.

**Air pollution/quality** - Research in this area will inform cities about their air quality options by a combined approach of (i) high-resolution local observations of urban and back-ground air quality, (ii) street-level air pollution prediction with microscale (PALM-4U) and regional modelling (e.g., WRF-Chem, ICON-ART, EURAD-IM), and (iii) a module for GERICS' adaptation toolkit for cities that will support urban planning in a changing climate with respect to air quality. We aim to (i) develop a high-resolution urban air quality inventory as well as (ii) develop a radical and secondary pollutant air quality metric for mitigation and adaptation strategies. This should be embedded in (iii) multi-dimensional designed heat-health nexus by adopting a socio-spatially dynamic understanding at the individual scale with urban heat exposure to produce compounded heat health vulnerabilities.

### Key Infrastructures

- On-going urban real-world laboratories and observatories in Leipzig/Karlsruhe/Istanbul, etc..

- Already existing planning tool boxes such as the "Adaptation Toolkit for Cities". This includes the development and operation of new, complex urban research infrastructures (e.g., observatories, real laboratories as the proposed "urban environmental observatory" UrbEnO) as well as technologies that open up new economic areas and services (e.g., urban sensing networks and data integration).

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Topics 1, 3, 4, 5, 7, 8, 9.

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## Program Objective *POR5*: Ecosystems- Sustain services and biodiversity

**Aim:** To synthesize data, models and theory of biodiversity change and the consequences for ecosystem function and services. The main common target is to explore, derive and design solutions for sustainable use of marine, terrestrial and freshwater ecosystems.

### Introduction

Marine, terrestrial and freshwater ecosystems provide numerous provisioning, supporting, regulating, and cultural services. They are essential for human life but threatened by climate change, land use change, chemical pollution and many other regional stressors from anthropogenic use or misuse. Biodiversity is critical to maintaining ecosystem services, yet the global biodiversity loss is accelerating. A thorough understanding of ecosystems, their biodiversity, structure and functioning, and their adaptive capacity or resilience to disturbances is a prerequisite for finding sustainable management options and requires answers to the following major questions:

How can ecosystems be sustained under changing boundary conditions to safeguard ecosystem services for the future? What management measures are needed to significantly improve the status and functioning of ecosystems? How can sustainable provision of services including secure drinking water and food production be harmonized with the protection of biodiversity? Are present protection measures sufficient to restore and maintain ecosystem services and biodiversity?

### Research within the *Program* to achieve this objective

We investigate anthropogenic effects on ecosystems in field and laboratory experiments and by modeling. Biodiversity and its change over time are identified with integrative approaches, including environmental DNA, high-resolution imaging time-series, remote sensing, and multi-omics approaches. We assess biodiversity changes using paleo-ecological data and recent time-series information on species diversity and genetic adaptation potential. Joint species distribution models predict the potential occurrence of marine and terrestrial species in the future (e.g., Hodapp et al., 2023). We use comprehensive data analyses and models to provide an assessment of essential drivers for ecosystem functioning, how functions change through the years, and how long it takes for the ecosystem to recover from damage (e.g., major pollution periods, Rewrie et al., 2023).

Specific attribution techniques allow, e.g., the impact of a changing biological carbon pump in the ocean on atmospheric $CO_2$ to be quantified. Simulations and projections with negative $CO_2$ emissions also enable assessment of the efficacy, permanency, and potential side effects of marine carbon dioxide removal (CDR) efforts on the biological carbon pump (Fischer et al., 2021). In the deep ocean, anthropogenic impacts are long-lasting, with resource exploitation threatening benthic ecosystems with low resilience to mining impacts and very slow recovery time scales (see also *POR7*). Our work on the environmental impacts of deep seabed mining (Boetius & Haeckel, 2018) directly contributes to draft documents of the Mining Code of the International Seabed Authority.

