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Innovating for Sustainability: The Global Climate Hub

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Innovating for Sustainability: The Global Climate Hub

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Abstract

Multiple challenges have emerged over the last decades, threatening human, socio-economic and environmental systems. Climate change impacts, degradation of limited natural resources, unsustainable demand, production and consumption practices, diseases, crises in the energy, food and biodiversity sectors, economic recessions, and many more, interconnected dynamic threats, require coordinated and efficient solutions. Under the UN's Sustainable Development Solutions Network (SDSN) we developed the Global Climate Hub (GCH), an international initiative for tackling such challenges. After 12 years of SDSN's action, we present the structure and ways of operation of the GCH, along with the principles that allow it to successfully bridge holistic scientific approaches with the society, for implementing fair and publicly acceptable sustainable pathways. The GCH's five innovations are analyzed, namely, the use of integrated 'cutting-edge models', with the support of 'digital AI-driven data-handling infrastructure', for the development of case-specific 'socio-economic narratives' and 'stakeholder engagement' for co-designing solutions. Moreover, the nine units of the GCH are scrutinized in terms of scope, methods, and tools. These cover a wide range of expertise in digital applications, climate science, land, water, food, biodiversity, and marine systems, energy and decarbonization, land and maritime transport, public health, solutions' application, policy, finance, labour markets, participatory approaches, education and training. This contribution provides a complete picture of a global, developing – and successful so far – vision for a climate-neutral, resilient and sustainable world.

Keywords: Sustainable Development Solutions Network; Global Climate Hub; Climate change; Sustainability; Integrated Assessment Models; Policy; Interdisciplinarity.

Main

In recent decades, our societies increasingly face unprecedented threats[1]. The impacts of climate change are more evident, alongside the degradation of the limited natural resources and ecosystems, unsustainable demand, production and consumption practices, biodiversity collapse, diseases, energy and food crises, recessions and depth crises[2], population crises with unequal growth and distribution, population movements due to geopolitical and climate crises, and various forms of inequality[3,4]. Addressing these interconnected challenges requires urgent and coordinated efforts for globally sustainable solutions, ensuring the resilience and well-being of present and future generations[5]. Admittedly, these solutions must be based on holistic and systemic approaches, to efficiently capture and manage the intricate interplays between environmental, economic, and social factors, while also being socially just and acceptable, to ensure their applicability[6].

Towards this direction, several initiatives work on integrated modeling, contributing valuable insights into the complex interactions between human-environmental systems on global and regional scales: The Intergovernmental Panel on Climate Change (IPCC[7]) is the most common example, a leading international body for climate change science through modeling approaches to provide policymakers with comprehensive impact assessments and potential adaptation and mitigation strategies. The Integrated Assessment Modeling Consortium (IAMC[8]) supports this effort by enhancing the understanding of global issues, such as climate change, and to improve the capabilities of integrated models. The Food, Agriculture, Biodiversity, Land-Use, and Energy Consortium (FABLE[9]) is another example bringing together leading research institutions to develop integrated models that explore sustainable pathways for food and land-use systems. Other initiatives focus on sustainable land systems (the Global Land Programme - GLP[10]), or emissions to the atmosphere (the Global Emissions InitiAtive - GEIA[11]). Organizations such as the World Bank and United Nations (UN) often engage in (global) modeling and assessment initiatives, seeking comprehensive policymaking insights. The UN's Sustainable Development Solutions Network (SDSN[12]) brings together scientific and technological expertise to assess climate, energy, socio-economic, water, or biodiversity issues and promote solutions for the achievement of the Sustainable Development Goals (SDGs) and the Paris Climate agreement. The SDSN sees the SDGs framework as the blueprint for addressing the multi-crisis described above. At the same time there are research groups working on specific Integrated Assessment Models (IAMs) and developing such tools that are increasingly used (such as IMAGE[13], GCAM[14], REMIND[15], MESSAGE[16], LandSHIFT[17], GLASS[18] models, to name a few).

All these initiatives signify a growing recognition of the imperative for interdisciplinary and overarching approaches to address the aforementioned multi-crises. As we are living in an era marked by increased collaboration among scientific fields, and by technological advances (such as big data and Artificial Intelligence – AI), the ground is becoming more conducive to this transition toward interdisciplinary and holistic responses to complex challenges[19]. Building on this 'materialization' of such an interdisciplinary space, and the opportunities it provides for innovation, we established a Global Climate Hub (GCH), under the SDSN – a 12-year-old initiative. This is a concerted effort to institutionalize cross-country interdisciplinary collaboration, that will be scientifically-based and policy-oriented.

The GCH supports and is complementary with the initiatives mentioned above, utilizes IAMs and leverages them (e.g., expanding existing models with socio-economic components, and/or creating new ones, bridging natural systems' IAMs with socio-economic models). Furthermore, the GCH employs cutting-edge technological advances for both its operation and the development of innovative solutions, thus extending them to society and implementation. It breaks new ground in terms of solutions' design and application based on stakeholder involvement: The inclusion of a societal perspective through continuous and committed stakeholder engagement for the (science-supported) design and implementation of solutions, and the global nature of the Hub (with various National Hubs), are unique elements over other initiatives. This implementation-oriented approach is another novel element: beyond the in-depth integration of different sciences to produce model-driven results, lies their use as the basis for co-designing solution pathways with stakeholders. This is a challenging and transdisciplinary process, but it pays off as the stakeholders become owners of the solutions, and this significantly increases the implementation potential[20].

In doing so, we aspire to 'mainstream' holistic approaches and bridge the gap between scientific understanding and actionable solutions. The aim of this study is to outline a tangible way to achieve this bridging, and call for further collaborations. In this article, we present the GCH for the first time with an in-depth analysis of the sciences involved and the principles that make it a viable response to the complex challenges our world faces.

