Future Priorities for Earth and Environment Research in Europe

This position paper complements the overarching Helmholtz FP10 position from 02/2024.

Introduction

The impacts of climate change, the loss of biodiversity, the pollution of terrestrial, marine and atmospheric realms all threaten human and environmental health, economic prosperity and social cohesion. Helmholtz Earth and Environment aims to contribute to an understanding of Earth System dynamics with a focus on how human activities will be made sustainable in this system. This entails key future concepts such as nature-positive production and defossilization of industry, sustainable circular (bio)economy and resource efficiency, multifunctional land and ocean use, carbon removal (technology and nature-based solutions), base-load-capable provision of renewable energy, water security, adaptation and resilience to climate change, biodiversity stewardship and ecosystem restoration.
Helmholtz Earth and Environment provides the fundamental knowledge required to address the challenges of rapid, natural and anthropogenic changes in the Earth System, and develops the scientific pathways, technologies and solutions for the stewardship towards a sustainable future of humanity within Earth System Boundaries[1]. This requires

- the operation of world-class observational infrastructures (satellite-based and *in situ)* which provide long time-series for tracking Earth System change together with the implementation of novel innovative technical and methodological developments.
- the generation, integration and communication of fundamental knowledge about Earth System dynamics including all components, essential feedback processes, and their interactions with human activities.
- risk assessments, knowledge exchange and co-creation as starting points for adaptive societal transformation pathways to shape science-based solutions for a sustainable and resilient human-environment relationship (i.e. shaping a 'good Anthropocene').

Future Directions

The most important overarching challenges for the next ten years are:

To understand Earth System dynamics and their impacts: Investigate the complex interactions, feedback mechanisms (including compound events) and element fluxes within the Earth System past and present using novel observation and modelling systems. Develop and improve high-resolution climate models and digital twins of all Earth System compartments to predict, project and investigate the impacts of global change and human adaptation and mitigation measures on weather extremes, regional climate, and ecosystem viability. This will involve using Artificial Intelligence and Large Language Models to their full extent as well as the development of Foundation Models and (near) real-time analytics across space and time including dynamic biological systems. Develop predictive models based on multi-scale observations of key climate processes to identify thresholds and tipping points in the Earth System, narrowing the gap between observational data and modelling. The coming decade is critical for this work as the Earth crosses the 1.5°C warming threshold. Develop and assess the effectiveness of comprehensive climate change adaptation and mitigation strategies and

[1] Rockström et al (2023): Safe and just Earth system boundaries, Richardson et al. (2023) Earth beyond six of nine planetary boundaries

pathways to net-zero Earth System interaction. Address water-related challenges, such as droughts, floods, pollution and water security. Advance next-generation forecasting and early warning systems to reduce the impacts of natural disasters and unprecedented climate extremes.

To maintain ecosystem functions and services: Identify and target ecosystem functions and services that can reduce anthropogenic impacts, supporting a sustainable management of natural resources. Support recovery, conservation and protection of species and ecosystems and biosphere-geosphere interactions. Investigate the trajectories towards future ecosystems to understand their functions and feedback with human activities. Investigate largely unknown areas and processes such as the deep sea, ocean floors, remote forests and the deep subsurface. Examine the impacts of extreme climate events on ecosystem stability and function, particularly in sensitive and high-risk environments such as permafrost and wetlands. Investigate the consequences of biodiversity loss on ecosystem function, resilience, and services, focusing on maintaining ecological balance in the face of global change. Develop ecological restoration and management strategies that enhance resilience and sustainability, considering the dynamic interactions within ecosystems and their external influences. Develop and test climate-smart agroforestry and aquacultural practices that are resilient to environmental changes and support sustainable food production. Integrate digital technologies and precision farming techniques to optimize agricultural practices and enhance productivity while reducing their ecological footprint.

To increase sustainability in resource management: Close knowledge gaps in resource conservation, occurrences of raw materials and developing regional, national and global resource-efficient and circular socio-techno-ecological frameworks for industry and societal transformation. Develop sustainable multi-use terrestrial and marine options for achieving net zero pollution and net zero carbon futures; this includes carbon removal strategies, geothermal energy and thermal energy storage solutions. Advance circular (bio)economy methods towards innovative solutions for food/feed, materials and the basis for chemical industry to maintain carbon and nitrogen as well as other materials, energy and chemicals in human use cycles, reducing the demand for primary resources and the concomitant impact on natural carbon and element cycles. Integrate resource efficient and circular economy principles into industrial and agri- and aquacultural production systems. Investigate the effects of pollutants on ecosystem health, focusing on how chemical pollutants interact with natural processes and influence ecosystem services.

To foster urban and rural climate resilient developments: Enable a strong transdisciplinary approach including AI methods to provide the required granular representation of the complex structures (as well as socio-economic activities) of cities and human settlements in Earth System simulations and projections. Develop strategies for the transformation of urban, rural and coastal areas to mitigate and adapt to the impacts of climate change, focusing on enhancing the resilience of infrastructure and communities. Test these strategies in urban real-world laboratories and demonstration projects. Address the interdependencies between water, food, air quality and energy systems in urban environments and their rural surroundings to ensure sustainable and resilient living.

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