We want to unravel the mechanisms determining biodiversity and stability in ecosystems below ground soil. In the Global Change Experimental Facility (GCEF), we established approaches to understand how ecosystems buffer climate change with different mechanisms dependent on management practices. Using, among others, data from TERENO, the eLTER RI (https://www.elter-ri.eu/) and other monitoring programmes incorporating innovative Citizen Science methods, Digital Twins of Biodiversity and Ecosystems (De Koning et al. 2023) will complement an extended soil - landscape model (BODIUM), a high-resolution soil functional map and a combined multi-objective landscape model. For freshwater ecosystems we identified the key anthropogenic drivers for essential ecological functions on a global scale (Brauns et al., 2022). AI-based identification devices facilitate the recording of the important elements of biodiversity. Future management and optimisation approaches aiming at maximising biodiversity and food security can build on our global meta-analysis of the trade-off between biodiversity and agricultural production (Seppelt et al., 2020).

**Finding governance solutions on land and at sea** - Sustaining ecosystems needs effective governance. Our work on Marine Governance focusses on understanding how modes of marine management develop and whether these are the 'best' solutions for sustainable use of the marine space under conditions of global and climate change (Peters, 2020). We test the consequences of alternative fisheries management for biodiversity conservation and fishery yields, with a newly developed Baltic ecosystem model, for example, showing that ecosystem-based fisheries management is the most effective strategy to recover the biomass of depleted stocks, increase the catch of herring and cod, and restore the endangered population of harbour porpoise with additional positive effects on phytoplankton and carbon sequestration (Scotti et al. 2022). Additionally, we explore the effects of marine protected areas (MPA) on fisheries and benthic-pelagic coupling in the North Sea and develop new prediction methods for coastal productivity. This supports the development of blue food and feed production methods, which provide livelihoods, and combat anthropogenic $CO_2$ and coastal eutrophication.

To improve and sustain agroecological research topics (incl. food security, see *POR6*), we will use model landscapes, stakeholder cooperation, adequate payments for farmers and German soil policy. In our contribution to the framework National Biodiversity Strategy for Germany and the 'Faktencheck Artenvielfalt', we will highlight the status and trends of biodiversity in Germany, its drivers, measures for protection and enhancement, and steps for appropriate land use changes. We will establishment the Integrated European Long-Term Ecosystem, Critical Zone and Socio-Ecological Research (www.elter-ri.eu) to provide EU-wide suggestions for implementing (nature-based) solutions, especially with respect to carbon storage, water provision, biodiversity protection and climate change adaptation.

We will develop solutions for pressing water problems and for adapting water systems to future conditions, particularly with focus on climate and land use change. One focus is on drinking water reservoirs, and strategies to ensure multi-purpose use and to raise preparedness to emerging water quality issues. We advise the National Water Strategy, which is based on a two-year National Water Dialogue with more than 200 stakeholders and essentially outlines ways to secure water supplies for humans and ecosystems under future climate scenarios. With this background we will operationalize strategies for a transformation towards resilient water landscapes including resilience towards extreme droughts on different time scales with short-term drought contingency plans and long-term adaptation strategies.

### Key Infrastructures

- Key to research on ecosystems is the access to research vessels, large sea-going instrument-tation (ROVs, AUVs, moorings), the large-scale research platform MUSE, Long Term Ecological

Research (LTER) observatories like HAUSGARTEN, Boknis Eck, Helgoland and Sylt Roads, the Cape Verde Ocean Observatory, and TERENO.
- Terrestrial experimental facilities including MOBICOS for freshwaters and the field station in Bad Lauchstädt with the Global Experimental Facility (GCEF) for agricultural systems are key platforms for analysing the impacts of Global Change on ecosystems.
- Experimental facilities (e.g. mesocosms, culture selections, aquaria), modelling and large-scale omics work complement our essential infrastructure and are crucial for hypothesis-driven studies, data interpretation and exploration.

### Contributions from *Program Topics* in *Changing Earth – Sustaining our Future*

Topics 4, 5, 6, 7, 9.