A Global Climate Hub

The UN SDSN's response to the multifaceted contemporary challenges is the Global Climate Hub (GCH), which came as an initiative for change, leveraging science-based solutions for a holistic and equitable sustainability transition. These solutions are developed at regional, national, and sub-national level based both on the scientific expertise of its members, and the engagement with local policymakers (representatives of central and/or local government) – there are dedicated teams of GCH scientists specialized across various fields, working in research projects, as well as a network of SDSN National Hubs, facilitating communication, outreach, and solutions' implementation. The overall philosophy of the GCH can be summarized in the combination of five critical innovations, for developing acceptable and implementable sustainable pathways. These work as a framework for the analysis of any problem:

I. <u>Cutting-edge models:</u> This includes the use/development of system-dynamics based cross-sectoral models. Based on the simulations and the different models' results, we develop holistic pathways at national level, for all major natural and infrastructure systems (e.g., water, atmosphere, land-use, food, energy, transport, marine-use systems, etc.). The involvement of 'non-experts' and civil society in the modeling process, allows the key stakeholders' perspectives to be embedded within it and provide validation for outputs.

II. <u>Powerful digital AI-driven infrastructure</u> that supports the handling of big data, their harmonization and management (as several data are not subject to the same units, time-steps or geographical coverage), their update, the development of digital twins, as well as the coupling of the various models and the results' visualization. This facilitates the integration of the above models.

III. Development of the socio-economic narrative for the just and equitable implementation of the science-based pathways. Based on the results of the natural and infrastructure systems (innovation I), the socio-economic narrative is built based on mathematical models simulating the economy (e.g., equilibrium modeling, welfare distribution, investments, behavioural responses, etc.). This is a country- or region-specific process fostering the co-ownership of the pathways across stakeholders, such as scientists and technology developers, policymakers, finance and business sectors, NGOs and civil society. Again, the two-way interaction with 'non-experts' is key.

IV. Stakeholder engagement: Transformative participatory stakeholder approaches (workshop-based) for co-designing the pathways in detail. Here, we exploit the capabilities of the new technologies – even virtual and augmented reality, digital storytelling, and gaming (all based on the previous innovations) to facilitate the stakeholders' experience and understanding. The stakeholder engagement can raise awareness and promote sustainable lifestyles and behavioural changes for the adoption of the solutions.

V. Openness: The whole process of analyzing, co-designing, presenting and applying sustainable pathways supports the widespread adoption of the principles of Open Science and Open Access to data, models developed, and in general scientific infrastructure. This is paramount for the efficient and effective progress of the solutions, as well as their reproducibility and transferability.

These innovations are interlinked and complementary, feeding each other with necessary information (Fig.1), to deliver optimal sets of technological, policy, fiscal and financial measures to address complex sustainability challenges, build and maintain cross-disciplinary collaborations and stakeholder engagement. Thus, the GCH ensures that the proposed solutions are holistic, innovative, publicly acceptable, transferable, feasible and applicable to the unique contexts of different countries, bridging the gap between the models it produces and the non-scientific community.

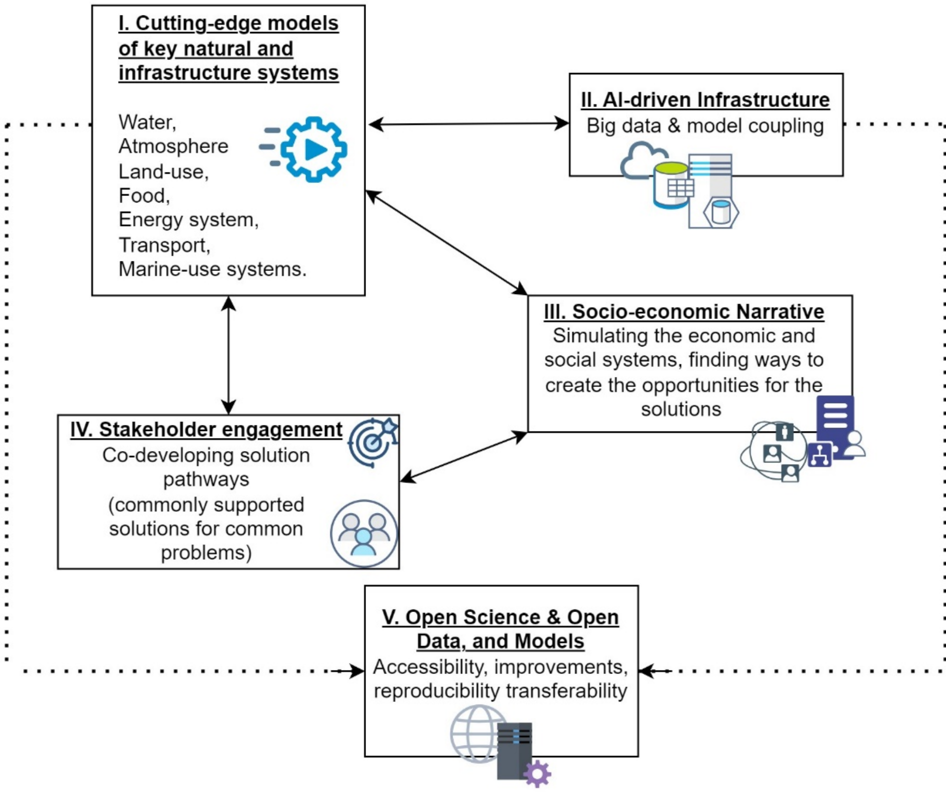

Figure 1. The five innovations of the GCH, summarizing its approach to sustainability problems, in an indicative schematic showing their interactions: Integrated models are used/developed (I), which are coupled and updated (II)to simulate real-world scenarios. Based on their insights and the stakeholders' input, the socio-economic narrative is developed, simulating the social and economic systems (III). The results so far are the basis to co-design solution pathways with the stakeholders (IV), within a two-way interaction with the models (I), ensuring realistic representation of the problems and solutions. Data and models are publicly accessible to enhance reproducibility (V).