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## Program Objective *POR6*: Food, feed, and water- Ensure availability for a growing population

**Aim:** To explore, derive and design solutions for ensuring plant production security, availability of freshwater resources, and sustainable management of agricultural and forest ecosystems.

### Introduction

The world population is projected to increase from currently 8 billion to ~9.7 billion in 2050 and ~10.4 billion by 2100. Sustainably supplying them with food, feed (or plant-based products in more general terms) and water presents a huge challenge. By 2050, the FAO estimates that we will need to produce 60 per cent more food to feed the world population. At the same time, water-related challenges will become increasingly urgent. At present, 2.1 billion people lack access to safely managed drinking water services and 4.5 billion people lack safely managed sanitation services. On top, water scarcity already affects today four out of every 10 people. Thus, plant production security (Watt et al., 2020) and the sustainable management of terrestrial ecosystems, in particular agricultural and forest systems, under climate change are key to securing plant and water resources for future generations (Vereecken et al., 2022).

### Research within the *Program* to achieve this objective

Within our *Program*, we aim to address these challenges by research on a more sustainable, climate-resilient, and climate-protective production and provision of food/feed, renewable bio-based resources and water.

**Increasing the sustainable production of food and feed** - Plants and plant production are key for human and animal nutrition and for providing renewable carbon sources for industry (see also *POR7*). In view of the increasing world population, the effects of human-induced climate change on plant production security (see also *POR2*) and other factors, there is an urgent need to increase plant yields with concomitant ecosystem conservation. Our research uses genomics (DNA) and transcriptomics (RNA) to analyze a variety of economically relevant plant species, providing novel insights into plant physiology, evolution, and crop domestication and new opportunities for plant breeding (Jayakodi et al., 2023; Gui et al., 2023).

Plant phenotyping, which enables non-invasive quantification of plant structure and function both in controlled environments and in the field, is a major bottleneck in basic plant research and modern breeding. Within the Program we aim at providing sufficient throughput and capacity to handle large-scale plant populations with high accuracy and low cost for measuring seed, shoot, and root traits or their proxies (Watt et al. 2020). This work is integrated into national and international networks to increase the capacity and availability of phenotyping infrastructures (DPPN, EPPN2020, IPPN, EMPHASIS). To secure food production and renewable carbon resources under climate change and for sustaining ecosystem functions, the Program develops robotic technologies, proximate and remote sensing as well as digital twins of agricultural production systems in close cooperation with the of Cluster of Excellence Phenorob (www.phenorob.de).

**Securing freshwater resources and aquatic ecosystems -** Present management practices are not well suited to tackling shifting hydroclimatic and societal boundary conditions as they are oriented towards past reference conditions. New concepts for safe ecological boundary conditions and future-oriented management strategies are needed. These must seamlessly integrate local to catchment-wide controls in a water landscape perspective.

Our conceptual base for the necessary transitions is a holistic view of the terrestrial water cycle, offering novel opportunities for resilience-oriented management (sensu Weise et al., 2020) of freshwaters and their catchments. This approach will utilize big (in terms of temporal and spatial resolution) monitoring data, a new generation of smart models and novel ecosystems analyses linking mutual feedbacks of ecosystem attributes and water quality.

A key scientific challenge is the robust quantification of water fluxes across scales now and in the future under extremes. Development of a large-scale typology of hydrological processes leading to streamflow events (Tarasova et al., 2020) has supported understanding the role of events generated by different mechanisms on nutrient export patterns from local to national scale, identifying the potentially hazardous types of events for maintaining water quality in the receiving water bodies.

This work is complemented by the mechanistic identification of key processes controlling matter fluxes within catchments. Major progress has been made in understanding matter input, transport and fate in catchments addressing the interplay of hydroclimatic variability and anthropogenic impacts in different landscape settings.

Our approach focusses on ecological structures, functions and their feedback to water quality. On a continental scale we could link catchment-wide matter fluxes to the local ecology by showing that treated wastewater is responsible for the observed poor ecological status of many European streams (Büttner et al., 2022). Our ecosystem-based approach is complemented by the development of energy-efficient and robust membrane technologies that enable the provision of safe drinking water and a significant reduction of environmental pollution through effective removal of micropollutants (Lofti et al., 2022).

**Observing trends and events as well as reliably predicting changing terrestrial ecosystems** - Exploring paths to a sustainable management of terrestrial ecosystems needs advanced simulation tools together with state-of-the-art terrestrial observation including large scale Helmholtz infrastructures such as TERENO (Terrestrial Environmental Observatories; www.tereno.net), which catalogues the long-term ecological, social and economic impact of global change at regional level. TERENO is complemented by MOSES – an infrastructure to observe short-term events. The data enable the advancement and validation of modular terrestrial system models comprising hydrological modules (such as river, groundwater and soil water modules), but also different vegetation modules are coupled to different regional climate and weather prognostic models and are professionally coded and sustained in cutting-edge model platforms like the TerrSysMP platform (https://github.com/HPSCTerrSys/TSMP) or LandTrans (https://git.ufz.de/mhm/mhm/-/releases/v5.11.1). These models contribute to a sustainable management of agronomic and forest ecosystems, e.g. by optimisation of irrigation systems or designing adaptation and mitigation strategies. By quantifying energy, water, nutrient, and greenhouse gas fluxes during short-term events such as weather extremes, abrupt permafrost thaw, or rapidly changing ocean currents with the MOSES infrastructure, we can acquire data to study potential long-term environmental impacts. Complimentary to such Earth observation systems, the indoor mesocosm research facility AGRASIM is able to experimentally analyze the impact of various parameters on plant growth and will serve as a platform for the development of a digital twin of the soil-plant-atmosphere system (Giraud et a., 2023).

The data and knowledge gained from observation and predictions are key in establishing a sustainable use of the land surface and are therefore highly relevant for stakeholders such as farmers, water authorities, companies and policy makers (e.g. https://wasser-monitor.de/wassermonitor.de; https://adapter-projekt.org/).

### Key Infrastructures

- plant phenotyping: plant phenotyping network DPPN, tomographic systems for plants (MRI, PET, CT), breedFACE (field phenotyping under elevated CO2); nfdi4plants.de, ELIXIR ESFRI (esfri.eu/elixir-life-science-data-tools-and-resources)
- TERENO, indoor mesocosm research facility AGRASIM, MOSES, MOBICOS riverine mesocosms, GRACE-FO and EnMAP satellite mission data, Zugspitze Geodynamic Observatory Germany, FLEX portfolio, BioökonomieREVIER, Wassermonitor, Dürremonitor
- Terrestrial Systems Modelling Platform, simulation tools like mGROWA, DENUZ, WEKU and MEPhos

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Topics 4, 5, 6, 7, 9.

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## Program Objective *POR7*: Circular economy – Enable more sustainable use of bio- and georesources

**Aim:** To provide science-based approaches to increase the sustainability of biological and geological resources and enable circular economies using world class infrastructures.

### Introduction

Humanity has reached or exceeded many of the "planetary boundaries" which define the sustainable limit of human life on Earth. Maintaining or attaining living standards similar to those of the developed world for a projected stable world population of over 10 billion will require more food and materials than have ever been required in human history (see also *POR6*). There is an urgent need to make do with the resources and forms of energy that are currently available and to enable an economy that is as circular as possible i.e. based on renewable energy, resource recycling and renewable carbon sources. This will involve a huge transition from chemical (fuel) to metal-intensive electrical energy systems, necessitating the identification of new resources and continued primary extraction of metals.

In this objective we aim to provide science-based approaches to identify, use, and process biological and geological resources by (i) developing biocatalysts and bioprocesses enabling the transition from fossil to renewable carbon sources for the production of chemicals and gaseous energy carriers, (ii) identifying concepts to discover and characterize raw material resources and potential environmental impacts of their use, (iii) investigating the use of the geosphere as a source of geothermal energy and for the storage of energy carriers and energy waste.