Examples of pathways can include technical solutions (e.g. for decarbonization), the consideration of existing technologies, circular economy, nature-based solutions, digitalization, innovation commercialization, sustainable finance and adaptation investment schemes (e.g., green bonds, Environment Social Governance – ESG metrics, and market incentives), and policy reforms (legislative and regulatory interventions to support the implementation and long-term viability of the pathways). To the best of our knowledge, this is a globally unique effort for science-driven, holistic, human-centric approaches aiming to sustainability, climate neutrality and resilience pathways at national level. Its nature, with the existence of national hubs in different countries ensures stability, continuation, and commitment for the long-term implementation of the solutions. This is also beneficial in terms of up-scaling potential, knowledge transfer, and international experience and capacity building across its dedicated teams.

The GCH is hosted by Athens University of Economics and Business (AUEB) and the "Athena" Research and Innovation Center in Information, Communication, and Knowledge Technologies (ATHENA RC), both integral components of the Alliance of Excellence for Research and Innovation on Aephoria (AE4RIA – in

Greek 'aephoria' is a synonymous concept to sustainable development). Within the GCH, AE4RIA plays a vital role in securing funding from competitive projects, ensuring the necessary resources to fulfill its multidimensional mission. The Research Centre for Atmospheric Physics and Climatology of the Academy of Athens also supports the GCH.

Nine units as necessary scientific areas for sustainability

The GCH consists of nine separate units/ working teams that have expertise to handle relevant research and practical applications (Table 1). These units are scientific areas, conceived as necessary 'steps' towards sustainability, as each one contributes a unique perspective and insight towards the development of customized strategies for climate neutrality, resilience, and sustainability. All units operate under the philosophy of the five innovations explained in the previous section, together or in combination with other units. They utilize advanced modeling suites to provide data-driven, scientific projections for variables of material importance such as economic activity, quality of ecosystem services, GHG emissions, biodiversity, energy production and consumption by source, transport, land-use and food systems, among others. Each unit has its own head(s) and members working on relevant research activities, as well as its own network to ensure the appropriate workforce and capacity.

Table 1. Description of the nine units, with their scope and indicative work-tools.

Units	Scope	Indicative Tools (flexibility in model-use)
1. Data, Platforms and Digital Applications	Data aggregation, connection and visualization, for improved understanding of processes and research practices.	OpenAIRE Research Graph[21] (linked information from trusted data-sources globally, assessing scholarly and policy information).
2. Atmospheric Physics and Climatology	Global and regional climate change, IPCC's scenarios and projections, downscaling, extreme phenomena, and air pollution.	General Circulation Models (GCMs), Regional Climate Models (RCMs), Weather Research and Forecasting (WRF)[22], Satellite Imagery, Remote Sensing.
3. Systems Nexus Modeling Unit: Land-Water-Food-Biodiversity-Marine Nexus	Modeling of land-use, water, food, biodiversity, and marine-use systems, their changes and interactions, aiming to their sustainable, climate-neutral and economically viable management.	System dynamics modeling and trade-off analyses based on sector-specific data (e.g. FABLE Calculator for food systems). Scenario analysis for possible climate, land, anthropogenic, or other changes' impacts on natural resources, and these physical systems.
4. Energy Systems & Emissions Modeling	Simulation of energy supply and demand, renewable energy pathways; greenhouse gas (GHG) emissions from all sectors; aiming to clear-energy efficiency, and cross-sectoral climate-neutrality/ decarbonization.	BALMOREL Energy-System model[23], LEAP[24], and other sector-specific models (e.g. SEAMAPS)[25]
5. Climate, Environment and Health	Health implications of climate change, natural and extreme phenomena, socio-economic assessments, and future pathways with a focus on interventions.	Public health and economic/ econometric models, aiming to understand direct and indirect effects, and develop technological, management, and economic instruments to improve well-being and tackle inequalities.
6. Innovation/ Acceleration	Partnerships among the academic, public, business, and technology sectors, to co-develop solutions for a green, sustainable economy.	Knowledge and innovation networks, start-ups, technology-holders.

7. Policy, Finance and Labour Markets for Just Transition	Social and economic facets of the sustainability transition, ensuring fairness, inclusivity and equity.	SDG indicators, just policies, novel financial instruments, and labour market reforms, based on models (e.g. GLOBIOM[26], ECM3[27]), and participatory processes.
8. Transformative and Participatory Approaches	Mobilizes community and policy dialogue to suggest policies customized in the lived realities of those they impact.	Systems Innovation Approach (SIA), Living Lab Modeler Tool, foresight methods such as Backcasting[28], stakeholder mapping, living Labs, participatory methods and workshops.
9. Education, Training, Upskilling and Reskilling	Development of educational and training programs to assist the work-force's sustainability transformation.	Training programs, upskilling, reskilling, digital employment, communications.

1. Data, Platforms and Digital Applications: This unit practically collects data, manages who is producing what (science and policy documents), monitors policies, and practices (Fig.2). These are achieved by the use of the OpenAIRE Graph, a free and open resource that brings together and interlinks hundreds of millions of metadata records from over 70,000 research and policy data sources trusted by researchers. It is hosted at OpenAIRE Member ICM, University of Warsaw Data Center. OpenAIRE uses AI mechanisms (AI-driven data infrastructure) to clean, curate, enrich, connect, and classify records. It is used in Scientific Discovery in the European Open Science Cloud, in Bibliometrics in Science, Technology and Innovation studies, and in Monitoring of research and open research. A typical example of OpenAIRE's operation could be to check e.g. the relations of scientific publications or policy documents to the SDGs and show their uptake[29]. This unit offers opportunities and the means for fast processing of extensive information, transparency and collaboration across other units and research teams, globally, while promoting open science. The OpenAIRE operates with the support of key technical groups from our members: CNR (Italy), AthenaRC (Greece), ICM (Poland), University of Bielefeld (Germany), University of Minho (Portugal), and all working teams globally make sure that data from their countries was fed into OpenAIRE.