### Research within the *Program* to achieve this objective

**Chemicals and energy from renewable resources** - Much of the petroleum-based energy used nowadays can and will be replaced by renewables. A similar turnaround is not immediately possible, however, for the production of all organic chemicals, 90% of which today come from fossil feedstocks, because renewable carbon sources such as biomass, i.e. presently underexploited lignocellulose, or carbon dioxide have structural and molecular properties different from those of petroleum (Izadi et al., 2022). Shifting from linear, petroleum-based production to circular, bio-based production requires novel production routes integrating biological and chemical knowledge with engineering and technological developments and innovation at all steps of the value chain. Our research is focused on the use and development of biocatalysts and bioprocesses for the sustainable production of chemicals and fuels (Della Corte et al., 2020; Helleckes et al., 2023). In this field of application, the use of lignocellulose presents a challenging task. Biorefineries using novel separation technologies enable the fractionation of lignocellulosic feedstock into cellulose-enriched pulp and fibres, monosaccharides of the hemicellulose fraction and lignin (Weidener et al. 2020).

Products in our focus are liquid fuels such as higher alcohols and alkanes, the gaseous energy carriers methane and hydrogen, middle-chain-length carboxylic acids used as platform chemicals or polymer building blocks, amino acids, aromatics, alternative sweeteners, pharmaceuticals, or bioactive secondary metabolites.

Although the economic efficiency and environmental benefits increase with the scale of production, even smaller scale biotechnological processes based on renewable carbon or on plastic waste will reduce our dependency on fossil carbon and provide opportunities for novel products only available with biocatalysts. As early as possible, the entire life cycle of such processes has to be analyzed and they need to be evaluated in the context of a regional or global bioeconomy. For example, it is important that the resulting material flows are evaluated against other sustainable alternatives and that the side effects of biomass production and transport, nutrient cycles and waste flows are also taken into account.

**The Geosphere as a source of metals, energy and storage solutions for energy products and waste** - Geothermal energy, carbon resources, and subsurface storage are located in upper crustal rocks which are modified by mass and energy transport processes. Stimulation treatments producing conductive hydraulic networks are required for geothermal systems, while low or no-flow conditions are necessary for nuclear waste repositories. Public acceptability of subsurface utilization requires optimization of stimulation treatments and monitoring to mitigate risks. Our goal is to assess geothermal resources for application in urban areas, focusing on deep heat storage and direct heat supply in deep sedimentary basins and volcanic regions. This includes developing optimized production strategies and minimizing hazards associated with reservoir stimulation (Bracke et al., 2022).

Subsurface storage is crucial for storing large quantities of energy from renewable sources, especially hydrogen and methane. The safe storage of nuclear waste requires a long-term research perspective on the processes that control the integrity of potential host rocks. We leverage the experience from carbon capture and storage research in the North German Basin and transfer it to other types of gas, heat, and nuclear waste storage. This includes the modelling of key processes and issues of scaling up to a full-sized facility and the assessment of far-field effects to enable science-based decisions on the site selection are addressed.

The major commodities that will drive the energy transition include strategic and critical metals such as copper, zinc, lithium, rare earth elements, tungsten, and cobalt. We focus on identifying the conditions that maximize metal fluxes in different mineral systems and the formation of the largest deposits (Zhou et al., 2021). This involves quantifying fundamental processes, characterizing exemplary systems and modelling the 4D evolution of these systems. Finally, the mineral systems approach is applied to explore new ways to find raw materials in the oceans (Stewart et al., 2022) and provide data for environmental monitoring campaigns.

### Key Infrastructures

- The Biofoundry Jülich combines a unique portfolio of technologies for automated microbial strain and bioprocess development, increasing the genetic space to be evaluated and speeding up the construction and phenotyping of producer strains. It is complemented by omics technologies, single cell analytics via FACS and microfluidics-based live cell microscopy, as well as cultivation devices from picoliter to 300-L scale. The ProVIS Center for Visualizing Biochemical Processes (UFZ) combines infrastructure for visualizing and quantifying biochemical processes and metabolic interactions in biological systems. The UFZ bioreactor pilot plant consists of modern bioreactor technology for the cultivation of different microorganisms like bacteria, yeast and fungi at scales between 0,5 and 100 litres along with devices for analytics along the bioprocess and cell separation.
- To study subsurface and oceanic processes, conduct experiments, and develop new monitoring techniques we have access to deep geothermal boreholes in Berlin, Potsdam, Groß Schönebeck, Iceland, Mexico, and Japan, as well as underground research labs in Switzerland and Germany. We are also involved in developing new underground labs, e.g., GeoLab and global monitoring and remote sensing infrastructure for large-scale geothermal and mineral

systems. Research on marine georesources uses the state-of-the art infrastructure and observational platforms at GEOMAR, e.g., ROVs, AUVs, crawlers, ocean bottom seismometers among others.

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Topics 3, 5, 6, 7, 8.

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## Program Objective *POR8*: Environmental Pollution- Protecting the environment and humans from chemical pollution

**Aim:** To develop and apply coherent concepts for understanding and assessing the interaction between environmental pollution and human and ecological health. We apply this strategy across disciplines to overcome current fragmented 'silo' approaches and provide options for solution-oriented chemical management strategies to ultimately support sustainable chemical use in a non-toxic environment.

### Introduction

In fewer than 100 years, synthetic chemicals have polluted our planet. This includes visible waste, such as plastics, and invisible chemicals that are omnipresent in soil, water, air, and all living organisms. Anthropogenic pollution commenced with industrialization and includes synthetic organic chemicals that are produced for diverse purposes ranging from pest control and improving health outcomes to inclusion in virtually all consumer products. Synthetic chemicals used in agriculture, consumer products, and plastic packaging end up in food sources, ground, surface, and wastewater, and air. Particulate air pollution is one of the largest global environmental health risks (see also *POR2*).

The properties that make synthetic organic chemicals so popular mean they often do not degrade in the environment or degrade very slowly, leading to a build-up in the environment over time. Even substitute chemicals that degrade can leave harmful traces or be degraded into persistent and toxic transformation products. Chlorine chemistry started in the early 1900s with pesticides such as DDT or industrial products including PCBs. The "dirty dozen" of chlorinated persistent organic pollutants (POPs) were phased out globally via the 2004 Stockholm convention but this failed to significantly reduce the overall pollution because POPs degrade slowly and new POPs emerged. Chlorine chemistry was followed by bromine chemistry, leading to equally problematic POPs. These and other "forever chemicals" require fundamentally new ways of regulation, monitoring and management (Joerss & Menger, 2023). Exposure to complex, environmentally relevant mixtures can trigger cocktail effects, where chemicals individually considered safe are together nonetheless toxic. Because existing regulations only consider chemicals on an individual basis, they fail to account for the collective action of chemical mixtures. Chronic, long-term exposure to low, allowable concentrations of chemical mixtures can initiate, trigger, or perpetuate disease. The association of synthetic chemicals with the decline in biodiversity (see also *POR6*) and adverse human health effects is undeniable.

### Research within the *Program* to achieve this objective

**Hazard and risk assessment of chemicals** - The current risk assessment paradigm dates back to the early 1970s, focusses on single chemicals and is slow and expensive as it often relies on animal testing. Current testing methods are severely outpaced by chemical innovation and the sheer number of new chemicals to assess. To address this challenge, we are developing novel hazard and risk assessment strategies and methods (e.g., Escher et al., 2023) focussing on alternative toxicity models including artificial intelligence-based *in silico* approaches, 2D and 3D cell models and alternative animal models such as zebrafish embryos. To make these new approach methods fit for application in hazard identification and risk assessment, essential fundamental research on mechanisms of toxicity and *in vitro* to *in vivo* extrapolation is ongoing. We develop and deploy state-of-the-art environmental and human biomonitoring to understand which chemicals and mixtures present the largest potential risk to society. Collectively, our work substantiates the urgency for regulation changes and raises public awareness about the presence and risk of chemical pollution.