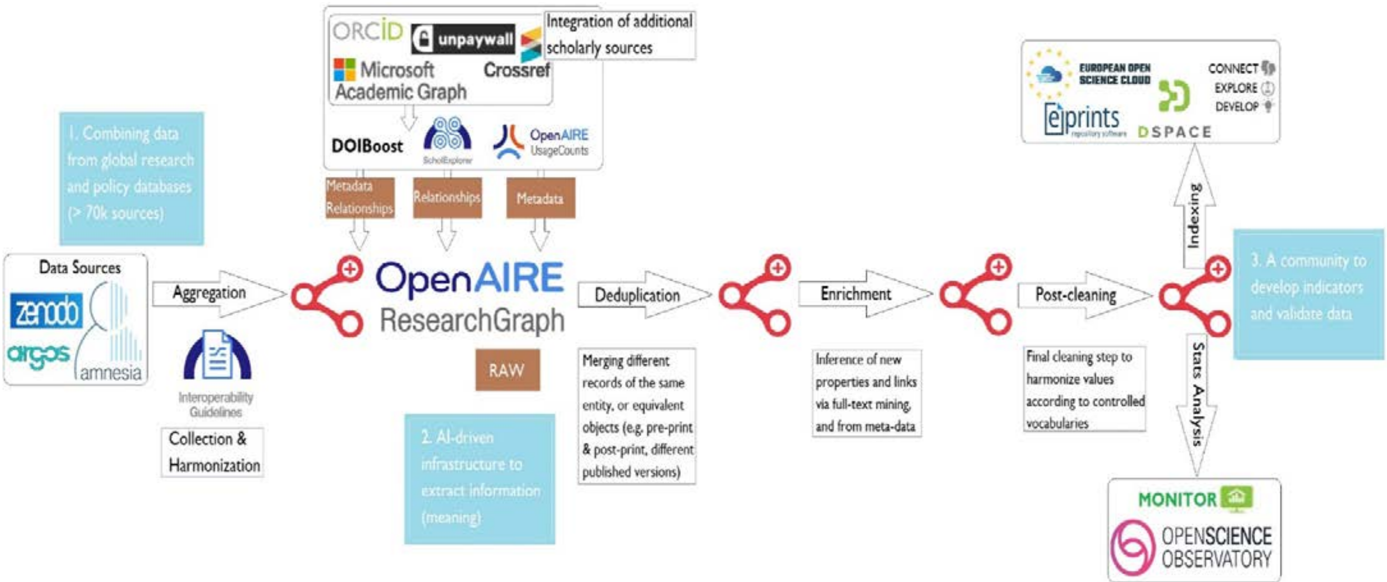

Figure 2. An indicative workflow of unit 1: Data extraction from open sources (e.g. zenodo, ORCID, etc.), information processing in OpenAIRE (data clearing and update), and the community of our members validating and further analyzing the data.

2. Atmospheric Physics and Climatology: This unit investigates the global and regional climate through analysis of satellite and terrestrial observations and simulations with climate models. Thus, it explains and forecasts climate variability, trends, extreme events and simulates their impact at various time scales. It also simulates air pollution phenomena and their interactions with climate change[30]. This information is crucial for the development of appropriate climate change mitigation and adaptation strategies, able to withstand and cope with climate related stresses. A typical application example of this unit's work is the provision of statistically downscaled climate change projections at regional scales, or air pollution dynamics, to be used as inputs from the other units, as future scenarios.

3. Systems Nexus Modeling: Land-Water-Food-Biodiversity-Marine Nexus: This is a wide unit, covering in essence the natural systems and their responses to factors such as climate change, land-use or marine-use changes, or anthropogenic changes. A wide range of simulation models (IAMs) are used, as each of these nexus systems (e.g. water management, or renewable energy/ hydropower production, land-agriculture-food nexus, marine-use, and biodiversity) have their specific models, or need custom-developed ones depending on the case study's characteristics (e.g. accounting for waste, GHG emissions, etc.). Moreover, these systems dynamically interact among them, and with all active sectors of a region (agriculture, industry, services, households)[31]. These interactions and trade-offs are simulated, under different scenarios, considering also: a) economic factors (GDP, governance, finance and investments), using state-of-the-art economic modeling, including the coupling of with economic models (e.g. GLOBIOM), economic valuation[32], and b) anthropogenic (social) factors (population dynamics, education, health, infrastructure, employment, income, behavioural trends, etc.). A typical example (Fig.3) would be a land-use change model (e.g. iCLUE model[33] predicting future land-uses), coupled with a water management model (e.g. WEAP[34,35] or CWatM[36] - which can be linked with the MESSAGE energy model,

the land and ecosystems model GLOBIOM, the IIASA-EPIC[37] agriculture model, the water quality MARINA[38] model, and the hydro-economy model ECHO[39]), and a food system model. For the latter, the FABLE Calculator[40] is used to simulate food, feed, non-food consumption, losses and waste, imports and exports, and production quantities for different products, testing the impacts of alternative climate or economic policy futures and management scenarios aiming, for instance to improved calorie consumption per capita, GHG emissions from agriculture and land-use change, biodiversity-resilient land management, and socio-economic analysis considering food security[41]. The marine-use system is another area covered by this unit, by improving the understanding and predictions on the interactions between various marine uses, such as shipping, fishing, tourism, offshore energy development, conservation, and environmental protection, by using Integrated Coastal Zone Management (ICZM) Models[42,43].