**Chemicals in the environment** - Although concentrations of certain chemicals have decreased over the last several decades, the diversity of synthetic chemicals used in commerce has exponentially increased. This includes the addition of novel entities such as nanoparticles and plastics, with the "plastisphere" having the potential to contribute to biodiversity loss and climate change. Our research contributes to better understand the sources, entry points and pathways into the environment and the impacts of globally increasing environmental pollution by chemicals and plastics. Polar environments are sentinel regions for the hazardous consequences of global anthropogenic pollution (Ebinghaus et al., 2023). Chemical pollution, climate change, and biodiversity loss are strongly interlinked planetary environmental crises. The continuing increase in extreme weather events will increase the risk chemicals pose due to additional inputs during storms and lower dilution in rivers with low water levels during droughts. We explore how chemical pollutants add to a multi-stressor situation, enhancing the loss of biodiversity in global environments. We investigate the complex transport pathways of the water cycle and sources such as mismanaged waste, wastewater treatment plant effluents, urban stormwater, road and agricultural runoff. Just as visible plastic pollution accumulates in open waters and beaches, invisible synthetic chemicals are also transported across the planet.

Air pollution was historically associated mainly with the emissions of sulfur dioxide and the photochemical production of ozone. Currently our research focus in air pollution are fine and ultrafine particles, which are emitted not only from combustion engines and traffic or industrial ablation processes but also form chemically from anthropogenic organic precursors. They are associated with a wide variety of health issues ranging from respiratory to neurological disease and cause millions of premature deaths worldwide.

**Chemical exposure and effects on wildlife and humans** - Synthetic organic chemicals increase the prevalence of non-communicable diseases including cancer or modulate immune and endocrine systems in such a way that humans are more vulnerable to communicable diseases. The detection of hundreds to thousands of chemicals in humans has progressed with novel (bio)analytical instrumentation and methods that facilitate non-target screening and bioanalytical mixture effect assessment in human biomonitoring.

The role of the microbiome for the protection from adverse effects of chemicals is a focal point of our research. The (eco)exposome concept recognizes the totality of measurable exposure accumulated throughout life as a major driver for adverse outcomes and health effects in humans and wildlife (Scholz et al., 2022). Our research has demonstrated that humans and wildlife carry a multitude of modern as well as banned persistent organic pollutants as complex mixtures that can potentially cause cocktail effects and we have joined forces with international researchers to better understand the global dimension of chemical pollution of wildlife and humans using a "One Health" perspective.

To fully understand the impact of chemical exposure, population-based studies are currently running that include both environmental and participants' biosamples with special attention to vulnerable age periods. We are contributing to national and international cohort studies and use state-of-the art model systems to confirm associations.

Researchers in the Earth and Environment Program in collaboration with the Health Program evaluate environment-health interactions to better understand the root causes of disease and the relative impact of (mixtures) of pollutants. A special emphasis is placed on unravelling the relationship between the exposome of children and diseases, focusing on dysregulated immune responses, growth, and (neuro)development in experimental models with a mechanistic focus (e.g., Leppert et al., 2020) and cohort studies.

Technical solutions to deal with pollution may even generate new problems and other chemicals, such as disinfection of drinking water that may lead to the formation of toxic disinfection by-products. Work in the Helmholtz Centres seeks to implement new treatments to deal with synthetic chemical pollution that deteriorates water quality.