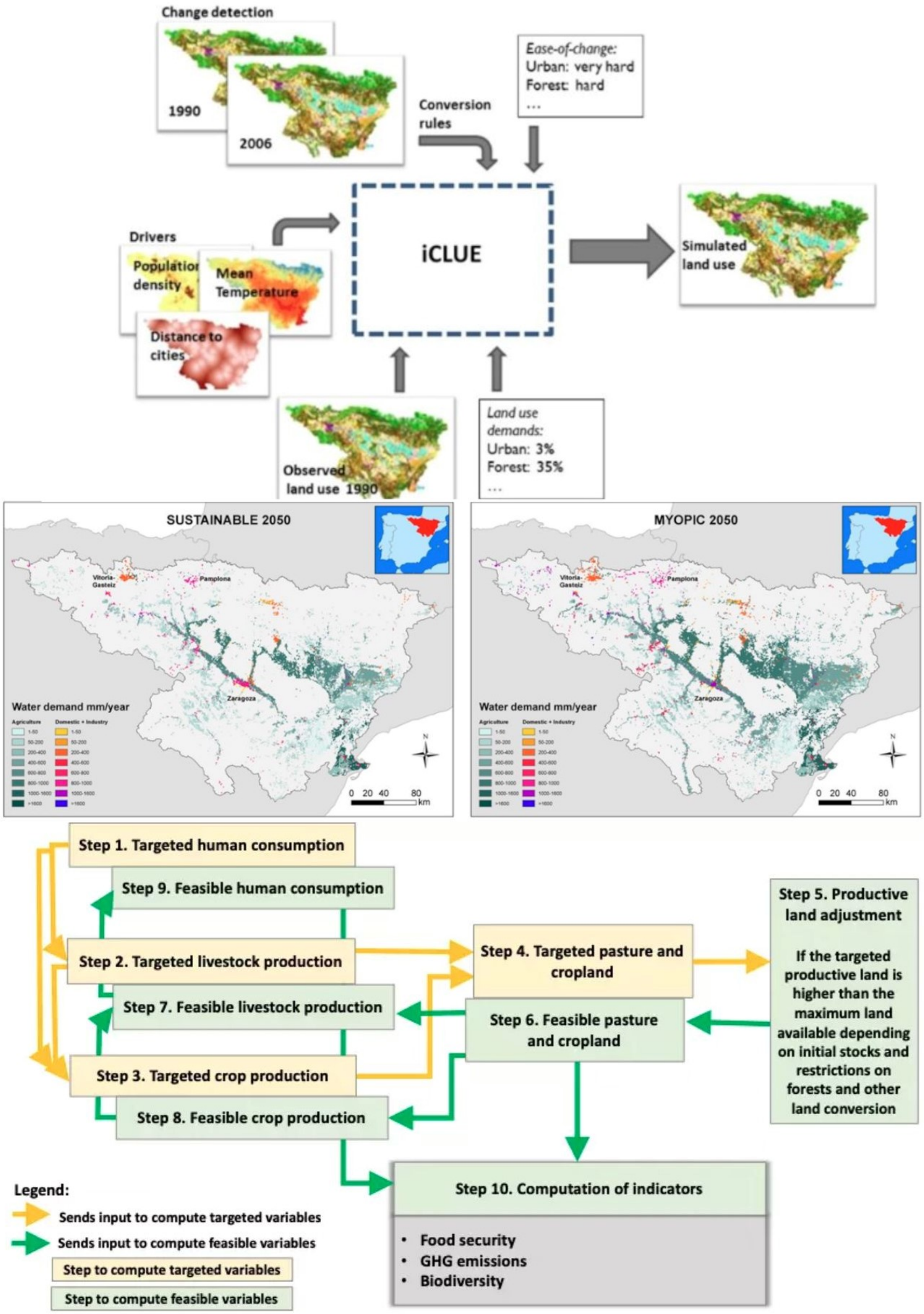

Figure 4. Indicative examples of the described processes considering: a) a land-use change model, b) a water management model, and c) the FABLE Calculator's full extent, step-by-step calculating sequence, with all parameters that can be analyzed. Sources: [9,44,45].

4. Energy Systems & Emissions Modeling: This modeling unit uses system dynamics approaches to simulate cross-sectoral energy systems (energy, land and sea transport, agriculture, industry, etc.), their GHG emissions and decarbonization potential, including technological and economic solutions. The models exploit simulation tools, optimization and stochastic techniques to develop decarbonization pathways of the energy systems. For instance, among the models (IAMs) used by this unit is BALMOREL, an open-source partial equilibrium model, analyzing the electricity and combined heat and power sectors, designed to aid in decision-making processes concerning energy policy, investment planning, and market design. We use this indicative example and further analyze it in Fig.4, to show the integrated nature of the followed approaches per sector. Another space we expand in this context, is the economic valuation of non-marketed goods and services and their integration in IAMs, like BALMOREL. The main role and usefulness of the valuation is to serve as a link to policy, by prioritizing actions for areas and ecosystem services that are degraded. Another example is the SeaMAPS[25] model, which we use for analyzing future fuel mix, emissions and underlying costs of the maritime industry.