### Key Infrastructures

-European Research Infrastructure on Long-Term Ecosystem Research (eLTER) to monitor and understand the complex interactions between people and nature over the long term.
- Atmospheric Simulation Chambers AIDA at KIT and SAPHIR at FZJ.
- CITEPro (**C**hemicals **i**n **t**he **e**nvironment **pro**filer): platform for high-throughput sample preparation, automated exposure of cell cultures and aquatic organisms to rapidly identify potential adverse effects of large numbers of chemicals and environmental/human samples.
- ProMetheus platform: untargeted and targeted measurement of proteins and metabolites, metaproteomics, mass cytometry and novel data evaluation workflows.
- LINA (UFZ) and LISA (HMGU/UFZ) cohorts consider chemical exposure during the human life course in the context of other stressors like socioeconomic, education, lifestyle.

### Contributions from *Program Topics* in *Changing Earth – Sustaining our Future*

Topics 1, 4, 5, 6, 7, 9.

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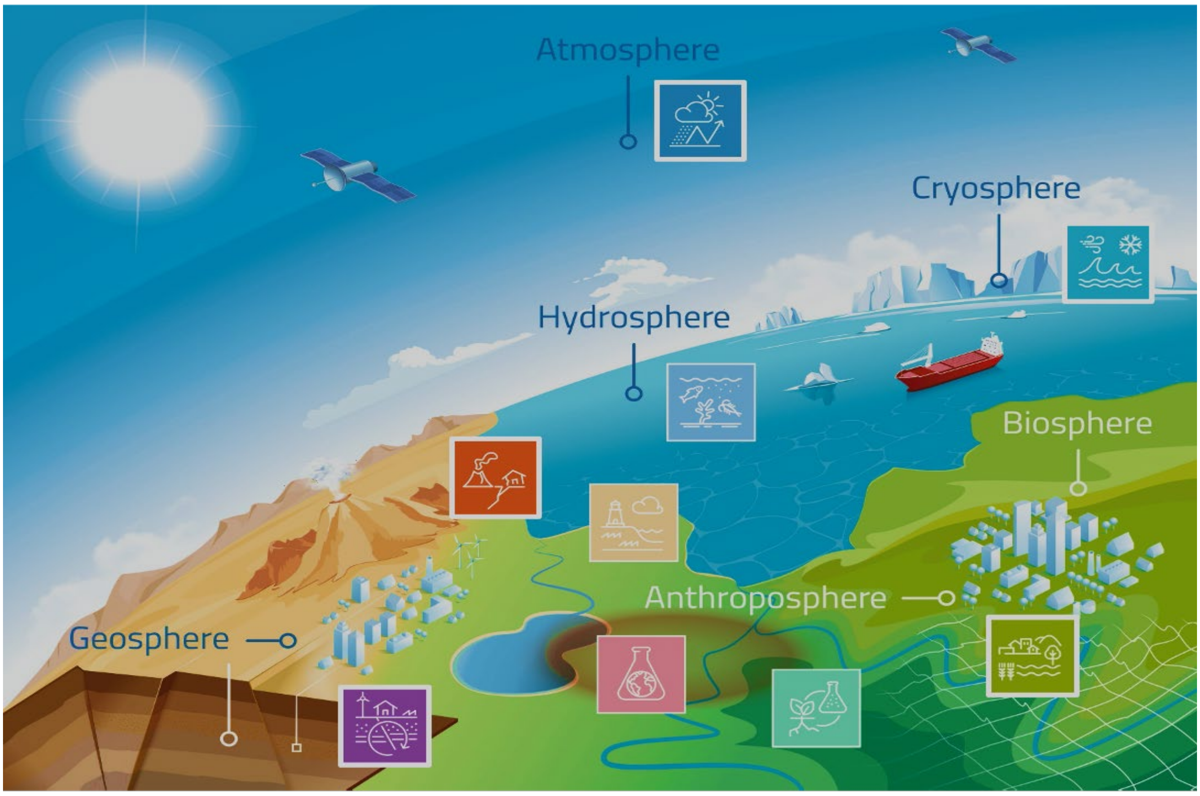


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