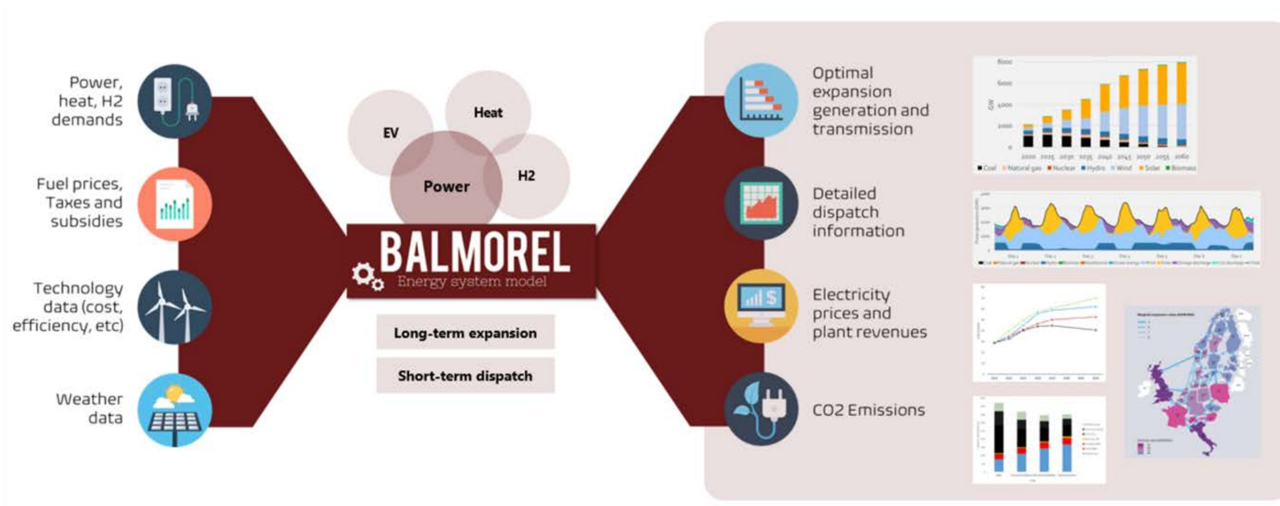

Figure 3. The BALMOREL energy system model, with its input and output parameters, and the functionalities of the model. The inputs can include power, heat, and hydrogen demands, fuel prices, taxes, subsidies, technology data (cost, efficiency, etc.), and weather data. The outputs refer to the optimal expansion of generation and transmission capacities, detailed dispatch information (which appears to include an hourly resolution of energy production by source), electricity prices and plant revenues, and CO2 emissions.

5. Climate, Environment, and Health: This unit covers a wide spectrum of multiple climate-driven and/or environmental drivers (floods, heatwaves, air pollution, sea-level rise, region-specific natural disasters such as earthquakes and tsunamis) and their various effects to human health (morbidity, mortality, disability, respiratory and cardiovascular diseases, psychological and mental effects, infertility). Other indirect effects resulting from poor food quality, water or energy disruptions, post-traumatic experiences,

etc.[46,47], are also within the scope of this unit, along with the associated direct and indirect economic costs. The ultimate aim is to develop strategies (specific adaptation measures) to reduce these impacts with tangible warning/protection/resilience-building portfolios for timely public response, enhancing the climate resilience of our societies, in an equitable manner.

6. Innovation/ Acceleration: This unit acts as a knowledge and innovation community (KIC), working towards accelerating the transition to a zero-carbon, climate-resilient society. With the support of the European Institute of Innovation and Technology (EIT), the EIT Climate-KIC Hub brings together partners from the business sector, academia, technology, and the public and non-profit sectors to create networks of expertise, through which innovative solutions can be developed, brought to market and scaled-up for impact[48]. Accelerating innovation is also part of our BRIGAID Connect Association[49], which is a cluster of companies that help increase Europe's climate resilience through solutions. BRIGAID creates communities that link innovators from its network with problem owners and enablers and help them build practicable solutions to drive positive environmental, economic, social and cultural impact. The Climate Innovation Window (CIW) [50], developed under the frame of BRIGAID (H2020 funded project), aims to be a reference portal for innovations on climate change adaptation, containing more than 120 innovations.

7. Policy, Finance and Labour Markets for Just Transition: The 17 SDGs complementarily aim to a climate-neutral, resource-efficient, technologically advanced, and socially fair world[51], so high-level political engagement and action are needed[6]. At the same time, research globally highlights the inequalities, as low-income, racial and ethnic minorities are found to be more vulnerable to extreme phenomena, climate changes, economic measures and policies[52,53]. This unit develops partial and ultimately general equilibrium models (e.g. GLOBIOM), putting into context the dynamic outcomes of the aforementioned units. This unit is dedicated to help countries realize the necessary transformations to achieve the SDGs[54] in a fair and equitable manner, identify and promote cutting-edge technological and policy pathways toward sustainability, covering all parts of the economy, reducing inequalities.

8. Transformative and Participatory Approaches: This unit works closely with stakeholders to ensure that the model outputs are not only representative of the local realities but that the proposed solutions and innovations (technological, social, financial and policy) are appropriate and fit for purpose within the local context[55]. The GHC has developed the "systems innovation approach (SIA)"[20,56] to ensure a scientifically-supported process of stakeholder engagement. SIA first works on a common understanding of the problems with the stakeholders, then brings the modeling outputs to the stakeholders within workshops/living labs, exploiting new technologies, games, virtual-reality, etc., and finally co-develops innovation pathways/solutions to the problems. The Living Lab Modeler tool[57] can be also used in the process to facilitate ongoing interaction between the stakeholders, exploit advanced visualization tools to accelerate in-depth comprehensiveness of complex issues, and support 'non-expert' involvement in the modeling process.

9. Education, Training, Upskilling and Reskilling: This unit highlights the role of human capital in the sustainability transition, by developing educational initiatives and training programs that prepare individuals for the emerging green jobs and digital employment landscape[58]. It is crucial to ensure that the sustainability transition will not lead to job loss, and this argument will not be an obstacle to the

transition[59,60]. Instead, upskilling, reskilling, and lifelong learning should overcome this challenge, by proper planning – the role of this unit. Environmental awareness and knowledge of the concept of sustainability will become a prerequisite of all jobs and a crucial aspect of citizenship. This requires new types of skills and mindsets to match new types of jobs, the 'green jobs', aligned with national, regional, local and sectoral sustainable strategies[61]. This unit develops such programs focusing on environmental education, sustainability, decarbonization, digitalization, sustainable industry, food systems, cities and communities. Exploiting the wide SDSN network and accommodating various forms of learning, this unit develops tailored training programs per country/region and sector.

Integration and Coordination: All nine units are necessary and complementary, as they offer unique insights. It is worth noting that the work of the presented units within the context of relevant research projects is in line with the SDGs, as the results from such holistic assessments can utilize and further develop SDG indicators and metrics for local and national goals and achievements.

The units can work independently and in combination, when needed. Their activities intersect with, and feed into, an overarching strategy for solving complex problems (theoretically and practically), following the philosophy of the five innovations (Fig.1). This ensures the provision of model-based, science-supported insights together with anthropocentric dimensions, such as governance, human sentiment, health, equity, and well-being. Given that the units consist of researchers and groups working around the world on diverse research areas, we pay particular attention to unify and coordinate them in projects that they need to collaborate. The international nature of the GCH's working teams is critical for multi-region reports and projects that require input and collaboration by multiple countries. It is also useful for employing several innovations such as technology transfers, information, dissemination, or strategies, and working practices related with the international experience of its members. These have been proved to be critical advantages for projects, solutions' design and application[20].

We undertake extensive efforts to integrate the units and facilitate the translation of their work, in contexts with highly case-specific characteristics. For example, this may include climate change scenarios (unit 2) **+** future land use changes, along with water availability and demand **+** agriculture **+** marine-use systems (integration within unit 3) **+** simulations of their energy and emissions (unit 4) **+** integrated economic models (unit 7). The AI-infrastructure (unit 1) acts as the integration tool for the other units, as it handles and updates their data and works on the coupling/integration of the different models used, while units 6 and 8 are crucial for the involvement and contribution of key stakeholders via the National and Regional UN SDSN Hubs. Overall, the coordination of the different units is a very demanding process, as it requires commitment, interdisciplinarity, and comprehensive understanding in order to "create a common language" based on the science and bring it to local stakeholders. This societal component of the GCH requires careful facilitation, communication, training, and education, but is crucial as it leverages things that conventional science cannot really address, regarding the design and implementation of acceptable solutions.

To our knowledge, this is a uniquely holistic and novel approach, very much needed to achieve real-world results. We strongly believe, and our experience shows that this kind of integration has the potential to solve the problems posed by the multi-crises of our times. All units and innovations mobilized by the GCH are needed, and if one is missing, then such complex problems cannot be properly solved. Finally, the openness of the whole process makes the outcomes of GCH public goods, as it offers to everybody the benefits of having the data, the models, the results, and a pathway to approach similar problems.

Making way into policymaking

The GCH aims to support sustainable policies and shape robust climate change policymaking through research-informed approaches. The GCH's route into influencing policy decisions is formed by the methodologically sound research it produces, tailored and responsive to the local needs and capacities of the region under consideration, as well as the stakeholder participatory approaches to co-develop solutions.

Of course, the integration of research findings into policy is challenging. There are multiple challenges, which can differ depending on the case, however, the main challenges we face are:

- the lack of political will to engage with science-supported approaches,
- the limited capacity/ability of policymakers to exploit existing regulatory frameworks that could support more sustainable and economically efficient policies (e.g. European Green Deal, Resilience and Recovery Fund, etc.), which often makes them argue about the limited resources they have, especially at the local level,
- the lack of efficient communication among central and regional/local governments, creating silo communication gaps between the general policy guidelines and their actual implementation.

To overcome these obstacles, the GHC implements the following strategies, as integral part of its projects: First, the use of participatory strategies is crucial. Extensive and consistent work is needed by the Hub's researchers and National Hub members to engage politicians from various levels of governance, and bring them in a dialogue with the other key stakeholders involved to the studied problems – including scientists, experts, non-experts, technology-holders, private actors, NGOs, etc. This also has the benefit to build communication bridges among the different policymakers, and also build capacity, equipping them with the tools to apply scientific findings effectively in their decision-making processes.

Our projects underscore the vital importance of education and workforce development, the GCH's Education, Training, Upskilling, and Reskilling unit works in tandem with entities such as the SDG Academy. This collaboration is pivotal to align both current and prospective labor markets with the needs of an evolving 'green' economy. Thus, this approach paves the way for innovative financial strategies to facilitate the transition to environmentally sustainable practices.

Another element that helps the GCH overcome any policy obstacles is the use of its extended network, the presentation of the work of its units and Regional/National Hubs, and the previous successful projects and applications. Figure 5 below shows the different SDSN networks, where the case-studies with the previous achievements, and extended outreach (e.g. the Hub's continuous presence at UNFCCC Conferences of the Parties showing its commitment to address climate and other complex challenges), have been proved to be inspiring and convincing arguments for policymakers and local stakeholders to engage and collaborate for the purposes of GCH.

Overall, despite the challenges, the GCH's comprehensive and collaborative approach is breaking new ground in fostering policymaking that is informed, impactful, and attuned to local contexts.

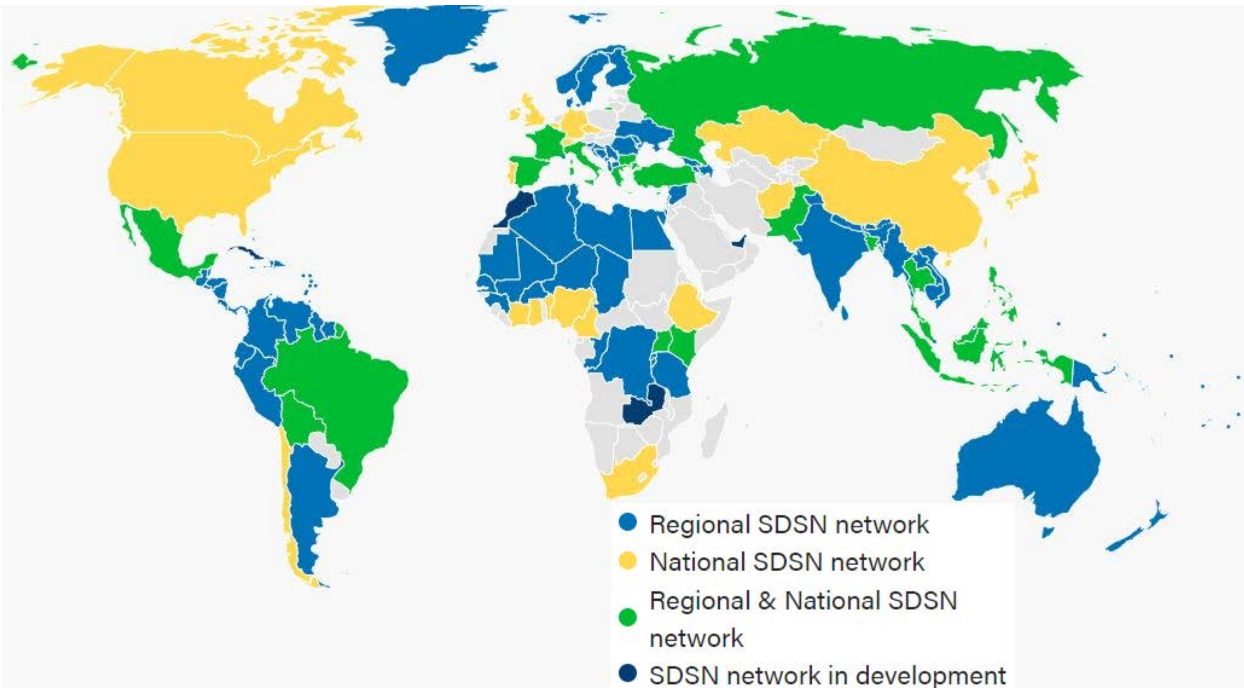

Figure 5. The GCH's 13 Regional Networks (Amazon, Andes, Australia-NZ-Pacific, Black Sea, Caribbean, Great Lakes, Mediterranean, Northern Europe, Sahel, South Asia, Southeast Asia, Western Balkans), including 42 National Networks within them, accounting over 1930 members. The networks under development include Cambodia, Cuba, DRC, Georgia, Morocco, Nepal, UAE, and Zambia. Source: [44]

The GHC has participated in research projects across most of the countries presented, while it has produced detailed assessments on sustainable pathways, and Sustainable Development reports for multiple regions, details on Europe's energy transition and optimum investment policies, supporting the European Union's 'Fit for 55' decarbonization targets[62]. In formulating viable net-zero pathways for land-use and agriculture, a major focus of the GCH's work so far has been to bridge the gap between land-use and the energy sector[45]. Furthermore, there has been extensive work on the sustainable transformation of shipping industry and ports, developing a strong coalition brings together 11 countries, 74 major shipping companies and members of civil society, making a clean break from the oil-derived sludge currently powering the world's largest vessels[63]. The Education-focused unit collaborates extensively with the SDG Academy[64], ensuring that educational programs align seamlessly with the essential transitions towards sustainability and digitalization. The partnership between AE4RIA and HUAWEI on the "Twin Skills for the Twin Transition: Defining Green Digital Skills and Jobs"[59] underscores our commitment to equipping current and future workforces with the skills required for the future jobs, 85% of which are projected to be new inventions. The GCH has also been part of the Lancet COVID-19 Commission on seizing the opportunity for a sustainable recovery[65]. A noteworthy accomplishment of the GCH is the refinement of the measurement of SDG performance at sub-national, regional, and corporate levels. Our Sustainable Development Reports have annually tracked progress on the SDGs since 2015. The GCH published in 2022 an assessment of Greece's SDGs achievements, identifying both leaders in sustainability efforts and the prevailing challenges to achieve all 17 SDGs[66]. The report, for the first time, shows that approximately 65 targets necessitate engagement at regional and local levels, emphasizing the crucial role of local stakeholders in the successful implementation of the SDGs. The GCH has developed a methodology for measuring SDGs performance at the corporate level, highlighting the influence of ESG on international equity returns and the alignment of financial asset portfolios with the SDGs[67].

Enhancing and expanding a global network for sustainable development

This article presented a global initiative to address multiple, complex, and interconnected challenges, with science-based and participatory approaches. For the first time we broke down the structure and operation of the GCH, analyzing its five innovations and nine units, which constitute a flexible and powerful approach for any sustainability problems, in any country/region.

A limitation of the present article is its very much high-level character and descriptive nature of complex concepts, due to the huge scientific space it should cover. The GCH's work includes multiple sciences, IAMs, sectors and countries, which has been applied and practiced over so many diverse contexts. So, it was impossible to choose and thoroughly showcase a certain example, within the limits of a paper. However, we believe that we provided a sufficiently detailed picture of the scope, the operation and structure of the GCH, along with the nature and logic of the main tools it can use, and the innovations/principles that make it uniquely successful.

Of course, we are continuously working on improvements of the processes and tools, trying to incorporate and exploit the benefits of new technologies. The present and future efforts of the GHC focus on the improvement of the integration of the modeling tools. For instance, we are carrying out extensive work on coupling multiple models such as BALMOREL, WEAP, FABLE, GLOBIOM, SeaMAPS, and ECM3, as well as with the valuation of non-marketed goods and services. Furthermore, there are efforts for increasing the efficiency of AI-supported geospatial and socio-economic data, in terms of data-gathering, processing, and visualizing. Currently, we are trying to fully transition to an 'open science' platform, making such data and models open access, aiming for direct model-running in the future, by any user.

Other future plans in terms of strategy and expansion are also underway. We have performed assessments and presented reports on sustainable pathways for EU-27, UK, the Balkans, and now we are extending to the Americas, Africa, and Asia/Pacific Region[44]. The future plans of the GCH are to leverage our approach at a global scale, first by homogenizing the modeling tools, then expanding them to these regions, and ultimately connect them to explore cooperative (region-wise) transition pathways. We hope to present a vision of the whole world at the next COP[68]. As mentioned in the introductory section, the GCH is open to other global and regional initiatives for tackling climate and other sustainability challenges, or IAM approaches, and welcomes all forms of collaboration.

The GCH offers to all its members an ongoing learning across the variety of disciplines and practical issues it touches. A key lesson from the GCH's experience so far is that while it is not easy to make changes and improvements in complex human-environmental and economic systems, it is doable, when there is scientific excellence, commitment and continuous engagement from local stakeholders, and open-minded cooperation among public and private actors. Most importantly, it is doable, when commonly-shared visions are developed based on solid scientific bases.

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